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Development and review of Euro 5 passenger car emission factors based on experimental results over various driving cycles

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HIGHLIGHTS

- 13 Euro 5 passenger cars measured over NEDC, Artemis and WMTC cycles
- Derived emission factors for regulated pollutants and compared with COPERT and HBEFA
- Pollutant emissions in line with Euro 5 emission standard in most cases
- NO_x consistently exceeded the emission standard values over more transient cycles.
- Current emission factors appear to reflect adequately Euro 5 performance.

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ABSTRACT

The emissions of CO_2 and regulated pollutants (NO_x, HC, CO, PM) of thirteen Euro 5 compliant passenger cars (seven gasoline, six Diesel) were measured on a chassis dynamometer. The vehicles were driven repeatedly over the European type-approval driving cycle (NEDC) and the more dynamic WMTC and CADC driving cycles. Distance-specific emission factors were derived for each pollutant and sub-cycle, and these were subsequently compared to the corresponding emission factors provided by the reference European models used for vehicle emission inventory compilation (COPERT and HBEFA) and put in context with the applicable European emission limits. The measured emissions stayed below the legal emission limits when the type-approval cycle (NEDC) was used. Over the more dynamic cycles (considered more representative of real-world driving) the emissions were consistently higher but in most cases remained below the type-approval limit. The high NO_x emissions of Diesel vehicles under real-world driving conditions remain the main cause for environmental concern regarding the emission profile of Euro 5 passenger cars. Measured emissions of NO_x exceeded the type-approval limits (up to 5 times in extreme cases) and presented significantly increased average values (0.35 g/km for urban driving and 0.56 g/km for motorway driving). The comparison with the reference models showed good correlation in all cases, a positive finding considering the importance of these tools in emission monitoring and policy-making processes.

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1. Introduction

The emissions of regulated air pollutants have been decreasing in the European Union (EU) over the past two decades. Nevertheless, 20% of Europe's urban population is still living in areas where pollutant concentrations (most prominently NO_x and PM) exceed established air quality standards. The Euro 5 emission standard (applicable in Europe from September 2009) for light duty vehicles was formulated with the aim to further reduce pollutant emissions from road vehicles, particularly nitrous oxides (NO_x) and particulate matter (PM) (Mamakos et al., 2013). The provisions of the Euro 5 standard, combined with the target set in parallel by the European Commission for the reduction of average CO_2 emissions to 130 g/km by 2015, led to important evolutions in both vehicle powertrains and exhaust after-treatment systems (Fontaras and Dilara, 2012; Weiss et al., 2012). Despite the progress made, which is clearly reflected in type-approval cycle results, there is still substantial evidence, mainly originating from experimental campaigns with portable emission measurement systems (PEMS), that Euro 5 vehicles exceed legal emission limits under certain driving

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conditions not covered by the type-approval cycle. This is especially the case for NO_x emissions from Diesel passenger cars (Weiss et al., 2011).

Pollutant emissions of road vehicles depend on many parameters including vehicle weight, engine capacity, fuel type, exhaust after-treatment technology, driving pattern, environmental conditions, road gradient and the level of maintenance of the vehicle (Faiz et al., 1996). The variable and complex nature of road vehicle emissions and the diversity of road vehicle types make it necessary to use *emission models* to support the compilation of regional or national emission inventories, the results of which are subsequently compared to existing emission ceilings to assess the performance of air quality policies.

COPERT (COmputer Programme to calculate Emissions from Road Transport) and the Handbook of Emission Factors (HBEFA) are the two reference vehicle emission models in Europe (Gkatzoflias et al., 2007; Hausberger et al., 2009; Kousoulidou et al., 2013). These models estimate emissions as a combination of vehicle fleet composition and activity data input by the user, and libraries of emission factors (EFs) included in the model (Kousoulidou et al., 2010, 2013). EFs are functional relations that predict the quantity of a pollutant that is emitted per distance driven, energy consumed, or amount of fuel used during a road transport event as a function of vehicle activity parameters (*e.g.* average velocity, or traffic situation). These are derived from experimental data collected during emission measurement campaigns performed both in emission laboratories (through chassis dynamometer testing) and on the road (using PEMS) (Franco et al., 2013). Alternatively, in lack of more specific information, EFs are estimated based on qualified assumptions and predictions of technology evolution (*e.g.*, following the introduction of a new emission standard).

One possible source of emission data is the type-approval test, but this only covers relatively mild driving conditions. Therefore, in order to develop and maintain accurate EFs, information regarding vehicle performance under real-world driving conditions is crucial. Emission data over repeatable and controlled chassis dynamometer driving cycles representative of real-world driving are key for supporting emission monitoring and inventorying tools (Barlow et al., 2009; Smit et al., 2010; Karavalakis et al., 2012). In the European context, the efforts to model road vehicle emissions are coordinated by the ERMES group (Franco et al., 2012), which brings together European research groups working on transport emission inventories and models under the coordination of the Joint Research Centre of the European Commission (EC-JRC). This activity is also of relevance for various countries outside Europe that base their emission inventorying systems on European methods and EF databases.

In an effort to assess the effectiveness of the introduction of the Euro 5 standard and to support the update of existing EF databases, emission data from a pool of thirteen passenger cars (both Diesel and gasoline) were collected and analysed. The test conditions covered a series of driving cycles, NEDC included. Distance-specific EFs were derived for each pollutant and sub-cycle, and these were subsequently compared to the corresponding EFs provided by the reference European models used for vehicle emission inventory compilation (COPERT and HBEFA) and put in context with the applicable European emission limits. The data produced were included in the EF database of the ERMES group to serve as a basis for future EF development.

