Study of Euro 6d-TEMP emissions – IFPEN for DGEC

Summary report – December 2020

I. Purpose of the document

The present study evaluates the **real-use emissions of Euro 6d-TEMP vehicles**. An experimental campaign was carried on 22 vehicles spanning a wide range of segments. For each vehicle, measurements of **CO_2 emissions, regulated and non-regulated pollutants (PN10, N_2O, CH_4 and NH_3)** are carried out under various conditions of use: WLTC certification cycles, compliant and very dynamic RDE tests, climatic conditions from -2 to +35 ° C.

The first part aims to compare the environmental impact of gasoline and diesel combustion engines, through a selection of 16 vehicles. These are 8 pairs of gasoline and diesel vehicles comparable two by two : multi-brand, multi-segment (from city car to SUV) and multi-technology (engine: power range, direct and indirect injection - pollution control: with and without particulate filter in gasoline, various technologies of NOx aftertreatment systems in diesel). These are non-new vehicles, taken from the French fleet with kilometers between 22,000 km and 58,000 km. In terms of hybridization, these vehicles are equipped, at most, with a stop-and-start system to cut off the engine during stops.

A second part aims to determine the contribution of hybridization. Six vehicles are evaluated: a couple of city cars for the comparaison of gasoline vs. hybrid, a couple of urban SUVs for the comparaison of hybrid vs. plug-in hybrid, and finally a couple of sedans for the comparaison of plug-in hybrid gasoline vs. plug-in hybrid diesel.

Finally, beyond the experimental characterization carried out and summarized here, an analysis of the sensitivity of emissions to vehicle utilisation is presented (focus on urban conditions and projection on predefined typical uses).

Note to the reader: Glossary available at the end of the report.

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II. Executive summary

Compliance with emission standards

With some exceptions, this experimental campaign shows that Euro 6d-TEMP gasoline and diesel vehicles on average comply with the normative thresholds in real use (RDE type cycle), including under very dynamic driving conditions or in cold and hot climatic conditions for non-new vehicles taken from the fleet. Exceptions relate to the NO_x emissions of diesel vehicles not using urea injection in their pollution control system, as well as to the fine-particle emissions of certain gasoline vehicles without a particulate filter and to the CO emissions of certain gasoline vehicles in very dynamic use.

Notable difference between technologies

Notable differences between the technologies remain: NO_x emissions remain higher for diesel and fine-particle emissions are higher for gasoline, even when taking into account the impact of regeneration of diesel vehicles.

Increase in urban use

Emissions levels are increasing significantly in urban use, in particular NO_x emissions: + 79% in gasoline and + 74% in diesel considering the standard urban RDE phases as compared to full RDE type driving. These emission levels are even higher when focusing on conditions more representative of urban use. The average diesel level in urban use then reached 172 mg/km against 40 mg/km for gasoline vehicles. Figure 3 shows the evolution of NO_x emissions as a function of the distance of the journey and illustrates the significant levels of diesel vehicles on the shortest journeys.

CO_2 emissions from PHEV: a recharging matter

The plug-in hybrid vehicles show levels of CO_2 emissions in this campaign which are extremely sensitive to the state of charge of the battery: they are equally capable of approaching zero emissions (daily recharging for soft driving trips shorter than the electric range) and of doing nothing but match its non-rechargeable counterpart (though without being worse). The real environmental impact of this vehicle technology therefore depends on its use and in particular on good practices in terms of user recharging frequency. Behavioral studies carried out at this stage[1] show that these practices are now much less virtuous than the standard hypothesizes, resulting in CO_2 emissions in real uses that are greater than WLTC type-approved values.

[1] https://theicct.org/sites/default/files/publications/PHEV-white%20paper-sept2020-0.pdf

The comparison of emissions between gasoline and diesel vehicles over the overall scope of the tests shows:

- **28% higher fuel consumption for gasoline** (+ 1.5L / 100km), **resulting in 11% higher CO_2 emissions**. On the scope of the study where the emissions of N_2O and CH_4 are measured, the CO_2 gap is halved **by taking into account these unregulated greenhouse gas emissions**.

- **NOx emissions of 89 mg/km for diesel compared to 20 mg/km for gasoline, i.e. 4.4 times higher**. More specifically, diesel NOx emissions levels are boosted by two vehicles without a urea pollution control system and equipped with an LNT system (at 203 mg/km on average). **When considering only vehicles with a urea depollution system (so-called SCR systems), the average NOx emissions reduce to 57 mg/km, or 2.8 times more than for gasoline vehicles**. As a reminder, the limit of the Euro 6d-TEMP standard is 80 mg/km for diesel vehicles and 60 mg/km for gasoline technology vehicles during laboratory tests, to which a tolerance of a factor of 2.1 is allowed on road tests (168 mg/km and 120 mg/km respectively). This tolerance will be reduced to 1.43 in Euro 6d (from 01/2020 for new types and from 01/2021 for all vehicles).

- **average fine-particle emissions for size ranges greater than 23 nm of $1.6*10^{11}$ #/km for gasoline against $1.1*10^{10}$ #/km for diesel (15 times lower), without taking into account the impact of periodic DPF particle filter regenerations. When considering the impact of regenerations, the average PN23 emissions level of diesel engines reached $5.8*10^{10}$ #/km, i.e. 2.6 times less than their gasoline counterparts on the scope of the study**.

- HC emissions of 23 mg/km for diesel compared to 19 mg/km for gasoline; as a reminder, the limit of the Euro 6d-TEMP standard is 100 mg/km of HC for gasoline vehicles and 170 mg/km of HC + NOx for diesel.

- **CO emissions of 434 mg/km for gasoline compared to 83 mg/km for diesel vehicles**; as a reminder, the CO limit of the Euro 6d-TEMP standard is 1000 mg/km and 500 mg/km of CO respectively for gasoline and diesel vehicles. The emissions levels are more variable in gasoline, with in particular a vehicle having emissions levels clearly above the normative threshold under dynamic driving conditions.

- average **NH_3 emissions of 11 mg/km for diesel compared to 15 mg/km for gasoline vehicles**, and very variable from one vehicle to another in both cases.

NB: The impact of periodic regenerations of diesel pollution control systems is taken into account by applying the coefficients determined experimentally for CO_2, CO, NOx, HC and PN.

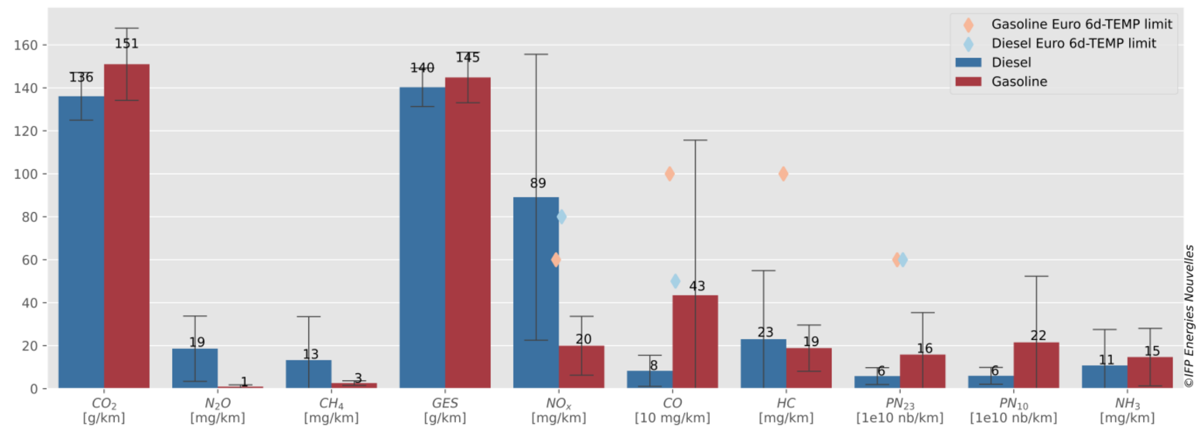

Figure 1 : Comparison of the average emissions of gasoline and diesel vehicles selected on the experimental protocol. Taking into account the impact of regeneration of diesel particulate filters. Measurements of N_2O, CH_4, GES, HC and PN10 on the scope of the dynamometer tests only. Error bars represent the standard deviation of each measurement sample.

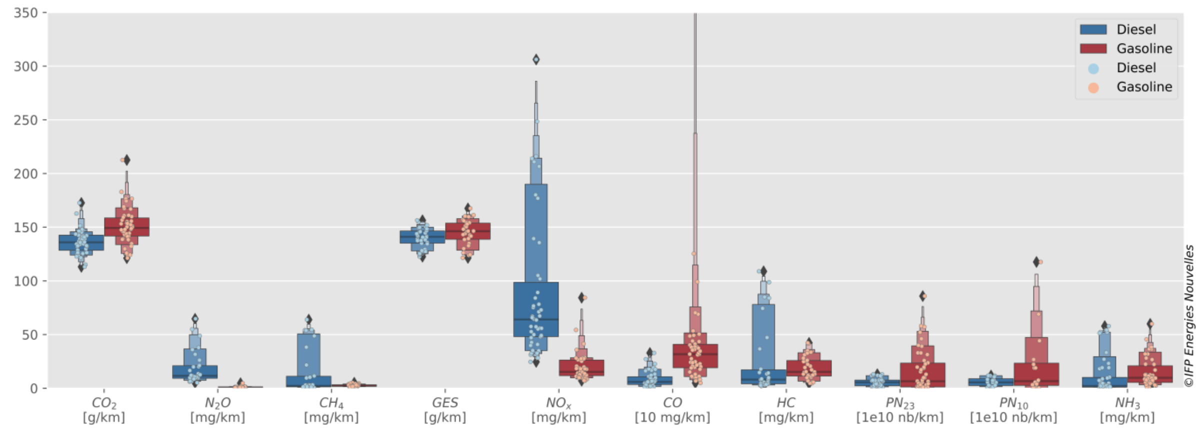

Figure 2 : Distribution of the emission levels of gasoline and diesel vehicles selected on the experimental protocol. Taking into account the impact of regeneration of diesel particulate filters. N_2O, CH_4, GES, HC and PN10 within the scope of the dynamometer tests only. Each point represents one test. The horizontal line represents the median of the sample. The most centrally located box extends from the 1st quartile (the 1st 4-quantile) to the 3rd quartile. The boxes, successively narrower than those which precede them, are delimited incrementally by the 8-quantiles, the 16-quantiles, the 32-quantiles and so on up to the extreme values of the data sample.

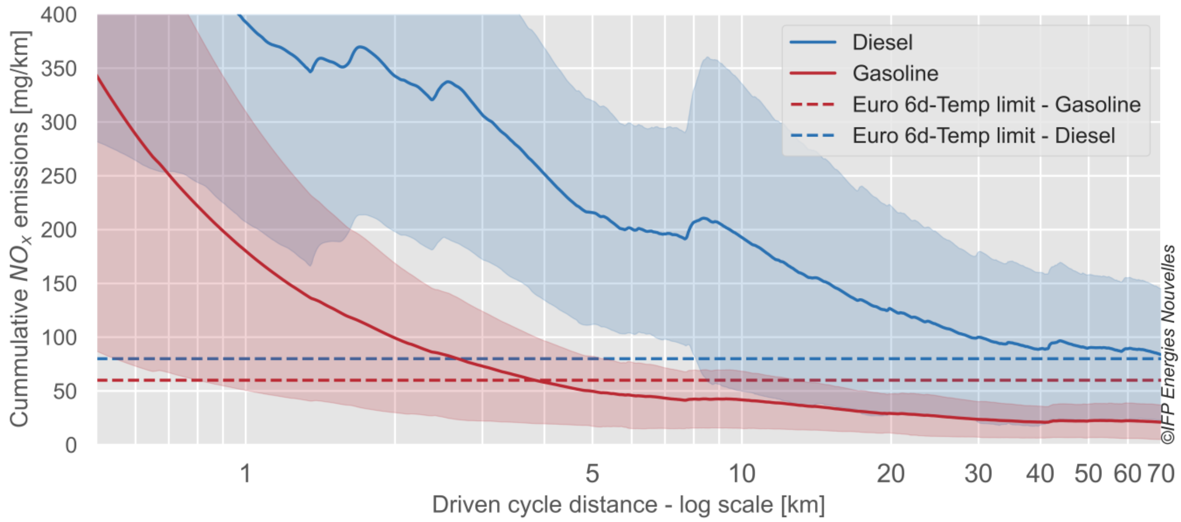

Figure 3 : Comparison of the evolution of cumulative NOx emissions as a function of the distance on the RDE test between gasoline and diesel vehicles (thick lines). The colored areas represent the standard deviation.

III. Introduction

There are two types of road transport emissions:
- greenhouse gases (GHG), responsible for global warming: a European objective of reducing average CO2 emissions by 15% from 2021 to 2025 and 37.5% by 2030 has been established, and a bonus / penalty policy is introduced in France to encourage the purchase of low-emitting vehicles.
- atmospheric pollutants, harmful to health, including nitrogen oxides (NOx) and fine particles: the evolution of European normative thresholds for pollutants over the last 15 years has been very significant, allowing a significant reduction in recent vehicle emissions. However, the gap has widened between type-approval and in-use emissions until Euro 6b standard and in particular for diesel vehicles[2].

Introduced from September 2017 for new types of vehicles and generalized in September 2019 for all vehicles, the Euro 6d-TEMP regulation includes the measurement of pollutant emission levels in real-world situations on open roads, called RDE. This protocol aims to reduce the gap between type-approval regulation and real-world use to ensure the environmental compliance of passenger cars in a broad range of uses.

Although RDE tests have only been part of the homologation process since Euro 6d-TEMP, a phase of monitoring emission levels on RDE vehicles has been initiated since Euro 6b, operated by manufacturers on new vehicles.

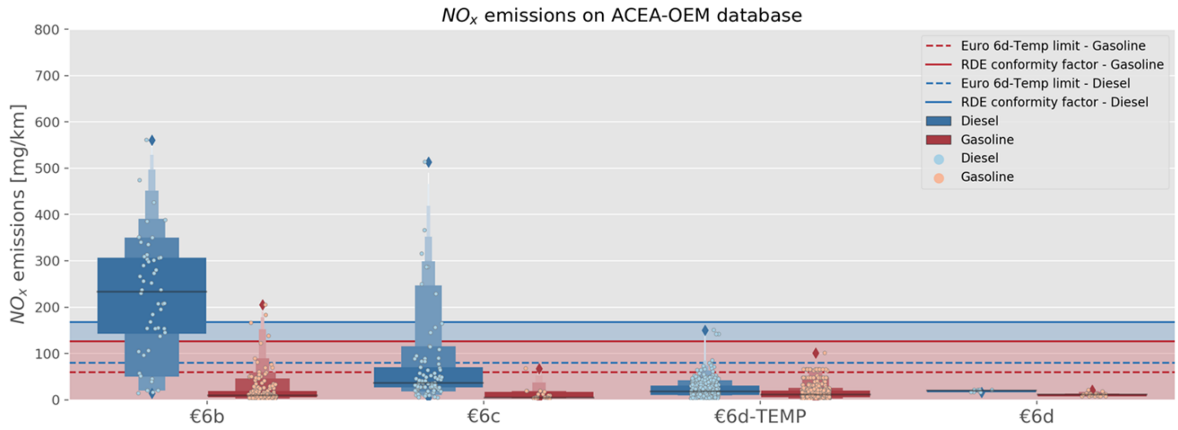

Figure 4 - Manufacturer's NOx emissions data on RDE. Sources: ACEA and JAMA

The results of 2,280 RDE cycles were collected from vehicle manufacturers, ACEA and JAMA[3], both of which are associations of automobile manufacturers, and then aggregated and edited by IFPEN. These results, shown in Figure 4[4], show a marked improvement in the levels of NOx emissions from diesel vehicles since Euro 6d-TEMP and the actual enforcement of the RDE.

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[2] Yoann Bernard et al., "Determination of real-world emissions from passenger vehicles using remote sensing data" (TRUE Initiative, June 5, 2018), https://www.theicct.org/publications/real-world-emissions-usingremote-sensing-data.

[3] https://www.acea.be/ ; http://www.jama-english.jp/

[4] This type of representation allows a visual rendering of the statistical distribution of the measurement sample. Each point represents one trial. The horizontal line represents the median of the sample. The most centrally located box extends from the 1st quartile (the 1st 4-quantile) to the 3rd quartile. The boxes, successively

As the penetration of Euro6 d-TEMP vehicles into the vehicle fleet is still low, they have not yet been characterized in real use and with substantial mileage (over 20,000 km). Recent studies are starting to provide data, such as the study by the TRUE consortium published by the ICCT in September 2019[5] based on measurements in Paris during the summer of 2018. This study notably records a 70% reduction in nitrogen oxide emissions on Euro 6d-TEMP diesel compared to their Euro 6b predecessor, but underlines the insufficient amount of measurements to conclude, confirming the need for further studies focused on these vehicles.

This study therefore aims to establish whether this reduction is effective for various real uses, for non-new vehicles taken from the fleet, and for the various regulated and non-regulated pollutants.

IV. Experimental protocol and vehicle selection

Presentation of the experimental test protocol

In order to find an exhaustive characterization of the actual use of vehicles, an experimental protocol spanning different driving styles and climatic conditions was set up. The detailed experimental protocol[6] [7] was published before the start of the test campaign, describing the tests carried out on the vehicles and the measuring instruments used. Table 1 summarizes the tests constituting the experimental protocol of the study.

Table 1 : Summary of data collected and tests carried out

Test	Driving	Conditions	Description	Elements of response for the project
WLTC OEM	Regulatory	Chassis dyno - OEM	Public data	Nominal behavior approved by the manufacturer
RDE OEM	Normal	On-road - OEM	Public data	Nominal behavior approved by the manufacturer
Lab - WLTC	Regulatory	Chassis dyno	Measurement: CO_2, NOx, CO, HC, CH_4, PN (>23nm et >10nm), NH_3, N_2O, NO/NO_2	Validates the conformity of the behavior of the vehicle taken in relation to the homologation; validates the PEMS measuring device
Lab – RDE ref	Normal	Chassis dyno	Measurement: CO_2, NOx, CO, HC, CH_4, PN (>23nm et >10nm), NH_3, N_2O, NO/NO_2	On an RDE cycle, common reference to vehicles; allows comparison between vehicles; validates the PEMS measuring device
RDE rege	Normal	Chassis dyno and road	Protocol for characterizing the impact of periodic regeneration emissions on diesel vehicles Measurement : CO_2, NOx, CO, HC*, CH_4*, PN (>23nm et >10nm*), NH_3, N_2O*, NO/NO_2 **on chassis dyno test only*	Impact of regulated and unregulated pollutants, periodic regenerations on taxiing representative of actual use
RDE normal	Normal	On-Road	Average RDE type route Measurement: CO_2, NOx, CO, PN>23nm, NH_3, NO/NO_2	
RDE severe	Severe	On-Road	Specific RDE type route: Target of critical driving cases: acceleration, slope, very congested ... loaded vehicle. We are aiming for the same severe test for	Sensitivity of polluting emissions to specific severe driving conditions

narrower than those which precede them, are delimited in an incremental way by the 8-quantiles, the 16-quantiles, the 32-quantiles and so on until the extreme values of the data sample.

[5] https://theicct.org/publications/on-road-emissions-paris-201909

[3] https://www.ifpenergiesnouvelles.fr/article/lancement-dune-etude-devaluation-des-emissions-vehicules-recents

[4] https://www.ecologique-solidaire.gouv.fr/controle-des-emissions-polluants#e4

			all vehicles. Measurement: CO_2, NOx, CO, PN>23nm, NH_3, NO/NO_2	
Lab – RDE	Normal	Climatic chassis dyno	RDE test @ -2°C Measurement: CO_2, NOx, CO, HC, CH_4, PN>23nm, NH_3, N_2O, NO/NO_2	Sensitivity of polluting emissions to ambient conditions: ○ a cold cycle (T = -2 ° C) ○ a hot cycle (T = 35 ° C)
Lab – RDE	Normal	Climatic chassis dyno	RDE test @ 35°C Measurement: CO_2, NOx, CO, HC, CH_4, PN>23nm, NH_3, N_2O, NO/NO_2	

The RDE standard provides limits and criteria for judging the severity of the driving style. The acceleration of the vehicle is constrained by a maximum value of $V*A_{pos}$ (product of speed and positive acceleration) and by a minimum value of *RPA* (relative positive acceleration). The differentiation is done by driving phases (urban, rural and highway). The values subject to the standard are the 95th percentile of the distribution of $V*A_{pos}$ for each phase and the average value of RPA for each phase.

