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Exhaust emission factors of greenhouse gases (GHGs) from European road vehicles

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Abstract

Background: Road transport is an important contributor to the European Union's total greenhouse gas emissions. This study aims at summarizing methane (CH₄) and nitrous oxide (N₂O) exhaust emissions from L-category, light-duty and heavy-duty vehicles in the European Union. The assessment is based on measurements carried out in the Vehicle Emission Laboratory of the Joint Research Centre between 2009 and 2019. The exhaust chemical composition from a fleet of 38 L-category vehicles Euro 1 to Euro 4 (2- and 3-wheelers, small quadricycles such as quads and minicars), 63 light-duty vehicles from Euro 5b to Euro 6d-TEMP (passenger cars, including hybrid vehicles), and 27 light commercial and heavy-duty vehicles from pre-Euro I to Euro VI (including lorries, buses and garbage trucks) was analyzed by Fourier-transform infrared spectroscopy.

Results: CH₄ emission factors monitored were from 1 to 234 mg/km for L-category vehicles (mean: 39 mg/km), from 0.1 to 40 mg/km for light-duty vehicles (mean: 7 mg/km), and from non-detectable to 320 mg/km for heavy-duty vehicles (mean: 19 mg/km). N₂O emission factors monitored were from non-detectable to 5 mg/km for L-category vehicles (mean: 1 mg/km), from non-detectable to 40 mg/km for light-duty vehicles (mean: 7 mg/km), and from non-detectable to 118 mg/km for heavy-duty vehicles (mean: 19 mg/km). According to the 100-year Global Warming Potential of these greenhouse gases, these emissions corresponded to a range from negligible up to 9 g/km of CO₂-equivalent for CH₄ and from negligible up to 32 g/km of CO₂-equivalent for N₂O.

Conclusions: The higher contributors of CH₄ were the two-stroke mopeds included in the L-category vehicles, while the higher emissions of N₂O were found in the modern (Euro 5–6 or Euro V–VI) diesel light- and heavy-duty vehicles. Among them, vehicles complying with Euro 6 and Euro VI standard were associated to higher N₂O emissions compared to those associated to Euro 5 and pre-Euro IV standards, which could be attributed to the introduction of the after-treatment systems designed to fulfill more stringent NO_x standards. These updated emission factors and unique on its kind database represent a source of information for legislators and modelers to better assess the greenhouse gas emission reduction in the EU transport sector.

Keywords: Greenhouse gases, CO₂, Methane, Nitrous oxide, On-road transport, Emission factors

Highlights

- Greenhouse gas emission factors from 128 L-category, light- and heavy-duty vehicles
- CH₄ emission factors ranged from 0 to 320 mg/km
- N₂O emissions ranged from 0 to 118 mg/km
- High CH₄ emissions from two-stroke mopeds included in the L-category vehicles
- High N₂O emissions from modern Euro6/EuroVI diesel light- and heavy-duty vehicles.

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Background

Methane (CH_4) and nitrous oxide (N_2O) are long-lived greenhouse gases (GHG), with atmospheric lifetimes of 12 and 121 years, respectively. Considering their radiative forcing, CH_4 and N_2O have a 100-year time horizon global warming potentials (GWP) of 28 and 265 CO_2 equivalent (CO_2 -eq), respectively [41]. Over the last 250 years (i.e. beginning of industrial revolution), CO_2 , CH_4 and N_2O global concentration in the atmosphere increased by 42%, 154% and 21%, respectively [5]. With an average growth of 9.4 ppb/year between 2014 and 2017, the increase of atmospheric CH_4 was speeding up during the last years [49]. Natural sources are the main contributors of global N_2O emission, with a rough estimate of 11 Tg N_2O -N/year [41]. However, with an emission rate of about 5.3 Tg N_2O -N/year, up to a third of the global N_2O emissions is most likely to be anthropogenic [13]. Industry sector and fossil fuel combustion are responsible of 15% of the N_2O anthropogenic emission [63]. With a share ranging from 50 to 60%, human activities are the main sources of global CH_4 emissions [7, 50]. In the European Union (EU), GHG emissions decreased in the majority of anthropogenic sectors between 1990 and 2014, however, road transport is still associated to the largest increase of CO_2 in this period with a growth of 124 MT, and 7 MT between 2013 and 2014 [28]. Moreover, 73% of the GHG emissions from transport sector in EU-28 came from the road sector in 2015, which represented ca. 19% of the total GHG emissions in the EU-28 [27].

Methane is a GHG and a precursor of tropospheric ozone. Together with other hydrocarbons, methane is released during incomplete combustion of fuel. CH_4 is particularly resistant to catalytic oxidation, and mostly associated to the cold start of the vehicles [45]. In a study carried out on light-duty vehicles equipped with a catalytic converter, it was found that catalyst light-off duration (e.g. time needed by the catalyst system to reach its required conversion efficiency) for methane was systematically longer than for the overall hydrocarbons [9]. Therefore, methane emission level from transport can be amplified when cold start events are repeated (e.g. over short trips), or lasting for an extended period (e.g. vehicle start up at low ambient temperature). CH_4 emissions are also associated to natural gas engines, for which the emission factors could exceed by a factor of 10 the emissions factor from conventional gasoline passenger cars [45, 48].

Nitrous oxide from transportation is formed during both, combustion and catalytic processes. Through fuel combustion, N_2O results from the gas-phase reactions of nitric oxide (NO) with either hydrogen cyanide (HCN) or ammonia (NH_3). Such process is, however, limited by the

concentration of the reactants in the exhaust, as well as the thermal stability of the N_2O generated in combustion conditions [38]. Modern catalytic converters for NO_x, CO and hydrocarbons removals have been associated with N_2O emissions ([37, 45, 67]). The widespread after-treatment system used nowadays for vehicle fueled with gasoline is the three-way catalyst (TWC). Such catalytic system removes pollutants in exhaust gas through oxidation of the CO and hydrocarbons and also by reduction of NO_x. However, the latter chemistry involved undesirable reactions between NO and nitrogen at the catalyst surface that results in N_2O formation [67]. In case of diesel fueled cars and trucks, a series of after-treatment systems were developed to tackle unwanted pollutants created from lean fuel combustion. The most commonly systems used are diesel oxidation catalyst (DOC), lean-NO_x trap/NO_x Storage Catalyst (LNT/NSC), and selective catalytic reduction (SCR). N_2O can be formed over a large range of chemical reactions, at different temperatures through chemistry involving ammonia (NH_3) as precursor. Extensive description of N_2O formation mechanism can be found in Guan et al. [37] and references therein.

Considering the importance of the transport sector in the global GHG emissions budget and the broad use of after-treatment systems (implemented to comply with the increasingly stringent emission standards), CH_4 and N_2O from mobile sources have been progressively regulated. In the United States, the Environmental Protection Agency (US-EPA) together with the National Highway Traffic Safety Administration (NHTSA) have set a regulation to control the GHG tailpipe emission from light-duty vehicles (LDV), with limits of 30 and 10 mg/mile for CH_4 and N_2O , respectively. The objective was to cap these emissions with standards aiming at avoiding future increase related to the implementation of new engines and technology. In addition, US-EPA also implemented a standard for heavy-duty engines, pick-up trucks and vans with a limit for N_2O of 0.10 g/bhp-h [29]. In China, through the China's stage 6 emission standard, a limit ranging from 20 to 30 mg/km was defined for tailpipe N_2O emission (to be applied from July 2020). In the EU, methane is directly regulated for the heavy-duty gas engines since the Euro III standard (in 2000) and the current limit is set to 0.5 g/kWh [22]. No specific CH_4 standard is defined for light-duty vehicles. However, methane is indirectly regulated through two limits set for total hydrocarbons (THC, 100 mg/km) and non-methane hydrocarbons (NMHC, 68 mg/km) starting from Euro 5 standard for gasoline LDV [24]. The same THC and NMHC limit values as those for light-duty vehicles are prescribed for L-category vehicles starting from the Euro 5 environmental step which be enforced from 2020 (Regulation EU 168/2013). A cost-benefit analysis to confirm

the measures of Regulation EU 168/2013 was performed in an environmental effect study carried out for the Euro 5 L-category step [19]. Regarding the N_2O , although the EU undertakes initiatives to promote clean and energy efficient vehicles (e.g. included in Horizon 2020 programme-[16, 23]), no standard is defined in the EU so far.

In the EU, Regulation (EU) 2019/631 is in force to encourage car manufacturers to contribute to the CO_2 reduction [14]. This regulatory text set mandatory fleet-average CO_2 emissions targets for passenger cars and light commercial vehicles, with a reduction phased in gradually over a period of time. While the overall target of the EU fleet-wide average emission for new cars is set to 95 g/km CO_2 from 2021, this target will be reduced further the subsequent years. In addition, this Regulation defined the Eco-innovation scheme which was set to encompass innovative technologies that contribute to CO_2 reduction but that cannot be assessed over the standard laboratory tests [20]. Through use of such technologies, a manufacturer can earn CO_2 credits of up to 7 g/km CO_2 , with a minimum reduction achieved by the innovative technology of at least 1 or 0.5 g/km CO_2 depending on the reference standard test procedure. This CO_2 credits are counted when calculating the EU overall target of the manufacturer. Regarding the heavy-duty vehicles, Regulation (EU) 20019/1242 defines CO_2 standards for average emissions, with a stepwise reduction of the targets from 2025 and 2030 [15].

GHGs emission factors from on-road transport are available in the literature, like from two-wheelers [8, 9, 69, 70], from passenger cars [3, 9, 32–34, 39, 40, 42, 44, 53, 66], and trucks and buses [2, 4, 31, 35, 36, 45, 46, 52, 59, 60]. However, most of these studies are based on either few vehicles, or vehicles complying with outdated emission standards. The novelty of this study is the presentation of current GHGs emissions factors measured from large fleet of vehicles belonging to the different vehicle categories. Vehicles complying with the latest emissions standards were investigated. The most important GHGs emissions, namely CH_4 , N_2O and CO_2 , have been estimated through experimental measurements of tailpipe emissions from a fleet composed of 128 in-service L-category, light-duty and heavy-duty vehicles tested between 2009 and 2019.