2. Materials and methods

2.1. Testing facilities and equipment

The experimental campaign comprised a series of emission measurements performed on the chassis dynamometer test cells of the Vehicle Emissions Laboratories (VELA) of the European Commission Joint Research Centre (EC-JRC) located in Ispra (Italy) between the years 2010 and 2012. The test cells comply with the legal requirements for the emission type-approval tests of passenger cars in Europe (EuP, 2007a). The emissions of regulated pollutants (NO_x, HC, CO, PM, CH_4) and CO_2 of the thirteen Euro 5 passenger cars (PCs) (six Diesel and seven gasoline) were measured over different transient driving cycles using the constant volume sampling technique according to the European statutory procedure. Laboratory-grade analysers were used for the CO, NO_x and HC measurements. Particulate matter was collected on Pallflex T60A20 filters and its mass was determined by weighing on a microbalance. More information regarding the testing equipment can be found in (Farfaletti et al., 2005). Additionally, *particle number* measurements were also conducted for the gasoline direct injection vehicles tested. The results of these measurements are not discussed in this paper as the description of the testing approach and the comprehensive interpretation of the results would require a lengthy analysis. Results on particle number emissions can be found in (Mamakos et al., 2013).

2.2. Test cycles and protocols

The driving cycles used for the emission tests were the NEDC, WMTC and CADC (see time–velocity traces and other relevant characteristics in Fig. 1).

- The NEDC (New European Driving Cycle) is the driving cycle used for emission type-approval of all Euro 3 and later light-duty vehicle models in Europe. Legal emission limits (expressed as mass of pollutant emitted per kilometre driven) refer to the emissions over NEDC. This cycle has been criticised for not being representative of real-world vehicle operation (Kågeson, 1998; Dings, 2013). NEDC is a cold-start cycle.
- The CADC (Common Artemis Driving Cycle) is a real-world simulation driving cycle that aims to represent average driving conditions in Europe (André, 2004). CADC is not used for type-approval. Instead, it was specifically designed for emission modelling purposes.
- The WMTC (Worldwide Motorcycle Test Cycle) was developed within the framework of a worldwide regulatory process towards the harmonisation of vehicle emission test procedures, intended for motorcycle testing. In this experimental campaign, it was applied as a less time-consuming alternative to CADC to allow for more repetitions.

The cycle and sub-cycle characteristics are presented in Table 1.

The daily protocol initiated with the NEDC (cold-start), followed by the more transient cycles. Three EUDC cycles were performed as preconditioning at the end of each measurement day before the vehicles were left to soak overnight in order to reach a stable temperature before the cold-start test. All emission tests were conducted at 22 ± 1 °C. In certain cases, a second UDC cycle was also run to allow for comparison between cold and hot start emission values observed over the particular cycle.

2.3. Vehicles and fuels

Thirteen Euro 5 passenger vehicles, six Diesel and seven gasoline ones, were used in the study. The test vehicles were selected independently of vehicle manufacturers. A wide range of engine capacities and vehicle sizes was covered in order to capture the diversity of the European passenger car fleet to the best possible extent (see Table 2). The average characteristics of the pool of vehicles selected resemble those of the average passenger car fleet in Europe for model years 2009–2011. The average mass of the sample was 1326 kg (compared to approximately 1360 kg of the fleet), the average engine capacity was 1600 cc (similar to the European fleet average ~1640 cc), and the average engine maximum power was almost equal to the average (77 kW compared to 78.5 kW) (EEA, 2012). However, as will be discussed in the Results section, there was a relative bias towards smaller Diesel vehicles that was counterbalanced by an opposing bias towards relatively larger gasoline vehicles. This was determined by the availability of the vehicles and the special interest in small-size Diesel passenger cars, whose sales are growing in the European market.

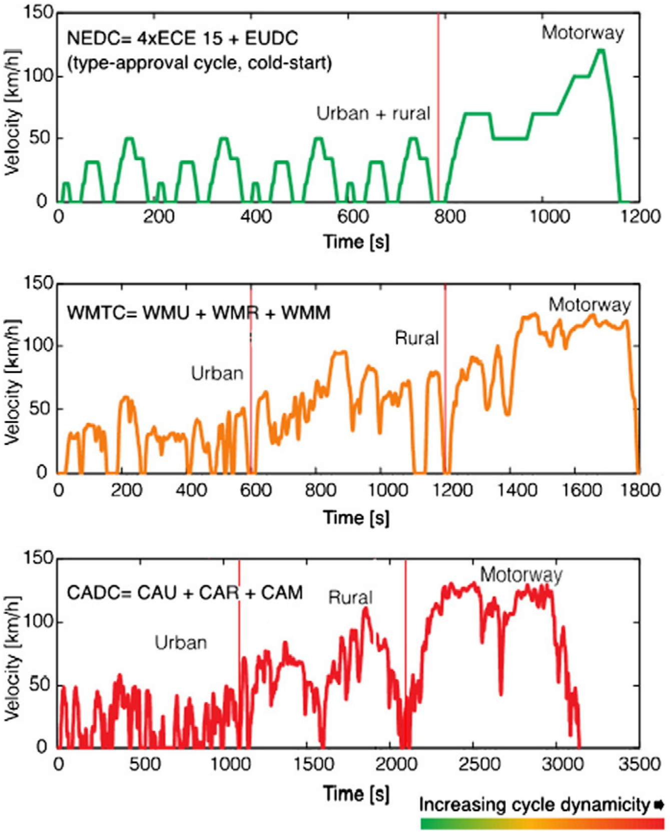

Fig. 1. Test cycles and sub-cycles used in the chassis dynamometer laboratory experiments.

