Emission characterization of in-use Diesel and gasoline Euro 4 to Euro 6 passenger cars tested on chassis dynamometer bench and emission model assessment

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Abstract

This paper focuses on CO_2 and regulated pollutants (NO_x, HC, CO, PM) emitted by eight Euro 4–6 gasoline and diesel vehicles with six different technologies. The emission factors were repeatedly measured on a chassis dynamometer bench using Artemis Urban with cold and hot start, Road and Motorway, WLTC and NEDC driving conditions. The influence of driving conditions and approved driving cycles on pollutant emissions was also investigated. The measured emission factors for regulated compounds were compared to the corresponding emission factors of the COPCETE emission model developed by the French Ministry of Ecology. The results indicate that the NEDC cycle, used for type-approval of emissions of regulated compounds, leads to underestimation of CO_2 (9–23%) and NO_x (1.2 to 2 times) emissions and overestimation of CO and HC (2 to 5 times) in relation to the Artemis cycles, which are real-world simulation driving cycles. The WLTC cycle for the worldwide harmonization of vehicle emissions shows similar HC, NO_x and CO emissions with the Artemis average cycle within uncertainty of the measurements. The NO_x emissions measured were 1.6 to 8 times greater than the type-approval limits. These high NO_x emissions produced by all the diesel vehicles tested under real-world driving conditions could serve as particle precursors and increase secondary organic aerosol formation. They are also indicative of the significant cause for concern regarding urban air quality and the increase in the portion of Euro 5 and 6 diesel vehicles in France's vehicle fleet. Regarding emission factor assessments, the emission levels measured are overall in fair agreement with the COPCETE predictions within uncertainties for CO_2 and regulated pollutants. Updating the database is vital in order to be able to produce more representative emission factors and better evaluate the health and environmental effects from vehicle emissions.

Keywords

Regulated pollutant emission factors; Driving conditions; Diesel particulate filter; Propulsion engine; COPCETE emission model

1 Introduction

Vehicle emissions are the main source of gaseous and particulate air pollution in urban areas. On both a regional and global scale, vehicle pollution may negatively impact human health and play a significant role in climate change and air quality (Aphekom, 2011; IPCC, 2011). European emission standards on regulated pollutants such as CO_2, CO, HC, NO_x, PM and PN for passenger cars (Euro 1 to 6) have become increasingly stringent in the past two decades. Nevertheless, road transport reportedly contributes about 20% of $PM_{2.5}$ and PM_{10} and about 50% NO_x emissions (EPA 2014 and 2012). NO_x may be an atmospheric particle precursor and lead to secondary particle formation. O'Driscoll (2016) showed that the variability in NO_x emissions with on-board PEMS measurement was significant and could exceed the type-approval limit by a factor of 22.

Road vehicle emissions depend on a host of parameters that include vehicle weight, engine type and capacity, fuel, exhaust aftertreatment technology, driving behaviors, road gradient and vehicle maintenance (Fontaras *et al.*, 2014; Franco *et al.*, 2013). A number of emission models (e.g. COPERT, HBEFA, PHEM and MOVES) are thus used to provide appropriate emission factors to predict amounts of pollutants emitted at national or local traffic levels in order to assess the performance of air quality policies (Fallah *et al.*, 2015; Fontaras *et al.*, 2014; Smit *et al.*, 2010). These models are built using data collected from vehicle emission measurement experiments. Various methods are used to quantify vehicle emissions, including chassis dynamometer tests under controlled conditions (Louis *et al.*, 2016; Alves *et al.*, 2015; Yang *et al.*, 2015; Forestieri *et al.*, 2013; Adam *et al.*, 2011; Livingston *et al.*, 2009; Caplain *et al.*, 2006; Schmitz *et al.*, 2000) and real-world measurements such as tunnel studies, remote sensing and on-road tests (Banitalebi *et al.*, 2016; Andersson *et al.*, 2014; Rubino *et al.*, 2010; Liu *et al.*, 2010; Ho *et al.*, 2009; Wehner *et al.*, 2009; Chen *et al.*, 2007; Ko and Cho, 2006; Zavala *et al.*, 2006; Chan and Ning, 2005; Jiang *et al.*, 2005; Kristensson *et al.*, 2004; Chan *et al.*, 2004). As described by Franco (2013), real-world measurements can be used to monitor a host of vehicle emissions under real driving conditions. However, the results are less accurate and repeatable than those obtained from chassis dynamometer studies and allocating emissions to specific vehicle classes is difficult. Chassis dynamometer tests are important sources of emissions data, as they are conducted under controlled conditions and thus provide more accurate and repeatable pollutant emission factors. However, they may be a poor representation of real-world emissions and may not be representative of the emissions of entire vehicle fleets, as only a few vehicles for each technology class can be tested. Several teams (O'Driscoll *et al.*, 2016; Ntziachristos *et al.*, 2016) recently focused on the use of on-board Portable Emission Measurement Systems (PEMS) for measuring regulated compound emission factors. Mean NO_x emission factor levels measured on-board Euro 6 passenger cars were twice as high as the those used in current models (Ntziachristos *et al.*, 2016). Moreover, chassis dynamometer measurements of Euro 5 and 6 vehicles with database updates remain an important means of comparison with PEMS measurements using various emission models. According to Rexeis (2013), eighty Euro 5 vehicles and twenty Euro 6 vehicles tested on a chassis dynamometer were added to HBEFA Version 3.2 to represent the composition of the entire fleet. Moreover, of the twenty Euro 6 vehicles (13 different vehicle models), only one was a Euro 6 gasoline car. In France, Euro 5–6 diesel and gasoline vehicles are estimated to account for 35% and 77% of the vehicle fleet, respectively, in 2015 and 2025 (André *et al.*, 2013). This change in the composition of the vehicle fleet indicates that a higher number of recent vehicles with different vehicle technologies should be tested and considered in the emission model database so as to produce more representative emission factors.