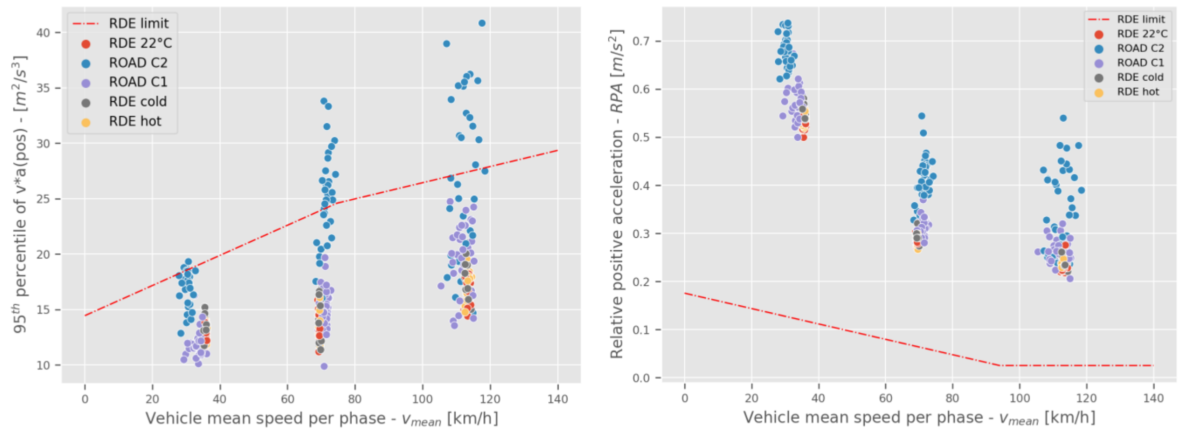


Figure 5 - Projections of the severity criteria of the RDE standard for each trial in the study; each point represents one of the 3 phases of a test (urban, rural and highway). The dotted red line describes the limit of the RDE standard.

The previous graph shows the severity of the so-called “Road C2” road tests compared to the rest of the tests. In summary, the study test protocol makes it possible to assess vehicle pollutant emissions over a wide range of driving styles in terms of dynamic conditions.

Sample of combustion engine vehicles in the study

The vehicles were selected so as to evaluate different manufacturers, segments and technologies while being representative of the French vehicle fleet by the study sample. The 16 thermal vehicles in the study are projected on 2019 sales of vehicles in France in a benchmark of CO_2 emissions and engine displacement in Figure 6. The brands of the vehicles selected represent 62% of sales in France 2019 (72% for diesel vehicles).

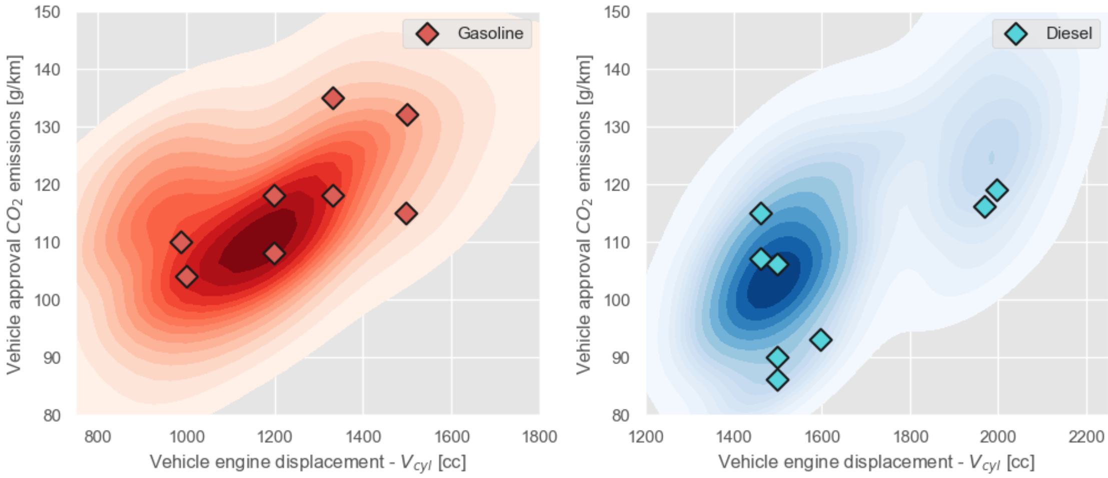


Figure 6 - Projection of the vehicles from the 2019 French sales study. The contours in the background represent the sales density for the year 2019.

Table 2 aggregates the characteristics of the different Euro 6d-TEMP vehicles with combustion engines selected for the study. For 8 petrol-powered vehicles, there are 8 different architectures of the exhaust gas aftertreatment system. This sample of vehicles represents an engine power spectrum that ranges from 83 hp. to 150 hp., which ensures the representativeness of the study vis-à-vis the bulk of current sales of gasoline vehicles in France.

Table 2 : Sample of thermal vehicles selected for the study (more exhaustive table available in Appendices)

Segment	Compact sedan	7-seater SUV	Compact SUV	Compact SUV	Family minivan	Compact sedan	City car	Compact sedan
Code	GV1 / DV1	GV2 / DV2	GV3 / DV3	GV4 / DV4	GV5 / DV5	GV6 / DV6	GV7 / DV7	GV8 / DV8
Power Gasoline/Diesel	125 /120 ch	130/130 ch	140/115 ch	150/150 ch	140/150 ch	136/115 ch	83/102 ch	126/120 ch
Mileage at start	21700km / 22000km	28800km / 24200km	24300km / 36400km	22300km / 32500km	21900km / 29100km	25100km / 42900km	29000km / 29400 km	26000km / 58000 km

The same is true for diesel vehicles, which differ from each other both in terms of post-treatment technology and engine power. Among these 8 vehicles, we find two vehicles which are equipped with NO_x depollution technologies which do not use urea injection in the form of Adblue™ (LNT technology, cf. glossary) unlike the 6 remaining vehicles.

Taking into account periodic regenerations of pollution control systems

The impact of periodic regenerations of diesel pollution control systems is taken into account by applying the ratios determined experimentally according to the Euro 6d standard methodology for CO_2, NO_x, CO and HC. The analyzes in progress show that the effects observed experimentally are close to those approved (see appendix page 34). The tests carried out also show a significant impact of the regenerations on the number of particles which must be taken into account.

V. Experimental results: emission levels of Euro 6d-TEMP conventional vehicles

Average emissions over the full protocol

The results presented in this part and a fortiori in the summary tables are **the average pollutant emissions over all the experimental tests**, described in the previous part. A distinction is systematically made between diesel and gasoline engines.

Consumption, CO_2 and greenhouse gases

The comparison of emissions between gasoline and diesel vehicles over the overall scope of the tests shows a **28% higher fuel consumption for gasoline** (+ 1.5L / 100km), **resulting in 11% higher CO_2 emissions**. On the scope of the study where N_2O and CH_4 emissions are measured, the GHG (greenhouse gas) gap is then **halved by taking into account these unregulated emissions**.

Fuel consumption and CO_2 emissions

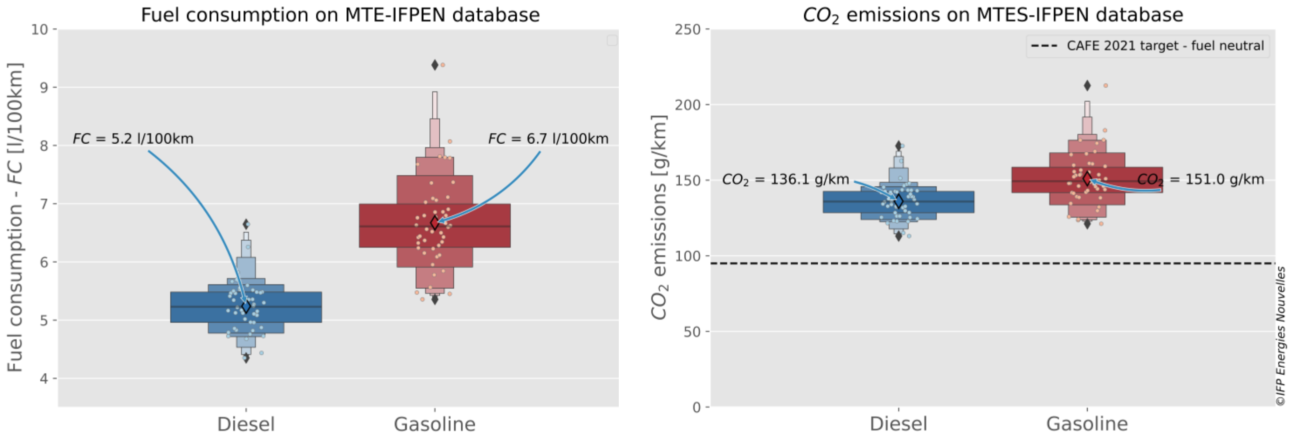


Figure 7 : Comparison of CO2 emissions and fuel consumption of gasoline and diesel vehicles over the full scope of the study

Units Type	FC [l/100km]	CO_2 [g/km]
Diesel	5.24	136.1
Gasoline	6.67	151

Emissions of N_2O and CH_4

N_2O and CH_4 are greenhouse gases (GHG) emitted by the engines of thermal vehicles which must be taken into account in the analysis of overall vehicle pollutants. For the N_2O this campaign establishes that diesel emits around 20 times more than gasoline. Regarding CH_4, diesel is also found to emit 5 times more than gasoline. Most of these excess emissions from diesel vehicles are attributable to vehicles fitted with an LNT in the exhaust gas aftertreatment line. They emit respectively 3.6 times and 22.6 times more N_2O and CH_4 than diesel vehicles which do not use them (see appendices for absolute values).

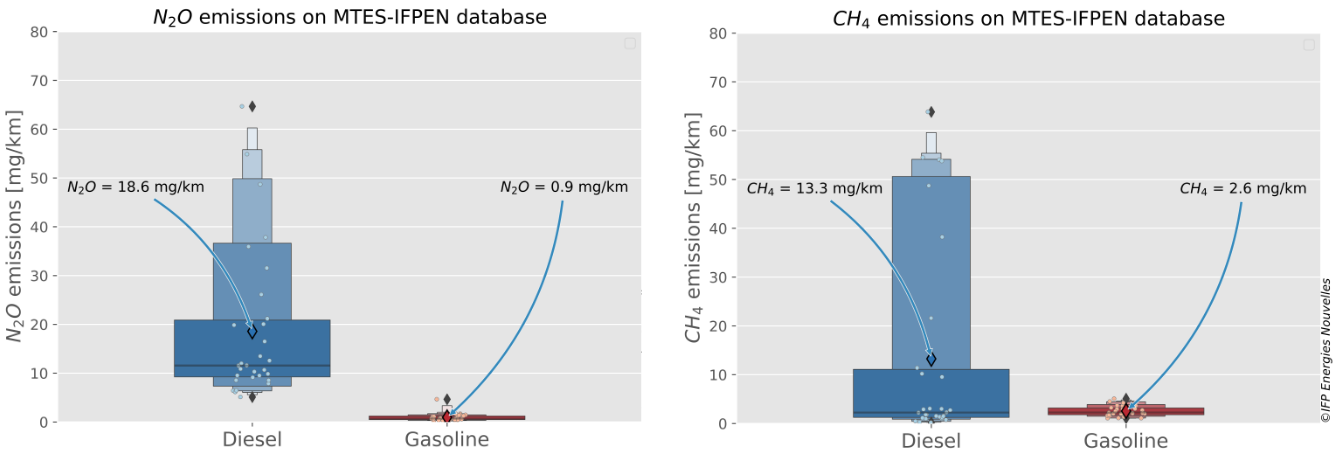


Figure 8 : Comparison of N_2O and CH_4 emissions from gasoline and diesel vehicles on the laboratory test scope (chassis dynamometer and climatic chassis dynamometer)

By incorporating these pollutants into GHG emissions, the gap between diesel and gasoline is reduced by half. This is mainly due to the strong global warming potential of these pollutants, respectively 298 and 30 for N_2O and CH_4 (i.e. 1 g of CH_4 is equivalent to 30 g of CO_2 in terms of global warming impact).

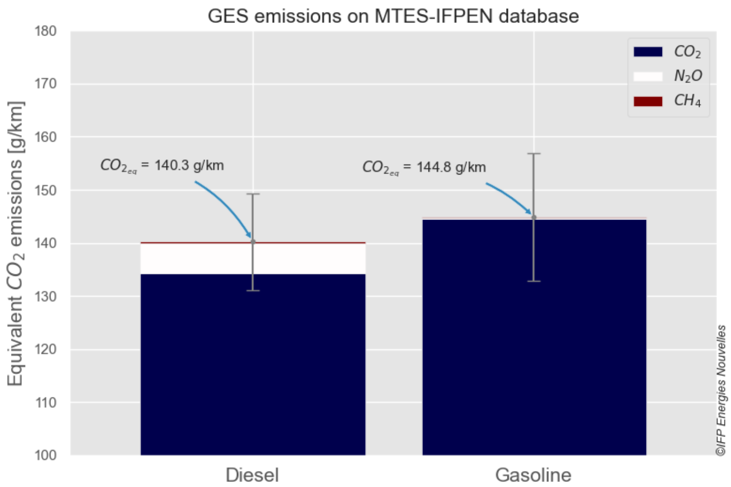


Figure 9 : Comparison of GHG emissions from gasoline and diesel vehicles on the laboratory test scope (chassis dynamometer and climatic chassis

Units / Type	CO_2 [g/km]	CH_4 eq CO_2 [g/km]	N_2O eq CO_2 [g/km]	$CO_{2,eq}$ eq CO_2 [g/km]
Diesel	134.3	0.3977	5.538	140.3
Gasoline	144.5	0.07693	0.2805	144.8

These pollutants are not regulated under the Euro 6d-TEMP standard, but their potential post-Euro 6 integration is under discussion, like the LEVIII section of the CARB regulations (framework specific to California).

Note that the emissions of N_2O and CH_4 were measured within the scope of the experimental protocol of the study with the road tests ruled out. This explains the fact that the $CO_{2\,eq}$ emissions are lower for gasoline in the adjacent table.

Local regulated pollutants

Emissions of nitrogen oxides, NO_x

The average NO_x emissions on the study protocol are **89 mg/km for diesel compared to 20 mg/km for gasoline, or 4.4 times higher**. As a reminder, the limit of the euro 6d-TEMP standard is 80 mg/km for diesel vehicles and 60 mg/km for gasoline technology vehicles during laboratory tests, to which a tolerance of a factor of 2.1 is allowed on road tests (168 mg/km and 120 mg/km respectively). This tolerance will be reduced to 1.43 in Euro 6d (from 01/2020 for new types and from 01/2021 for all vehicles).

More specifically, diesel NO_x emission levels are boosted by two vehicles without a urea pollution control system and equipped with an LNT system which has significantly higher emission levels. When considering only vehicles with a urea depollution system (SCR systems, for Selective Catalyst Reduction), the average NO_x emissions reduce to 57 mg/km, i.e. 2.9 times more than for vehicles gasoline.

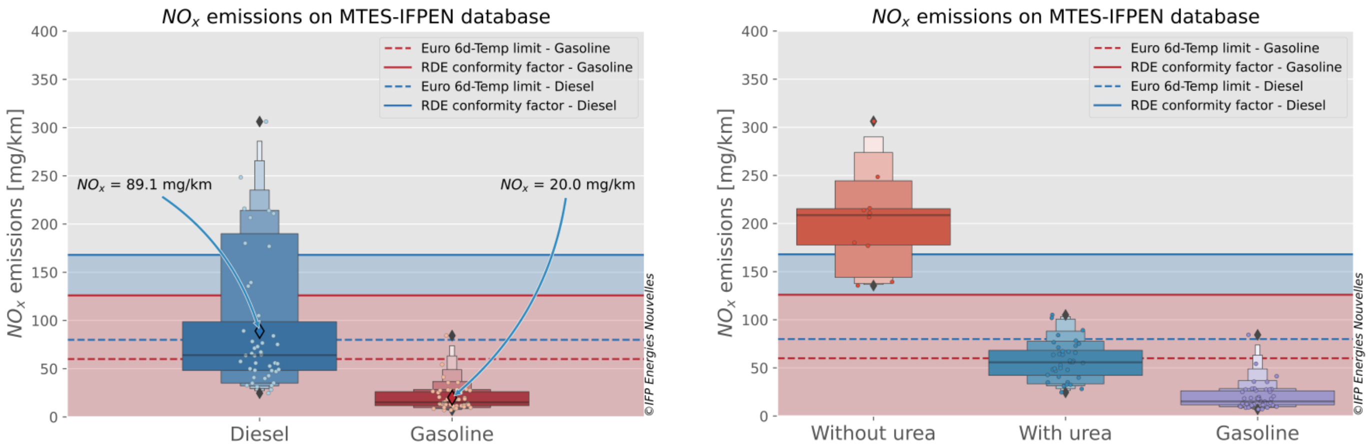


Figure 10 : Comparison of NOx emissions from gasoline and diesel vehicles over the full scope of the study

Type	Pollutant Unit EATS	count	vehicle number of tests	NO_x [mg/km]
Diesel	With urea	6	36	57.3
	Without urea	2	10	203.4
Gasoline	TWC	8	46	20.0

LNT-type pollution control systems operate by alternating phases of storing NO_x emissions and then purging phases during which NO_x is desorbed and reduced through excess fuel operation of the engine. Significant emissions of NO_x at the exhaust were observed during these purging phases, which could be explained by poor control of these events, or by deterioration of the catalyst (sulfur poisoning or thermal deterioration) at the origin of a partial reduction of NO_x. The vehicles in question totaled 22,000 and 58,000 km respectively at the start of testing.

Regulated fine-particle emissions PN_{23}

The average fineparticle emissions for size ranges greater than 23 nm are $1.6*10^{11}$ #/km in gasoline compared to $1.1*10^{10}$ #/km in diesel (14 times lower), without taking into account the impact of periodic regenerations of the DPF particulate filter (left part of Figure 11).

Emissions levels are highly variable in gasoline, with in particular a vehicle with indirect injection and without a particulate filter which exceeds the threshold of $6*10^{11}$ #/km.

It should be noted that this gap between gasoline and diesel is reduced significantly by taking into account the impact of periodic regenerations of diesel particulate filters. However, taking into account these high number of particulate emissions is not part of the Euro 6d-TEMP standard. Within the framework of the present study, correction coefficients of the emissions of PN23 were determined experimentally using the methodology applied normatively on the emissions of CO_2, CO, HC, NOx and PM mass particles.

Taking into account the impact of regenerations, **the average PN23 emission level for diesel engines reached $5.8*10^{10}$ #/km, 2.6 times less than their gasoline counterparts on the scope of the study**.

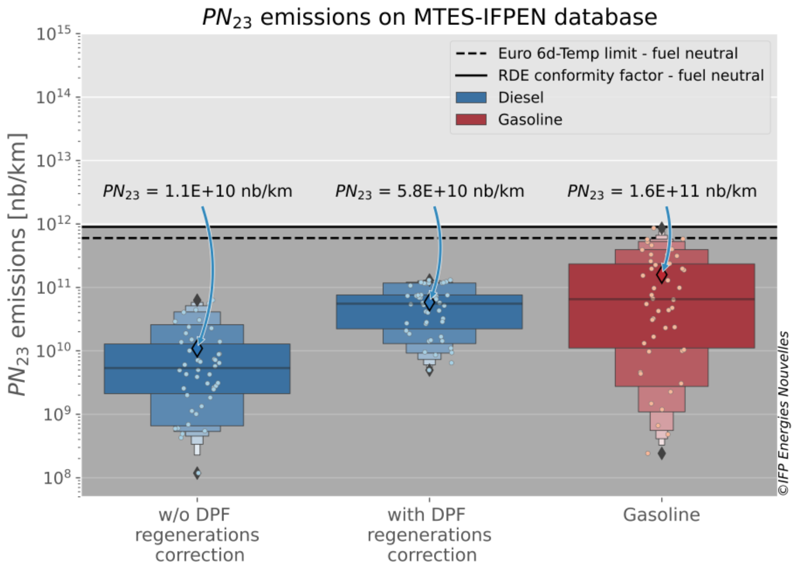


Figure 11 : Comparison of number of particulate emissions over 23 nm from gasoline and diesel vehicles over the full scope of the study

Unburnt hydrocarbon emissions, HC and carbon monoxide CO

Over the full experimental scope of the study, **HC emissions amount to 24 mg/km for diesel compared to 19 mg/km for gasoline**; as a reminder, the limit of the Euro 6d-TEMP standard is 100 mg/km of HC for gasoline vehicles and 170 mg/km of $HC + NOx$ for diesel.