It should be noted that GS5, GS6 and GS7 were *gasoline direct injection* vehicles, representing a relatively new gasoline technology that is rapidly spreading in modern passenger car fleets.

Diesel vehicles were fuelled with conventional Diesel fuel compliant with the EN590 fuel standard and including up to 7% biodiesel blendstock. Gasoline vehicles were fuelled with EN228 compliant gasoline which, according to European legislation, may contain up to 5% ethanol. The sulphur content limit for both fuels is 10 ppm.

2.4. Reference emission models

The results of the measurements were compared against the respective EFs of the two most commonly used road vehicle emission models in Europe, COPERT and HBEFA. COPERT is the main road transport emission model of the EMEP/CORINAIR Atmospheric Emissions Inventory Guidebook (AEIG), and is used by most European member states in their official reporting of national inventories of emissions from road transport (Ntziachristos and Samaras, 2009). The general approach to the development of the EFs in COPERT is to plot the aggregated results of various driving sub-cycles with respect to the average velocity of the specific sub-cycles and then fit a polynomial trend line to the experimental data using mathematical regression. The resulting formula of the trend line is the EF that expresses vehicle emissions as a function of mean velocity. COPERT provides such polynomial EFs for several combinations of pollutants and vehicle classes covered by the model.

Table 1
Test sub-cycle characteristics.

Test cycle	Sub-cycle ID	Traffic situation	Average velocity [km·h^{-1}]	Duration [s]
NEDC/NEDC$_{hot}$	UDC/UDC$_{hot}$	Urban driving	18.7	195
	EUDC	Extra-urban driving	62.6	400
CADC	ARU	Urban driving	17.5	921
	ARR	Rural driving	60.4	981
	ARM	Motorway driving	116.4	736
WMTC	WMU	Urban driving	24.3	600
	WMR	Rural driving	54.3	600
	WMM	Motorway driving	94.3	600

Table 2
Vehicle characteristics.

Engine type	Vehicle code	Engine capacity (l)	Max. power (kW)	Inertia class (kg)	Mileage before measurement (km)
Gasoline	GS1	1.2	44	1250	1909
	GS2	1.3	55	1130	42146
	GS3	1.4	82	1250	3590
	GS4	1.8	92	1360	11772
	GS5	1.9	100	1250	8353
	GS6	1.9	110	1590	1441
	GS7	2	130	1590	12461
Diesel	DS1	1.2	55	1250	6402
	DS2	1.3	58	1250	1160
	DS3	1.6	60	1360	3408
	DS4	1.6	55	1130	1058
	DS5	1.6	55	1130	10978
	DS6	2	103	1700	13535

The Handbook of Emission Factors (HBEFA) from road transport is intended to be used at finer geographical scales (down to street canyon level). This model needs detailed input data describing traffic, and is mostly used by countries where such data are available (Germany, Austria, Switzerland, Sweden, the Netherlands and Switzerland). The EFs of HBEFA depend on qualitative descriptions of 'traffic situations' (Hausberger, 2010). A key element of the HBEFA methodology is the use of the vehicle simulation model PHEM for emission calculation over different traffic conditions (Hausberger et al., 2009). In the present study, PHEM was used for simulating the performance of Euro 5 passenger cars over the CADC cycle. The results were then used for the comparison between measurements, COPERT and HBEFA EFs.

3. Results and discussion

The results of the measurements are summarised in Fig. 2 (gasoline vehicles) and Fig. 3 (Diesel vehicles). The latter also include the corresponding emission limits for Euro 5a[1] passenger cars and error bars representing the standard deviation of the measurements. It should be stressed that UDC is the cold-start urban sub-cycle of NEDC, and so results over these sub-cycles are not directly comparable with those retrieved over the corresponding urban sub-cycles of CADC or WMTC, which are hot-start cycles. Particle mass (PM) emission results are presented in Fig. 4.

3.1. Gasoline vehicles

Regulated pollutant emission levels of all vehicles tested remained below the type-approval limit for all pollutants and over the majority of cycles (Fig. 2), with the expected exception of UDC due to the cold-start effect.

CO and HC emissions were in the order of 0.5 g/km and 0.05 g/km respectively over NEDC, figures that represent approximately half the amount allowed by the legislation. Some notable CO emission values

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[1] The Euro 5 emission standard was introduced in 2 phases. The first (Euro5a) was valid for type-approval until September 2011, followed thereafter by Euro5b. The difference between the two lies in PM limits (5 mg/km for Euro5a compared to 4.5 for Euro5b for both gasoline and Diesel). Euro 5b includes limits for Diesel particle number emissions. Euro 5a emission standard also excludes revised measurement procedure for particulates, particle number standard and flex fuel vehicle low temperature emission testing with biofuel otherwise included in Euro 5b. Highest or second-highest rolling resistance tyres (according to ISO 28580) must be selected for type-approval under Euro 5b.