In order to support updating databases of existing emission factors, six in-use Euro 5–6 diesel (additive and catalyzed DPF) and gasoline (direct injection, propulsion (located at the rear of the vehicle) and traction engines) passenger cars have been tested with Artemis (Urban, Road and Motorway), WLTC (Worldwide harmonized Light vehicles Test Cycle) and NEDC (New European Driving Cycle) driving cycles. Two Euro 4 vehicles were also tested for comparison with Euro 5 and 6 gasoline and diesel vehicles. The impact of driving conditions and vehicle technologies was investigated. The measured emission factors for regulated pollutants were also compared with those obtained from COPCETE emission model.

2 Materials and Methods

2.1 Experimental set-up

Emission measurements were performed on a chassis dynamometer bench. Vehicle tailpipe exhaust was diluted with filtered ambient air through the CVS (Constant Volume Sampler) system before bag sampling, on-line measurement and filter collection. The total flow of CVS was set at 13 $m^3\ min^{-1}$ for the Artemis Motorway and WLTC cycles and at 9 $m^3\ min^{-1}$ for the Artemis Urban and Road and NEDC cycles.

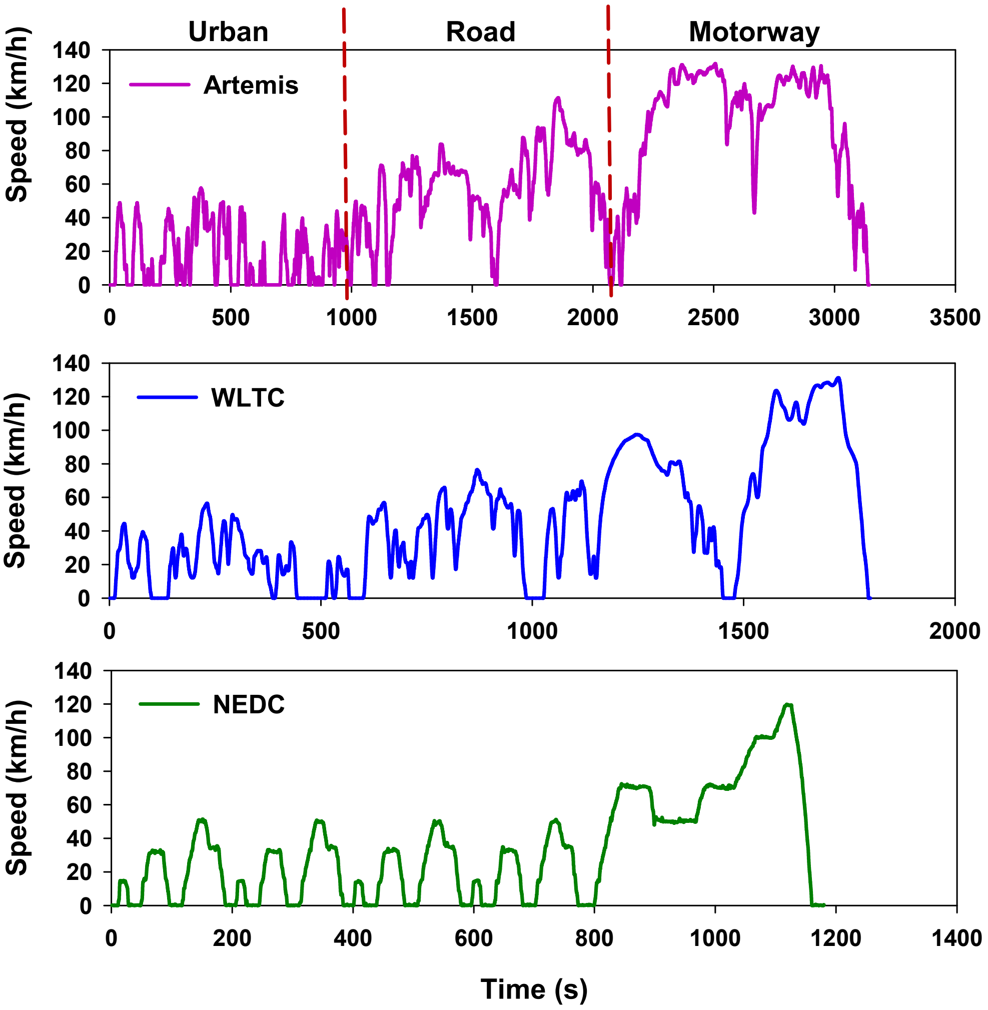


Figure 1. Artemis Urban, Road and Motorway, WLTC and NEDC driving cycles

All eight vehicles were tested with the NEDC and Artemis driving cycles, except for the two Euro 6 vehicles. Emissions from the WLTC cycle were also monitored. André (2004) gives a detailed description of the Artemis driving cycles. In brief, the Artemis cycle contains urban, road and motorway conditions with average speeds of around 17, 61 and 116 km h^{-1}; sampling times of around 15, 14 and 12 minutes; and driving distances of 4.5, 14.7 and 23.7 km, respectively. NEDC and WLTC are European and world-approved driving cycles with cold start (Fig. 1). The average speeds, sampling times and driving distances are 34 and 47 km h^{-1}, 20 and 30 minutes, 11 and 23 km, respectively. For the WLTC, only driving profil has been used.

2.2 Vehicle characteristics and fuels

Eight currently in-use vehicles with six different technologies were tested: one Euro 4 gasoline vehicle, one Euro 5 gasoline vehicle with direct injection system (G-DI) and one Euro 6 gasoline G-DI vehicle; one Euro 4 Diesel vehicle with catalyzed particulate filter (DPF cat), one Euro 5 Diesel DPF cat, one Euro 6 Diesel DPF cat with NO_x trap, and two Euro 5 Diesel vehicles with additive particulate filter (DPF add). The two Euro 4 vehicles were tested for comparison with Euro 5 and 6 gasoline and diesel vehicles. All the vehicles were equipped with a traction engine, except for Euro 6 G-DI, which had a propulsion engine (located at the rear of the vehicle). The specific characteristics of the tested vehicles are presented in Table 1. All the tested vehicles were private vehicles so as to be representative of current in-use vehicle conditions. They were loaded onto the chassis dynamometer by coastdowns. The resistance values have been estimated by regulated method with their equivalent inertia mass including the driver and measurement equipment (empty mass + 100 kg for NEDC and Artemis cycles, empty mass + 100 kg + 15% of payload for WLTC cycle), aerodynamic force and road resistance force. For each driving condition (urban, road and motorway Artemis cycles), the gearshift is calculated considering the relative engine speed at the change (in % of the optimal engine speed), the engine speed (in rev./mn) at maximum power and the gear ratio (km/h at 1000 rev/min).