In the case of CO emissions, gasoline is more polluting than diesel with an average score of 434 mg/km against 83 mg/km for diesel vehicles; as a reminder, the CO limit of the Euro 6d-TEMP standard is 1000 mg/km and 500 mg/km of CO respectively for gasoline and diesel vehicles.

For gasoline vehicles, the average CO emissions are increased by a few trips that place more stress on the engine at high load and during which the GV8 vehicle uses an **enrichment strategy** to lower the exhaust temperature.

Regarding diesel vehicles, **significant excess emissions of HC and CO are attributable to diesel vehicles using LNT** (NO_x treatment without urea) rather than SCR (NO_x treatment with urea). Indeed, the NO_x treatment principle of LNT technology is based on an engine richness operated in an active and discontinuous manner. NO_x are first stored and then processed during events called DeNOx purges which then force the engine to run at high speed. This phase results in excess emissions of HC and CO which can no longer be converted by the LNT (which is only able to process them in normal operation, i.e. in lean mode). In this analysis reference system, **the excess emissions of HC and CO are respectively 10 times and 3.7 times greater in the case where an LNT catalyst is present** compared to other post-treatment devices (see table below).

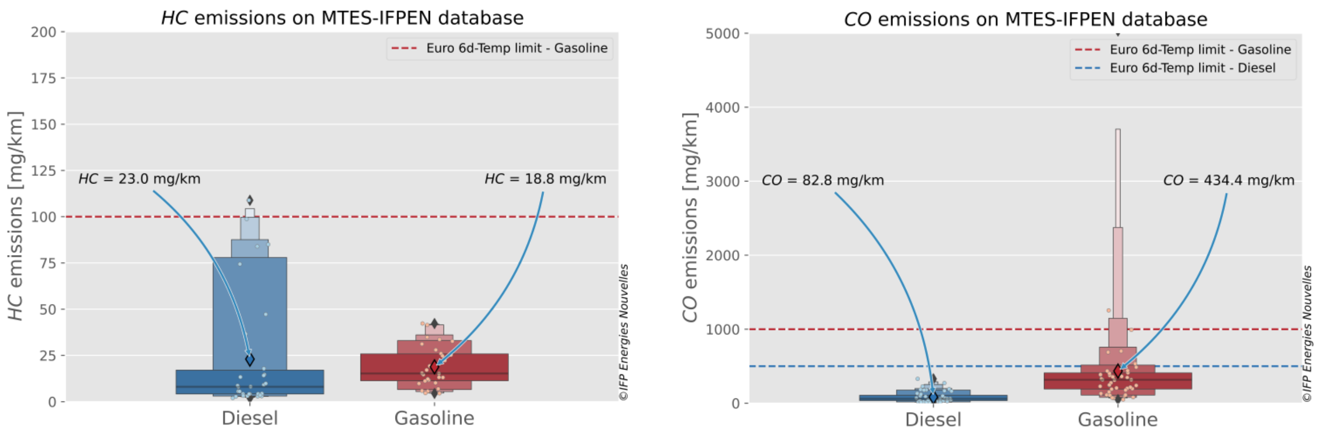


Figure 12 : Comparison of HC and CO emissions from gasoline and diesel vehicles on: laboratory tests for HC, the full scope of the study for CO

	Pollutant		vehicle		CO	HC
	Unit	count	number of tests	[mg/km]	number of tests	[mg/km]
Type	EATS					
Diesel	w LNT	2	10	193.5	6	83.0
	w/o LNT	6	36	52.1	24	8.0
Gasoline	TWC	8	46	434.4	30	18.8

Unregulated local pollutants

NH_3 ammonia emissions

NH_3 emissions are not part of the regulatory framework of the Euro 6-dTEMP standard. They nevertheless contribute to the degradation of air quality as **precursors of very fine particles and as a gas toxic to humans above a certain concentration threshold**.

In the case of gasoline, ammonia is a reaction product in 3-way catalytic converters (TWCs) through *in situ* production of hydrogen during excursions into rich engine operation (cold start, high acceleration or driving at high speed). In the case of diesel vehicles, these emissions result from the treatment of NO_x by urea in the SCR catalyst. The NH_3 releases then depend on the urea injection control strategy and the function of the last catalyst in the exhaust gas aftertreatment line: NH_3 storage (better capacity for the SCR than the SCR-F) or **catalyst dedicated to the treatment of NH_3** (known as ASC, see glossary).

In the experimental scope of the study, the average NH_3 emissions are **11 mg/km for diesel compared to 15 mg/km for gasoline vehicles**. However, in the case of diesel, this average value is pulled upwards by one technology in particular.

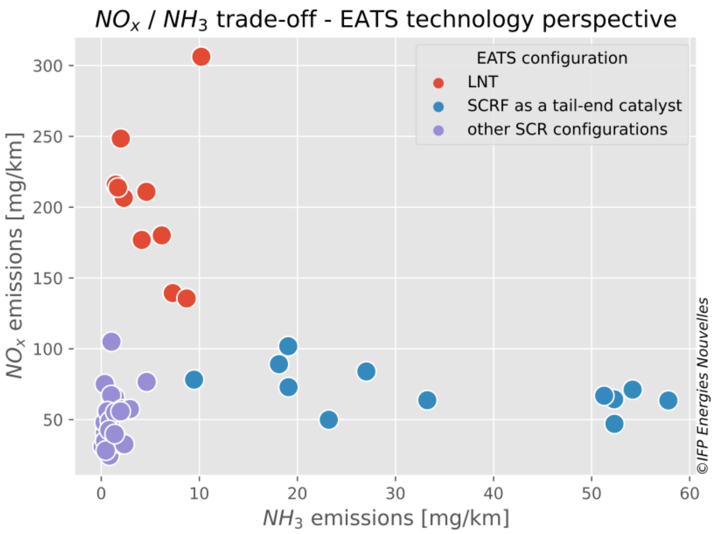


Figure 13 : Compromise of NH3 and NOx emissions in a NOx treatment technology benchmark (each point represents the final cumulative score of a diesel vehicle test).

Figure 13 shows the trade-off of NH_3 and NO_x emissions as a function of the NO_x treatment technologies. It has previously been mentioned that diesel vehicles equipped with LNTs have much higher levels of NO_x emissions. The use of a more efficient SCR for the decontamination of NO_x is therefore to be favored, but the question of the compromise with an increase in NH_3 emissions could arise. Indeed, SCR systems can generate NH_3 due to whether a poor management of urea injection or a lack ofammonia storage capacity of catalysts. This graph nevertheless shows that certain vehicles equipped with SCRs manage to effectively depollute NO_x while maintaining very low NH_3 levels. More precisely, only vehicles whose SCR depollution line ends with a SCR-F-type catalytic block (see Glossary), which is less efficient in terms of NH_3 storage , exhibit high ammonia emissions.

Unregulated fine-particle emissions PN_{10}

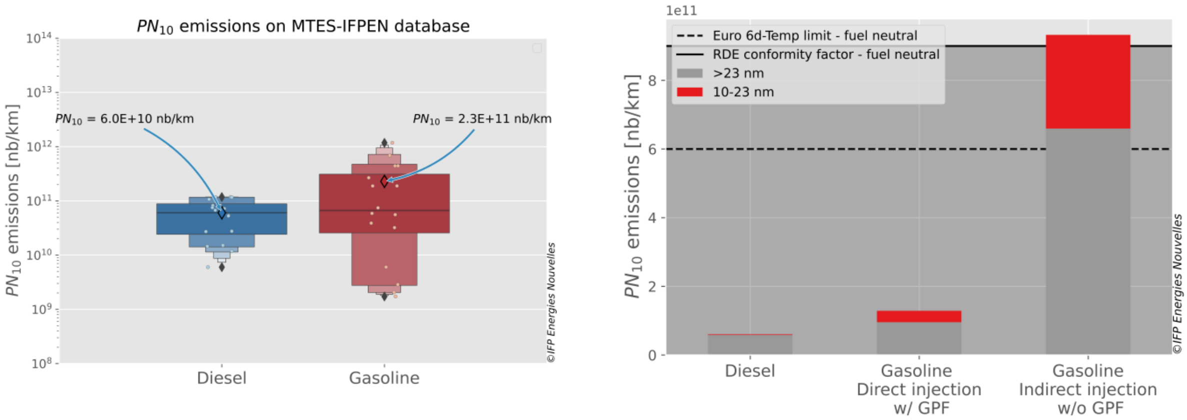


Figure 14 : Comparison of number of particle emissions of more than 10nm from gasoline and diesel vehicles on the scope of non-climatic chassis dynamometer tests

Type	Pollutant Unit EATS	count	vehicle number of tests	PN_{23} [nb/km]	number of tests	PN_{10} [nb/km]	number of tests	$10-23\ nm$ [%] of PN
Diesel	DPF or SCRF	8	46	5.83e+10	16	6.03e+10	16	6.83e+00
Gasoline	Direct injection with GPF	7	40	1.20e+11	14	1.29e+11	14	3.32e+01
	Indirect injection w/o GPF	1	6	4.12e+11	2	9.32e+11	2	3.00e+01

For gasoline vehicles equipped with direct injection, the average PN10 emissions are 2 times higher than those of diesel vehicles. **In the case of a vehicle with indirect injection (and without a GPF particle filter), this level of excess emissions of gasoline compared to diesel then amounts to 7**. This result does not allow a general conclusion to be drawn regarding this technology given that it concerns only one gasoline vehicle among the eight in the study.

Note: As the PN10 measurement was not systematically available on the characterization tests of periodic regenerations, the levels of PN10 emissions from diesel vehicles presented above are corrected by the coefficients determined on the PN23.

In addition, the share of particles with sizes between 10 nm and 23 nm among all the PN10 emitted (i.e. all particles of size> 10 nm) is generally higher for gasoline than for diesel, from around 30% for the first versus 7% for the last (see table above). In absolute terms, gasoline therefore emits more fine particles and these have the particularity, more impacting on the health plan, of being smaller than those emitted by diesel vehicles.

Focus on temperature sensitivity and driving style

The experimental protocol of the study makes it possible to assess the emission behavior of vehicles over a wide temperature range (RDE at -2 ° C, +22 ° C and +35 ° C) and for different driving styles (normal and severe). The table below summarizes the average pollutant emission scores for each type of test.

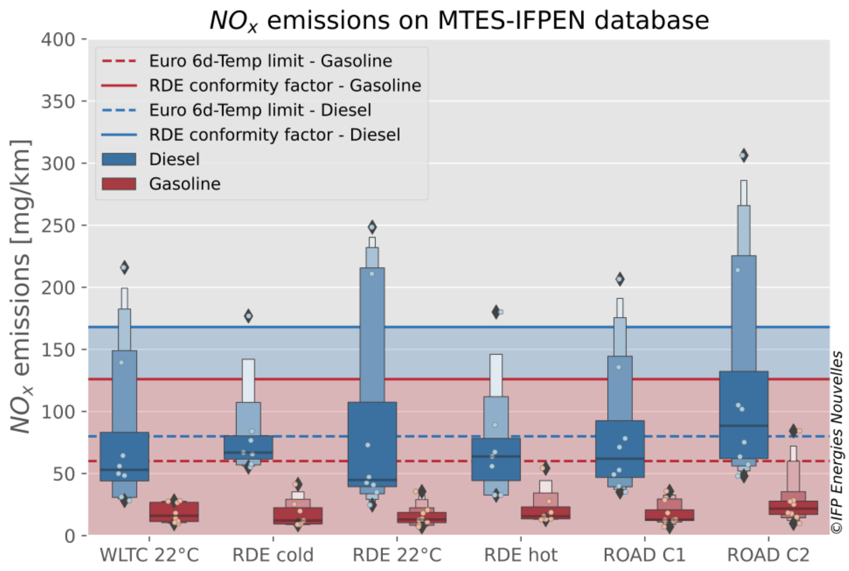


Figure 15 : Comparison of NOx emissions from gasoline and diesel vehicles for each type of test performed

Test type	Pollutant Units Fuel	CO_2 [g/km]	NO_x [mg/km]	CO [mg/km]	HC [mg/km]	CH_4 [mg/km]	NH_3 [mg/km]	N_2O [mg/km]	PN_{23} [nb/km]	PN_{10} [nb/km]
RDE 22°C	Diesel	130.9	90.27	62.87	20.16	13.45	10.06	16.35	5.9e+10	6.177e+10
	Gasoline	144.2	15.79	372.8	10.75	2.091	16.79	0.8545	1.386e+11	2.099e+11
RDE cold	Diesel	135.7	83.24	94	23.16	10.41	13.26	21.49	4.901e+10	N/A
	Gasoline	142	17.94	331	29.89	3.019	14.83	0.6859	1.257e+11	N/A
RDE hot	Diesel	136	74.45	61.52	15.11	9.593	9.293	15.35	5.425e+10	N/A
	Gasoline	143.1	22.23	258	10.17	1.955	14.87	1.045	8.167e+10	N/A
ROAD C1	Diesel	133.5	83.53	67.89	N/A	N/A	9.817	N/A	6.363e+10	N/A
	Gasoline	151.5	17.37	374.2	N/A	N/A	12.68	N/A	1.62e+11	N/A
ROAD C2	Diesel	145.3	121.3	111.8	N/A	N/A	11.58	N/A	6.485e+10	N/A
	Gasoline	174.9	28.24	929.8	N/A	N/A	17.94	N/A	2.355e+11	N/A
WLTC 22°C	Diesel	135.1	79.13	97.52	32.67	18.76	10.74	21.1	5.746e+10	5.886e+10
	Gasoline	148.1	18.21	305.7	24.85	3.173	15.26	1.161	1.934e+11	2.485e+11

The cold and hot tests on a climatic bench ("RDE cold" at -2 °C and "RDE hot" at +35 °C) cause excess emissions for diesel and gasoline vehicles compared to those of the same tests at 22 ° C**. For diesel vehicles with SCR, the "RDE cold" tests**, which imply a longer heating time (and therefore a higher activation time) of the pollution control system, induce excess emissions of **+54% of NO_x** compared to the same tests at standard temperature 22 ° C. The same applies to gasoline vehicles which, in "RDE cold" tests, exhibit **+ 16% CO emissions and +165% HC emissions** compared to the case of standard temperature tests.

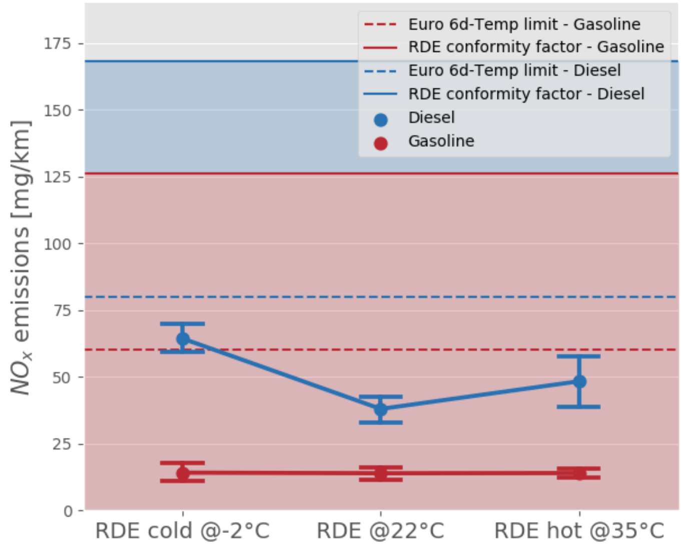


Figure 16 : Ambient temperature sensitivity of NOx emissions on the experimental scope of the RDE tests carried out on conventional chassis dynamometers (@ 22 ° C) and climatic (@ -2 ° C and @ 35 ° C). For this graph, only diesel vehicles without LNT are considered.

Concerning the sensitivity of the emission levels to the driving style, an increase is noteworthy for severe road tests ("Road C2") compared to those meeting the criteria of the RDE standard ("Road C1"). To take only these, **the NO_x emissions in diesel are up 45% on severe RDE tests compared to those in RDE compliant**. In essence, the CO emissions on the Road C2 are at 930 mg/km, i.e. above those on the Road C1 tests with 374 mg/km, which represents an increase of +149%. However, among the sample of gasoline vehicles, one element shows a very high level of excess CO emissions on severe RDE: by excluding it from the scope, excess CO emissions in gasoline are reduced to 38% between compliant and dynamic RDE.

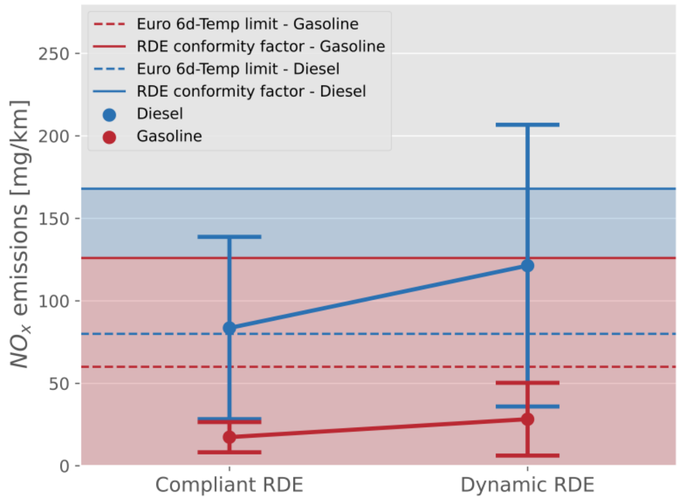


Figure 17 : Driving style sensitivity of NOx emissions on the experimental scope of the RDE road tests

VI. Experimental results: contributions of hybridization

This part of the study aims to characterize the contribution of different levels of hybridization in GHG (greenhouse gas) emissions and local pollutants. To do so, a sample of 6 vehicles was evaluated over the same experimental protocol:

- a couple of city cars compared to gasoline vs. hybrid;
- a couple of urban SUVs in hybrid vs. plug-in hybrid,
- a couple of sedans compared to plug-in hybrid gasoline vs. plug-in hybrid diesel.

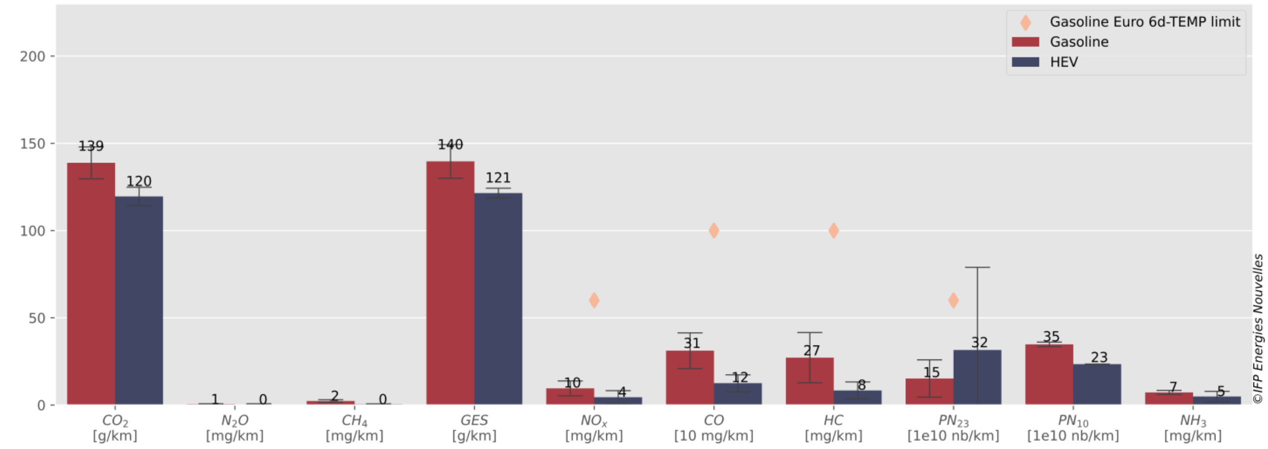
Table 3 : Technical specifications of the selected non plug-in and plug-in hybrid electric vehicles.