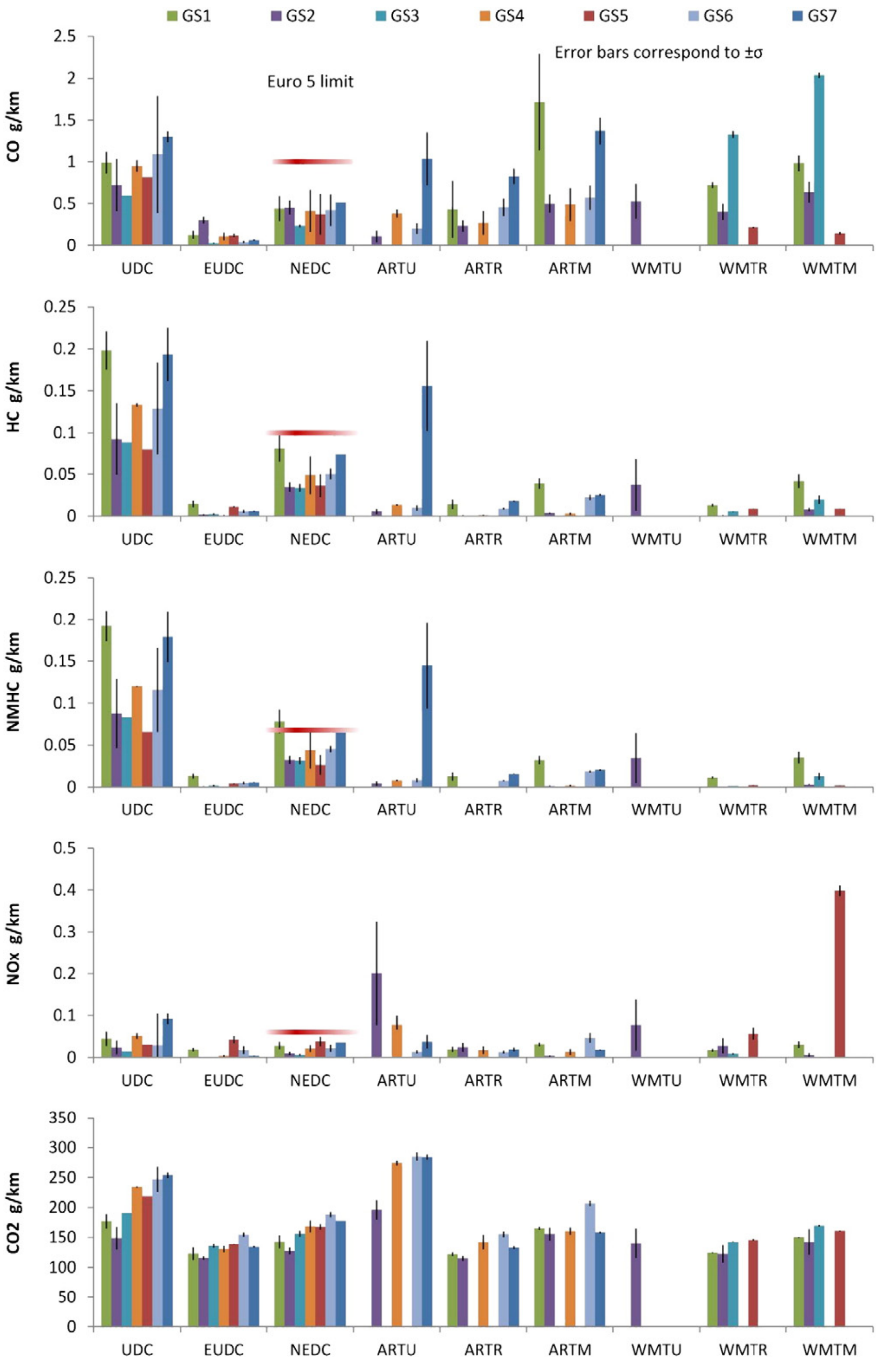

Fig. 2. Summary of experimental results by pollutant, test vehicle and sub-cycle (gasoline vehicles).

above the 1 g/km limit occurred under motorway conditions in the cases of vehicles GS1 and GS3. The latter exhibited the highest emission levels during the tests, reaching approximately 2 g/km, but the high spread of results and the low values observed over WMTC motorway suggest the occurrence of an individual emission event rather than a more systematic behaviour. In the case of GS7, it is possible that the vehicle engine was tuned to a relatively low air-fuel ratio for higher power and more transient operation. With regard to urban air quality, it is important that emissions remained consistently below the limits over the urban sub-cycles of CADC and WMTC. With respect to HC, emissions above the type-approval limit occurred only for GS7 over CADC urban, but the high variability of the results does not suggest a repeatable behaviour.

NO_x emissions of gasoline vehicles remained below the legal limit of 0.06 g/km for most tests. The exceedances observed were marginal and within the uncertainty of the measurements. Exceptions to this were GS2 over CADC urban (0.2 g/km) and GS5 over WMTC motorway (0.4 g/km). In the first case, the increased standard deviation indicates