Materials and methods

Chassis dynamometer experiments

To assess GHG tailpipe emissions from on-road transportation, chassis dynamometer measurement campaigns were conducted at the European Commission Joint Research Centre (JRC) Ispra, Italy, in three Vehicle Emission Laboratories (VELA). The data were collected during 11 years from 2009 to 2019. The facility dedicated

to L-category vehicles emissions measurement was composed of a chassis dynamometer (one roller with 48" diameter, inertia range 150–3500 kg, Zoellner GmbH, Germany), a Constant Volume Sampler (CVS, flow rate range 1.5–11.25 m^3/min) with a critical flow venturi, and gas analyzer benches (CEB II and AMA i60 for the raw exhaust and for the dilution tunnel and bags, AVL, Graz, Austria). The facility dedicated to light-duty vehicles emissions measurement was composed of a chassis dynamometer (two rollers with 48" diameter, inertia range 454–4540 kg, MAHA Haldenwang, Germany), a Constant Volume Sampler (CVS, flow rate range 3–30 m^3/min) with a critical flow venturi, and gas analyzer benches (MEXA-7100 for the raw exhaust and MEXA-7400 for the dilution tunnel and bags, HORIBA, Japan). The facility dedicated to heavy-duty vehicles emissions measurement was composed of a chassis dynamometer (two rollers with 72" diameter, inertia range 800–30,000 kg, Zoellner GmbH, Germany), a Constant Volume Sampler (CVS, flow rate range 10–150 m^3/min) with four critical flow venturi, and gas analyzer benches (AMA i60 for both the raw exhaust and the dilution tunnel and bags, AVL, Graz, Austria). The exhaust flow rate was calculated using the difference between the total flow and the diluted flow rates and very often cross-checked with the CO_2 tracer method. A maximum 10% uncertainty was estimated [30]. A description of the experimental system is illustrated in Additional file 1: Figure S1.

The vehicles were tested at 22–25 °C, over their type-approval test cycles applicable in EU, and over their foreseen test cycles defined in the upcoming legislation that are considered more realistic. Thus, these GHG emission factors can better represent tailpipe emission reported so far for the in-service EU fleet. The L-cat were driven over the R47, R40 (according to Directive 2002/51/EC [25]) and the Worldwide harmonized Motorcycle Testing Cycle (WMTC stage 3—according to Regulation 134/2014 [18]). LDV were tested over the New European Driving Cycle (NEDC - according to Regulation No. 83 [62]) and the Worldwide harmonized Light vehicles Test Cycle (WLTC Class 3—according to Regulation 2017/1151 [17]). The HDV were tested over the chassis dynamometer version of the European Transient Cycle (ETC). Unlike the engine dynamometer version (Directive 1999/96/EC [26]), the ETC chassis version is not used for type approval testing. One Euro VI HDV was tested with the Worldwide Harmonized Vehicle Cycle (WHVC), which was developed based on the same set of data used for the development of the engine type approval Worldwide Harmonized Test Cycle (WHTC), the type approval cycle of Euro VI engines. Unlike the WHTC, the WHVC is not used for regulatory testing. In addition, tailpipe GHG emissions from several heavy-duty vehicles were

also monitored over on-road tests, and over laboratory test reproducing the on-road conditions (in-service conformity–ISC–cycle including vehicle speed and road slope). Driving cycles used in this study are illustrated in Additional file 1: Figure S2.

Vehicle fleet

Table 1 summarizes the main features of the 128 vehicles studied. The fleet was composed of 38 L-category vehicles (L-cat), including mopeds (category L1e), motorcycles (L3e), tricycles (L5e) and quadricycles (L6e–L7e), with engine capacity ranging from 30 to 1170 cm³, engine power from 0.5 to 92 kW, emission standard from Euro 1 to Euro 4. A substantial part of the L-cat was selected in the scope of the environmental effect study on the Euro 5 step of L-cat [68]. The fleet of light-duty vehicles (LDV) was composed of 63 vehicles equipped with positive and compression ignitions engines, as well as hybrids (gasoline), dual-fuel (Gasoline/Liquefied petroleum gas (LPG)) and flexi-fuel (running with up to 85% ethanol) vehicles. The LDV engine capacity ranged from 875 to 2996 cm³, engine power from 51 to 330 kW, and emission standards from Euro 5b to Euro 6d-TEMP. A large part of the LDV were selected in the scope of the EC-JRC contribution to the preparation of the European Union market surveillance of vehicle emissions, and more details on the selection procedure can be found in the corresponding reports ([10, 64]). The fleet of light commercial and heavy-duty vehicles (HDV hereinafter) was composed 4 light commercial and 23 heavy-duty vehicles, including semi-trailers, garbage trucks and buses. These vehicles were mostly equipped with compression ignitions engines. In addition, tailpipe emissions from one light commercial

vehicle and one truck equipped with dual-fuel engines using Compressed Natural Gas (CNG; CNG/Diesel), and one truck with dual-fuel engine using LPG (LPG/Diesel) were measured. The light commercial and heavy-duty vehicle engine capacity ranged from 1560 to 12,920 cm³, engine power from 73 to 368 kW, and emission standard from Pre-Euro I to Euro VI (from Euro 3 to Euro 6b for the 4 light commercial vehicles). Fuel used was market CNG (> 85% methane), LPG, diesel (B5 or B7) or gasoline fuel (E5 or E10), unless otherwise specified (E85).

A minimum of two tests were carried out for each combination of vehicle and cycles investigated. When two different driving cycles were carried out for one vehicle, the emission factors reported is the average of the mean emission factor obtained over each cycle. Values reported for dual-fuel vehicles were those recorded when CNG and LPG fuels were used. More technical details on the fleet as well as on the cycles used can be found in Additional file 1: Tables S1–S3.

Measuring equipment

N₂O and CH₄ measurement were carried out using Fourier-transform Infrared spectroscopy (FTIR) technique. For this scope, two FTIR instruments were connected to the raw exhaust at the vehicle tailpipe, using a heated polytetrafluoroethylene sampling line (191 °C). The first FTIR spectrometer (Nicolet Antaris IGS Analyzer-Thermo Electron Scientific Instruments LLC, Madison, WI, USA) was equipped with a multipath gas cell with 2 m of optical path, a downstream sampling pump (6.5 l min⁻¹ flowrate) and had the acquisition frequency of 1 Hz with a working pressure of 860 hPa. The second FTIR spectrometer (Multigas analyzer 2030-MKS,

Table 1 Summary of the vehicles tested

Category	Fuel	Number of vehicles tested	Min engine capacity (cm ³)	Max engine capacity (cm ³)	Min engine power (kW)	Max engine power (kW)
L-cat	Gasoline + oil	10	30	50	0.5	5
	Gasoline	24	50	1170	1.2	92
	Diesel	3	400	480	4	4.9
	Gasoline hybrid	1	278	–	18.2	–
LDV	Gasoline	26	875	1997	51	155
	Diesel	28	1248	2993	55	195
	Gasoline hybrid	5	1395	2996	73	330
	Dual-LPG	1	1368	–	88	–
	Flex-fuel (E85)	3	1596	1600	112	132
LCV and HDV	Diesel	24	1560	12,920	73	368
	Dual-LPG	1	12,920	–	340	–
	Dual-CNG	2	2999	3920	100	110

L-cat covers mopeds, motorcycles and quads. Light-duty vehicles (LDV) are passenger cars. Light commercial vehicles (LCV—4 in total) are included in the heavy-duty vehicles (HDV) category

Wilmington, MA, USA) was equipped with a multipath gas cell with 5.11 m of optical path, an upstream heated pump (10 l min⁻¹ flowrate) and had an acquisition frequency of 1 Hz with a working pressure of 1013 hPa. The two FTIR spectrometers were made up with a Michelson interferometer (spectral resolution: 0.5 cm⁻¹, spectral range: 600–3500 cm⁻¹) and a liquid nitrogen cooled mercury cadmium telluride detector. Results obtained with the two instruments were found in good agreement with the VELA results obtained following regulated measurement procedures (less than 10% differences for the commonly measured pollutants, like CO, CO₂, NO_x and CH₄). The FTIR spectrometers detection limits were 0.6 and 0.4 ppmv for CH₄ and N₂O, respectively. More details on FTIR technique as well as on the CH₄ and N₂O emission factor calculation can be found in the literature [8, 57]). The CO₂ measurement was conducted on bags sampling connected at the dilution tunnel, using non-dispersive infrared analyzer, following the requirements defined in EU Regulations [17, 18, 25, 62]. It has to be noted that CO₂ emission factors depend substantially on the road load simulated by the chassis dynamometer. In this study, a mix of tabulated road load values (defined in the Regulation [62]), and calculated road load values (using an approach derived from a JRC database of vehicles for which road loads were known and provided by Original Equipment Manufacturer (OEM)—more details can be found in [61]) were used. Finally, for LDV to be consistent with NEDC data, no correction was applied on the CO₂ emission factors obtained from WLTC (no correction based on the states of charge of the battery, or on the ambient temperature).

In addition to the descriptive statistics, statistical inferences were conducted to investigate the effect of engine technology and vehicle emission standard on GHGs emissions. For the hypothesis testing, multiple pairwise comparisons of each group were achieved. For the LDV, two different driving cycles were applied (NEDC and WLTC), the statistical inference was conducted only on the emissions obtained over the WLTC. This approach was adopted to avoid the driving cycle type to be a confounder in the inference analysis, as NEDC was only applied on LDV compliant with the Euro5b and Euro6b standard (Additional file 1: Table S2). Finally, as the requirements for one-way ANOVA test were not verifiable due to the low number of vehicles per group (non-normal distribution in each factor level), an alternative non-parametric method was applied (Kruskal–Wallis test—5% significance level). The statistical analysis was carried out with R software (version 3.3.2).

In “Results” section, the range of CH₄, N₂O and CO₂ tailpipe emissions are presented for the whole fleet of vehicle studied. Discussions on these emissions, and on

the effect of the fuel and engine technology are included in “Discussion” section.

Concluding, the chassis dynamometer measurements ensured well-controlled conditions for the instruments, and on the other hand, using realistic cycles (WMTC, WLTC) we believe that the emission factors are representative of the real on-road operation of the vehicles. This will be further discussed in “Comparison of data with the literature values” section.