Table 1: Technical characteristics of the **eight tested vehicles**

Vehicle	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8*
Size class	1.6 HDI	1.4 HDI	2.0 D	1.5 DCI	1.5 DCI	1.2 i	1.4 TSI	0.9 DI
Technology	Diesel	Diesel	Diesel	Diesel	Diesel	gasoline	gasoline DI	Gasoline
Standard	Euro 5	Euro 5	Euro 4	Euro 5	Euro 6b	Euro 4	Euro 5	Euro 6b
Empty weight (kg)	1185	1020	1345	1090	1087	1030	1241	864
Equivalent inertia mass (kg)	1360	1080	1380	1130	1130/1250	1130	1360	910/1020
A0 (N)	88.68	80.05	106.7	88.68	88.68	88.68	106.7	71.417 for NEDC and Artemis 80.05 for WLTC
A1 $(N/(m/s)^3)$ and A3 $(N/(m/s)^3)$	0	0	0	0	0	0	0	0
A2 $(N/(m/s)^2)$	0.427	0.413	0.429	0.47	0.426	0.447	0.413	0.464 for NEDC and Artemis 0.466 for WLTC
S (m^2)	2.374	2.152	2.56	2.306	2.24	2.259	2.37	2.288
Cx	0.3	0.32	0.31	0.34	0.32	0.33	0.29	0.34

Mileage (km)	39,600	45,150	130,485	87,073	4700	61,719	20,822	2,164
Gearbox type	Manual (5)	Manual (5)	Manual (6)	Manual (5)	Manual (5)	Manual (5)	Tiptronic (7)	Manual (5)
Artemis and WLTC transmission ratio (1000 tr/min)								
Gear 1 (km/h)	9.44	8.43	8.79	8.99	9.63	7.13	9.7	8.35
Gear 2 (km/h)	17.47	15.93	15.27	16.36	18.34	12.91	16.11	15.20
Gear 3 (km/h)	28.16	24.64	22.90	25.40	29.09	18.84	23.9	22.41
Gear 4 (km/h)	39.84	33.92	33.81	35.67	40.22	24.89	32.64	28.32
Gear 5 (km/h)	49.5	42.4	46.56	48.60	54.39	30.3	30.98	35
Gear 6 (km/h)			56.80				38.48	
Gear 7 (km/h)							45.7	
Registration date	06/06/2012	07/22/2011	05/18/2010	02/17/2012	12/31/2015	06/25/2007	06/08/2012	12/11/2015
Aftertreatment	Oxidation catalyst		Oxidation catalyst			Three-way catalyst		
	Additive DPF		Catalyzed DPF		Catalyzed DPF + NOx trap			

* The Euro 6 gasoline vehicle (No. 8) was equipped with a propulsion engine (located at the rear of the vehicle). All the other vehicles were equipped with a traction engine.

All the experiments were performed using commercial fuel (less than 10 ppm sulfur content) from the same filling station to minimize the impact of fuel composition on emissions. All the diesel and gasoline vehicles were filled with fuel meeting the requirements of EN 590 and EN 228, respectively.

2.3 Analytical methods and conditions

All the regulated compounds were monitored using the Horiba emission measurement system. Carbon monoxide (CO) and carbon dioxide (CO_2) were monitored by non-dispersive infrared spectroscopy. Total hydrocarbons (THC) were measured by flame ionization detection. Nitric oxide (NO) and nitrogen oxides were monitored by chemiluminescence. All gas-phase regulated compounds were monitored by two different methods: on-line analysis and bag collection. Particulate mass was collected on Pallflex filters (47 mm) and determined using a microbalance.

The Artemis Urban with hot start, Road and Motorway cycles were repeated either 6 or 10 times. Only two repeat experiments were performed for the Artemis Urban and WLTC cycles with cold start. One NEDC measurement was taken on each vehicle. The experimental conditions and pollutants are presented in Table 2.

Table 2. Experimental conditions and Pollutants

Vehicle		Driving cycle	CVS (m^3 min^{-1})	Repeat test number	Pollutants
No. 1	D Euro 5 DPF add*	NEDC cold start WLTC cold start Artemis Urban cold start	9 13 9	1 2 2	CO_2 CO HC NO_x PM
No. 2	D Euro 5 DPF add				
No. 3	D Euro 4 DPF cat#				
No. 4	D Euro 5 DPF cat				

No. 5	D Euro 6 DPF cat	Artemis Urban hot start	9	10
No. 6	G Euro 4	Artemis Road hot start	13	6
No. 7	G Euro 5 DI[$]	Artemis Motorway hot start	13	6
No. 8	G Euro 6 DI			

*DPF add: Additive Diesel Particle Filter

[#]DPF cat: Catalyzed Diesel Particle Filter

[$]DI: Direct Injection system

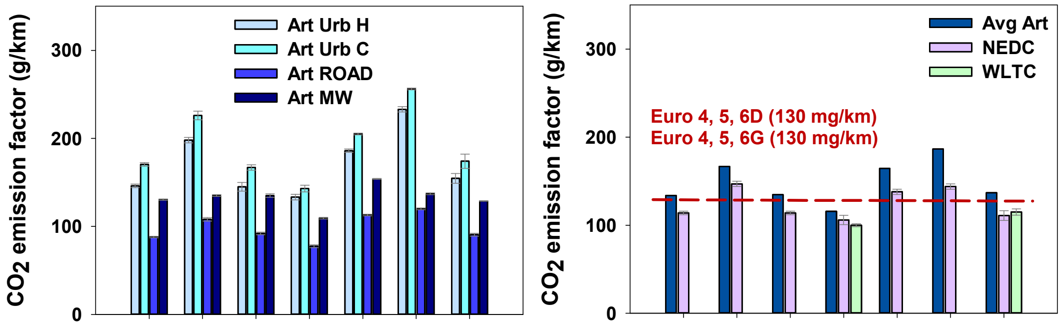
2.4 Reference emission model

The results of the measured regulated compound emission factors were compared with the COPCETE emission model developed by the French Ministry of Ecology (Fallah *et al.*, 2015; CETE Normandie, 2010). COPCETE was developed using the methods and equations of the COPERT IV methodology (Ntziachristos *et al.*, 2009), but with a mesoscopic approach. It makes it possible to estimated vehicle emissions according to vehicle exhaust, fuel evaporation and equipment wear. It takes into account road gradients and lengths, traffic densities (urban or rural road), fleet compositions (number of passenger, light-duty and heavy-duty vehicles, buses), and average speeds. In our case, the IFSTTAR Euro 4–6 fleet was used for 2016 and 2025 emission estimations. Only Artemis urban, road and motorway driving conditions with hot start have been taking account in this comparaison. For cold start, the emission models are less robust to make the prediction.The parameters used as the input data are presented in section 3.2.