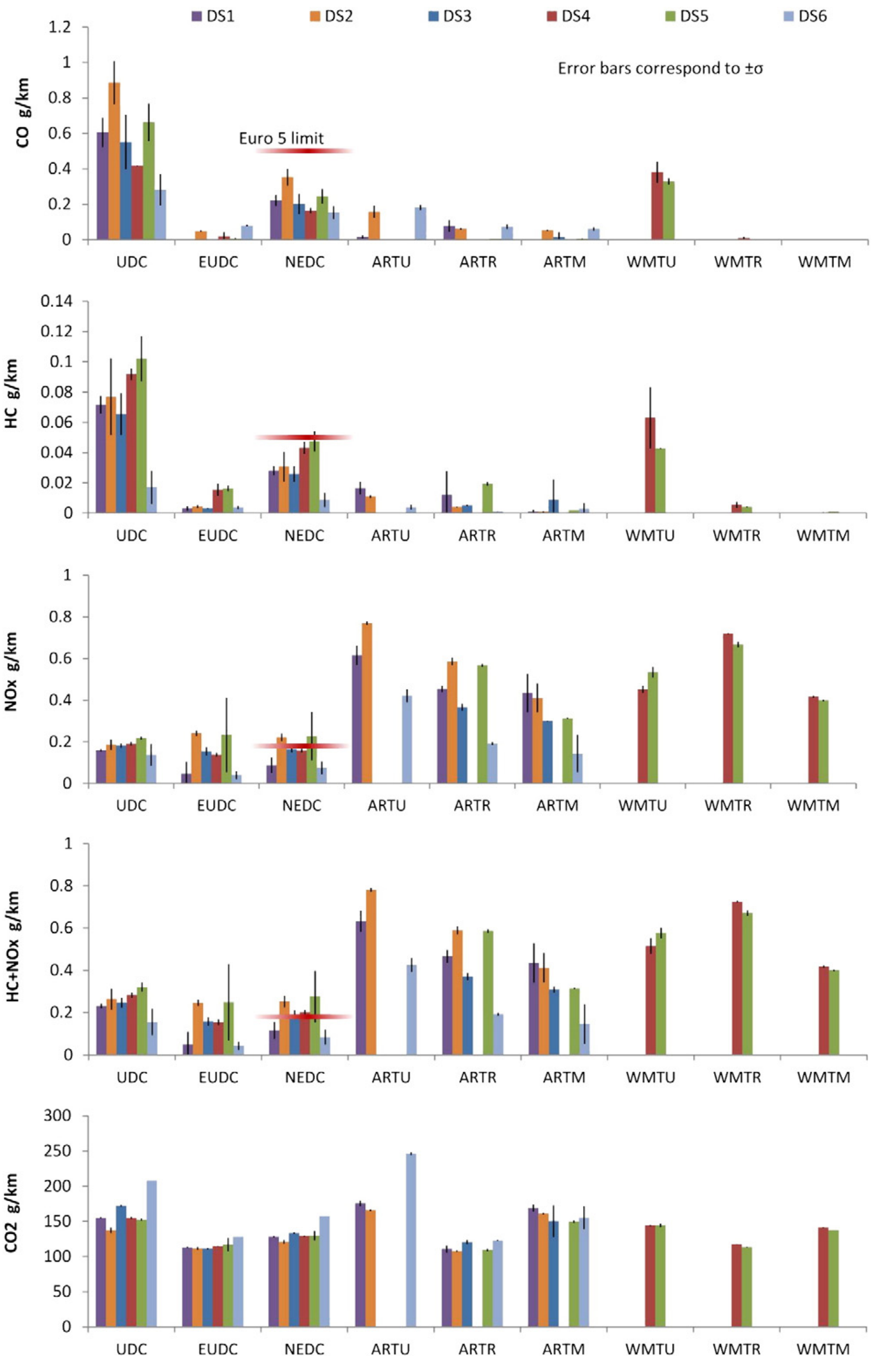

Fig. 3. Summary of experimental results by pollutant, test vehicle and sub-cycle (Diesel vehicles).

the presence of an individual emission event, while in the second case it is clear that the values observed (six times higher than the allowed limit) are indicative of the emission performance of the vehicle. Direct injection fuelling in combination with a lean fuel mix strategy, aiming to increase efficiency, possibly explains the increased NO_x emissions over high load conditions. Such behaviour did not occur for the other two direct injection vehicles. The NO_x emission profile of GS5 resembles that of modern Diesel vehicles that also exceed NO_x emission limits outside the regulated cycle. Given the fact that GDI technology is increasing its share in the European market and that lean-burn combustion can be a measure for reducing CO_2 emissions, the NO_x performance of gasoline vehicles should be more closely monitored in the future.

GDI vehicles were also measured with respect to particle mass emissions (Fig. 4a), as foreseen by the European legislation. In this case, only NEDC and the entire CADC cycle were tested. The results were in the order of 1 mg/km, remaining well below the regulated limits.

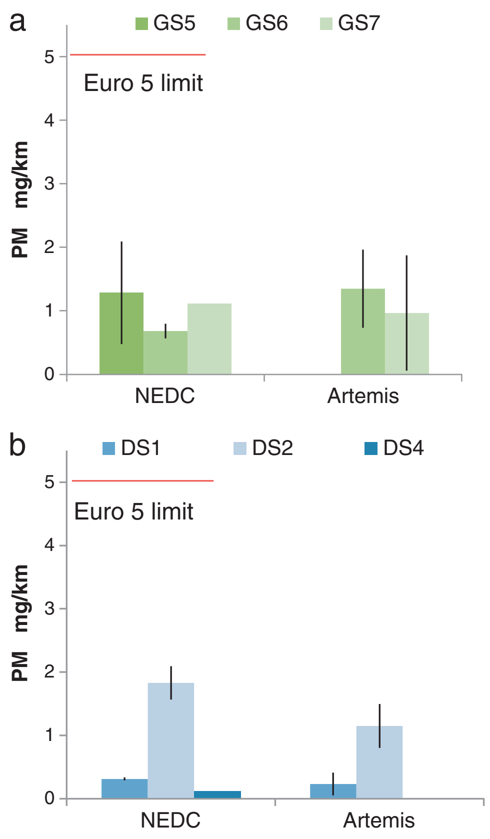

Fig. 4. PM emission results over NEDC and CADC (entire cycles) for gasoline (a) and Diesel vehicles (b).