Results

CH₄ emission factors

Methane emissions from the fleet of vehicles studied are presented in Fig. 1. The average emissions of CH₄ from the L-cat ranged from 3 to 109 mg/km (with one exception 232 mg/km). L-cat vehicles equipped with 2-stroke engines, mainly mopeds and one motor assisted bicycle (fueled with 50:1 vol/vol gasoline/lube oil mix—Veh. 1–10) displayed average CH₄ emissions ranging from 10 to 109 mg/km. These vehicles were complying with the Euro 1 and Euro 2 standards. Vehicles fueled with gasoline only (Veh. 11–30 and 34–38) displayed average CH₄ emissions ranging from 7 to 73 mg/km with one specific vehicle (Veh. 28) displaying substantially high levels of CH₄ emissions, 232 mg/km. This specific vehicle was a tampered high-performance motorcycle. As this study aimed at investigating the realistic GHG emissions from in-use vehicles, the value provided a good indication of what can be expected from the illegal practice of tampering L-cat vehicles to obtain more delivered power (results from this outlier vehicle were not taken into account in the further statistical analysis). One hybrid-gasoline L-cat vehicle was included in the fleet (Veh. 29), and tested in charge sustaining mode (i.e. using mostly the combustion engine). Not surprisingly, CH₄ emission of this vehicle was in the range of the emissions obtained with the L-cat fueled with gasoline only. Regarding the vehicles fueled with diesel (three commercial tricycles and light quadricycles—Veh. 31–33), the range of methane emission factors was relatively lower compared to the other L-cats, with a maximum emission factor of 5 mg/km.

Average methane emissions from the LDV ranged from < 1 to 40 mg/km, with gasoline and hybrid vehicles (tested in charge sustaining mode) emitting between < 1 and 10 mg/km, and diesel vehicles emitting between 2 and 40 mg/km. The three vehicles fueled with a mixture of gasoline with 85% v/v ethanol (E85) (Veh. 99–101) displayed CH₄ emissions from 9 to 20 mg/km, while the dual-fuel vehicle (Veh. 98) had an average CH₄ emission of 2 mg/km.

Methane emissions from 27 HDV, including four light commercial vehicles were up to 320 mg/km. Apart from three dual-fuel vehicles (two dual CNG—Veh. 105 and

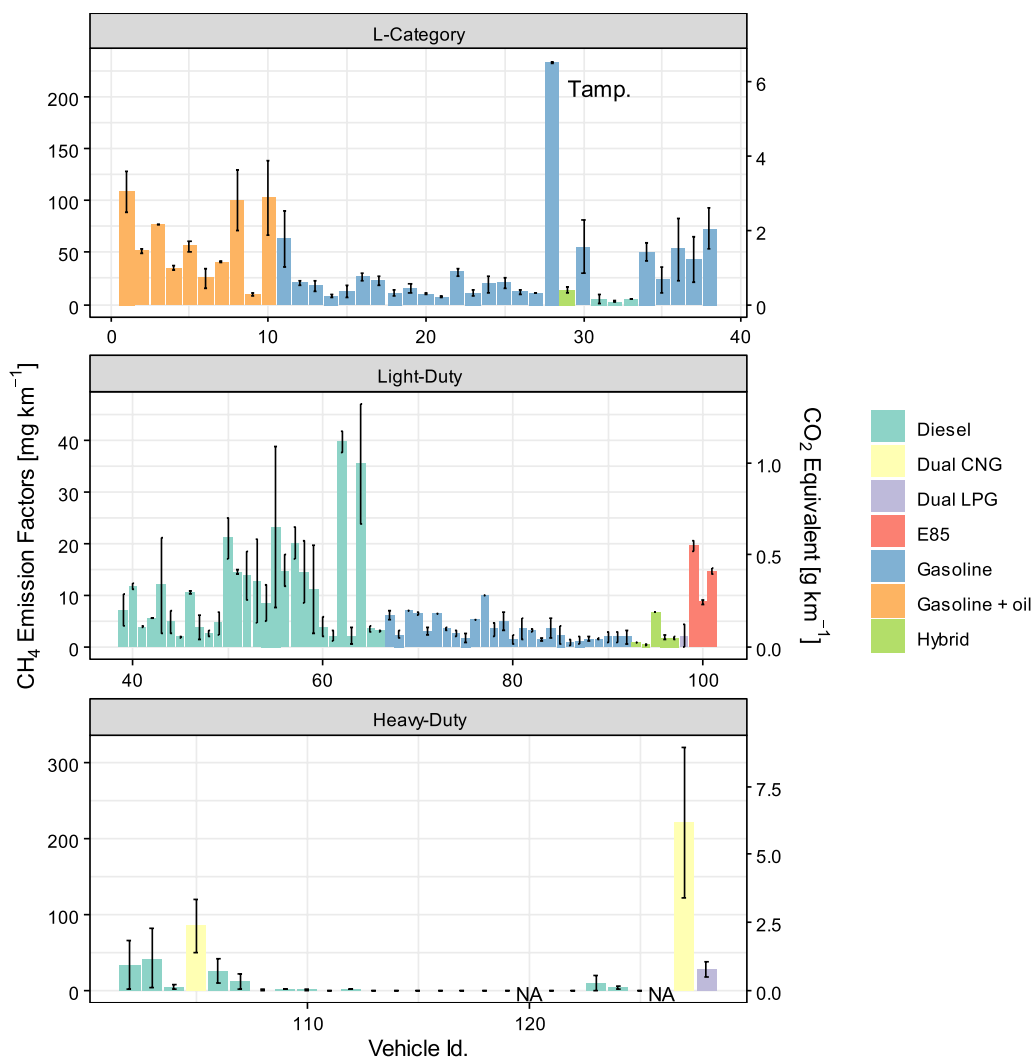


Fig. 1 Methane (CH₄) emission factors from L-category, light-duty and heavy-duty vehicles. “NA” stands for not available. Error bars stand for min and max values. “Hybrid” category includes hybrid-gasoline vehicles. Label “Tamp.” stands for tampered vehicle (Veh. 28)

127, one dual LPG–Veh. 128), all the HDV were equipped with a diesel compression ignition engine. All diesel vehicles were associated to CH₄ emission ranging from below the detection limit of the instruments to 42 mg/km. Dual-fuel LPG/diesel vehicle emitted 28 mg/km of CH₄. However, the dual-fuel CNG vehicles running with CNG were the highest emitter of CH₄, with tailpipe emission ranging from 50 to 120 mg/km, and from 122 to 319 mg/km for Veh. 105 (CNG/gasoline) and Veh. 127 (CNG/diesel), respectively. It has to be mentioned that two HDV vehicles Euro V and Euro VI (Veh. 120 and 126) were only tested on-road without instrumentation capable to measure CH₄.

N₂O emission factors

Nitrous oxide emissions from the fleet of vehicles studied are presented in Fig. 2. The average emissions of N₂O from the L-cat ranged from below the detection limit of the instruments to 4.5 mg/km. Two-stroke vehicles, fueled with a mixture of gasoline and lubricant oil (Veh. 1–10), displayed N₂O emissions mostly lower than 1 mg/km, apart from Veh. 9 which displayed on average 2.4 mg/km. Vehicles fueled with gasoline only (Veh. 11–30 and 34–38) and hybrid-gasoline vehicle (Veh. 29) displayed N₂O emissions ranging from 0.1 to 4.5 mg/km. The tampered vehicle (Veh. 28) displaying abnormally high level of CH₄ was not associated to equivalently high emission of N₂O (1.5 mg/km).

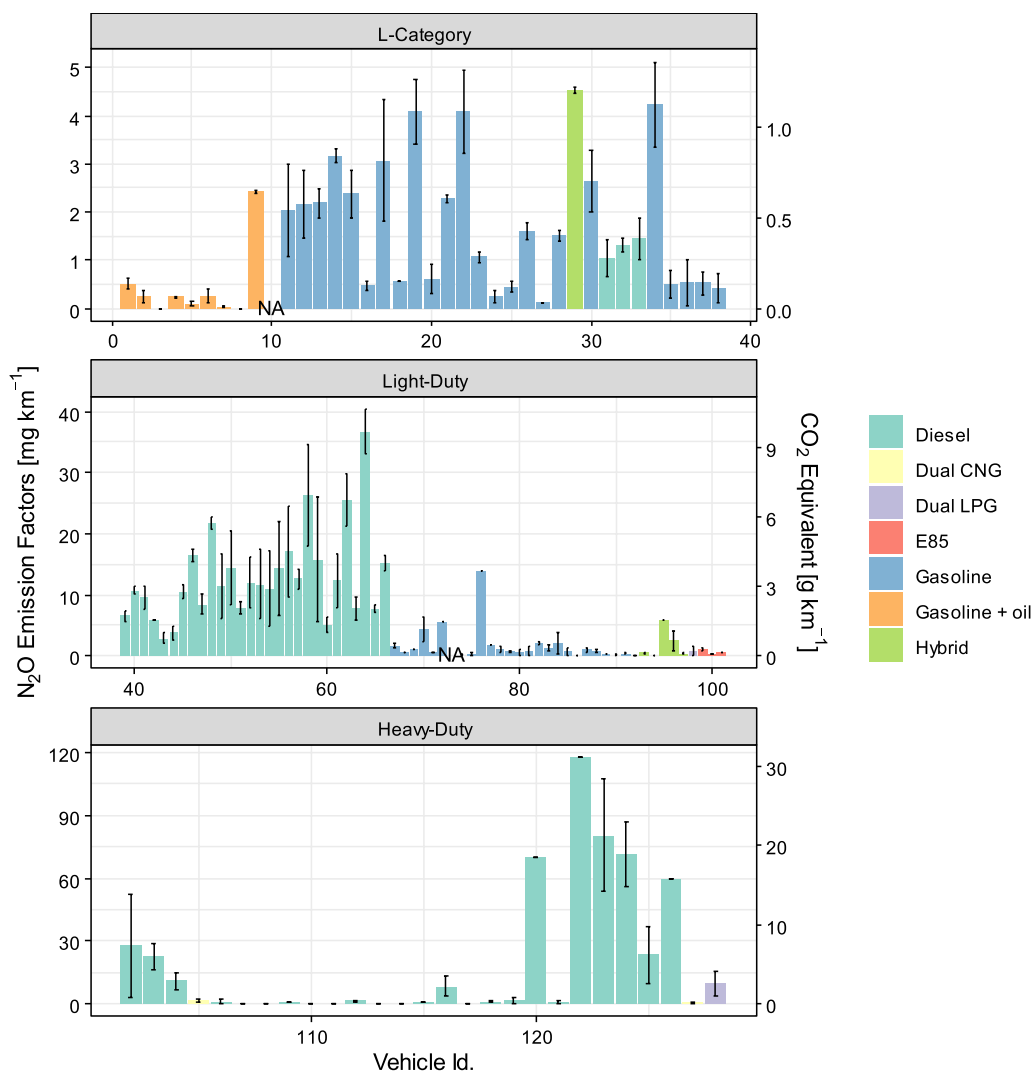


Fig. 2 Nitrous oxide (N₂O) emission factors from L-category, light-duty and heavy-duty vehicles. “NA” stands for not available. Error bars stand for min and max values. “Hybrid” category includes hybrid-gasoline vehicles

Regarding the vehicles fueled with diesel (Veh. 31–33), the average N₂O emissions were between 1 and 1.4 mg/km.