3 Results and discussion

3.1 CO_2 and regulated pollutant emissions

The emission factors for CO_2, CO, NO_x and HC for all the Euro 4–6 diesel and gasoline vehicles tested are presented in Figure 2 (Appendix B). The emissions from the Artemis Urban with cold (Art Urb C) and hot start (Art Urb H), Road and Motorway (Art MW) cycles are presented in Figure 2 (left). The comparison of all Artemis average emissions with NEDC (purple bars) and WLTC (green bars; for Euro 6 vehicles only) approved driving cycles are presented in Figure 2 (right). The error bars are the standard deviation of the repeat tests performed under the same experimental conditions (Table 2). With the exception of the NEDC cycle, they represent analytical error. Since the PM emissions were very low (near background) for all the vehicles tested under all driving conditions, the PM emission factors are not presented in this paper.



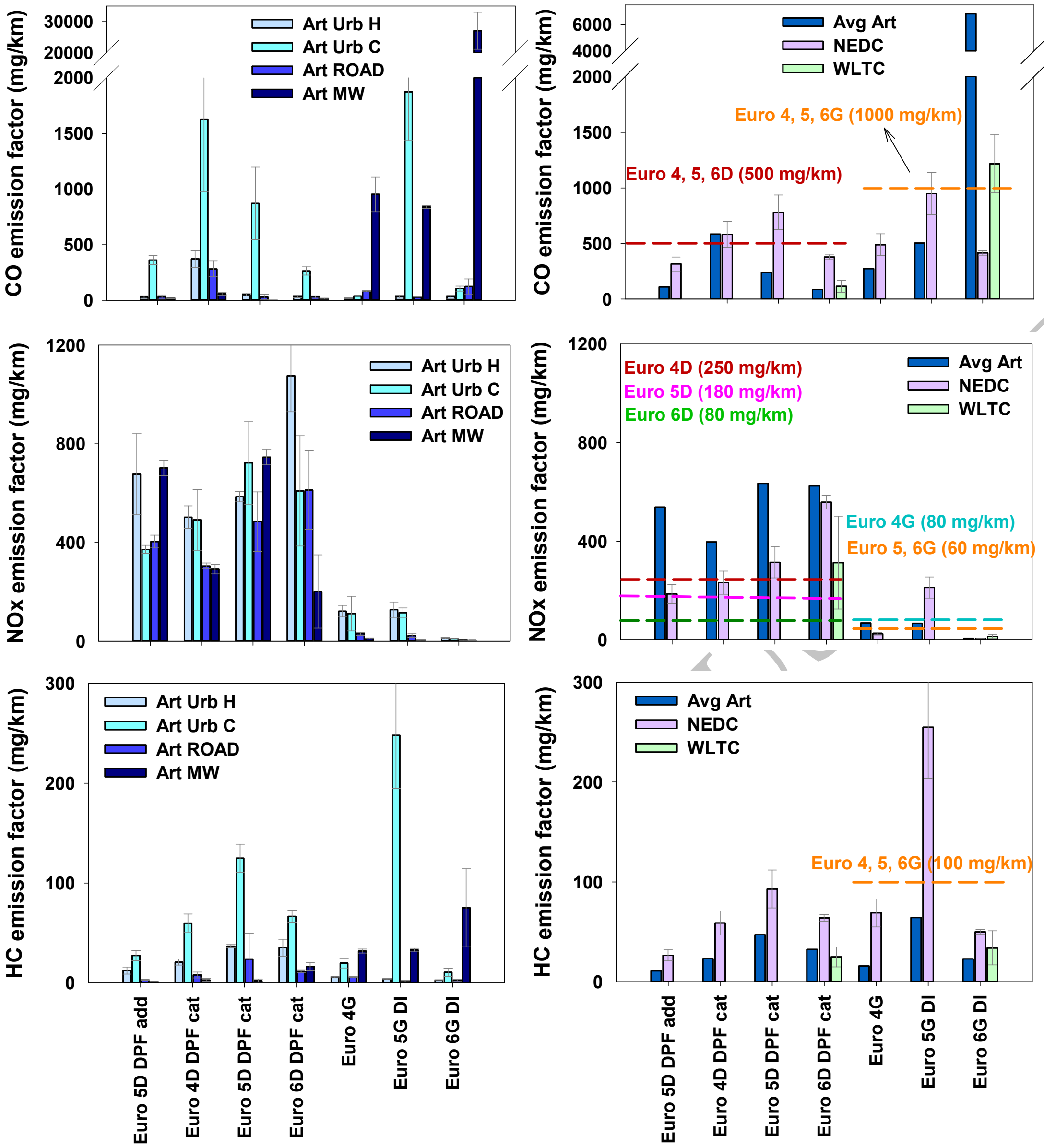


Figure 2. CO_2, CO, NOx and HC emission factors obtained under Artemis Urban with hot (Art Urb H) and cold start (Art Urb C), Road (Art ROAD) and Motorway (Art MW) driving cycles (left) and comparison of Artemis average emissions (Avg Art) with NEDC and WLTC emissions (right) for all the tested vehicles. The dotted lines denote Euro 4, 5 and 6 emission standards for diesel and gasoline vehicles.