3.2. Diesel vehicles

Emission levels of all Diesel vehicles remained below the type-approval limits for all pollutants except NO_x (consequently exceeding also the NO_x + HC limit). Good emission performance was recorded over the majority of cycles (Fig. 3), with the expected exception of UDC due to the cold-start effect.

With respect to CO and HC, all vehicles tested showed good performance over all cycles. Average emission levels over NEDC were at 0.22 g/km for CO and 0.06 g/km for HC, whereas the respective values over the hot-start cycles were much lower (0.06 g/km for CO and 0.01 g/km for HC). In several occasions, the concentration values recorded at the exhaust pipe were below those of the background ('zero' emissions).

NO_x emissions were close to the legal limit of 0.18 g/km over NEDC. In particular cases, marginally higher values were also observed, but these were within the uncertainty range of the measurement. Over the more transient hot-start cycles, NO_x emissions were notably higher, reaching up to 0.76 g/km (DS2 over CADC urban) and with only one vehicle staying below the Euro 5 limit (DS6; 0.16 g/km over CADC motorway). The average emission levels observed were 0.56 g/km over the urban sub-cycles, 0.50 g/km over the rural profiles and 0.35 g/km under motorway conditions. These observations agree with existing studies showing that NO_x emissions of modern Diesel vehicles increase significantly outside of the regulated duty cycle. Hausberger (2010) measured the emissions of seven Euro 5 Diesel passenger cars on a chassis dynamometer and also observed high increases of NO_x emissions under the CADC cycle as compared to the NEDC. A likely cause for this is that the NEDC cycle covers a narrow range of engine operating points, and so manufacturers are not incentivised to optimise the NO_x emission behaviour of vehicles in the higher load, 'real-world' ranges. Also, passenger cars are generally optimised for *fuel efficiency*, which is positively perceived by the user of the vehicle but has a known environmental trade-off in the form of increased real-world NO_x emissions. Further tests with portable emission measurement systems (Rubino et al., 2007) have cast a doubt on the effectiveness of the upcoming Euro 6 emission standard towards the reduction of NO_x emissions from Diesel passenger cars (Weiss et al., 2012). Finally, the fact that the highest emission levels occurred over urban driving profiles raises concerns regarding the impact of the dieselization of the passenger car fleet upon the air quality of European cities.

Whole-cycle PM emissions were measured for vehicles DS1, DS2 and DS4 over NEDC and CADC (Fig. 4b). PM levels were found to be substantially lower than the Euro 5 limit (averaging at 0.5 mg/km) in all cases over both cycles. Whereas the reduction of Diesel NO_x emissions still poses a substantial challenge to vehicle manufacturers and regulators, the reduction of Diesel PM emissions from Euro 4 to Euro 5 can be deemed a success (thanks to the widespread adoption of DPF).

3.3. CO_2 emissions

The CO_2 performance of gasoline vehicles over NEDC was in the order of 160 g/km, about 15 g higher than the reported gasoline average for years 2009 and 2010 (EEA, 2012). However, it should be noted that the average mass and engine capacity of the vehicles tested were higher than the average (by 140 kg and 200 cc, respectively). The highest CO_2 emissions occurred over urban conditions, reaching up to 290 g/km, whereas the lowest occurred over extra-urban or rural conditions (averaging at 133 g/km). Diesel CO_2 emission levels were on average 133 g/km over NEDC, with the highest emitter (DS6 over urban conditions) standing at 158 g/km and the lowest at 107 g/km (DS2 over rural conditions). This is about 5 g/km lower than the average

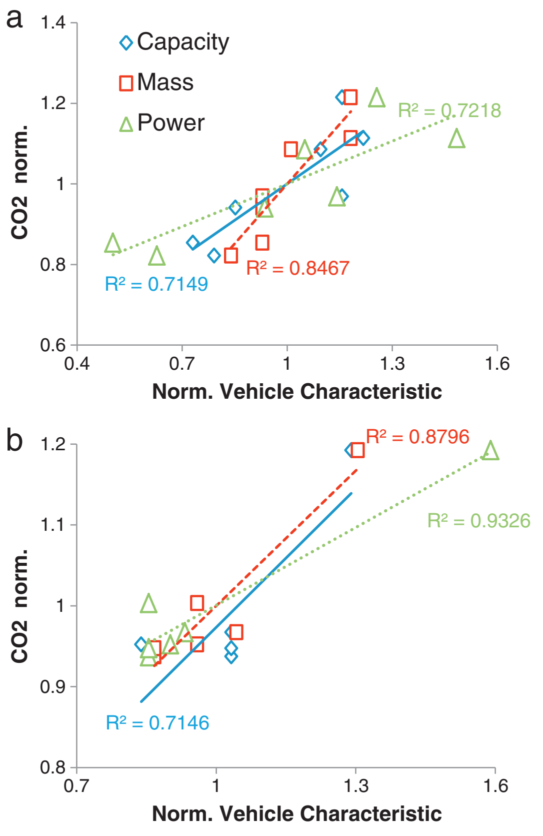

Fig. 5. Average normalized CO_2 emissions as function of normalized vehicle characteristics for gasoline (a) and Diesel (b) vehicles tested. For each of the two vehicle groups, CO_2 was normalized against the fleet average emissions over each cycle. Vehicle characteristics were normalized by the fleet average value.