Nitrous oxide emissions from the LDV ranged from 0.1 to 37 mg/km, with gasoline and hybrid vehicles (tested in charge sustaining mode) emitting between 0.1 and 14 mg/km, and diesel vehicles emitting between 3 and 37 mg/km. The three vehicles fueled with a mixture of gasoline with E85 (Veh. 99–101) displayed slightly lower N₂O emissions compared to those from the gasoline vehicles, with values lower than 1.5 mg/km, while the dual-fuel LPG/gasoline vehicle (Veh. 98) had an average N₂O emission of 1 mg/km.

Nitrous oxide emissions from HDV ranged from below the detection limit of the instruments to up

to 118 mg/km. The distance-based N₂O emissions obtained with the dual-fuel LPG/diesel vehicle was 9.5 mg/km. The two CNG vehicles had average N₂O emissions of 1.4 and 0.4 mg/km (Veh. 105 and 127, respectively). It has to be noticed the significant N₂O emissions obtained from the two HDV vehicles Euro V and Euro VI tested on the road (Veh. 120 and 126), with values ranging from 60 to 70 mg/km. These results are presented in more details in the literature ([46]; [52]). For the HDV tested over ISC cycles (reproducing on-road cycles), no systematic difference was found on the N₂O emissions when compared with the results obtained with the standard laboratory driving cycle (ETC or WHVC).

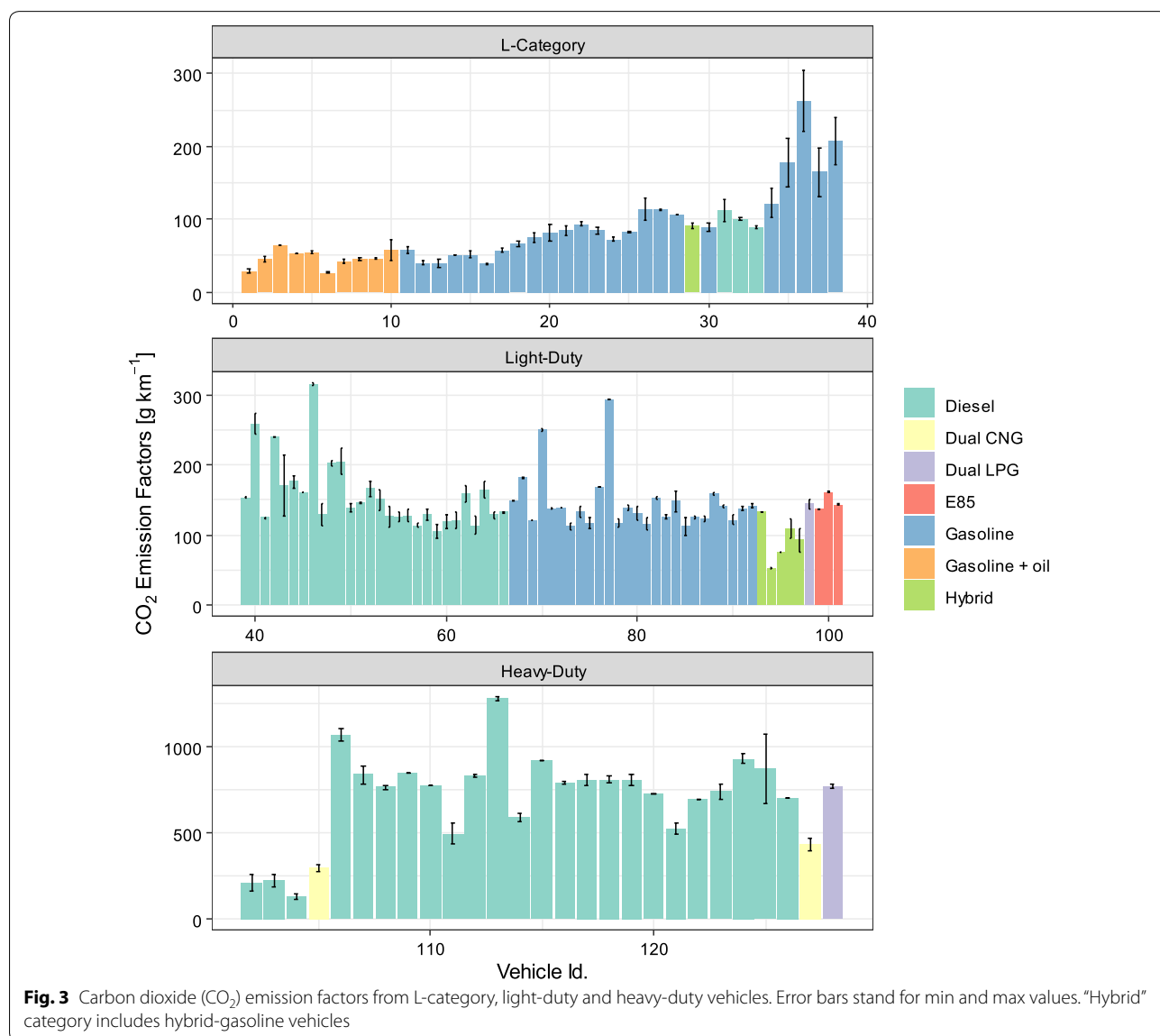
CO₂ emission factors

Carbon dioxide emissions from the studied fleet are presented in Fig. 3. The average emissions of CO₂ from the L-cat ranged from 27 to 263 g/km. Mopeds fueled with a mixture of gasoline and lubricant oil (Veh. 1–10) displayed CO₂ emissions from 27 to 64 g/km. Vehicles fueled with gasoline only (Veh. 11–30 and 34–38) and hybrid-gasoline vehicle (Veh. 29) displayed average CO₂ emissions ranging from 39 to 263 g/km, with the highest emitters among the heavy quadricycle and high-performance motorcycles. Regarding the vehicles fueled with diesel (Veh. 31–33), the CO₂ emissions ranged between 89 and 112 g/km.

Carbon dioxide emissions from the LDV ranged from 53 to 315 g/km, with gasoline emitting between 112 and 294 g/km, gasoline hybrid vehicles (tested in charge

sustaining mode) emitting between 53 and 133 g/km and diesel vehicles emitting between 105 and 315 g/km. Carbon dioxide emissions from the LDV ranged from 53 to 315 g/km (144 ± 41 g/km—mean \pm one standard deviation), with gasoline emitting between 112 and 294 g/km (143 ± 36 g/km), gasoline hybrid vehicles (tested in charge sustaining mode) emitting between 53 and 133 g/km (92 ± 30 g/km) and diesel vehicles emitting between 105 and 315 g/km (157 ± 48 g/km).

Although the average CO₂ emissions of diesel vehicles were higher relative to average CO₂ emissions of gasoline vehicles, it has to be noted that the characteristics of the vehicles included in the two groups were not comparable. For the diesel group, the average engine capacity was ca 2.0 l (with values ranging from 1.3 to 3.0 l), and the



average power was 110 kW (with values ranging from 55 to 195 kW). For the gasoline group, these values were lower compared to the diesel group, with average engine capacity of ca 1.3 l (with values ranging from 0.9 to 2 l), and the average power of 80 kW (with values ranging from 51 to 155 kW). More details on the CO₂ emissions of some of the LDV vehicles included here can be found in the literature [65]. The three vehicles fueled with a mixture of gasoline with 85% v/v ethanol (E85) (Veh. 99–101) displayed CO₂ emissions ranging from 137 and 162 g/km. Average CO₂ emissions from HDV ranged from 129 to up to 1300 g/km.

Discussion

Comparison of data with the literature values

Unlike regulated emissions, very few data related to the unregulated GHG emissions from L-cat are available in the literature. In particular, one high-performance motorcycle was a tampered vehicle (tailpipe replaced with an aftermarket sport one—Veh. 28). The effect of tampering on nine two-wheelers was investigated by Zardini et al. [70], and it was found that tampered vehicles were associated to an increase of factor of up to 27 for what regards hydrocarbons emissions, considering the original manufacturer configuration as a baseline. However, the effect of tampering was not visible on the N₂O emission of this vehicle. This finding is in good agreement with the study from Zardini et al. [70] where the effect of the removal of the two-way catalyst did not influence the emitted nitrogen containing species, but mostly THC and CO.

The large amount of CH₄ emitted by the Euro II dual-fuel CNG truck was in the same order of magnitude as the average CH₄ emissions from CNG vehicles reported in the extended study conducted by Dalianis et al. [12]. This level of emissions was also in good agreement with the emission factors from another study with a truck equipped with an Euro V compliant CNG engine (ca. 200 mg/km over equivalent chassis dynamometer tests) [36]. However, these values remained lower than the values from three urban buses equipped with CNG engine for which 6.3 g/km average CH₄ emission was reported [35]. These CH₄ emissions were also lower than the average emission reported by Thiruvengadam et al. [60] from three tractors equipped with natural gas engine and TWC (1.1 g/km).