- Comparison between Artemis Urban, Road and Motorway cycles

The CO_2 emissions ranged between 88 and 256 g km^{-1} for Artemis cycles depending on the vehicle mass, capacity, fuel type and driving conditions. The gasoline vehicles emitted 9–24% more CO_2 than the diesel vehicles. Vehicle mass appears to have the greatest influence on CO_2 emissions for both diesel and gasoline vehicles, as they increased with the mass of the vehicles. A similar observation was reported by Fontaras (2014). No significant difference in CO and HC was observed in any of the vehicles tested using the Artemis Road driving condition. However, under the Artemis MW condition, gasoline vehicles produce (on average) 300 and 10 times more CO and HC emissions, respectively, than diesel vehicles. In the case of the Euro 6 gasoline DI vehicle, the CO emissions under MW for reached 2.7.10^4 mg km^{-1}, i.e. about 40 times higher than for the other Euro 4 and Euro 5 DI gasoline vehicles tested (about 900 mg km^{-1} for MW). During our experiment, we observed that the exhaust temperature from the Euro 6 gasoline DI vehicle with propulsion engine, which was measured at the outlet of the exhaust tailpipe, under the MW condition (average speed around 92 km h^{-1}) was very high (around 600 °C). This exhaust temperature was three times higher than that of the traction engine vehicles (around 200 °C) under all the tested driving conditions. Similar CO emission behavior was observed in the Euro 6 G-DI during the WLTC cycle for the high and extra-high speed phases when the exhaust temperature reached 600 °C. According to Ghazikhani (2014), CO emissions at an exhaust temperature of 300 °C are four times higher than at 200 °C with 10% ethanol fuel. As the exhaust temperature increases with vehicle speed, the required combustion time decreases, in turn increasing CO emissions. The exhaust temperature at 600 °C in our study may explain in part the high CO emissions under the Artemis MW condition for the Euro 6 G-DI propulsion vehicle. However, only one propulsion vehicle was tested during our study. Further tests will be necessary both to confirm whether this high CO emission behavior is an individual emission event or a systematic behavior and to provide more appropriate CO emission factors under high exhaust temperatures with propulsion engines. Depending on the driving conditions, the diesel vehicles emitted 5 to 100 times more NO_x than the gasoline vehicles. The Euro 6 G-DI vehicle emitted 6 to 10 times less NO_x (3–13 mg km^{-1}) than the other tested gasoline vehicles.

- Cold start effect between Artemis hot and cold start

Cold start emissions were measured on all the tested vehicles after a 14-hour stopover period. All the Artemis urban cold distances during our experiment were about 2.5–3.3 km, which is consisted with Faves (2009). In general, the Artemis Urban cold start driving condition produces 14% and 10% more CO_2 emissions than hot start. It also produces 7 and 10 times more CO and 3 and 21 times more HC emissions, respectively, for diesel and gasoline vehicles. The excess CO and HC cold-start emissions occurred when the catalyst conversion efficiency was low. Cold start produced 17% and 10% fewer NO_x emissions than hot start. Similar results were shown by Alves (2015) with Euro 3–5 gasoline vehicles (class < 1.4L) and Euro 4–5 diesel vehicles (1.4-2L class).

- Comparison with approved driving cycles

Compared with the NEDC cycle, the diesel and gasoline vehicles emitted 9–19% and 19–23% more CO_2, respectively, during the Artemis (Urban Cold start + Road + Motorway) average emissions cycle. The two Euro 6 vehicles showed that the Artemis average cycle produced 16–19% more CO_2 emissions than the WLTC cycle. No significant difference was observed between the NEDC and WLTC cycles. The WLTC-NEDC quotients were 0.94 and 1.04, respectively, for the Euro 6 D DPF and G-DI vehicles tested. This is consistent with Pavlovic (2016) and Marotta (2015). All the vehicles tested produced 2 to 5 times fewer CO and HC emissions during the Artemis average cycle than during the NEDC cycle. The CO and HC emissions were similar between the Artemis average cycle and WLTC. The sole exception was the Euro 6 G DI vehicle. Due to the high exhaust temperature at high speed, it emitted four times more CO during the Artemis average cycle compared to the WLTC cycle and 12 times more CO compared to the NEDC cycle. All the vehicles tested produced 1.2 to 2 times more NO_x during the Artemis average cycle than during the NEDC cycle. The sole exception was the Euro 5 G-DI vehicle, which produced three times more emissions during the NEDC cycle than during the Artemis average cycle. The results indicate that NEDC cycle used for emission type-approval, which is not representative of real-world vehicle operation, leads to underestimation of CO_2 and NO_x

emissions and overestimation of CO (except with Euro 6 G-DI) and HC compared to the Artemis average cycle, which represents simulated real-world driving conditions. The WLTC cycle for the worldwide harmonization of vehicle emissions shows similar HC, NO_x and CO emissions with the Artemis average cycle within uncertainty the measurements. The only exception is the Euro 6 G-DI propulsion vehicle, which may represent an individual emission event. However, only two Euro 6 vehicles were tested using the WLTC cycle in this study. Further testing will be necessary in order to clarify the impact of the pollutant emissions during the WLTC cycle.

Comparisons with European emission standards show that the Euro 5 D DPF, the Euro 4 G and the Euro 6 G-DI vehicles meet EU emission standards under the NEDC driving cycle. The other vehicles tested showed NO_x, CO and HC emissions above the Euro standards. In particular, the NO_x and HC emissions for the Euro 5 and 6 D DPF cat and Euro 5 G DI vehicles were 2 to 7 times higher than the Euro 5 and 6 standards. During the WLTC tests, the Euro 6 diesel vehicle produced higher HC+NO_x emissions (339 mg km^{-1}), which exceed the Euro 6 emission standards. All the Euro 4 and Euro 5 DI diesel and gasoline vehicles tested exceeded the European NO_x emission standards by a factor of 1.6 to 8 under Artemis Urban cold and hot start conditions. A similar result was observed by Fontaras (2014) with a Euro 5 gasoline DI vehicle, which produced NO_x emissions that were six times the urban condition limit value. The exceedance of NO_x emissions was also observed under the Artemis Road and Motorway conditions for all the diesel vehicles tested. The high NO_x emissions under real-world driving conditions indicate the significant cause for concern regarding urban air quality and capacity of the increase in the number of Euro 5 and 6 diesel vehicles to cause secondary particle formation in the atmosphere. All the vehicles tested exceeded the European Commission's CO_2 limit (130 g km^{-1}) under the Artemis Urban condition. In the case of the Euro 5 DI vehicle, this limit was exceeded by a factor of two. The excess emissions observed may be due to catalyst aging, vehicle conditions and maintenance, all of which are highly significant factors of pollutant emissions. In terms of urban air quality and the climate, it is important that these regulated pollutant emissions remain below European limits.