	City car		Compact SUV		Sedan	
	Conventionnal	HEV	HEV	PHEV	PHEV Essence	PHEV Diesel
Test mass	1301 kg	**1310 kg**	1663 kg	**1725 kg**	1885 kg	**1970 kg**
CO_2 WLTP EOM	136 g/km	**114 g/km (-16%)**	114.3 g/km	**31.3 g/km (-73%)**	CS : 146 g/km Weighted: 31 g/km	CS: **140 g/km (-4%) Weighted: 30.5 g/km (-2%)**
Gearbox	BM6	**CVT**	DCT6		9-speed automatic transmission	
Engine	1.5L 4cyl 82 kW atmo. Indirect injection	**1.5L 4cyl 54 kW atmo. Indirect injection**	1.6L 4cyl 77 kW atmo. Direct injection		2.0L 4cyl 155 kW turbo Direct injection	2.0L 4cyl 143 kW turbo Direct injection
Battery HT	-	**0.94 kWh – 144 V**	1.56 kWh – 240 V	**8.90 kWh – 360 V**	**13.5 kWh – 365 V**	
Electric motor	-	**45 kW**	32 kW	**45 kW**	90 kW	
After-treatment	TWC	TWC	CC TWC + UF GPF		2*TWC + GPF	DOC SCRF-SCR
Electric range announced	-	-	-	58 km	56 km	57 km

From gasoline to non-rechargeable hybrid vehicles (HEV)

This paragraph summarizes the comparison on the experimental protocol of a conventional city car (1.5L 82kW indirect injection gasoline engine) with its hybrid counterpart (same model, 1.5L 54kW indirect injection gasoline engine coupled to a 45kW electric machine and a 0.9kWh battery, resulting in an additional 30kg mass on the empty weight).

Electric driving - The fully electric driving rate of the hybrid vehicle is highly dependent on the type of driving. On the scale of complete cycles operated, it varies between 23% and 42% of the distance traveled.



Test type	Fuel	CO_2	N_2O	CH_4	GES	NO_x	CO	HC	CH_4	PN_{23}	PN_{10}	NH_3
		[g/km]	[mg/km]	[mg/km]	[g/km]	[mg/km]	[10 mg/km]	[mg/km]	[mg/km]	[1e10 nb/km]	[1e10 nb/km]	[mg/km]
Gasoline	Gasoline	138.8	0.5	2.3	139.6	9.5	31.1	27.1	2.3	15.2	34.8	7.2
HEV	Gasoline	119.5	0.4	0.5	121.5	4.4	12.5	8.3	0.5	31.5	23.4	4.9

Figure 18 : Comparison of the average emissions of the gasoline and hybrid vehicle selected on the experimental protocol.

GHG - The hybrid vehicle has CO_2 emissions that are on average 14% lower over the assessed scope. This gain is sensitive to the conditions of use. **This gain is in fact 33% on urban parts, while it is zero (+ 0.6%) on motorway sections**. Taking into account unregulated GHGs CH_4 and N_2O has little influence on this finding. Since their measurement is not available for road tests, the CO_2 scores (calculated over the entire experimental scope) are found to be equivalent to the GHG scores.

Local pollutant emissions – The two gasoline and hybrid vehicles presented controlled emission levels and below the Euro 6d-temp thresholds regardless of the cycles operated. Hybridization allows in this study case a substantial reduction in CO and NOx emissions (-60% and -54% respectively), but a significant increase in particles.

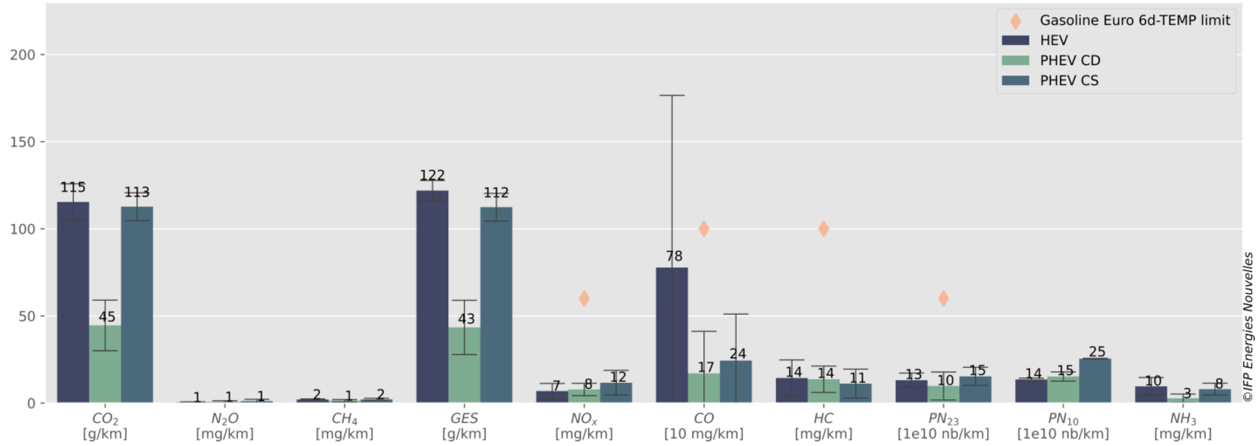
From hybrid to rechargeable hybrid (PHEV)

This paragraph summarizes the comparison on the experimental protocol of a non-rechargeable hybrid SUV (1.6L 77kW direct injection gasoline engine coupled to a 32 kW electric machine and a 1.6kWh battery) with its plug-in hybrid counterpart (same model, same gasoline engine coupled to a 45kW electric machine and an 8.9kWh battery, inducing a 104kg mass increase in empty weight).

Electric driving - The driving rate in all-electric mode of the hybrid vehicle strongly depends on the type of driving. On the scale of the complete cycles operated, it varies between 28% and 46% of the total distance. When the PHEV vehicle has its battery empty, it is in charge sustaining mode[8] and will then have the same all-electric driving capacities as its hybrid counterpart. With a full battery start, the running rate in all-electric mode reaches 64% to 100% depending on the cycles operated due to

[8] Plug-in hybrid vehicles operating mode: PHEV have very distinct operating modes depending on the state of charge of the battery: predominantly electric operation when the battery is charged, preferentially consuming electrical energy from recharging (Charge Depleting mode - CD) then hybrid operation close to a non-rechargeable vehicle when the battery is empty (Charge Sustaining mode - CS). PHEV vehicles were evaluated in both of these modes of operation throughout the protocol.

their variable lengths and dynamics (the detail of the corresponding electric autonomy depending on the conditions of use is established in the next sectionof this report).



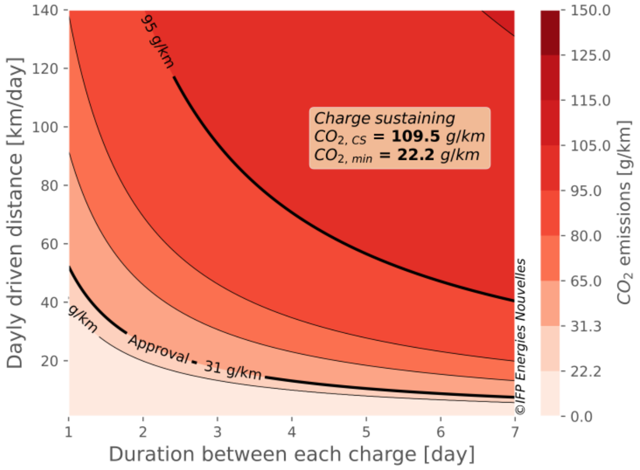
Test type	Fuel	CO_2	N_2O	CH_4	GES	NO_x	CO	HC	CH_4	PN_{23}	PN_{10}	NH_3
		[g/km]	[mg/km]	[mg/km]	[g/km]	[mg/km]	[10 mg/km]	[mg/km]	[mg/km]	[1e10 nb/km]	[1e10 nb/km]	[mg/km]
HEV	Gasoline	115.4	0.5	2.0	121.9	6.9	77.7	14.4	2.0	13.1	13.5	9.6
PHEV CD	Gasoline	44.6	0.8	1.3	43.4	7.8	17.0	13.7	1.3	9.8	15.2	2.7
PHEV CS	Gasoline	112.7	1.1	2.1	112.4	11.7	24.4	11.1	2.1	15.3	25.5	8.0

Figure 19 : Comparison of the average emissions of the non-rechargeable hybrid (HEV) and plug-in hybrid vehicle selected on the experimental protocol.

GES - With a charged-battery start (CD mode), the PHEV vehicle recorded average CO_2 emissions of 45 g / km on the tests carried out. If the emissions are indeed zero on a WLTC test because the cycle distance is less than the electric range, the heat engine starts on the RDE tests because of the distance being greater than the electric range but also earlier on high p**ower demands due to more dynamic driving**. The 45 kW on-board electric machine cannot cater for all power demand levels for this vehicle weighing more than 1.7 tons.

By operating with an empty battery (CS mode), the plug-in hybrid vehicle behaves similarly to the non-plug-in hybrid vehicle (113 and 115 gCO_2/km respectively). The additional mass induced by the excess battery has no significant impact. However, the environmental impact of the production of this under-exploited battery surplus must be taken into account: with an assumption of 106 gCO_2/kWh, the PHEV battery represents an additional emission to the production of approximately 780 kg of CO_2, i.e. the equivalent of an additional **4 gCO_2/km over 200,000 km**.

The actual emissions of a PHEV vehicle therefore depend on the weighting between the full battery and empty battery modes. Figure 20 shows a map of CO_2 emission levels according to the battery charging frequency and the daily distance achieved. **It illustrates this strong dependence of emissions from PHEV vehicles on the charging frequency.**



Illustrative examples:

CO_2 [g/km]	*Recharge every day*	*Recharge every 3 days*	*Recharge every week*
20 km/ day	22	43	82
50 km/ day	29	84	100
130 km/ day	80	102	108

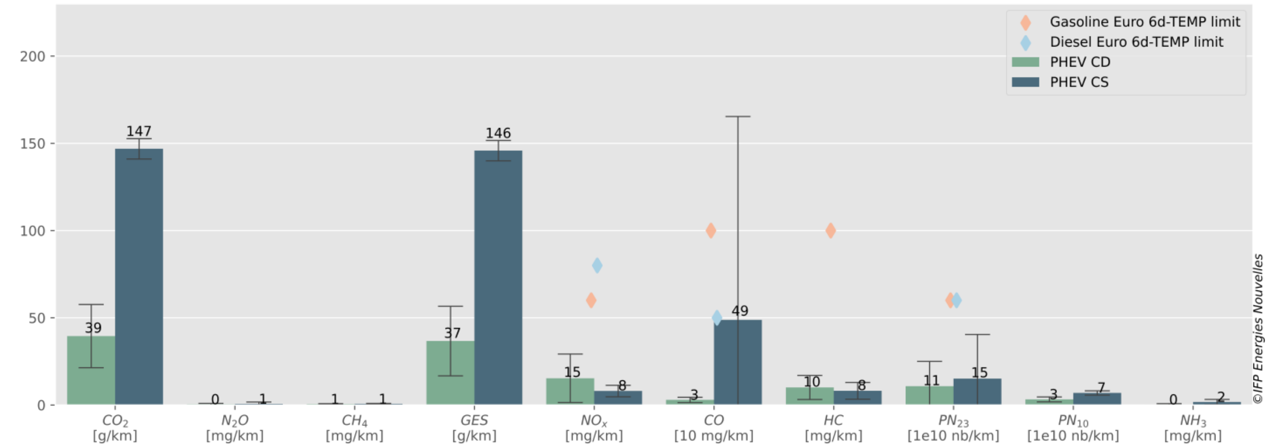
Figure 20 : CO_2 emissions of the PHEV vehicle depending on the frequency of recharging and the length of daily journeys. The approved CO_2 score is also shown (Approval). The considered scope does not include climatic tests which will be treated separately in this document.

Local pollutant emissions - Despite this very different electric driving rate in CS and CD mode, the PHEV vehicle has average **levels of local pollutant emissions that are generally comparable in these two modes**. These levels are also close to those of the non-rechargeable hybrid vehicle, with the exception of CO, for which the non-rechargeable vehicle has higher emissions (greater sensitivity to driving style). Compared to the sample of conventional gasoline vehicles tested in this study, **these two HEV and PHEV vehicles have lower than average emissions** (with the exception of the CO of the HEV).

PHEV: diesel vs gasoline

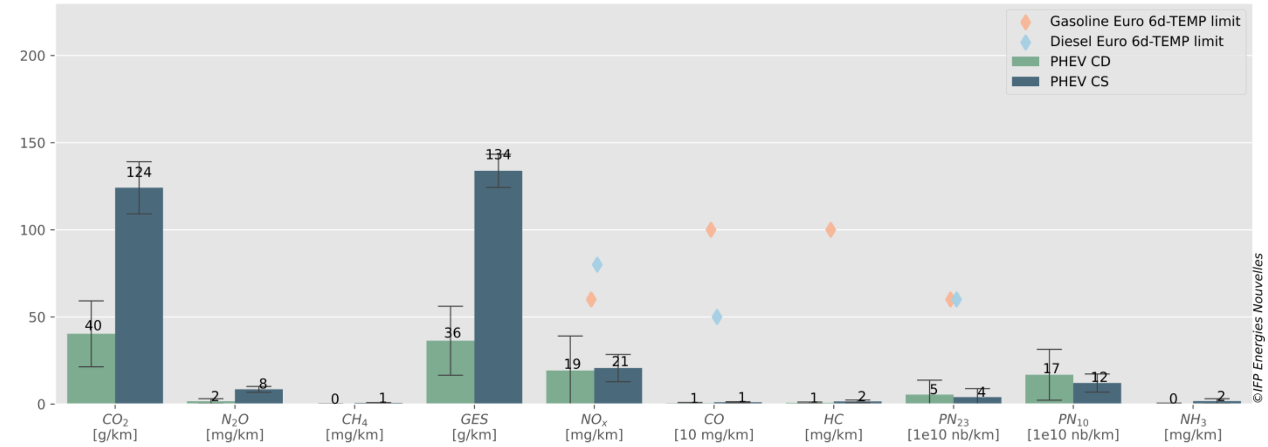
This paragraph summarizes the comparison on the experimental protocol of a plug-in hybrid gasoline sedan (2.0L 155kW direct injection gasoline engine coupled to a 90 kW electric machine and a 13.5 kWh battery) with its plug-in hybrid diesel counterpart (same model, 2.0L 143kW diesel engine coupled to the same electrical components, having an excess of 80kg on empty weight).

Electric driving – The two gasoline and diesel vehicles tested have identical electrical characteristics (battery and machine). The driving capacities in all-electric mode which have been evaluated are expectedly very close. With an on-board electrical power of 90 kW, early start-ups of the heat engine in charge-depleting mode are more seldom than with the PHEV carrying an electrical power of 45 kW, mentioned in the previous paragraph. Note that this difference in behavior is only observed on the most dynamic driving cycles.



Test type	Fuel	CO_2	N_2O	CH_4	GES	NO_x	CO	HC	CH_4	PN_{23}	PN_{10}	NH_3
		[g/km]	[mg/km]	[mg/km]	[g/km]	[mg/km]	[10 mg/km]	[mg/km]	[mg/km]	[1e10 nb/km]	[1e10 nb/km]	[mg/km]
PHEV CD	Gasoline	39.5	0.4	0.5	36.7	15.3	2.9	10.1	0.5	10.8	3.2	0.3
PHEV CS	Gasoline	146.8	0.6	0.7	145.8	8.0	48.8	8.1	0.7	15.1	6.9	1.7

Figure 21 : Comparison of the average emissions in CS and CD mode of the gasoline plug-in hybrid vehicle selected on the experimental protocol.



Test type	Fuel	CO_2	N_2O	CH_4	GES	NO_x	CO	HC	CH_4	PN_{23}	PN_{10}	NH_3
		[g/km]	[mg/km]	[mg/km]	[g/km]	[mg/km]	[10 mg/km]	[mg/km]	[mg/km]	[1e10 nb/km]	[1e10 nb/km]	[mg/km]
PHEV CD	Diesel	40.3	1.6	0.1	36.3	19.3	0.5	0.8	0.1	5.4	16.8	0.3
PHEV CS	Diesel	124.1	8.5	0.7	133.8	20.7	1.1	1.5	0.7	4.0	12.1	1.7

Figure 22 : Comparison of the mean emissions in CS and CD mode of the diesel plug-in hybrid vehicle selected on the experimental protocol.

GHG - In full battery operation, CO_2 emissions are very comparable for gasoline and diesel, respectively 15 and 14 gCO_2/km on average. Maintaining an empty battery state of charge, the average emissions are respectively 147 and 124 gCO_2/km, **a gain of 16% for the PHEV diesel vehicle compared to its gasoline counterpart**.

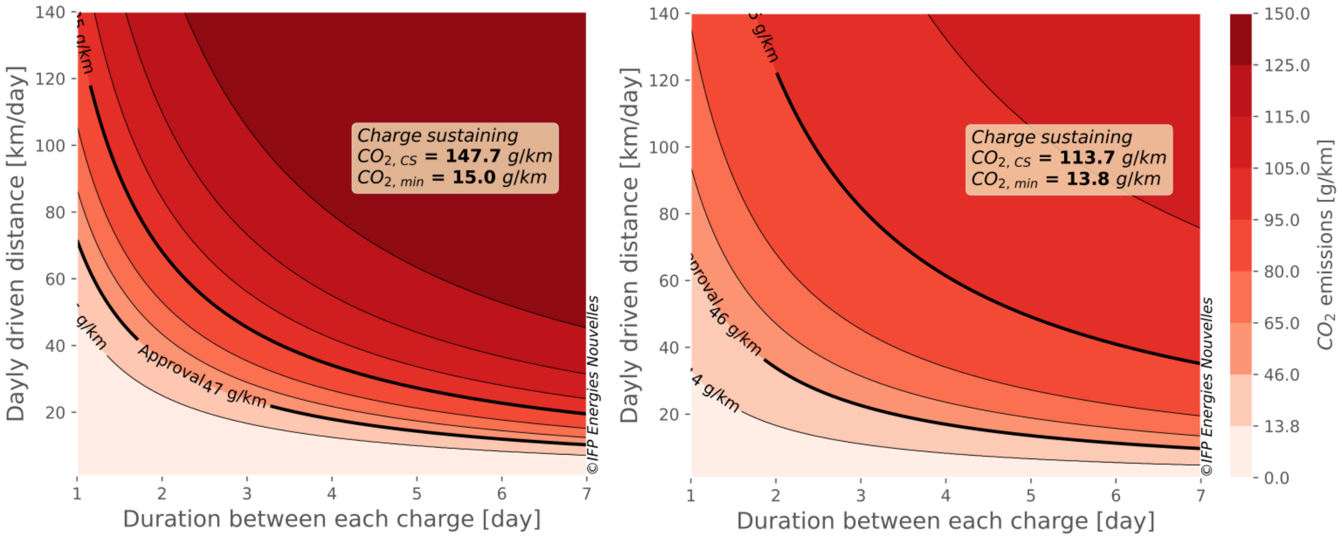


Figure 23 - CO2 emissions from PHEV gasoline (left) and diesel (right) vehicles, depending on the frequency of recharging and the length of daily trips. The approved CO2 score is also shown (Approval). Tests on a climatic chassis dynamometer are excluded from the considered scope.

Local pollutant emissions - The PHEV gasoline vehicle exhibits significant CO and PN emissions on very dynamic uses. Apart from these points, the emissions of local pollutants from the gasoline and diesel plug-in hybrid vehicles tested are controlled, below the Euro 6d-temp standard and the average for conventional vehicles assessed elsewhere in this study. Both gasoline and diesel vehicles show significant increases in NO_x and PN emissions on cold tests at -2 °C, but with levels still under control and below standards.

Electric range of PHEV vehicles and sensitivity to ambient temperatures

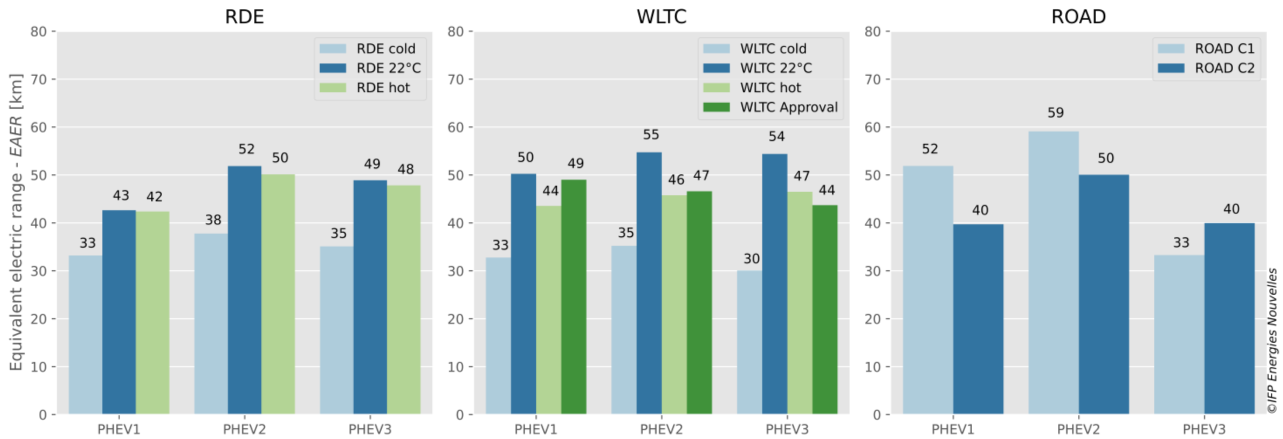


Figure 24 : Recalculated electrical equivalent range of the three PHEV vehicles of the study by type of test. The entire experimental perimeter is considered.