Data related to the N₂O emission factors from modern LDV are also very scarce. Distance-based N₂O emission factors obtained for modern gasoline LDV (Euro 5 and Euro 6) were in good agreement with those obtained from a US type-approved super ultra-low emission vehicle (SULEV) compliant LDV, whose N₂O emission were found to be lower than 6 mg/km [3]. N₂O from the gasoline LDV measured were also found in the same order

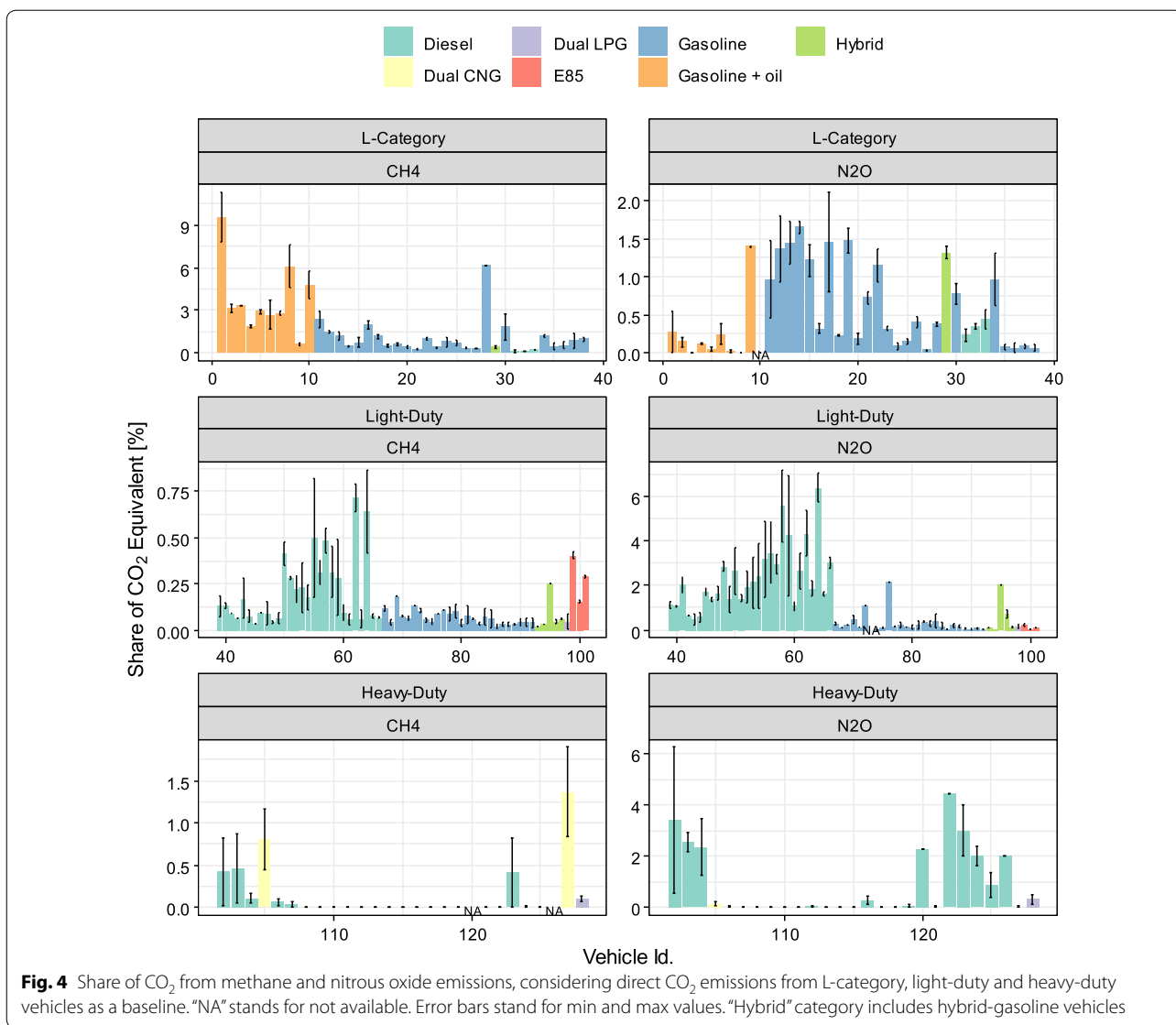
of magnitude compared to another studies, such as one on plug-in hybrid vehicle [53], and one including new and aged gasoline Tier 2 standard vehicles analyzed at the Environmental Canada and California Air Resources Board between 2001 and 2007 [34]. However, the same study reported average values of 4 and 6 mg/km for diesel vehicles complying with Euro 3 and Euro 4 standards, respectively, thus substantially lower than values reported for Euro 5 and Euro 6 diesel LDV included in the present study. Lang et al. [44] reported N₂O distance-based emission factors from gasoline LDV within a range from 45 to 21 mg/km, decreasing with the increase of the standard stringency. N₂O from four diesel Euro 6b vehicles (station wagon and van) were reported with values of up to 7 mg/km and 1 mg/km for vehicles tested in laboratory and on-road, respectively [66]. In a study from Giechaskiel et al. [33], it was found that retrofitting a Euro 5b vehicle with a SCR system increased the N₂O emissions on average about 16 mg/km, which represented 2–3 times higher emissions compared to the values obtained with the same non-retrofitted vehicle.

In the data reported by Thiruvengadam et al. [60], N₂O emissions from 2 US-EPA 2010 emissions compliant trucks without SCR system were found ranging from 23 to 38 mg/km, thus in line with the data reported for the Euro VI HDV of this study. In the study carried out by Graham et al. [35], two diesel heavy-duty vehicles certified under the California 2004 Tier 1 emission standards were tested in diesel and LPG configurations. Nitrous oxide emissions obtained from the LPG mode was found in a slightly higher level compared with this study, with an average of 20 mg/km. However, with an average of 14 mg/km, emissions from the two heavy-duty vehicles tested in the study of Graham et al. were found in the same range of those from the Euro V HDV included in this study.

Impact of GHG emissions on CO₂-related policy

Considering the GWP defined by the IPCC, it was found that the reported CH₄ and N₂O tailpipe emissions from the transport sector may reach up to 32 g/km of CO₂-equivalent (CO₂-eq.g—Figs. 1 and 2, right scales). While the methane emissions were in order of magnitude of up to few CO₂-eq.g for the L-cat and the HDV fueled with CNG, the nitrous oxide emissions ranged from few CO₂-eq.g to up to several tens of CO₂-eq.g for the diesel LDV and HDV, respectively.

The CO₂-eq.g from CH₄ and N₂O emissions expressed in share, considering the tailpipe CO₂ emissions of the vehicles as a baseline, are presented in Fig. 4. Among all vehicles tested, the highest level of CO₂-eq.g derived from methane was found for two-stroke L-cat (range from 0.5 to 11% of the tailpipe CO₂ emitted), gasoline



L-cat (range from 0.2 to 3% of the tailpipe CO₂ emitted—tampered Veh. 28 excluded) and for two HDV (Veh. 105 and 127 fueled with CNG: from 1 to 2%). The range of the share of CO₂-eq.g from methane measured for the LDV was in line with data from older vehicles available in the literature [47]. Regarding the CO₂-eq.g derived from nitrous oxide, the highest shares were observed for L-cat with the gasoline and gasoline hybrid vehicles (range from less than 0.1 to 2%). However, as regards LDV and HDV, the highest shares of CO₂-eq.g from nitrous oxide were associated to diesel vehicles, with range from 0.2 to 7.2% (LDV) and from less than 0.1 to 6.3% (HDV).

On average, modern LDV included in this study displayed N₂O emissions equivalent to 1.8 CO₂-eq.g, with some diesel LDV vehicles displaying more than 6 CO₂-eq.g. This level of emission was well above the

threshold of 1 g/km CO₂ defined in e.g. Eco-innovation scheme ([20]—see also “Background” section). Consequently, by taking out of the account current GHG emissions like N₂O, such efforts implemented to reduce tailpipe CO₂ emission from LDV might be jeopardized.

Effect of the fuel and engine technology on CH₄ and N₂O emissions from L-cat and LDV

Table 2 presents the CH₄ and N₂O median emissions of the vehicle studied. The relationship between fuel/engine technologies and GHGs tailpipe emissions of L-cat and LDV were investigated through multiple group comparisons. This statistical analysis was not carried out on the HDV as only three non-diesel vehicles were tested. Figure 5a displays the CH₄ and N₂O tailpipe emissions for the L-cat vehicles fueled with diesel, gasoline

Table 2 Summary of the median emissions of CH₄ and N₂O from the vehicles tested

Category	Fuel	Standard	Number of vehicles tested	CH ₄ (mg/km)	N ₂ O (mg/km)	
L-cat	Gasoline + oil	Euro 1/2	10	53.6	0.2	
	Gasoline	Euro 2/3/4	23	20.7	1.6	
	Diesel	Euro 2	3	5.0	1.3	
	Gasoline hybrid	Euro 3	1	13.7	4.5	
LDV	Gasoline	Euro 5	2	4.8	3.1	
		Euro 6b/c	13	3.2	0.9	
		Euro 6d-TEMP	7	1.7	0.3	
	Diesel	Euro 5	2	3.6	6.2	
		Euro 6b/c	16	10.3	13.5	
		Euro 6d-TEMP	5	3.6	15.2	
		Gasoline hybrid	Euro 5	2	0.8	0.3
	LCV and HDV	Flex-fuel (E85)	Euro 6b	2	4.5	3.2
			Euro 5	3	14.7	0.5
		Dual-LPG/Gasoline	Euro 5	3	14.7	0.5
Euro 6b			1	2.3	0.9	
Diesel		Euro 3 ^(*)	1	33.4	27.9	
		Euro 6b ^(*)	2	23.6	16.8	
		Dual-CNG/Gasoline	Euro 6b ^(*)	1	84.8	1.4
	Pre-Euro I	1	25.8	1.1		
	Euro II	5	1.6	<0.1		
Dual-LPG/Diesel	Euro III	1	0.3	<0.1		
	Euro IV	1	2.4	1.3		
	Euro V	10	0.1	0.8		
	Euro VI	5	1.8	71.4		
	Dual-LPG/Diesel	Euro V	1	27.9	9.5	
	Dual-CNG/Diesel	Euro II	1	220.8	0.4	

^(*) Light commercial vehicles (4 in total) are included in the HDV category. For the LDV, results were calculated from the WLTC only. "Hybrid" category includes hybrid-gasoline vehicles

and gasoline with lubricant oil (2-stroke mopeds with 25 km/h or 45 km/h maximum speed, belonging to the L1e sub-category). For the hypothesis testing, multiple pairwise comparisons of each group were achieved. As discussed before, the tampered L-cat with Id.28 was removed prior to the analysis.