3.2 Assessment of regulated pollutant emission factor using the COPCETE model

Euro 4–6 diesel and gasoline vehicles are required to comply with European emission standards under type-approval experimental conditions and are expected to account for 85% of the French vehicle fleet by 2025 (André *et al.*, 2013). It is important to know whether the measured pollutant emission levels under real-world driving conditions remain at acceptable levels, and whether the emission factors from models can be used to predict the actual emissions of vehicle categories under study. For all regulated compounds, the measured emission factors shown in Figure 3 represent the average of all the diesel and gasoline vehicles tested under Artemis Urban with hot start, Road and Motorway driving conditions. The COPCETE prediction was obtained using the average velocities of Artemis Urban (17 km h^{-1}), Road (61 km h^{-1}) and Motorway cycles (116 km h^{-1}) with distances of 4.5, 14.7 and 23.7 km, respectively; and velocities of 10 to 130 km h^{-1} with an increment of 10 km h^{-1} and an average distance of 12 km (average distance recommended in France by the French Environment and Energy Management Agency (ADEME)). The emission factors estimated from the Euro 4–6 gasoline < 1.4 L category vehicles and the Euro 4–6 Diesel 1.4–2.0 L category vehicles were used for the comparison. IFSTTAR's 2011 French vehicle fleet composition was used in COPCETE to estimate emissions for 2016 and 2025.

Two series of emission factors for regulated pollutants under hot start driving condition were estimated with the 2016 and 2025 Euro 4-6 gasoline and diesel passenger car fleets. Figure 3 shows the comparison between CO_2, CO, NO_x and HC hot-start emission factors (red and green dots) and COPCETE estimations (solid lines) for the Euro 4–6 gasoline and diesel vehicles. The 2016 and 2025 COPCETE estimations are similar for CO_2, CO and HC diesel and gasoline emissions. The two estimation curves thus are overlaid. The estimated NO_x emission factors for diesel vehicles at speeds between 10 km h^{-1} and 130 km h^{-1} is 1.5 times higher for 2016 than for 2025. In comparison, they are slightly higher for gasoline vehicles at low speeds (10–60 km h^{-1}). The emission levels measured in our experiment are in general agreement with the COPCETE predictions within uncertainties considering that the COPCETE model is used to predict emission levels for vehicles that belong to the same category, not individual vehicle emissions. The Diesel NO_x emission better matches the 2016 COPCETE estimation at low and medium speeds. At high speed, the Euro 4 and 6 D DPFcat vehicles fit better with the 2025 COPCETE prediction (Fig. 4, left, Appendix A). One exception was observed for CO emission at high speed (Artemis Motorway) due to the high CO emission at high exhaust temperature from the Euro 6 gasoline DI vehicle with propulsion engine (Fig. 2). The CO emissions from the Euro 4 and Euro 5 DI gasoline vehicles tested are well in line with the predicted emissions (Fig. 4, right, Appendix A). Moreover, comparing with the COPERT model (Fontaras et al., 2014), We observed the similar estimation results between COPCETE and COPERT models. Except for NOx emissions from Diesel vehicles, the COPERT NOx estimation is higher than the COPCETE estimation. In addition, the chassis dynamometer measurements match better with the COPCETE prediction than the COPERT. The result shows that the emission model has a positive impact on the policy-making process. However, additional tests on larger vehicle sample are necessary in order to be able to reach solid conclusions that take into account the measurement variabilities and emission estimation uncertainties.