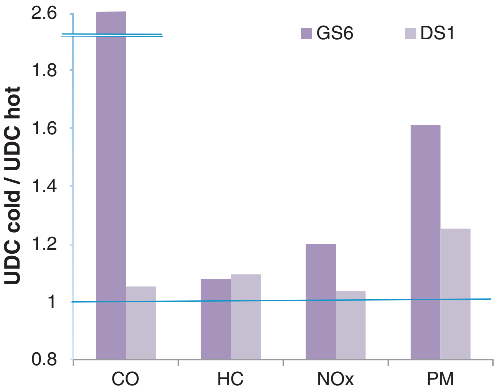

Fig. 6. Ratio of excess cold-start emissions over UDC cycle ($T_{amb} = 22$ °C).

value reported in Europe for the period of 2009–2011 (EEA, 2012). This is an expected observation as the average mass and engine capacity of the Diesel sample were also lower than the European average during the same period by about 200 kg and 200 cc. Over the more transient cycles, CO_2 levels were generally higher reaching 175, 115 and 152 g/km over the urban, rural and motorway cycles respectively.

An investigation of the correlation between specific vehicle characteristics and CO_2 emissions (see Fig. 5) reveals the important influence of mass, engine power and capacity on CO_2 emissions. For both gasoline and Diesel vehicles, CO_2 appears to be strongly associated with these characteristics in a proportional way. Mass appears to be the factor with the highest influence on CO_2 for both gasoline and Diesel vehicles, with capacity coming second. Maximum engine power by itself is not a characteristic that increases CO_2 emissions, although it might be correlated with less fuel-efficient engine management, greater engine capacity, size and generally higher driving resistances. Such influences were expected and have been previously described in literature.

3.4. Cold-start emissions

During type-approval tests, a substantial fraction of the regulated and unregulated gaseous compounds is emitted during the cold-start phase of the NEDC, *i.e.*, the initial seconds before the catalyst reaches the optimal operating conditions (urban part of the cycle, UDC). Vehicles GS6 and DS1 were measured over hot-start NEDC in addition to the cold-start type-approval measurement. This allowed the estimation of the excess cold-start emission ratio over UDC. These results are summarised in Fig. 6. Further information regarding the evolution of emissions over cold-start can be found in (Clairotte et al., 2013; Dardiotis et al., 2013).

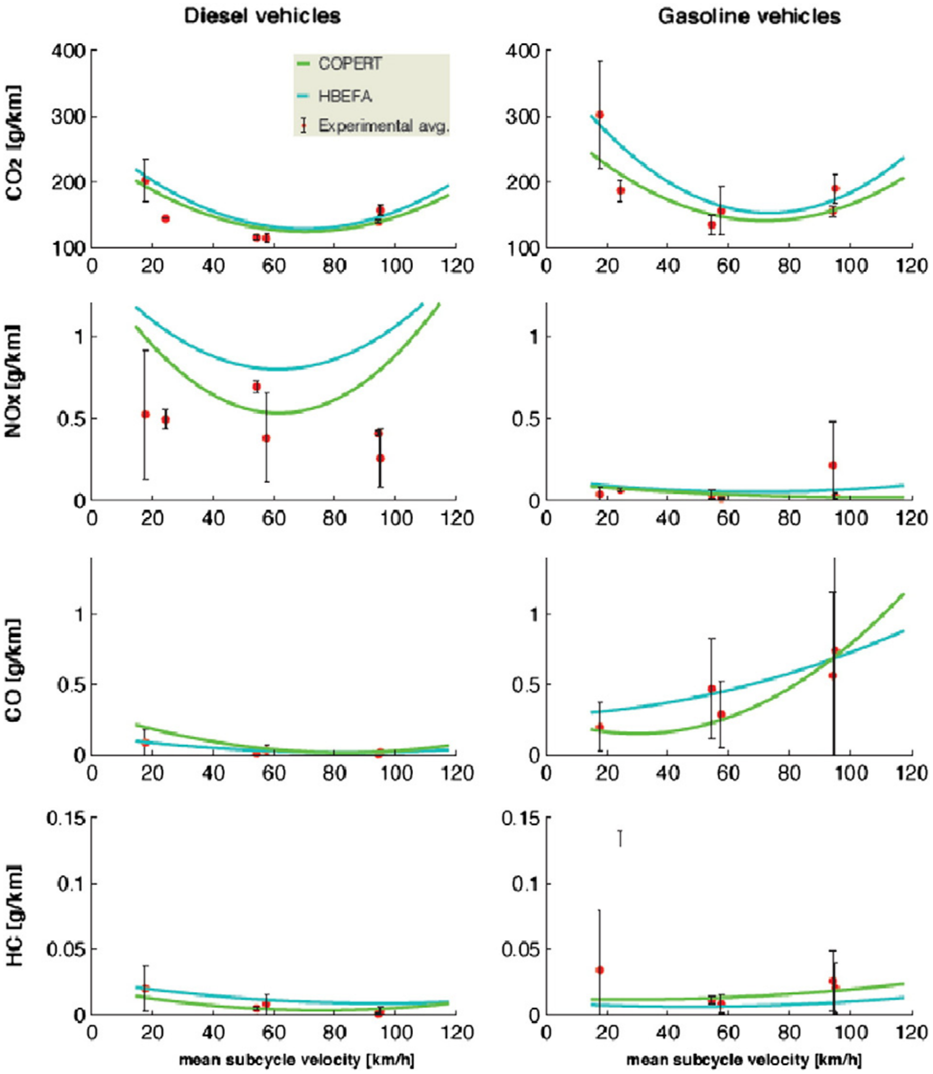

Fig. 7. Comparison of average experimental (hot) distance-based emission factors to model predictions.