The median emissions of CH₄ were 5.0, 20.7 and 53.6 mg/km for L-cat fueled with diesel, gasoline and gasoline with oil, respectively (Table 2, Fig. 5a-left panel). It was found that vehicles fueled with gasoline and lubricant oil (two-stroke mopeds) emitted significantly more CH₄ than the vehicles fueled with gasoline only and diesel (*p* value of 0.007 and 0.007, respectively). The difference was confirmed also by comparing mopeds only. The unburnt lubricant significantly contributed to higher CH₄ (and THC). Comparing mopeds and the rest vehicles, the high CH₄ of moped might be explained by the less sophisticated after-treatment system installed on them compared to the one installed on the other category of L-cat gasoline vehicles. In addition, the vehicles fueled with only gasoline (four-stroke mopeds, light

to high-performance motorcycles, and quadricycles) emitted significantly more CH₄ compared to the vehicle fueled with diesel (commercial tricycles and light quadrimobiles) (*p* value = 0.0008). The lower engine out emissions and the presence of a DOC on two of the three diesel vehicles might explain this trend. However, it has to be kept in mind that the sample size of L-cat diesel vehicles was very small (only three vehicles—Additional file 1: Table S1).

For what concerns the N₂O emissions of L-cat, the median emissions were 1.3, 1.6 and 0.2 mg/km for vehicles fueled with diesel, gasoline and gasoline with oil, respectively (Table 2, Fig. 5a-right panel). It was found that vehicles fueled with gasoline emitted significantly more N₂O than the vehicles fueled with gasoline and lubricant oil (*p* value = 0.0014). This difference was confirmed also when comparing only mopeds with and without lubricant at the fuel. This trend could be explained by due to the presence of TWC among the vehicles fueled with gasoline. However, the absolute levels and

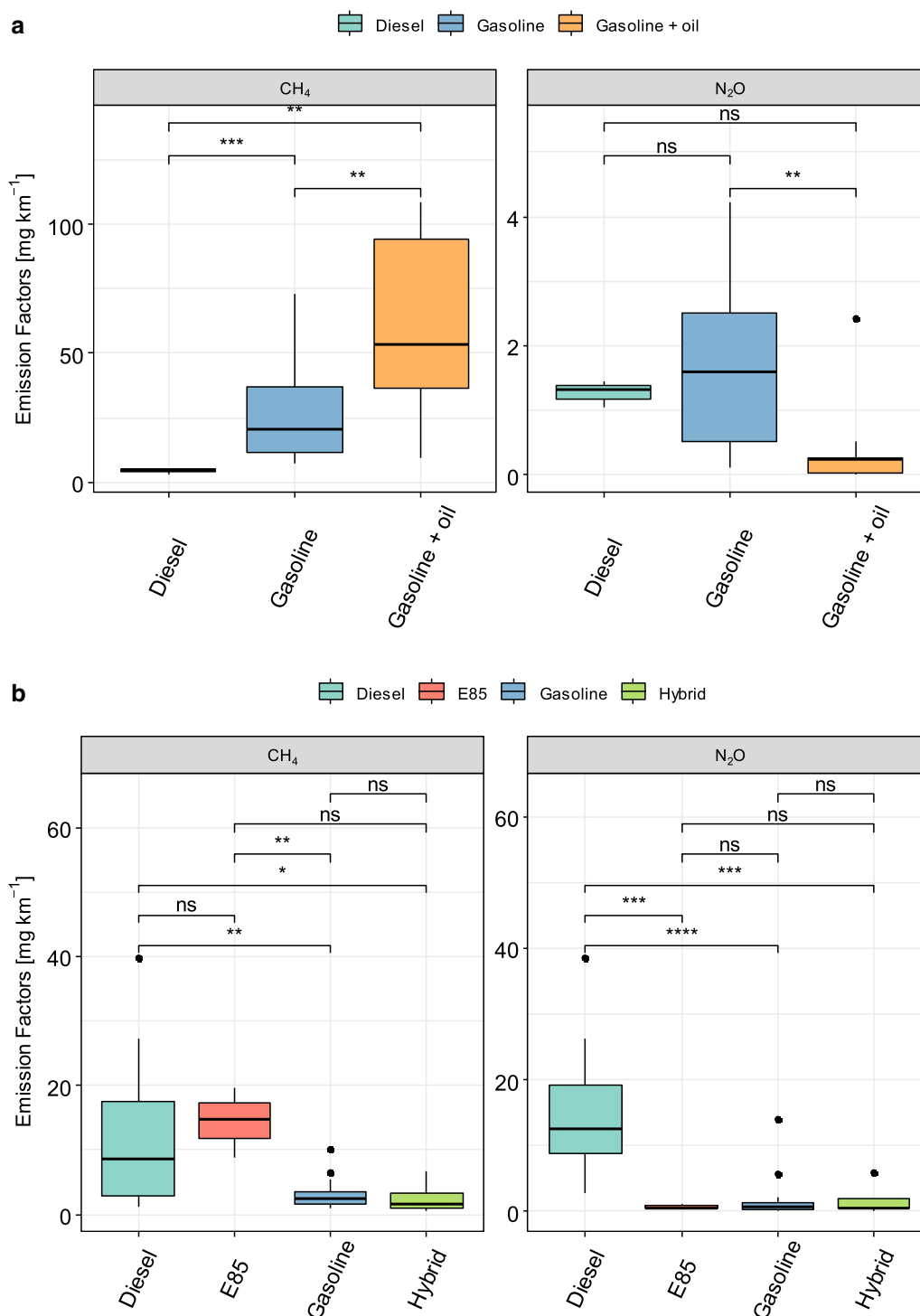


Fig. 5 Effect of fuel/engine technology on the CH₄ and N₂O average emissions from L-category (top panels-a) and light-duty (bottom panels-b) vehicles. "Hybrid" category includes hybrid-gasoline vehicles. Kruskal–Wallis statistical test with ns: $p > 0.05$, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, **** $p \leq 0.0001$

differences were very low (< 2 mg/km). No significant difference was found for the other comparisons.

The latest legislative development related to the L-cat included the revision of type approval of mopeds and motorcycles, with the implementation of the Euro 4 (enforced period 2016-2018) and Euro 5 (being mandatory for new types of vehicles as of January 2020) standards. With lower emission limits, and more realistic driving cycles, the effect of the proposed standards on the tailpipe emissions of GHGs from L-cat may be substantial. The two-stroke mopeds (fueled with mixture of gasoline and lubricant oil) will have to undertake a significant effort to shift to the new regulated limits [11]. The upcoming Euro 5 standard will probably be associated with a larger share of four-stroke and a net decrease of the two-stroke mopeds (fueled with gasoline and lubricant oil) for which it will be technically challenging, and not economically convenient, to comply with the new limits. Consequently, with the implementation of the new standard, it can be expected a substantial reduction of the CH_4 emissions emitted by the L1e vehicles. However, considering that the total fleet of L-cat in EU was composed of ca. 14 M of mopeds (L1e) in 2015, with a share of 2% of new registration per year (320,000 new vehicles in 2016 according to the European Association of Motorcycle Manufacturers [1]), the effect of the Euro 5 standard on the CH_4 emissions from L-cat will be visible in several years from now.

The relationship between fuel/engine technology and GHG tailpipe emissions from LDV is presented in Fig. 5B. The median emissions of CH_4 were 14.7, 8.5, 2.4 and 1.6 mg/km for LDV fueled with E85, diesel, gasoline and for the hybrid vehicles, respectively. Vehicles fueled with diesel emitted significantly more CH_4 than the vehicles fueled with gasoline and the hybrid vehicles (p value of 0.003 and 0.03, respectively). This finding, in connection with the after-treatment devices, is discussed later in this section. In addition, the flex-fuel vehicles fueled with E85 emitted significantly more CH_4 compared to the vehicle fueled with gasoline (p value = 0.002). Higher methane emission from relatively old flex-fuel vehicles (Tier 0 US standard) was already reported in the literature [43]. In addition, chassis dynamometer studies on a Euro 4 and Euro 5 flex-fuel vehicles, reported also more CH_4 emissions when fuel with 85% ethanol was used [9, 51, 56, 58]. As explained in that study, CH_4 emissions were highly related to the cold start of the vehicles (together with unburned hydrocarbons), and fuel with high ethanol content may produce more water at the catalyst surface, making CH_4 oxidation difficult. These two facts may explain a longer period before catalyst light-off, and thus, the greater methane emissions observed with E85 compared to gasoline fuel.