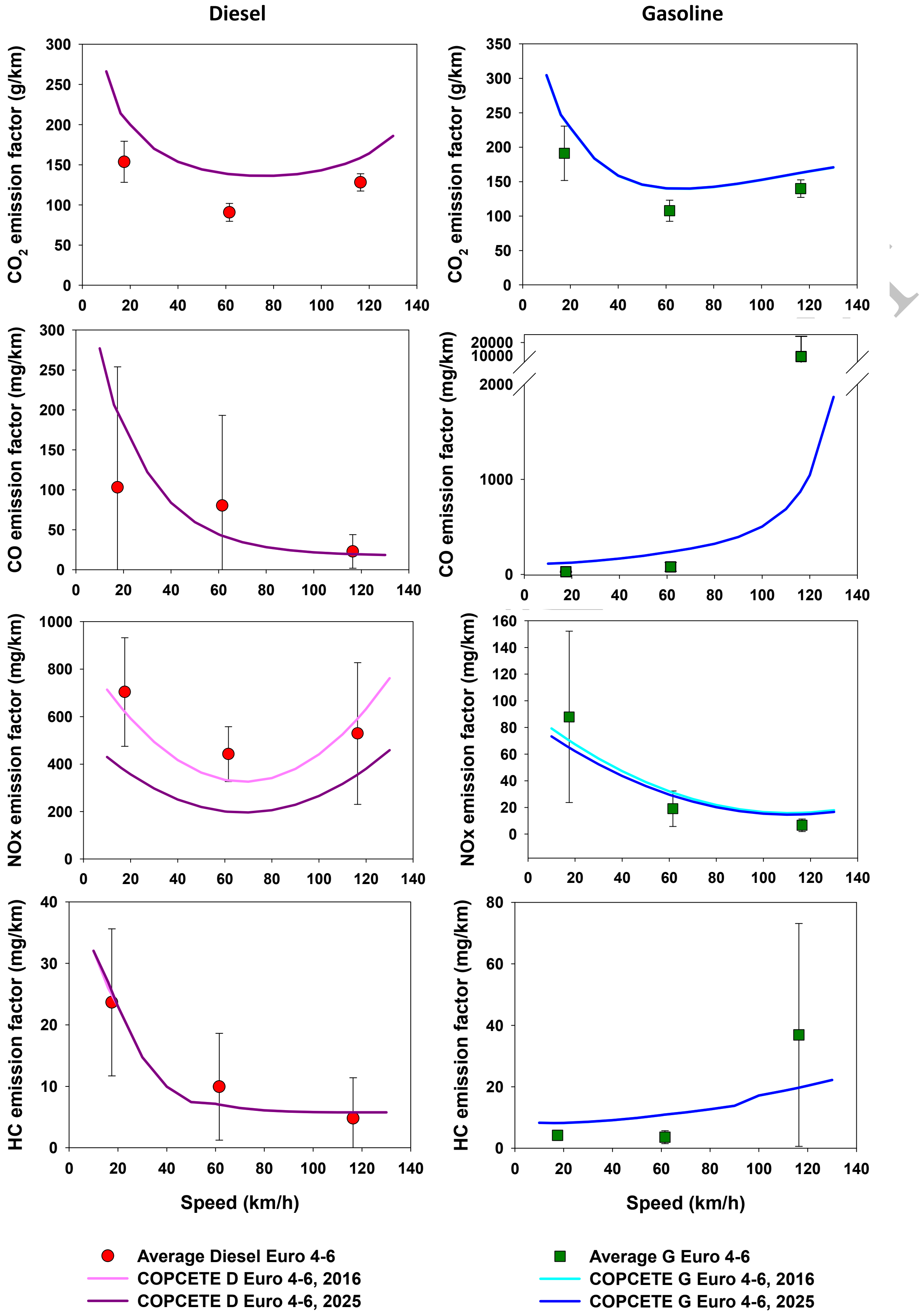


Figure 3. Comparison between average emission factors for Euro 4–6 diesel (left) and gasoline (right) vehicles measured using Artemis urban, road and motorway hot start driving cycles and the COPCETE model prediction for the 2016 (pink and light blue) and 2025 fleets (purple and dark blue).

4 Conclusions

Eight Euro 4–6 gasoline and diesel vehicles currently in use and fitted with six different technologies were tested as part of this study. Only a few vehicles of each type were tested in relation to the entire passenger car fleet. Nevertheless, they provide some understanding on emission behaviors under different driving conditions. The Euro 5 and 6 vehicle emission factors obtained were used to update the model databases of existing emission factors, which currently comprise only eighty Euro 5 vehicles and twenty Euro 6 vehicles as a representation of the entire fleet.

Six driving conditions were used in this study: Artemis Urban with cold and hot start, Road, Motorway, NEDC and WLTC. The Euro 6 gasoline DI propulsion vehicle exhibited very particular CO emission behavior, which reached $2.7.10^4$ mg km^{-1} during the Motorway cycle when the exhaust temperature rose to 600 °C at high speed. However, only one propulsion vehicle was tested during our study. It is difficult both to confirm whether this high CO emission behavior is an individual emission event or a systematic behavior and to provide appropriate CO emission factors under high exhaust temperatures with propulsion engines. The cold start driving condition has a significant impact of emissions, producing 7 and 10 times more CO and 3 and 21 times more HC emissions, respectively, for diesel and gasoline vehicles. The results also indicate that the NEDC cycle, used for type-approval of emissions of regulated compounds, leads to underestimation of CO_2 (9–23%) and NO_x (1.2 to 2 times) emissions and overestimation of CO and HC (2 to 5 times) in relation to the Artemis cycles, which are real-world simulation driving cycles. The WLTC cycle for the worldwide harmonization of vehicle emissions shows similar HC, NO_x and CO emissions with the Artemis average cycle within uncertainty of the measurements. However, only two Euro 6 vehicles were tested using the WLTC cycle in this study. Further testing will be necessary in order to clarify the impact of the WLTC driving cycle. The NO_x emissions measured from all the diesel and Euro 4–5 gasoline vehicles tested exceeded the type-approval limits by a factor of 1.6 to 8. The high NO_x emissions under real-world Urban, Road and Motorway driving conditions indicate the significant cause for concern regarding urban air quality and capacity of the increase in the number of Euro 5 and 6 diesel vehicles to cause secondary particle formation in the atmosphere.

In terms of the emission factor assessment, the emission levels measured in our experiment are in general agreement with the COPCETE predictions within uncertainties for CO_2 and regulated pollutants considering that the COPCETE model is used to predict emission levels for vehicles that belong to the same category, not individual vehicle emissions. The result shows that the emission model has a positive impact on the policy-making process. However, additional tests on larger vehicle sample are necessary in order to be able to reach solid conclusions that take into account the measurement variabilities and emission estimation uncertainties. Moreover, updating the database is vital in order to be able to produce more representative emission factors and better evaluate the health and environmental effects from vehicle emissions.