Figure 25 illustrates the impact of test temperature on PHEV CO_2 emissions depending on its use. In particular, for the cold tests, significant CO_2 emissions are observed for the most favorable scenario, that is to say a short daily distanceachieved and a daily recharge, in comparison with the tests carried out at 22 °c and 35 °c. This is attributable to **the start of the combustion engine to provide heating for the passenger compartment** in the absence of an electrified heating system on this model of vehicle. In general, maintaining thermal comfort involves additional energy expense resulting in a decrease in electric range (see Figure 24) and therefore an increase in CO_2 emissions for the same use.

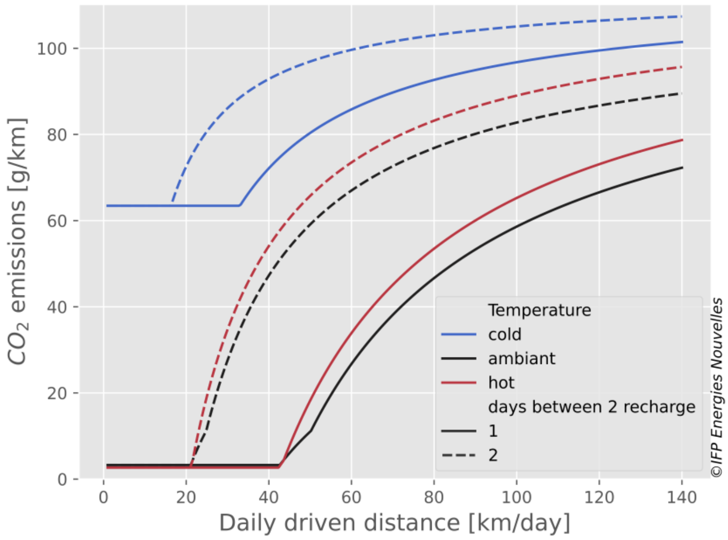


Figure 25 : Impact of the test temperature on CO_2 emissions according to use for PHEV gasoline SUV : comparison of RDE tests on cold (-2 °c), nominal (22 °c) and hot (35 °c). Road tests are excluded from the considered perimeter to isolate the temperature effect on identical routes.

In other words, the farther the test temperature from ambient (22°C) the shorter the daily driven distance at which CO_2 emissions start to increase. In addition, the impact of the charging frequency is also illustrated: CO_2 emissions are higher for a greater number of days between two recharges. In fact, the portion of all-electric mode operation decreases as the number of days between two recharges increases. And the share of emissions in battery charge sustaining mode is becoming more and more preponderant in the total CO_2 emissions score.

For the two PHEV sedans, as for the PHEV SUV presented above, **maintaining the thermal comfort of the passenger compartment results in additional on-board energy consumption and results in a reduction in electric range**. However, the two PHEV sedans have an electrified passenger compartment heating technology which eliminates the need for thermal engines on cold tests with full battery (CD mode). This allows these PHEVs to display almost zero CO_2 emissions until the battery is completely discharged regardless of the climatic environment of the tests.

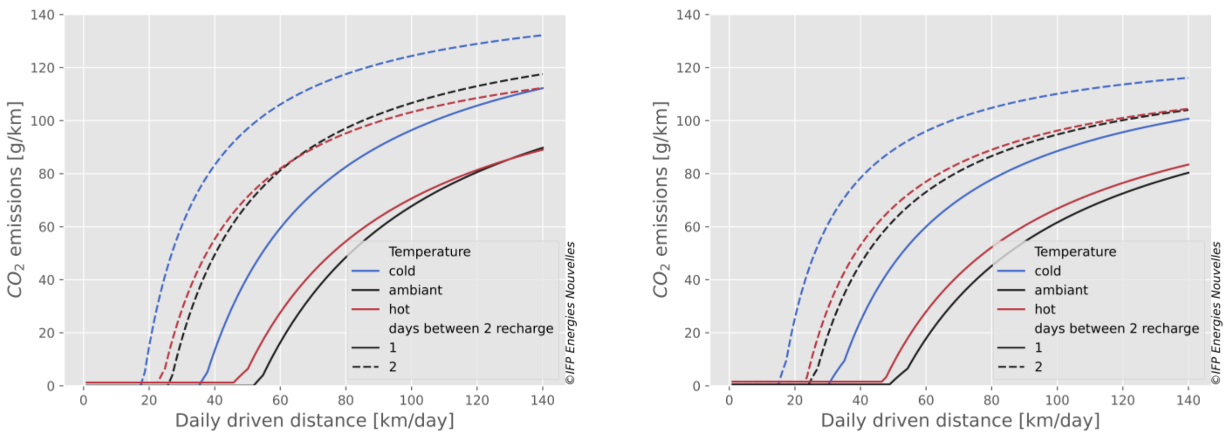


Figure 26 : Impact of test temperature on CO_2 emissions as a function of use. The scope considered consists of the RDE and WLTC tests on a climatic chassis dynamometer (gasoline on the left, diesel on the right).

VII. Emission levels for typical real uses

Chapter V demonstrates that the Euro 6d-TEMP standard has overall made it possible to achieve emission levels in real use that comply with Euro 6 regulatory limits, over a well-defined perimeter of use corresponding to RDE tests, or even extended in terms of driving severity. However, the RDE tests are not representative of daily use, especially in terms of travel distance. This chapter discusses the environmental performance of Euro 6d-TEMP vehicles tested in these typical targeted uses.

Behavior on typical targeted uses

Emissions levels are rising significantly in urban use. In particular, NOx emissions: + 79% in gasoline and + 74% in diesel when considering the standard RDE phases, and even more by focusing on conditions truly representative of urban use (very short and slow journeys, cf. Appendices). The average diesel level in urban use then reached 172 mg/km, i.e. a level of excess emissions of + 100%.

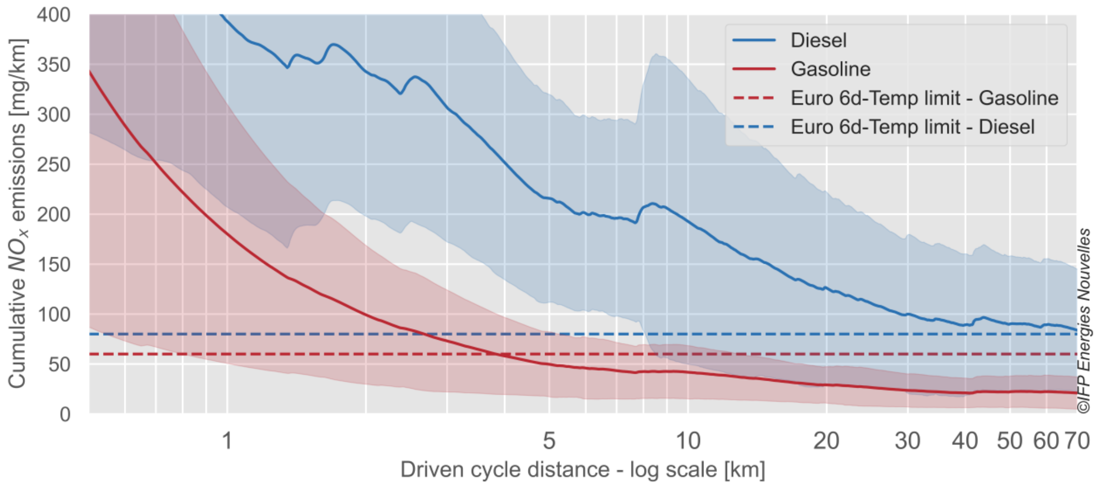


Figure 27 : Evolution of cumulative NOx emissions as a function of the distance on the RDE test

Figure 27 shows the evolution of cumulative NO_x emissions during an RDE trip. All the RDE tests on the road or in the laboratory are represented in this graph; the solid line represents the dynamic mean while the colored area on either side of this line represents the standard deviation of the data. The logarithmic scale makes it possible to highlight **the difficulty for diesel engines to achieve the emission levels dictated by the standard in the first kilometers of operated journeys**. The changes in other emissions as a function of the distance on the RDE test are presented in Appendix 4. They show in particular the significant excess emissions of CO, HC and PN from gasoline vehicles on short journeys, but with faster dynamics making it possible to pass under normative thresholds from a distance covered of 10 km.

It is useful to note that most trips taken in real-world use do not always look like an RDE cycle, especially when it comes to the distance of the cycle. For example, **half of the journeys in the city centers of large French agglomerations are less than 5 km**: it is easy to understand that the level of NO_x emissions from a **full RDE test of about 80 km is not representative of actual use**. It is therefore necessary to correct the pollutant emissions determined on the tests of the standard (RDE or WLTC tests) based on knowledge of the actual journeys on the scale of a city or a region (cf. Appendices for methodology).

Figure 28 illustrates the differences in NO_x emissions depending on the analysis chosen :

- The first two kilometers: cumulative emissions over the first 2 km ("1 st 2 km").
- Emissions corrected by real-world usage: cumulative emissions weighted by usage factors (see Appendices, "RDE $_{UF\text{-}weighted}$").
- Urban phase: the cumulative emissions calculated over the urban phase of the test ("RDE $_{urban}$").
- Full RDE tests: the cumulative emissions calculated over the entire test ("RDE $_{tot}$").

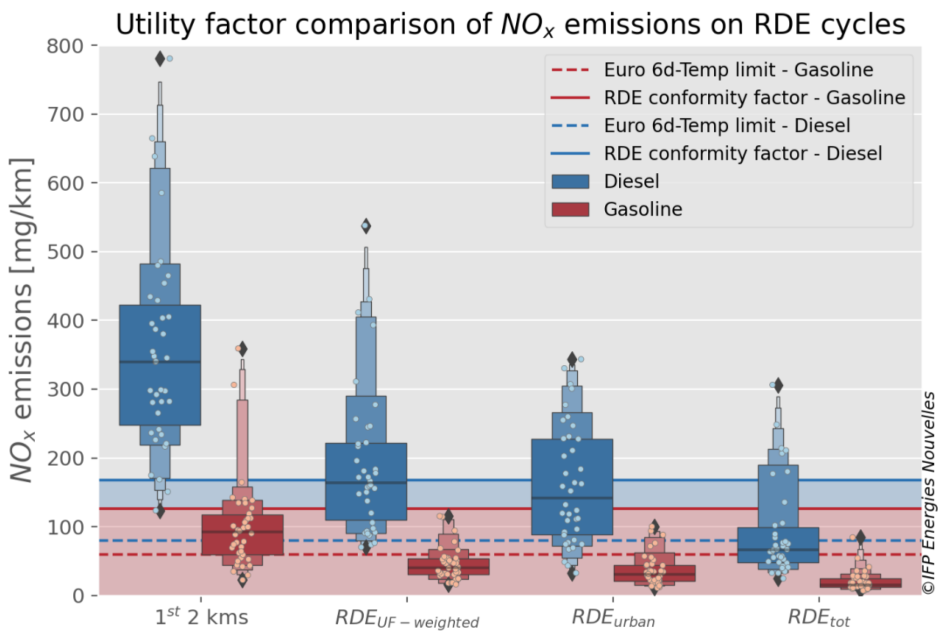


Figure 28 : NOx emissions on full RDE tests, urban or weighted by actual use.

The table below summarizes the results of the study for regulated pollutants according to the types of score presented in the previous graph.

Pollutant	Units	Type	RDE total	UF-weigthed	First 2 kms	Urban phase
CO_2	[g/km]	Diesel	136.3	171.5	182.8	162.1
		Gasoline	151.6	192.7	208.1	182.8
NO_x	[mg/km]	Diesel	91.19	190.6	352.7	160.2
		Gasoline	20.33	45.51	99.95	36.43
CO	[mg/km]	Diesel	79.71	300.4	874.7	220.3
		Gasoline	461.5	941.3	2303	667.6
HC	[mg/km]	Diesel	19.51	52.27	118.6	53.3
		Gasoline	16.65	133.3	443.2	109.3
PN_{23}	[nb/km]	Diesel	5.849e+10	7.237e+10	1.06e+11	6.558e+10
		Gasoline	1.511e+11	4.602e+11	1.213e+12	3.715e+11

Generalization to various typical uses

The RDE regulatory procedure allows the measurement of pollutant emissions and CO_2 of a vehicle on an open road under real use conditions. The purpose of this procedure is to reduce the difference between approved consumption and consumption measured in use. The RDE procedure therefore defines conditions of use (distribution and distance between town, road and motorway, minimum and maximum dynamism, ambient temperature, etc.) making it possible to cover a majority of uses. However, a user with his specific use will be able to emit more or less than during RDE taxiing. For example, polluting emissions are much higher on a short trip (of the order of a few kilometers) when the post-treatment system has not yet been started compared to an RDE trip of about 80km (see Figure 27). The aim of the approach proposed here is to:

1. define several simplified annual uses that represent uses with which a user can easily identify,
2. and then estimate the emissions associated with these uses by projection of the measurements taken.

1. Definition of typical uses

A use is defined according to:

- an annual mileage, including an annual mileage to go on vacation,
- and a number of daily trips, divided between town, road and motorway, some of which are made with a cold start, meaning that the vehicle, its engine and its after-treatment system are at temperature ambient at the start of the journey.

Four strongly differentiated uses (type of road and distance of journeys) are defined:

- A representative use of a taxi operating around twenty trips per day, mainly in town (built from the data presented here[9]).
- Two average drivers: one in town and one in the countryside (constructed from the data presented here[10]) driving their vehicle during 2 round trips per day: one to go to work and one to go to another point of interest: activity, trade...
- A salesperson making one round trip per day on a long journey (140km) mainly on the motorway.

The characteristics of these uses are defined in Table 4.

Table 4 : Characteristics of predefined standard uses

	Taxi in urban area	Average driver in rural area	Average driver in urban area	Salesman with highway trips
Kilometers per year	57 700 km	13 000 km	8 000 km	60 000 km
of which to go on vacation	0	2500 km	2500 km	0
Number of trips per day	20	4	4	2
of which with a cold start	2	4	4	2
Daily trip distance	13,7km	12,5km	6,5km	140km

[9] https://www.statistiques.developpement-durable.gouv.fr/les-taxis-et-vtc-en-2016-2017-rapport-de-lobservatoire-national-des-transports-publics-particuliers

[10] https://www.statistiques.developpement-durable.gouv.fr/enquete-nationale-transports-et-deplacements-entd-2008

% of urban area driving	80%	40%	80%	10%
% of rural driving	10%	30%	10%	10%
% of highway driving	10%	30%	10%	80%

2. Use case emissions projection

For an use u the emissions m_i^u of the species i (CO_2, NO_x …) are constructed from emission measurements and are calculated according to:

$$\boldsymbol{m_i^u} = \sum_{type} \boldsymbol{m_i^{type}} \boldsymbol{pct^{type}} + \boldsymbol{m_i^{D\grave{a}F}} \text{ with } type \in \{urban, rural, highway\}\text{, où}$$

- m_i^{type} are the emissions per type of road corresponding to the emissions measured during RDE tests in accordance with the standard ("Road C1") on the phase corresponding to the type of road,
- pct^{type} the percentage of road type of use deduced from the table above,
- and $m_i^{D\grave{a}F}$ the emissions of species i associated with a cold start identified during the first kilometers of RDE runs. These excess emissions depend on the distance of the journey and correspond to CO_2 emissions when the engine is not yet hot and pollutant emissions when the aftertreatment system is not activated.

This projection method is applied to the vehicles of the study for the emissions of CO_2, NO_x, CO and PN23. Figure 29 shows the projected and averaged emissions for 3 vehicle categories: the 8 diesel combustion vehicles, the 8 gasoline combustion vehicles and the 2 gasoline PHEV vehicles. Emissions m_i^u are shown as a bar with the impact of cold start above in blue. Sensitivity to more dynamic driving style (determined from RDE "Road C2" tests under "severe" driving conditions) is shown as a red line. Finally, the gain brought by the possibility of driving entirely electric with a PHEV vehicle is represented in the form of green “bricks” and indicates the sensitivity to the number of recharges that the user performs per week: the greater the number of recharges and the more emissions are reduced compared to emissions in charge maintenance, that is to say without recharging (green dotted line).

This figure illustrates the match between the type of vehicle and the use of a user.

- The sensitivity of a cold start is greater for an average driver in town: in fact with this use the driver uses his vehicle on short journeys and mainly in town, the after-treatment system is therefore less efficient than for another use.
- Sensitivity to driving style depends on the type of vehicle engine and usage. Driving dynamics have more influence on NO_x emissions with a diesel combustion vehicle and on CO and PN23 emissions with a gasoline combustion vehicle. In addition to motorization, use also influences sensitivity to driving style: for example, a driver making motorway journeys with a gasoline PHEV will have high CO and PN23 excess emissions if he adopts dynamic driving.
- The gain in CO_2 emissions of a PHEV vehicle is strongly linked to use. For example, a taxi driver who uses his vehicle all day long will earn much less than an average driver... provided that the latter regularly recharges the battery of his PHEV vehicle.

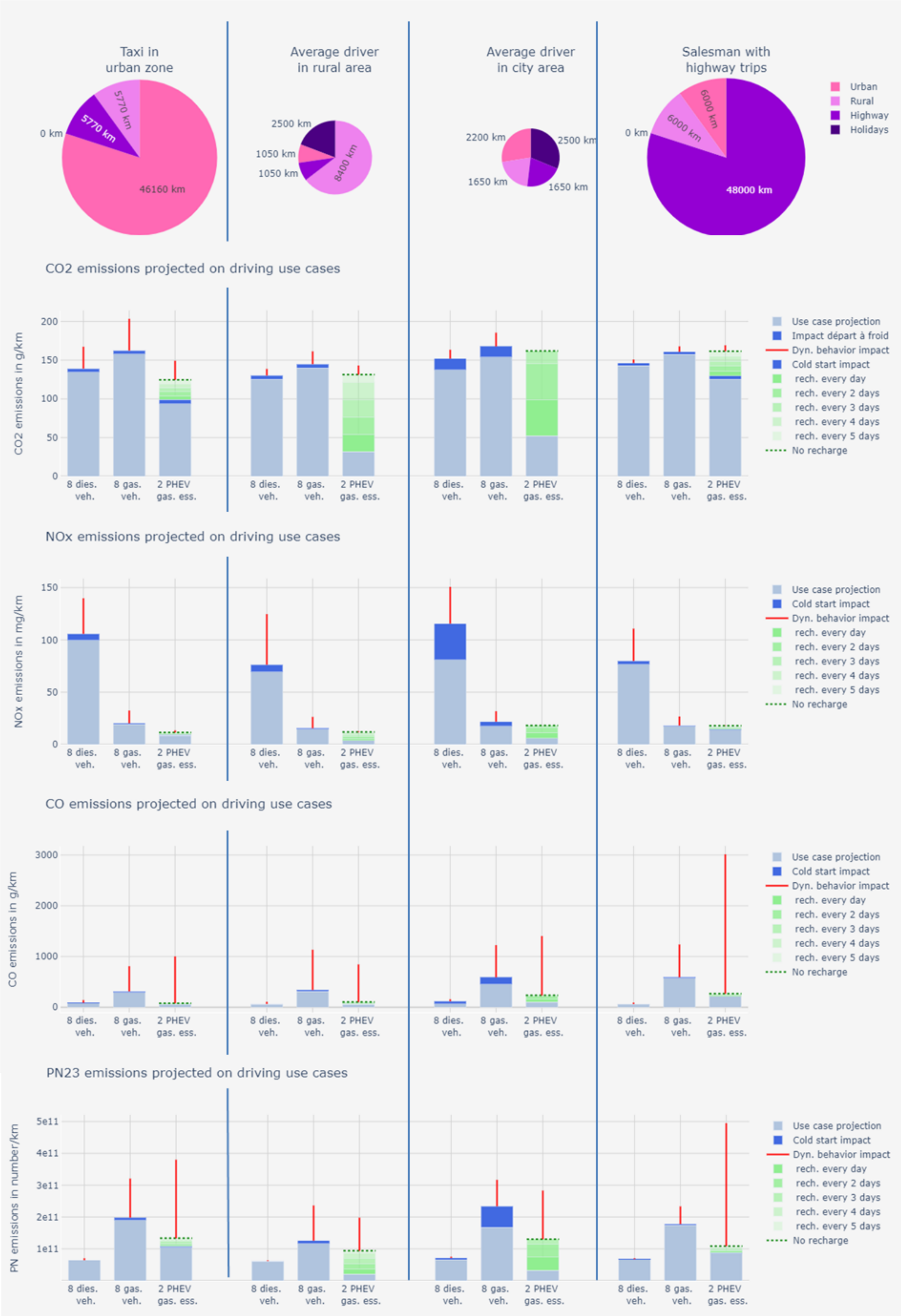


Figure 29 : Comparison of average emissions of CO_2, NOx, CO and PN23 projected on uses for diesel and gasoline combustion vehicles, and gasoline PHEV vehicles

Figure 30 : Comparison of CO_2 and NOx emissions projected on uses for gasoline and diesel compact SUV vehicles (GV3 and DV3)

The approach presented above shows the link between a user's use and their broadcasts. A more detailed example can be constructed as shown in Figure 30, which compares the CO_2 and NO_x emissions of DV3 and GV3 vehicles on the 4 predefined uses. The main conclusion is that the emissions projected for uses remain of the same order of magnitude as the emissions measured. In fact, the approach to projected emissions in use proposes conservatively aggregating the emissions measured over different phases without extrapolating the data that could lead to unrealistic emissions. Then the uses can be compared: for example the NO_x emissions of an average driver in town with the diesel vehicle are significant with a third coming from the cold start. For such use, a gasoline vehicle would reduce NO_x emissions with equivalent CO_2 emission performance.