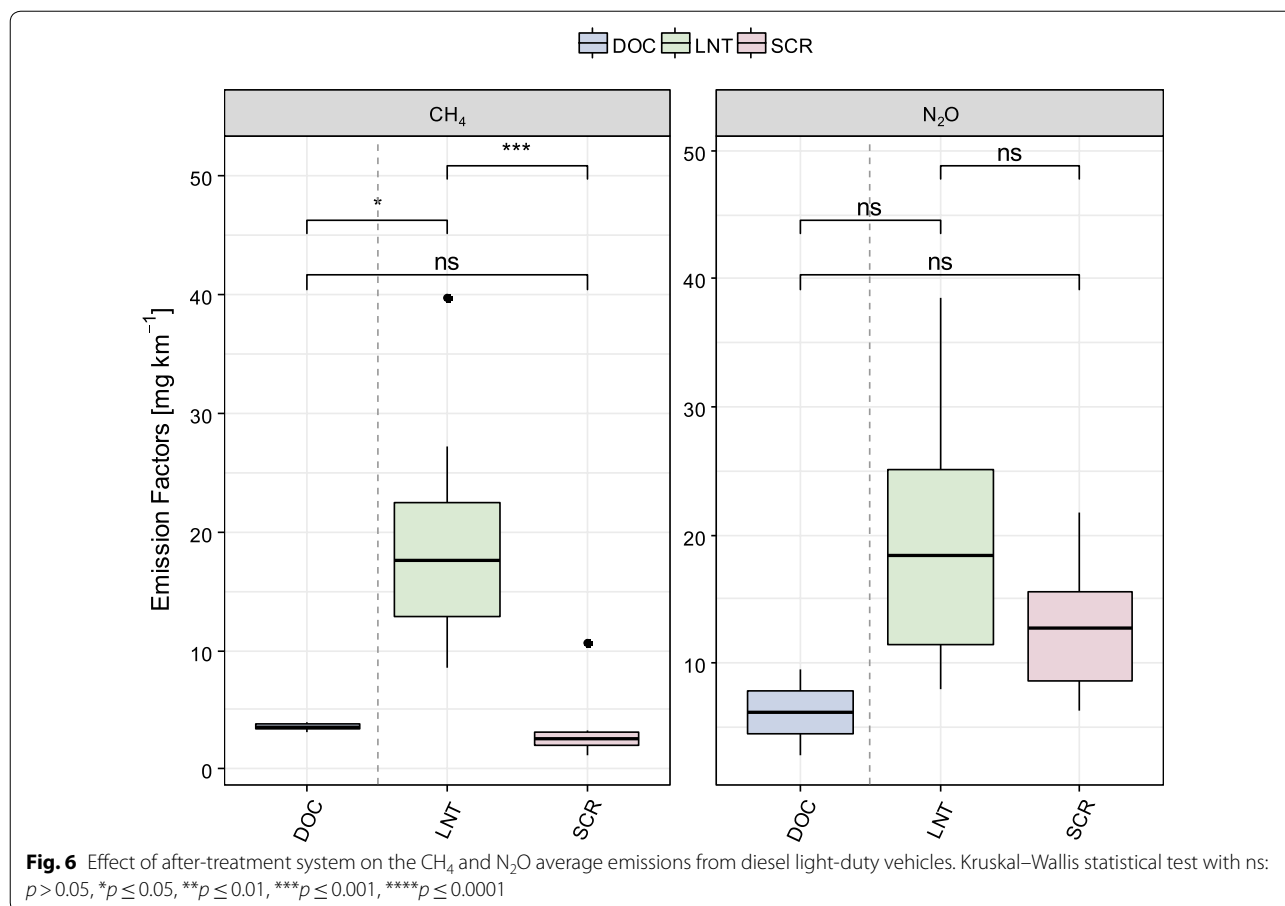
Median emissions of N_2O were 12.6, 0.7, 0.5 and 0.5 mg/km for LDV fueled with diesel, gasoline, E85 and for the hybrid vehicles, respectively (Fig. 5b). It was found that vehicles fueled with diesel emitted significantly more N_2O than the vehicles fueled with gasoline, E85 and the hybrid vehicles (p value of $4 \cdot 10^{-10}$, 0.0008 and 0.0002, respectively). These findings are consistent with the results obtained over on-road tests where N_2O emissions from two LDV gasoline were found non-detectable while two LDV diesel where emitting up to 27 mg/km [54]. High N_2O emissions from diesel fueled LDV (ca. 20 times more than gasoline fueled LDV) were investigated more in details considering the type of catalyst implemented on diesel vehicles (see Additional file 1: Table S2).

Figure 6 presents the effect of after-treatment systems on the Diesel LDV GHG emissions. In terms of CH_4 tailpipe emissions, Euro 6 vehicles equipped with LNT/NSC systems emitted significantly more than Euro 6 vehicles equipped with SCR only (p value = 0.0002), as well as than Euro 5 vehicles equipped with DOC only (p value = 0.03). Such differences might be explained by the operational principle of the LNT/NSC systems which work as active NO_x absorbers. These systems store NO_x during lean air-to-fuel ratio operation of the vehicles. Then, through brief regenerating periods, NO_x is released and catalytically reduced to nitrogen during rich air-to-fuel ratio. Such regenerating periods are more prone to release CO and hydrocarbons (including CH_4) and could explain the higher CH_4 emissions associated to LNT/NSC systems.

In terms of N_2O tailpipe emissions, it appeared that vehicles equipped with LNT/NSC or SCR after-treatment systems were associated to more emissions than Euro 5 ones equipped with DOC, as well as Euro 6 ones equipped with SCR only (18.4, 6.2 and 12.8 mg/km, respectively). However, these differences were not found significant according to the statistical test applied (p value > 0.05). The statistical inferences were based on a small sample composed of 20 vehicles, but these findings can be considered as a good insight of the effect of after-treatment systems on the GHG emissions.

Trend along with emission standards

Table 2 and Fig. 7a present the relationship between the emission standard and the CH_4 and N_2O emissions from LDV. On the tailpipe methane emissions, for diesel, gasoline and hybrid vehicles, no significant effect was found for the shifting from Euro 5 to Euro 6b standards. Regarding the shifting from Euro 6b to Euro 6d-TEMP standards, only a significant reduction of the CH_4 emissions of the gasoline vehicles was found (p value: 0.03). Regarding the N_2O tailpipe emissions, no statistically significant difference was found on the diesel, gasoline and hybrid



vehicles, with the shift from the Euro 5 to the Euro 6b, and neither with the shift from the Euro 6b to the Euro 6d-Temp. However, for the diesel vehicles, it appeared that the median emissions of N₂O tended to increase together with the standard (median emissions of 6.2, 13.5 and 15.2 for Euro 5b, Euro 6b and Euro 6d-TEMP, respectively). For diesel LDV, transition from Euro 5 to Euro 6 standard came together with a sharp reduction of the NO_x standard (from 180 to 80 mg/km, respectively). To comply with this more stringent limit, existing technology designed to reduce NO_x engine out emission, like the exhaust gas recirculation (EGR), has to be complemented with additional one, such as LNT/NSC and SCR. As described in the previous section, these after-treatment technologies were associated to higher N₂O emission compared to the technology implemented in Euro 5 (only DOC) [32, 33]. The same occurred for the HDV, where tailpipe N₂O emissions were found significantly higher for vehicles complying with Euro VI compared to those complying with Euro V standard (p value: 0.004, see Fig. 7b). Unlike for the LDV, it has to be noted that HDV were largely equipped with SCR after-treatment technology to comply with NO_x limit defined in Euro V

standard. The Euro VI defined emission limit of 10 ppm for NH₃, calculated as an average concentration obtained over the World Harmonized Transient Cycle (WHTC) and Steady-State Cycle (WHSC) for heavy-duty engines [21]. This provision together with a decrease of ca. 4–5-fold of the NO_x limits implied for HDV after-treatment a more intensive use of the SCR and also the complement with ammonia oxidation catalyst (AMOX). Veh. 126 included in this test fleet was a Euro VI compliant heavy-duty vehicle equipped with an AMOX. On-road N₂O emissions from this truck was already described by the authors in the literature [46]. In summary, this study showed that based on the Engine Control Unit (ECU) signals recorded, N₂O peak emissions were related to the injection of urea in the SCR. Association of substantial nitrous oxide emissions with the use of SCR after-treatment system in HDV was also reported in the test bench study from Borillo et al. [6]. In this test campaign, significantly greater N₂O emissions were associated to a Euro V engine equipped with and SCR after-treatment system, compared to the same engine with SCR disabled (44 mg/kWh and 13 mg/kWh, respectively). Substantial N₂O emissions from Euro V and Euro VI engines equipped

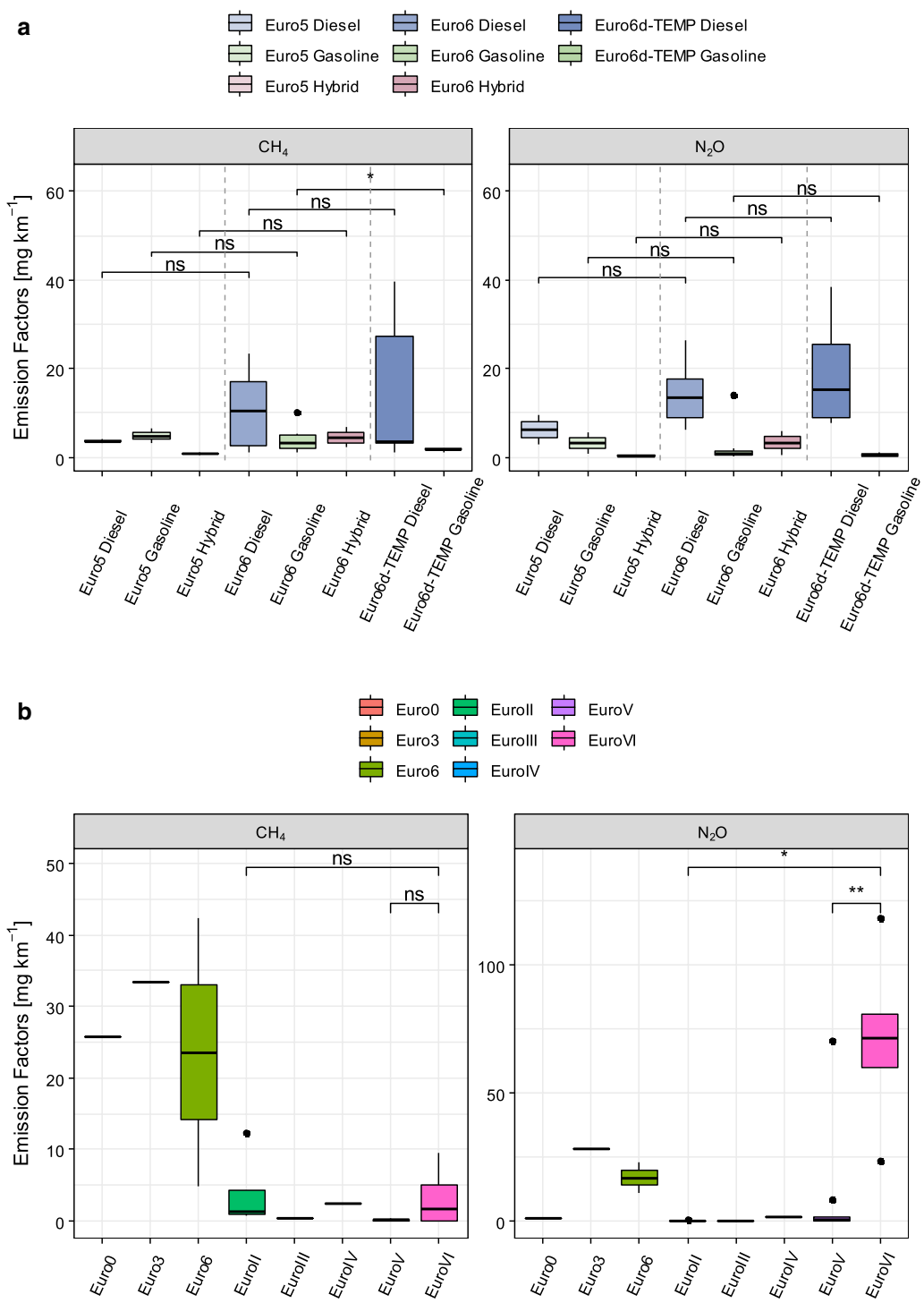


Fig. 7 Effect of Euro standards on the CH₄ and N₂O average emissions from light-duty (top panels-**a**) and diesel heavy-duty (bottom panels-**b**) vehicles. “Hybrid” category includes hybrid-gasoline vehicles. Horizontal lines stand for the unique values from group composed of one vehicle only. Kruskal–Wallis statistical test with ns: $p > 0.05$, * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, **** $p \leq 0.0001$

with SCR were also reported by Tadano et al.[59] and Giechaskiel et al.[31].