4. Assessment of existing EFs

Since Euro 5 vehicles comply with strict emission limits under type-approval conditions, the key environmental issue is whether the emission levels of regulated pollutants remain at acceptable low levels during real-world driving, and whether EFs from the models used for the compilation of emission inventories can predict the actual emissions of this vehicle technology class with reasonable accuracy. These issues have direct implications in the design of air quality policies and the achievement of long-term environmental goals. The performance of Euro 5 vehicles over non-standard cycles has been discussed in Section 3 of the paper. In order to obtain an indication of the performance of inventorying and emission projection tools, EFs representing the average sub-cycle emissions of all Diesel and all gasoline vehicles tested were derived from the measurements. These experimental results were compared with model predictions by overlaying them in the same plot (Figs. 7 and 8). The predictions of COPERT were obtained by substituting the average sub-cycle velocities for WMTC and CADC in the corresponding EFs for Euro 5 vehicles (COPERT 4 version 1). For the comparison, the EFs for gasoline vehicles belonging to the 1.4–2.0 l category and Diesel belonging to the <2.0 l category were used. Specific corrections to the baseline COPERT emission factors were applied for NO_x (23% increase), Diesel fuel consumption/CO_2 (−7.38%) and gasoline fuel consumption/CO_2 (−12.8%) according to the methodology proposed in Katsis et al. (2012). The predictions for HBEFA (version 3.1) were obtained by simulating the CADC cycle with model PHEM for the average Euro 5 passenger car contained in PHEM version 10.4.2 (EuP, 2007b, 2008; Hausberger et al., 2009). The mass and the power of the vehicle model were set to match the average values of the sample in order to obtain comparable results. Fig. 7 presents the results for CO_2, NO_x, CO and HC, and Fig. 8 presents those for PM for Diesel vehicles.

In general, the measured emission levels are in reasonable agreement with the predictions of the reference models, taking into account that these models are not meant to predict the emissions of individual vehicles, but rather of vehicles within the same technology class or subclass (*e.g.*, Euro 5 of a given engine capacity range). The predicted CO_2, CO and HC emissions are well in line with the experimental results for both Diesel and gasoline vehicles, as are the gasoline NO_x emissions (exception made of some outlying points attributable to inter-vehicle variability). Both models provide good estimates of CO_2 emissions over all traffic conditions and in particular for gasoline cars their results almost coincide. In the case of Diesel cars HBEFA appears to better capture the performance of the higher emitters, while COPERT is on the lower side of the tested sample. Given the variability of the measurements and the uncertainties associated with such emission calculation exercises, further investigation on a much broader vehicle sample would be necessary before reaching solid conclusions. Finally, good agreement between measurements and model predictions for DPF-equipped Diesel passenger cars was also observed in the case of PM (Fig. 8).

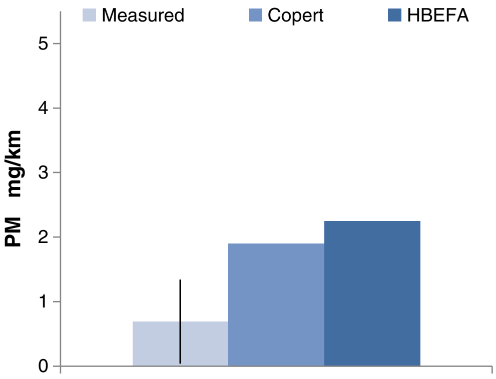

Fig. 8. Average measured PM emissions for Diesel PCs *vs.* model predictions.

5. Conclusions

The measurement results presented in this paper cover only a small number of vehicles with respect to the entire Euro-5 certified passenger car fleet, but they provide some insight into the general characteristics of the emission profile of this vehicle technology class. Results regarding the particular pool of vehicles indicate good compliance with legislated limits over both the type-approval test cycle and the more transient, real-world simulation cycles. Only Diesel NO_x emissions were found to repeatedly exceed the Euro 5 limit outside the type-approval conditions. This observation is consistent with the results of similar studies performed on-road using PEMS systems. The findings suggest that similar problems might appear in the future in the case of lean-burn gasoline direct injection vehicles. The results also indicate a good agreement between the average emission levels measured and the predictions of existing models and inventories used in Europe for most of the pollutants investigated. There are, however, discrepancies that should be addressed. Due to the limited number of vehicles tested, no solid conclusions can be reached regarding specific revisions of the models. Modelling efforts behind COPERT and HBEFA helped signal a problematic aspect of the real-world emission profile of Euro 5 Diesel vehicles, which is already being taken into account for the deployment of the Euro 6 norm. In order to capture the rapid evolutions made in the passenger car fleet, particularly in view of the efforts put in energy consumption and CO_2 emissions reduction, additional experimental data are needed, and therefore a coordinated Europe-wide test campaign for producing and validating the necessary data to update existing EFs and continue to develop the emission models is necessary. This will allow to better support both emission monitoring and policy-making.

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