Acknowledgments

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Appendix A

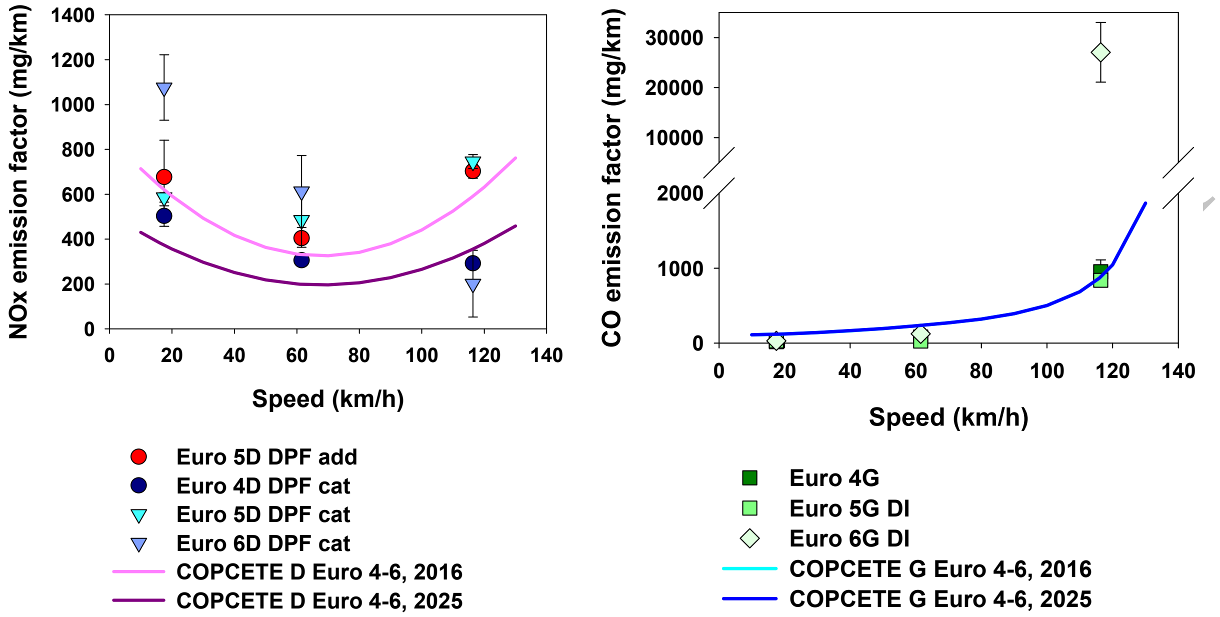

Figure 4. Comparison between average emission factors for Euro 4–6 diesel and gasoline vehicles measured using Artemis urban, road and motorway hot start driving cycles and the COPCETE model prediction for the 2016 (pink and light blue) and 2025 fleets (purple and dark blue). Left: Diesel NO$_x$ emissions. Right: Gasoline CO emissions.

Appendix B

Emission factors for regulated pollutants from Euro 4–6 diesel and gasoline vehicles

Vehicle	**No. 1**					**No. 2**				
Standard	**Euro 5 Diesel DPF**					**Euro 5 Diesel DPF**				
Artemis cycle	URB H	URB C	ROAD	MW	NEDC	URB H	URB C	ROAD	MW	NEDC
CO_2 (g/km)	150 ± 1	172 ± 2	89 ± 0.5	131 ± 0.3	114 ± 2	142 ± 3	169 ± 2	87 ± 1.2	130 ± 1	114 ± 2
NO_x (mg/km)	763 ± 188	413 ± 25	424 ± 13	495 ± 20	212 ± 43	591 ± 140	332 ± 7	384 ± 39	910 ± 42	162 ± 33
HC (mg/km)	12 ± 2	27 ± 6	2 ± 0.3	2 ± 0.3	35 ± 7	13 ± 5	28 ± 4	4 ± 0.5	0.3 ± 0.04	18 ± 4
CO (mg/km)	42 ± 14	572 ± 32	37 ± 19	14 ± 2	448 ± 90	17 ± 8	153 ± 52	24 ± 19	24 ± 4	185 ± 37

Vehicle	**No. 3**					**No. 4**				
Standard	**Euro 4 Diesel DPF**					**Euro 5 Diesel DPF**				
Artemis cycle	URB H	URB C	ROAD	MW	NEDC	URB H	URB C	ROAD	MW	NEDC
CO_2 (g/km)	198 ± 3	226 ± 5	108 ± 2	135 ± 1	147 ± 3	145 ± 5	167 ± 3	92 ± 1.5	135 ± 2	114 ± 2
NO_x (mg/km)	503 ± 46	492 ± 123	305 ± 12	292 ± 19	233 ± 47	586 ± 21	723 ± 167	485 ± 121	746 ± 31	315 ± 63
HC (mg/km)	21 ± 3	60 ± 9	8 ± 3	3 ± 1.5	59 ± 12	37 ± 3	125 ± 14	24 ± 26	2.3 ± 1.7	93 ± 19
CO (mg/km)	372 ± 75	1625 ± 650	282 ± 71	58 ± 11	582 ± 116	50 ± 10	871 ± 326	29 ± 25	3 ± 0.3	781 ± 156

N°5 Euro 6 Diesel

	ArtROAD	**ArtUrb C**	**ArtUrb H**	**ArtMW**	**WLTC**	**NEDC**
CO_2 (g/km)	80 ± 2	140 ± 4	130 ± 4	108 ± 1	100 ± 2	107 ± 2
CO (mg/km)	30 ± 9	263 ± 66	34 ± 12	16 ± 4	100 ± 25	380 ± 95
NO_X (mg/km)	613 ± 160	610 ± 160	1076 ± 146	201 ± 149	323 ± 85	559 ± 128
HC (mg/km)	12 ± 1	67 ± 17	35 ± 9	16 ± 4	25 ± 6	64 ± 16

Vehicle	**No. 6**					**No. 7**				
Standard	**Euro 4 gasoline**					**Euro 5 gasoline**				
Artemis cycle	URB H	URB H	URB H	URB H	URB H	URB H	URB H	URB H	URB H	URB H
CO_2 (g/km)	186 ± 2	205 ± 1	113 ± 1	154 ± 0.5	138 ± 3	233 ± 3	233 ± 3	233 ± 3	233 ± 3	233 ± 3
NO_x	122 ±	112 ±	30 ± 6	11 ± 2	26 ± 5	128 ±	128 ±	128 ±	128 ±	128 ±

(mg/km)	24	70				31	31	31	31	31
HC (mg/km)	6 ± 0.8	20 ± 5	6 ± 0.5	32 ± 2	69 ± 14	4 ± 0.6	4 ± 0.6	4 ± 0.6	4 ± 0.6	4 ± 0.6
CO (mg/km)	21 ± 4	39 ± 1	83 ± 6	954 ± 157	490 ± 98	32 ± 13	32 ± 13	32 ± 13	32 ± 13	32 ± 13

No. 8 Euro 6 gasoline

	ArtROAD	ArtUrb C	ArtUrb H	ArtMW	WLTC	NEDC
CO_2 (g/km)	91 ± 2	174 ± 5	155 ± 6	129 ± 0.3	115 ± 3.6	111 ± 3
CO (mg/km)	125 ± 67	105 ± 23	32 ± 13	$(27 \pm 6).10^3$	1217 ± 165	417 ± 92
NO_X (mg/km)	4 ± 0.5	10 ± 1.4	14 ± 2	3 ± 1	15 ± 2	6 ± 2
HC (mg/km)	2 ± 1	11 ± 1	3 ± 5	75 ± 39	34 ± 9	50 ± 13

ArtUrb C/H: Artemis urban with cold or hot start

ArtROAD: Artemis road

ArtMW: Artemis motorway