This analysis demonstrates the importance of the match between vehicle and use. The implementation of tools allowing individuals to make a relevant choice of vehicle suitable for their own use is therefore an important lever in the objective of reducing emissions. As in the "*Je change ma voiture*" [11] tool, a user could be offered to inform his use via a questionnaire and to obtain precise information on the emissions of the vehicles of the study projected on his own use, allowing him to choose a vehicle suitable for its use.

[11] https://jechangemavoiture.gouv.fr/jcmv/

VIII. Conclusion

Compliance with emission standards

With some exceptions, this experimental campaign shows that Euro 6d-TEMP gasoline and diesel vehicles on average comply with the normative thresholds in real use of the RDE type, including under very dynamic driving conditions or in cold and hot climatic conditions for non-new vehicles taken from the fleet. Exceptions relate to the $\boldsymbol{NO_x}$ emissions of diesel vehicles not using urea injection in their pollution control system, the fine particle emissions of certain gasoline vehicles without a particle filter and the $\boldsymbol{CO}$ emissions of certain gasoline vehicles in very dynamic use.

Notable difference between technologies

Notable differences between the technologies remain, however: NO_x emissions remain higher in diesel and fine particle emissions are higher in gasoline, including taking into account the impact of regeneration of diesel vehicles.

Increase in urban use

Emissions levels are significantly higher in urban use, in particular NO_x emissions: + 79% in gasoline and + 74% in diesel considering the standard urban RDE phases compared to full RDE type driving. These emission levels are even higher by focusing on conditions more representative of urban use (very short and slow journeys, see Appendices). The average diesel level in urban use then reached 172 mg/km against 40 mg/km for gasoline vehicles.

Sensitivity to use

The sensitivity of the emission levels to the conditions of use (short journeys, outside temperature, driving style, etc.) has been demonstrated. In order to cover the spectrum of vehicle use more broadly, an analysis phase made it possible to extend the experimental findings to other use cases using digital tools. This approach makes it possible to use the experimental data generated to project pollutant emission levels by calculation on specific life cases representative of different real uses (type of use, driving style, driving conditions).

IX. Annex

Annex 1 - Summary tables of study vehicles. 33

Annex 2 - Taking into account the impact of periodic regenerations of pollution control systems . 34

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Annex 1 - Summary tables of study vehicles.

Table 5 : – Sample of diesel vehicles selected for the study.

Segment	Compact sedan	7-seater SUV	Compact SUV	Compact SUV	Family minivan	Compact sedan	City car	Compact sedan
Code	DV1	DV2	DV3	DV4	DV5	DV6	DV7	DV8
Engine	4-cyl 1.5L 120 ch	4-cyl 1.5L 130 ch	4-cyl 1.5L 115 ch	4-cyl 2.0L 150 ch	4-cyl 2.0L 150 ch	4-cyl 1.5L 115 ch	4-cyl 1.5L 102 ch	4-cyl 1.6L 120 ch
Type	Turbo - DI	Turbo - DI	Turbo - DI	Turbo – DI	Turbo - DI	Turbo - DI	Turbo - DI	Turbo - DI
AFTS HC/CO	LNT (x2)	DOC	DOC	DOC	LNT + cDPF	DOC	DOC	**LNT**
AFTS particules	DPF	SCRF	SCRF	SCRF	cDPF	SCRF	DPF	DPF
AFTS NOx	**LNT (x2) + pSCR**	SCR + SCRF	SCR + SCRF	SCR + SCRF	SCR	SCR + SCRF	SCR	**LNT**
AFTS NH3	Aucun	Aucun	Aucun	**ASC**	Aucun	**ASC**	Aucun	Aucun

Table 6 : – Sample of gasoline vehicles selected for the study.

Segment	Compact sedan	7-seater SUV	Compact SUV	Compact SUV	Family minivan	Compact sedan	City car	Compact sedan
Code	GV1	GV2	GV3	GV4	GV5	GV6	GV7	GV8
Engine	4-cyl 1.5L 125 ch	3-cyl 1.2L 130 ch	4-cyl 1.33L 140 ch	4-cyl 1.5L 150 ch	3-cyl 1.5L 140 ch	4-cyl 1.33L 136 ch	3-cyl 1.2L 83 ch	3-cyl 1.0L 126 ch
Type	Turbo - DI	Turbo - DI	Turbo - DI	Turbo – DI (Désactivation de cylindres)	Turbo - DI	Turbo - DI	**Atmo - PFI**	Turbo - DI
AFTS NOx/HC/CO	TWC	TWC	TWC	TWC UF	TWC	TWC (x2)	TWC	TWC
AFTS Particules	cGPF	raw GPF	cGPF	cGPF	raw GPF	raw GPF	**Aucun**	cGPF

Annex 2 - Taking into account the impact of periodic regenerations of pollution control systems

The Diesel Particulate Filter (DPF) is a periodically regenerating system. Low exhaust temperatures in nominal engine operating mode do not allow regeneration. A specific mode is necessary. Its period of occurrence is usually longer than an RDE test, often between 300 and 600 km. Conversely, gasoline particulate filters (GPF) operate at higher exhaust temperatures than those observed on diesel engines, favoring continuous regeneration of the filter and less or no need for active regeneration, thus a conventional mode of operation. The possible impacts of the regeneration of a GPF are therefore included and captured within a simple RDE test.

To take these phenomena into account, the approval procedure provides for a test method for monitoring the emissions of a vehicle equipped with a periodically regenerating system. It consists in measuring on the one hand the factors of excess emissions of the various pollutants (CO2, CO, HC, NOx, PM) on these periodic regeneration phases, and on the other hand their occurrence by determining the distance between the regenerations and the distance regeneration. Figure 31, taken from the certification protocol, illustrates this method. All of this data is capitalized in a test sheet alongside the approval test report.

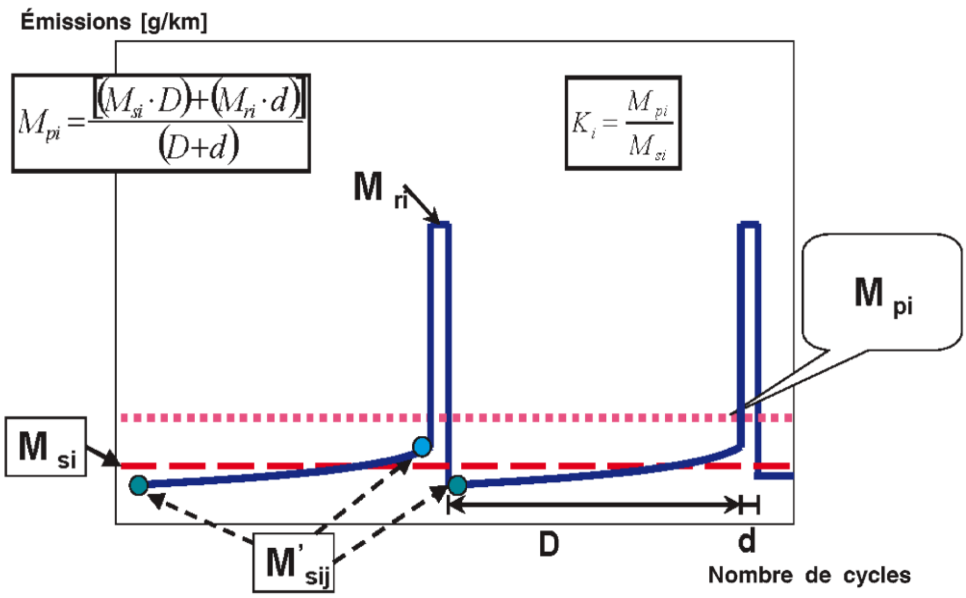


Figure 31 - Illustration of the method of controlling the emissions of a vehicle equipped with a periodically regenerating system - OJ of EU_Commission reg. 2017-1151 supplementing reg. EC n ° 715-2007, p.536

The protocol of the present study addresses this aspect in two stages. First, the approval data relating to this test method for the vehicles in question are made available to IFPEN by the DGEC in order to carry out an analysis and a summary. Second, an experimental characterization of these phenomena is carried out on the selected vehicles, in order to determine these excess emission factors and the inter-regeneration distances on vehicles extracted from the fleet with significant mileage and on an RDE cycle representative of actual use. Figure 32 shows that the impacts established during vehicle approval and during this test campaign are similar on the pollutants to which this correction applies according to the standard. It also shows that the greatest impact is observed on the number of particles whereas the current standard does not recommend this taking into account.

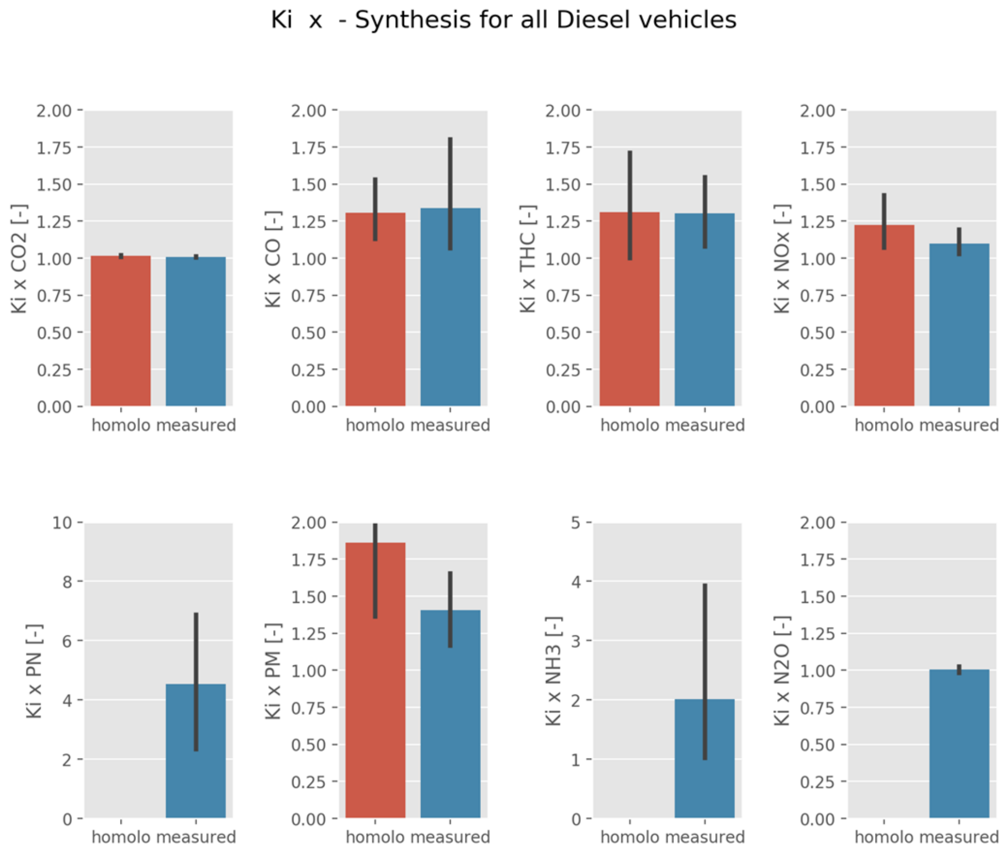
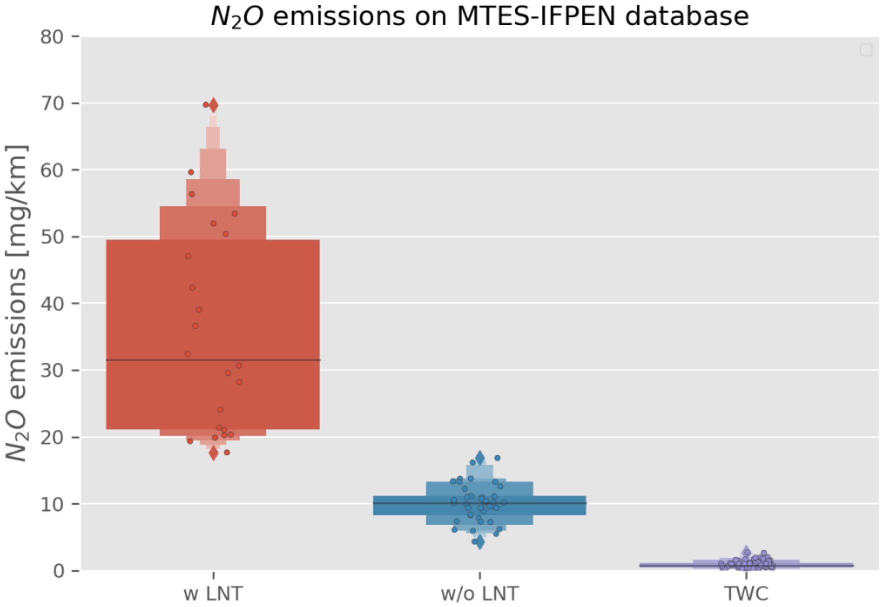


Figure 32 : Comparison of excess emission factors linked to periodic regeneration of pollution control systems

Appendix 3 - CH_4 and N_2O emissions in the presence of an LNT



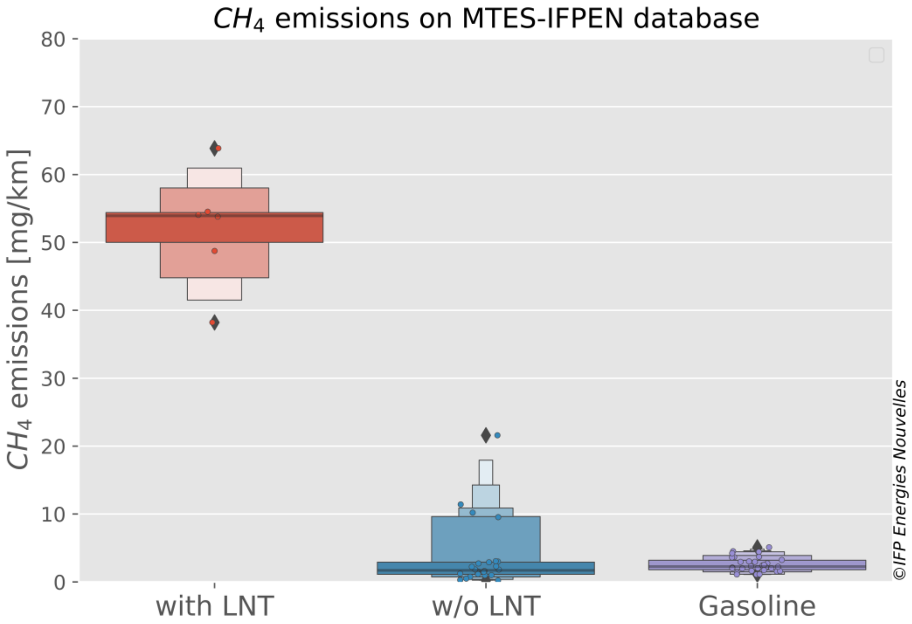
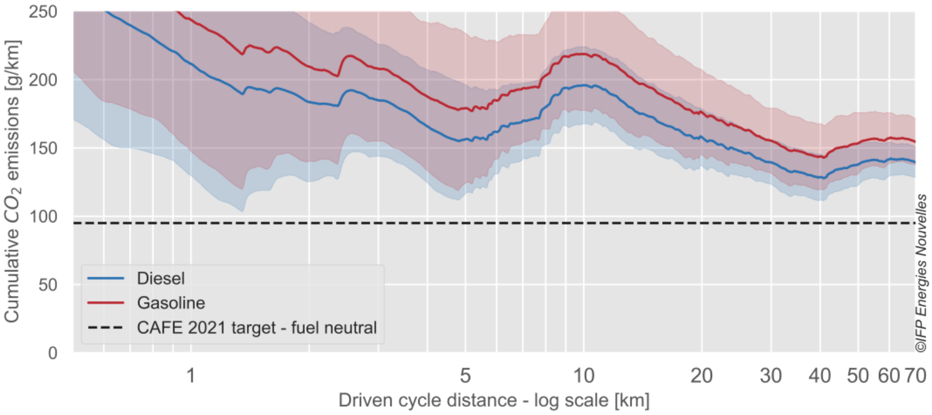
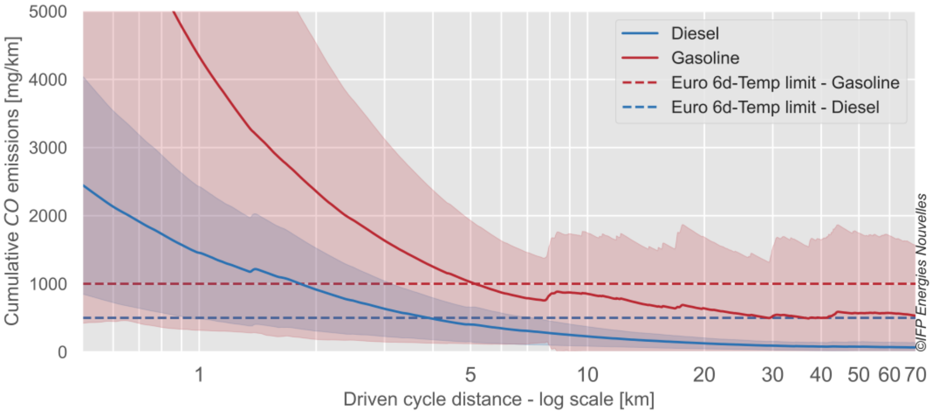
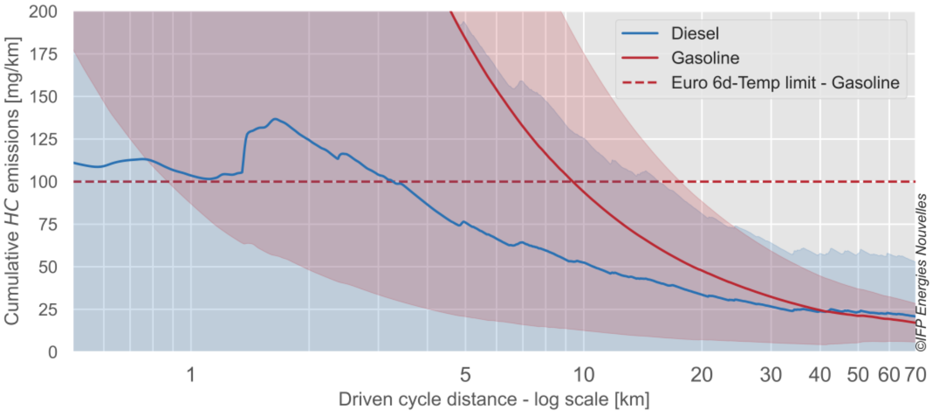


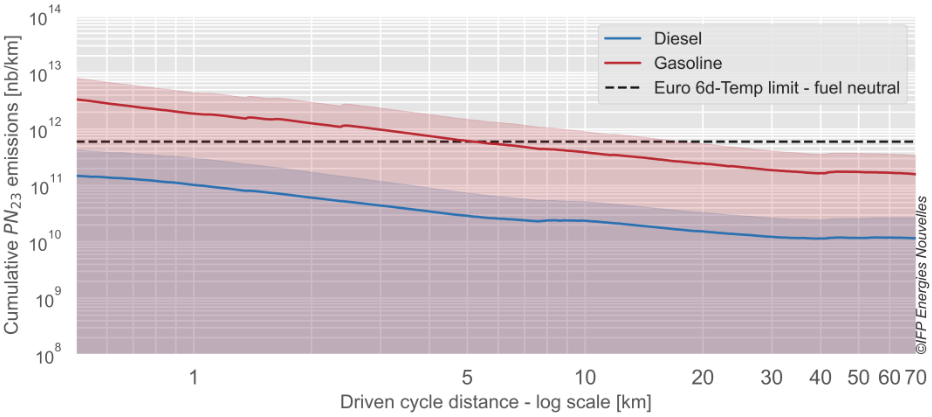
Figure 33 : Comparison of N_2O and CH_4 emissions according to the types of pollution control of diesel and gasoline vehicles.