In the review from Wallington and Wiesen [67], the N₂O emissions from global transport were expected to decrease, with a projection of 0.064 Tg N₂O-N/year by 2030. According to this study, with such value on-road transport would contribute to 60% of the total N₂O emissions from global transport. However, that study assumed a decrease of emissions from light-duty vehicles together with the setting of new emission standards [67]. This projection was mostly based on the emission inventory from Graham et al., which included a majority of light-duty gasoline vehicles, belonging to standards up to Euro 4 [34]. Figure 8 gives a picture of the share of CO₂, N₂O and CH₄ emissions in the total GHG emissions

of the fleet studied. The shares were calculated based on the total CO₂-eq.g from these three compounds. Considering the findings from our study, and assuming a global implementation of the latest after-treatment technologies, it is likely that the contribution from on-road transport will increase to reach significantly more the 60% of the total N₂O emissions from global transport by 2030 reported by Wallington and Wiesen [67]. In addition, this trend is not expected to change in coming years with the introduction of Worldwide harmonized Light vehicles Test Procedure (WLTP) and the complementary Real-Driving Emissions (RDE) test. The major revision of EU legislation on the type approval of light-duty vehicles may likely be associated with both a broader implementation, and a more intensive use of modern after-treatment

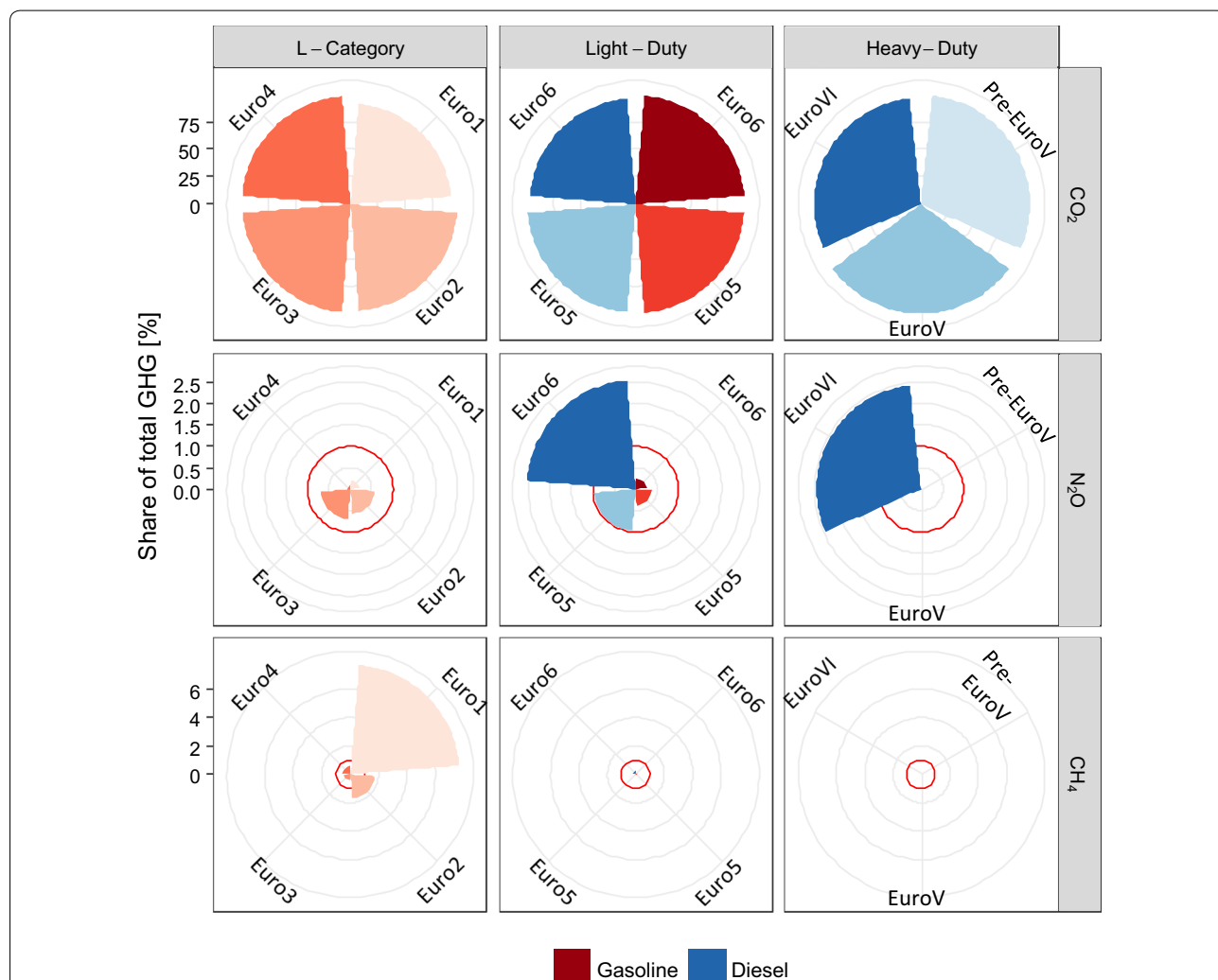


Fig. 8 Share of CO₂, N₂O and CH₄ emissions, considering the total GHG emissions from L-category, light-duty and heavy-duty vehicles as a baseline. The facets present the share of each GHG (CO₂, N₂O and CH₄) in the total GHG associated to the vehicle category and standard, and the scale is shown on the left. Diesel L-category as well as dual fuel heavy-duty vehicles are excluded. As a help to the eyes, 1% is represented with a red circle

system (higher urea injection flow, more frequent LNT/NSC regeneration) so that diesel light-duty vehicles will be able to comply with the more stringent NO_x standards [52, 55, 65]. In such context and without setting a standard on the tailpipe N₂O emissions from diesel LDV and HDV vehicles, the regulation defined to reduce GHG emissions from on-road transportation will have lower impact on climate change mitigation.

Conclusions

Greenhouse gas emissions from on-road transport were measured from 128 vehicles from 2009 to 2019. This unique database covered vehicles of different technologies and standards closing the gap in the literature. CH₄ average emissions were 39, 7.4 and 19 mg/km for L-category, light- and heavy-duty vehicles, respectively, with a range between negligible to 320 mg/km. 2-strokers mopeds and a truck dual-fuel CNG appeared to be the largest emitters in their vehicle categories (median emissions of 54 and 221 mg/km, respectively). However, tailpipe emissions of CH₄ from two-wheelers are expected to decrease in EU with the introduction of stringent THC limits in the new legislation concerning type approval of mopeds and motorcycles, with the Euro 5 being mandatory by 2020. Light-duty diesel and gasoline vehicles emitted on average 11 mg/km and 4 mg/km, respectively. Statistical analysis showed that LNT equipped diesel vehicles emitted more than SCR or only DOC equipped vehicles. N₂O average emissions were 1.4, 6.7 and 19 mg/km for L-category, light- and heavy-duty vehicles, respectively, with a range between negligible to 118 mg/km. The highest N₂O emission factors were associated to the modern diesel light (mean 13 mg/km) and heavy-duty vehicles (mean 19 mg/km). This trend was found to increase together with the emissions standards (Euro 5 to Euro 6 and Euro V to Euro VI). The implementation of sophisticated after-treatment system such as LNT/NSC and SCR is most likely to be the cause of such a shift. The implementation of the Euro 6d-TEMP (mandatory for new type approval since September 2017) for light-duty vehicle includes a new driving cycle (WLTC), and Real Driving Emission tests that may be associated with a more intensive use of after-treatment systems. In this context, N₂O emissions can be expected to further increase. Consequently, without setting a standard on the tailpipe N₂O emissions from light- and heavy-duty vehicles, the regulation defined to reduce GHG emissions from on-road transportation might be incomplete.

Supplementary information

Supplementary information accompanies this paper at <https://doi.org/10.1186/s12302-020-00407-5>.

Additional file 1. Supplementary Material

Abbreviations

AMOX: Ammonia oxidation catalyst; ANOVA: Analysis of variance; CNG: Compressed natural gas; CVS: Constant Volume Sampler; DOC: Diesel oxidation catalyst; ECU: Engine Control Unit; ETC: European Transient Cycle; EU: European Union; FTIR: Fourier-transform infrared spectroscopy; GHG: Greenhouse gases; GWP: Global warming potential; HDV: Light commercial and heavy-duty vehicles; JRC: Joint Research Centre; L-cat: L-category vehicles; LCV: Light commercial vehicles; LDV: Light-duty vehicles; LNT: Lean-NO_x trap; LPG: Liquefied petroleum gas; NEDC: New European Driving Cycle; NMHC: Non-methane hydrocarbons; NSC: NO_x Storage Catalyst; OEM: Original Equipment Manufacturer; RDE: Real-Driving Emissions; SCR: Selective catalytic reduction; SULEV: Super ultra-low emission vehicle (SULEV); THC: Total hydrocarbons; VELA: Vehicle Emission Laboratories; WHTC: Worldwide Harmonized Test Cycle; WHVC: Worldwide Harmonized Vehicle Cycle; WLTC: Worldwide harmonized Light vehicles Test Cycle; WLTP: Worldwide harmonized Light vehicles Test Procedure; WMTC: Worldwide harmonized Motorcycle Testing Cycle.

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Disclaimer

The opinions expressed in this study are those of the authors and should in not be considered to represent an official opinion of the European Commission.

Authors' contributions

The study was designed by MC, BC and CA. MC followed the testing, processed the data and conducted the statistical analysis. AZ, RS, JP and VV helped in post-processing FTIR data. MC drafted the original manuscript. BG, AZ, RS, JP and VV, reviewed original manuscript and contributed on specific aspects. All authors read and approved the final manuscript.

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Consent for publication

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Competing interests

The authors declare that they have no competing interests.

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