Appendix 4 - Evolution of cumulative emissions as a function of the distance on the RDE test









Appendix 5 - Weighting of emissions by UF usage factors

To determine a cumulative emissions score more representative of the actual use of vehicles, usage factors were calculated from a database of actual journeys collected from thousands of non-professional drivers by the smartphone application Geco air developed by IFPEN. Figure 34 below represents the UF usage factors (for the Anglo-Saxon Utility Factor) calculated for the urban Parisian journeys available in Geco air. The cumulative emissions are then calculated according to the following formula:

$$UF_{tot} = \int_0^{d_{cycle}} UF(x)dx$$

$$UF - weighted\ NO_x[mg/km] = \int_0^{d_{cycle}} NO_x(x).UF(x)dx/UF_{tot}$$

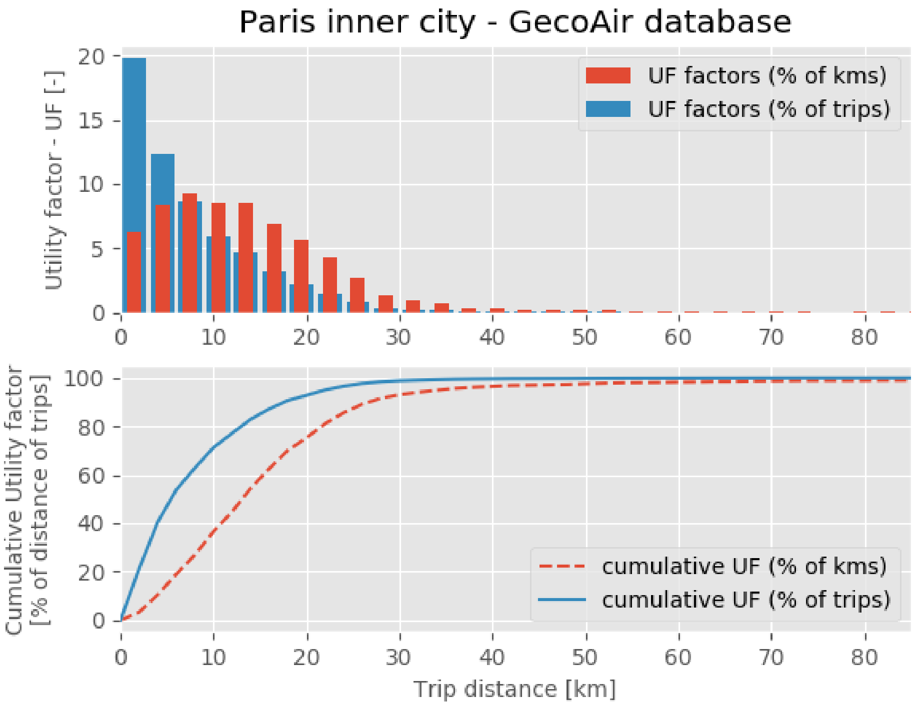
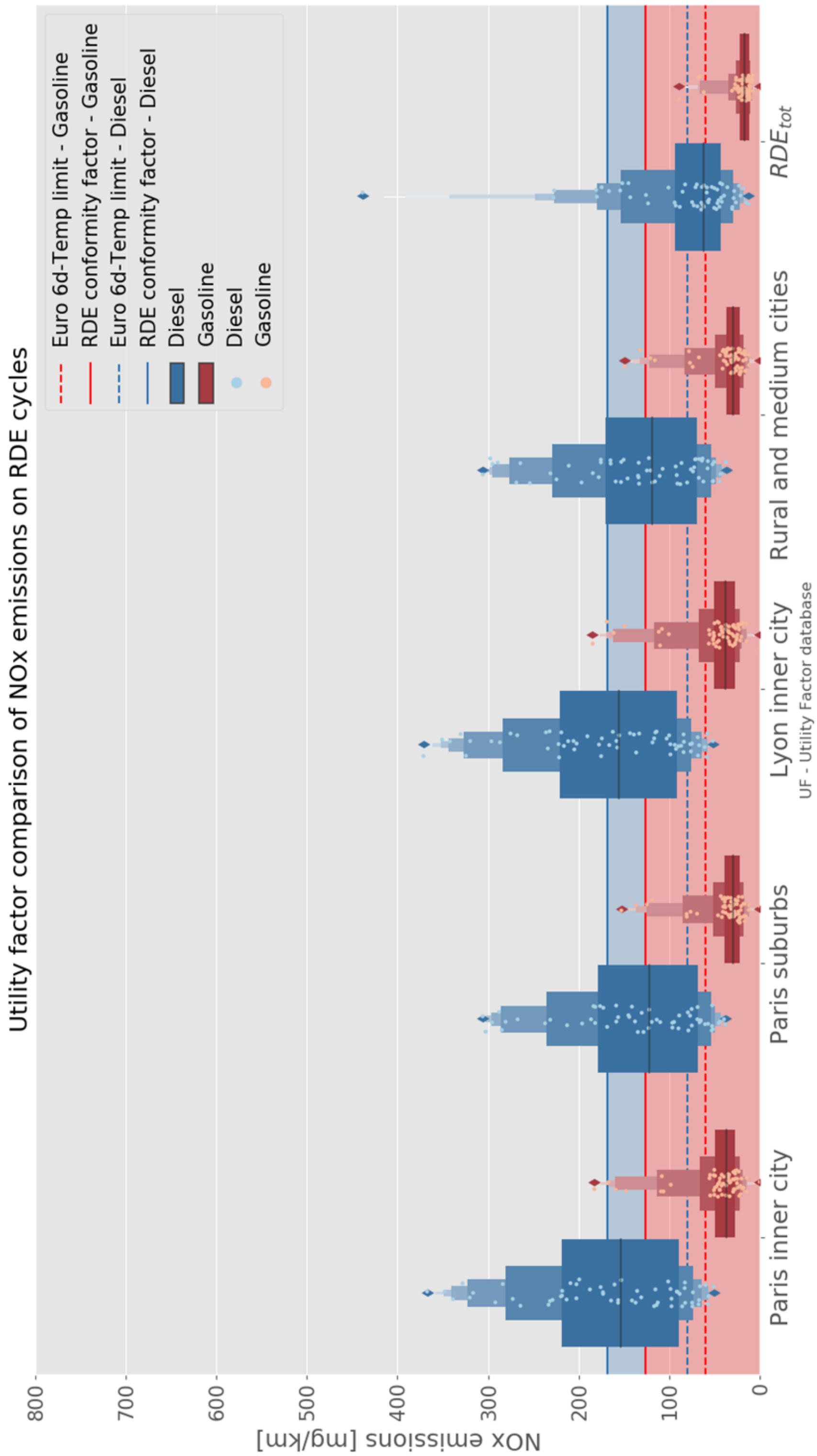


Figure 34 : Usage factors according to the distance of the journey established from the actual usage database

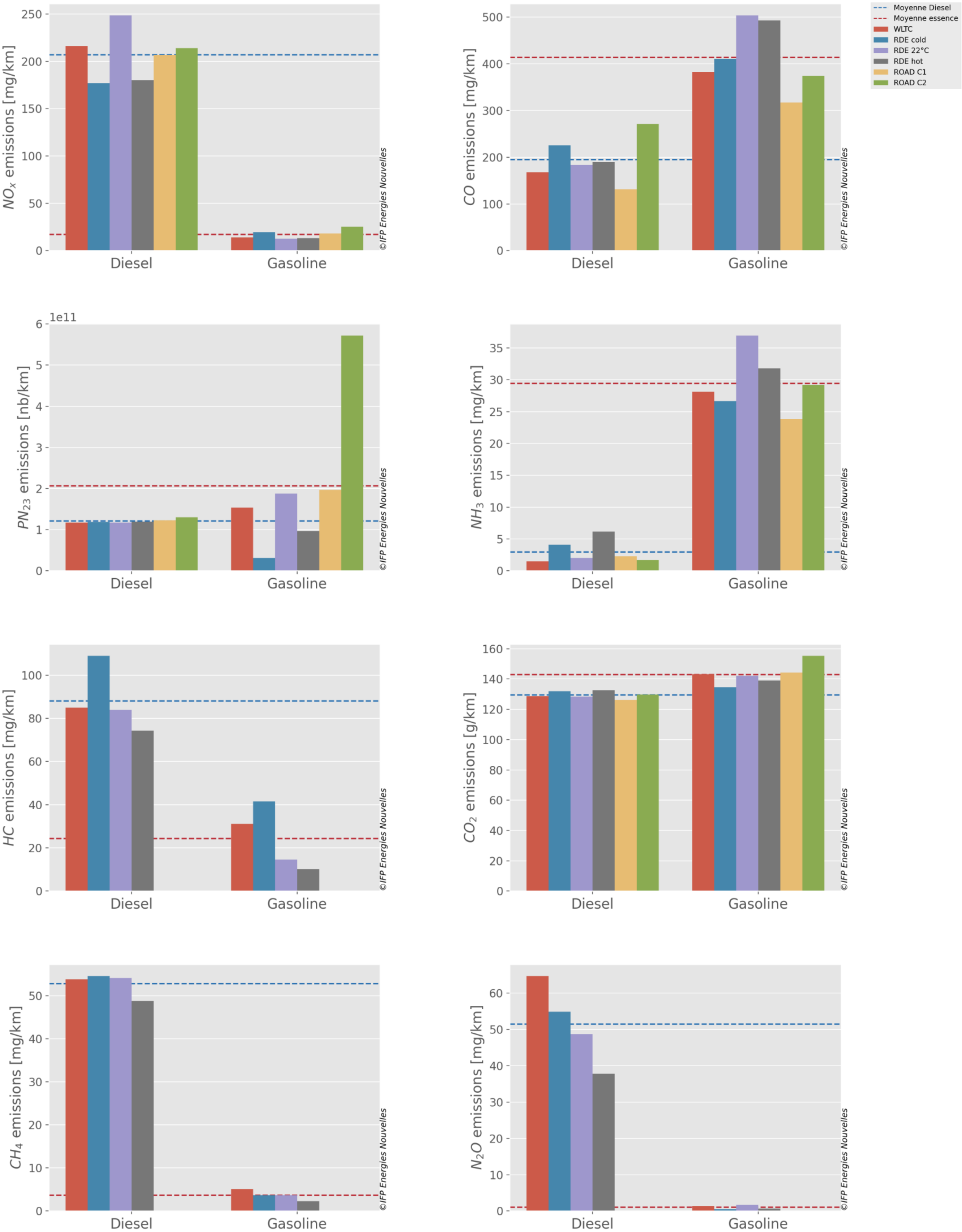
This weighting method tends to exacerbate the emissions of pollutants in urban phases which are generally located at the start of the cycle. Depending on the database used, the excess pollutant emissions in the urban phase (attributable to the heating of the catalyst or to degraded combustion modes) will be more or less weighted in the final score.

The figure below shows the impact of different trip databases on the weighting of pollutant emissions. Note that the use of usage factors from medium cities and rural journeys results in lower emission scores than for their urban counterparts.

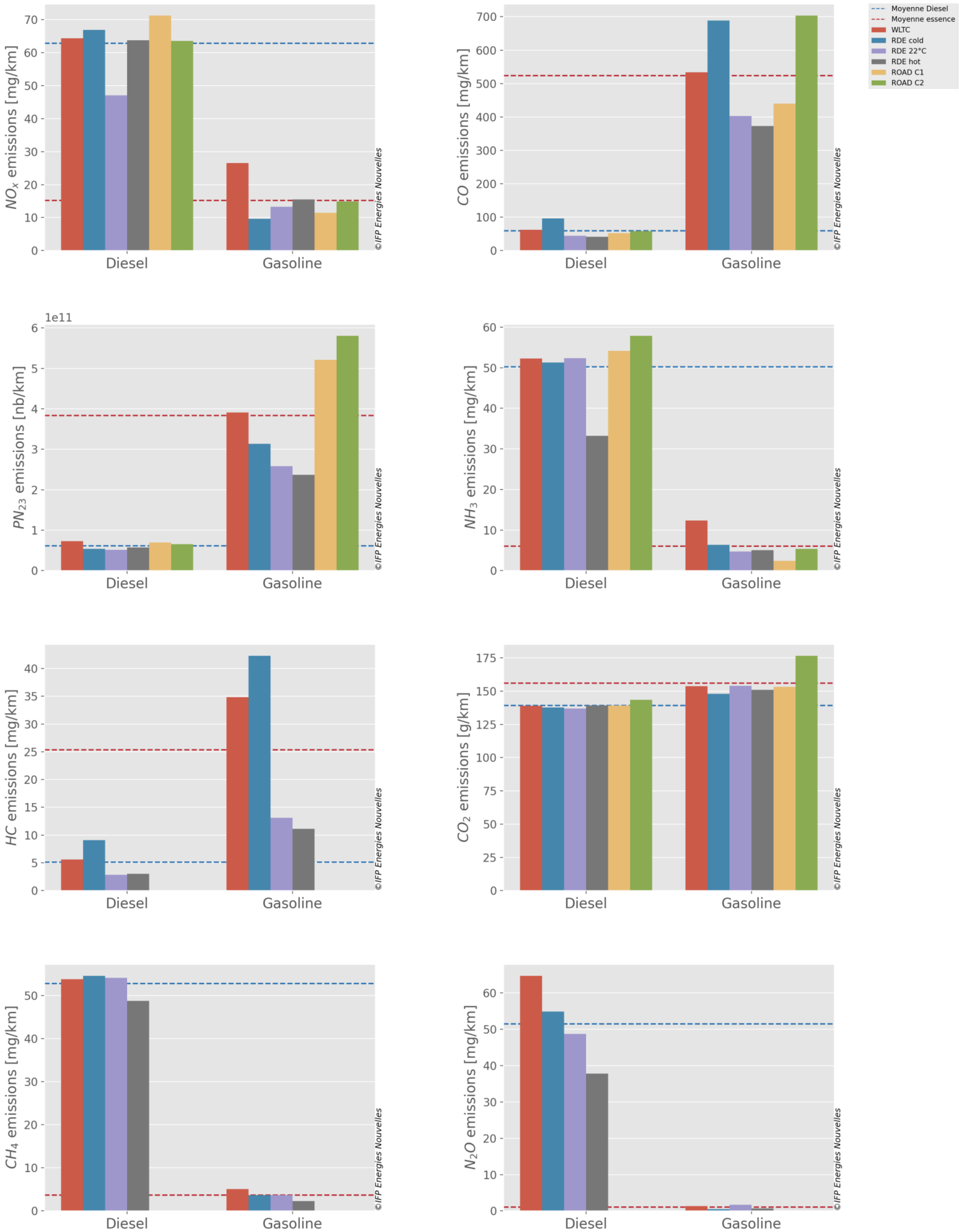


Utility factor comparison of NOx emissions on RDE cycles
Euro 6d-Temp limit - Gasoline
RDE conformity factor - Gasoline
Euro 6d-Temp limit - Diesel
RDE conformity factor - Diesel
Diesel
Gasoline
Diesel
Gasoline
NOx emissions [mg/km]
0
100
200
300
400
500
600
700
800
Paris inner city
Paris suburbs
Lyon inner city
Rural and medium cities
RDE_tot
UF - Utility Factor database

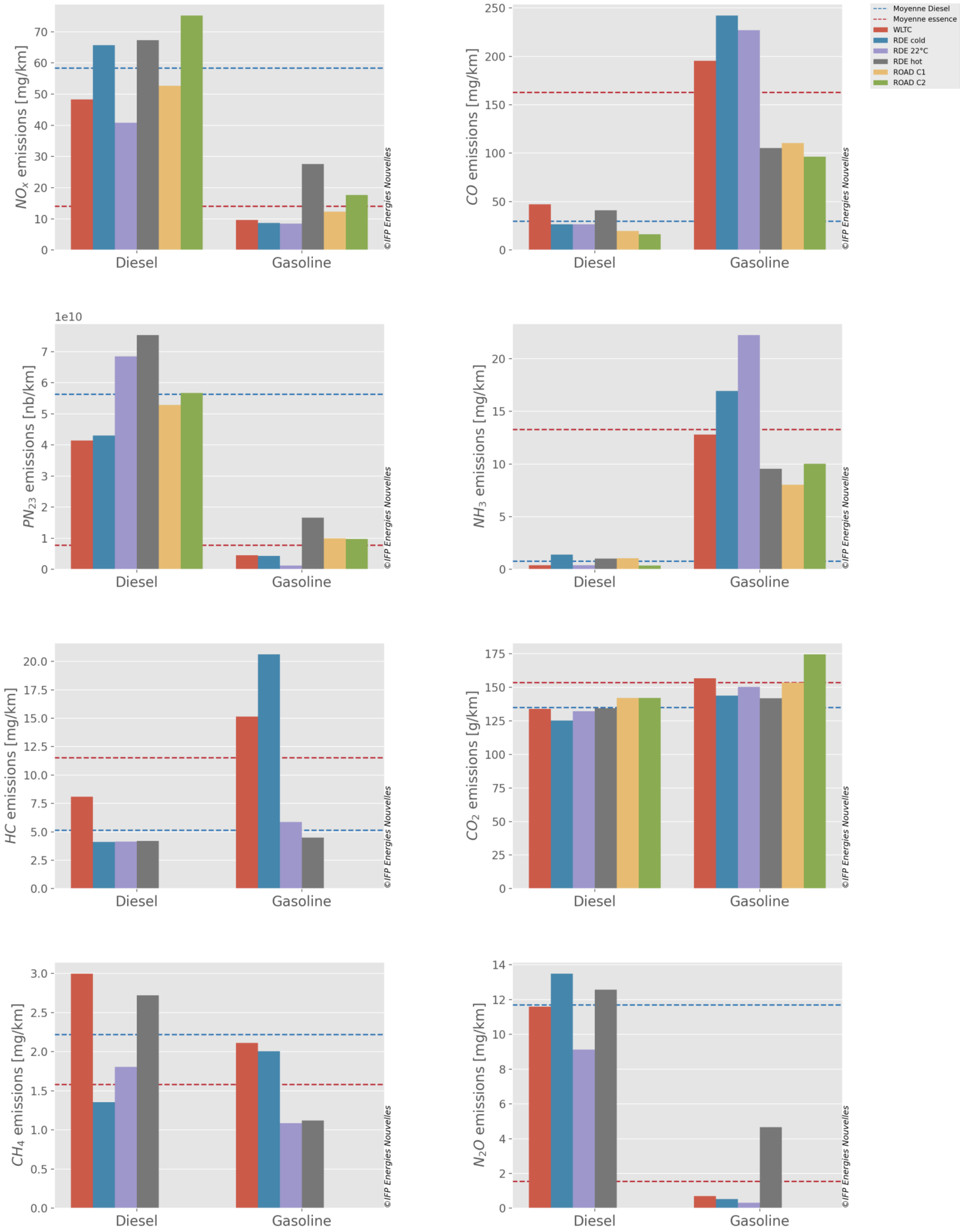
Appendix : DV1 & GV1 ; Compact sedan



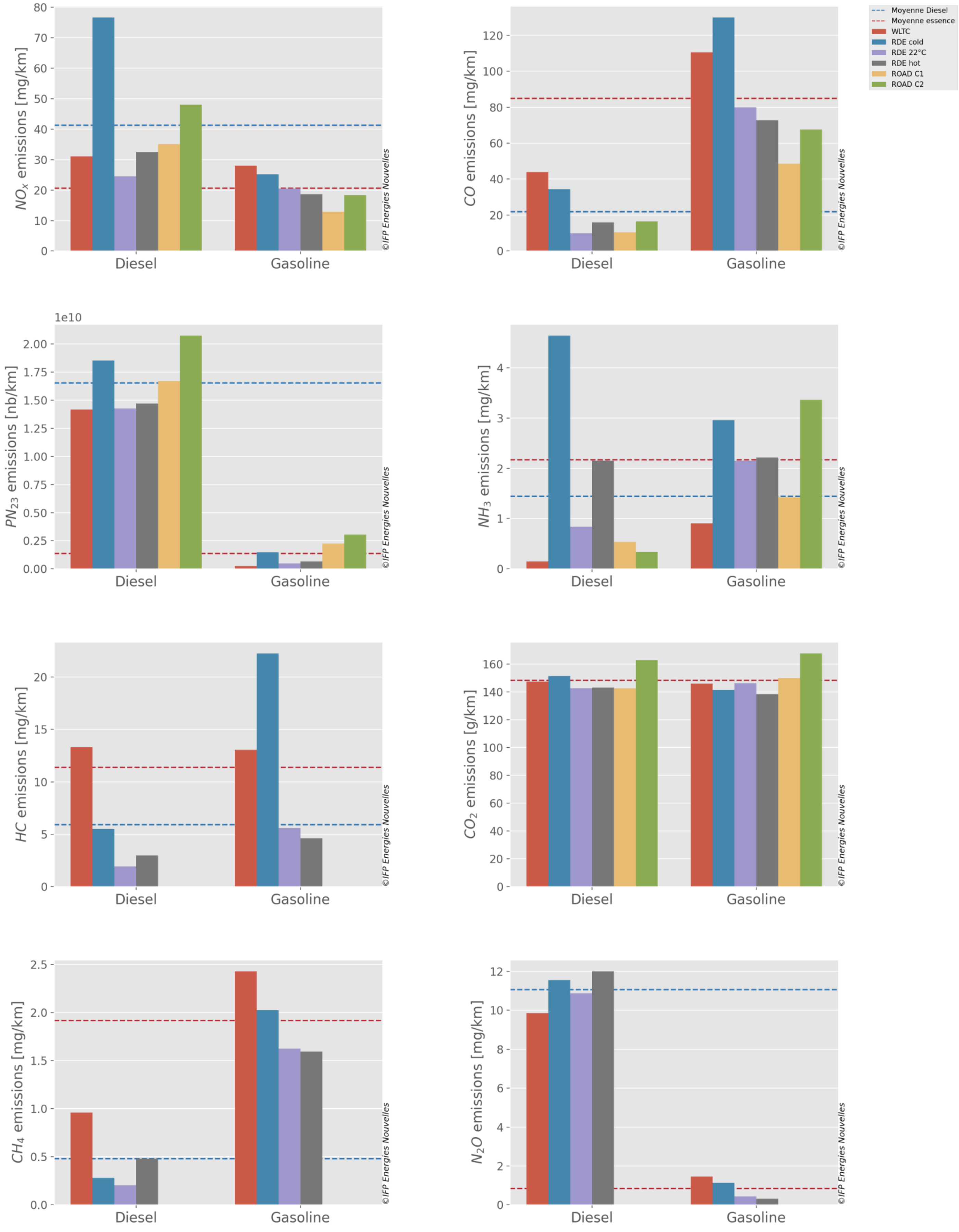
Appendix : DV2 & GV2 ; 7-seat SUV



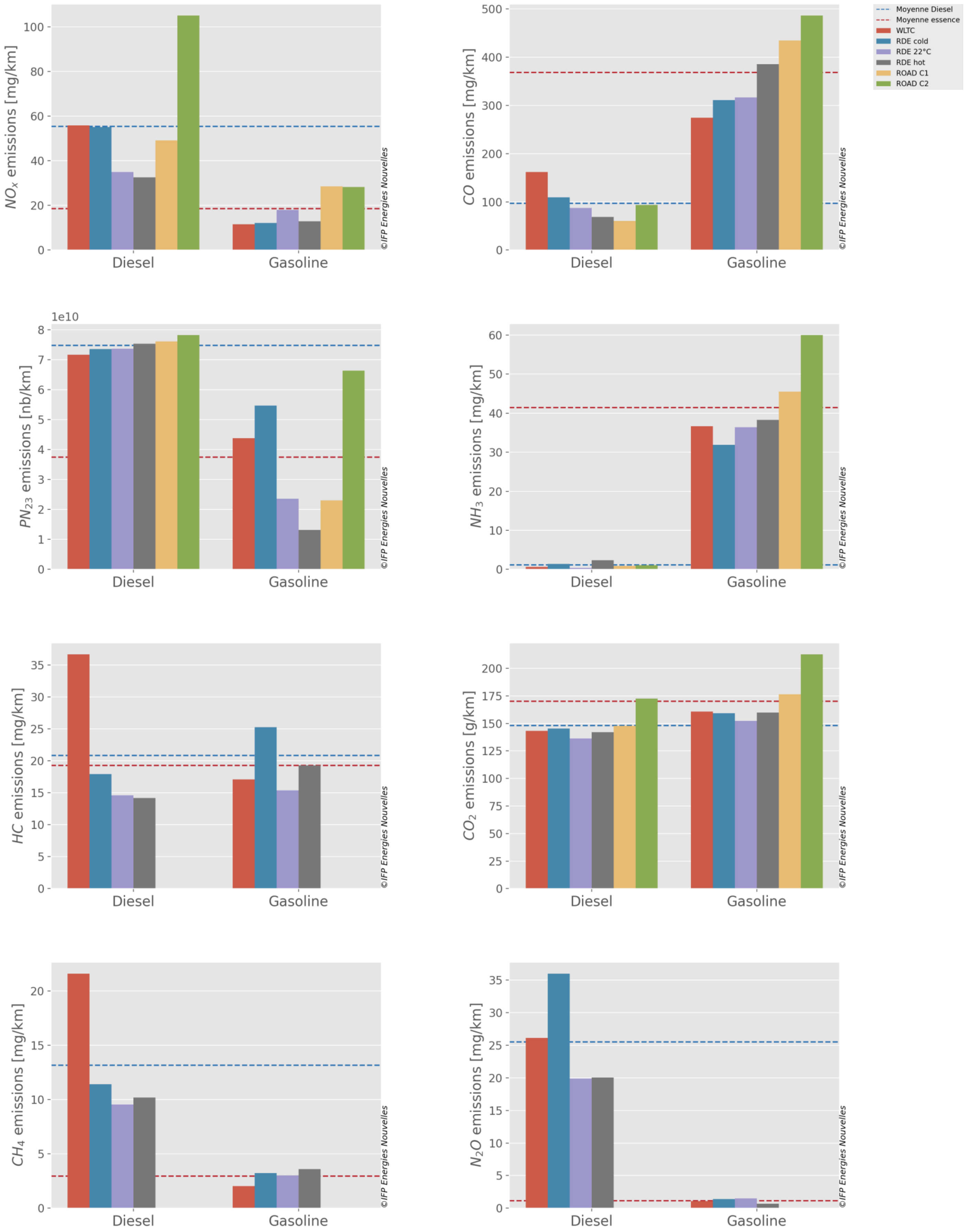
Appendix : DV3 & GV3 ; Compact SUV



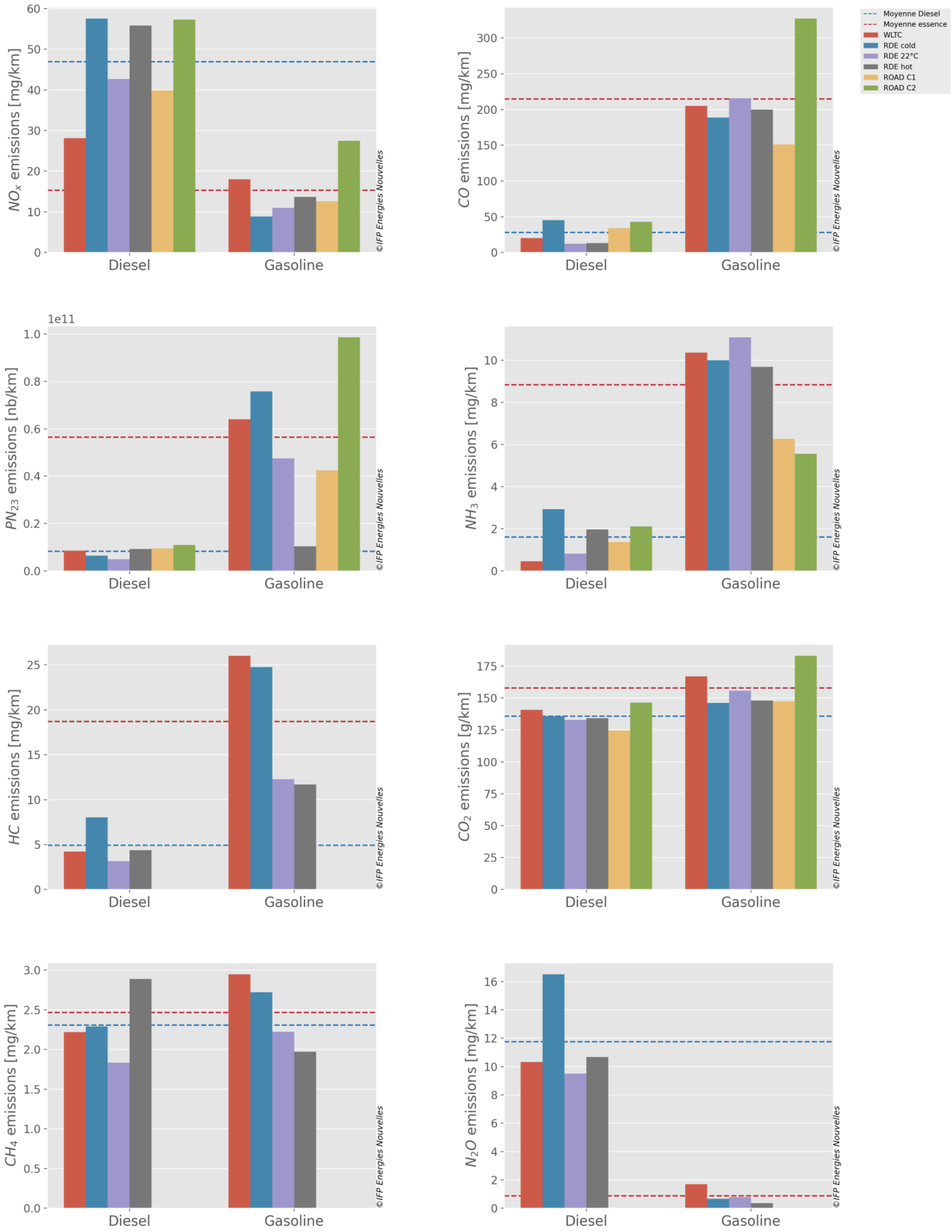
Appendix : DV4 & GV4 ; Compact SUV



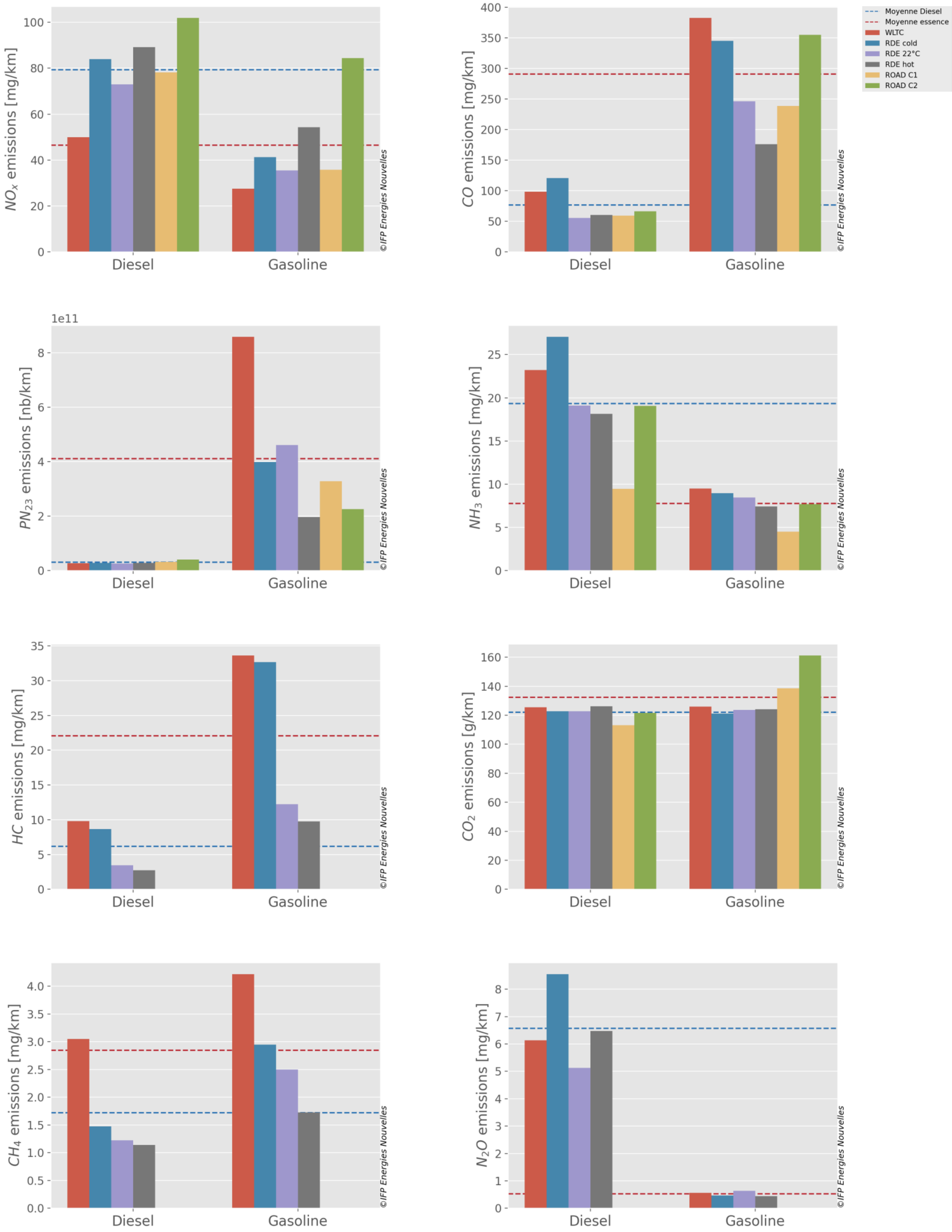
Appendix : DV5 & GV5 ; Family minivan



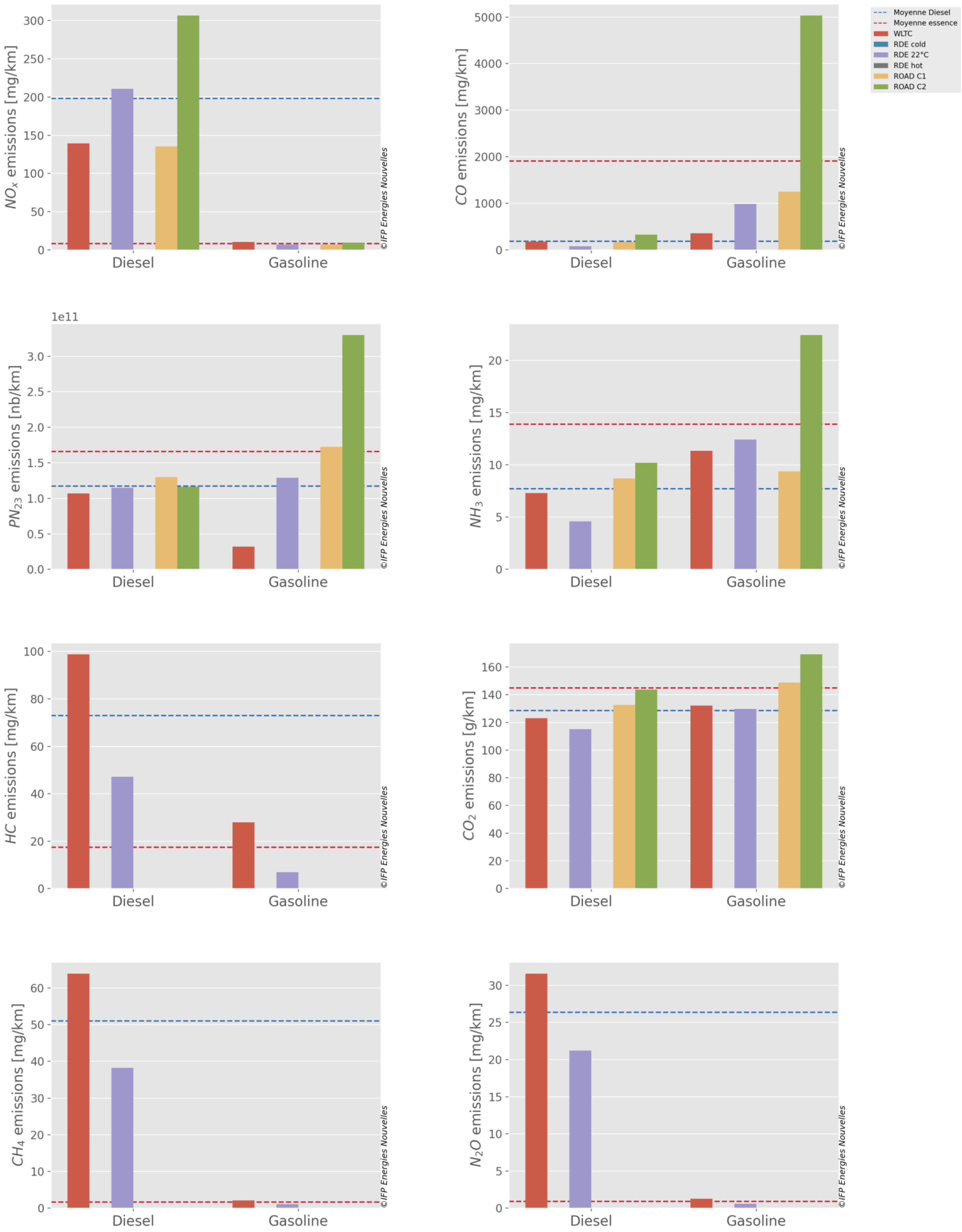
Appendix : DV6 & GV6 ; Compact sedan



Appendix : DV7 & GV7 ; City car



Appendix : DV8 & GV8 ; Sedan



Glossary

PM – Particle Mass
PN – Particle Number
CO_2 – Carbon dioxide
GWP- The Global Warming Potential of a gas is the mass of CO_2 that would produce an equivalent impact on the greenhouse effect.
N_2O – Nitrous oxide - greenhouse gas, GWP 298
CO – Carbon monoxide
(T)HC – Total mass of hydrocarbons
CH_4 – Methane, greenhouse gas, GWP of 30
LNT – Lean NOx Trap
NMHC – Mass of non-methane hydrocarbons
NO_x – Nitrogen oxides
NO – Nitrogen monoxide
NO_2 – Nitrogen dioxide
TWC - Three Way Catalyst
DPF – Diesel Particulate Filter
GPF - Gasoline Particulate Filter
ASC - Ammonia Slip Catalyst
SCR – Selective Catalytic Reduction
CC/UF : catalyst location, Close-Coupled or Under-Floor
c/raw : coated or raw (non-coated)
RDE – Real Driving Emissions
PEMS – Portable Emission Measurement System
OBD – On Board Diagnostic, refers to all of the on-board hardware diagnostic capabilities in vehicles to control the components affecting the vehicle's polluting emissions during its lifetime, and meets regulatory requirements .
CVS - Constant Volume Sampling
GDI - Gasolne Direct Injection
PFI - Port Fuel Injection
Turbo/Atmo – Engine supercharged by turbocharger (turbo) or not (atmo).
HEV – *Hybrid Electric Vehicle*
PHEV – *Plug-in Hybrid Electric Vehicle*
CS – *Charge Sustaining*
CD – *Charge Depleting*