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POTENTIAL OF NATURAL GAS POWERED VEHICLES IN REDUCING CO2 AND POLLUTANT EMISSIONS UNDER REAL-WORLD DRIVING CONDITIONS

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ABSTRACT - Natural gas powered vehicles (NGVs) represent a promising approach to reduce vehicle CO_2 and pollutant emissions. These vehicles use compressed natural gas (CNG) as engine fuel, profiting from its considerably lower carbon content per unit energy to save vehicle CO_2 emissions. Another benefit of NGVs is that they can rely on approved powertrain and exhaust aftertreatment solutions that generally demand only minor adaptations to CNG. Finally, the environmental impact of NGVs regarding greenhouse gas emissions can be greatly reduced when employing methane gas from renewable sources.

Therefore, an experimental investigation on a chassis dynamometer test bench has been carried out with a sample of 13 in-use NGVs to determine their emission performance regarding CO_2 and both regulated and unregulated gaseous pollutants. The vehicle sample consisted of 12 Euro-4 and 1 Euro-5 NGVs including original equipment manufacturer (OEM) completions and both OEM and external retrofits. Test runs with the statutory driving cycle for Europe NEDC have been performed as well as the European real-world driving cycles CADC and IUFC15. The latter two are based on car driving behaviour studies and reflect representative urban, rural and motorway driving.

The results obtained show an acceptable pollutant emission performance of the considered NGVs, having only 2 vehicles failing statutory hydrocarbon (HC) emission limit compliance. But emissions of HC and nitrogen oxides (NO_x) are remarkable in real-world urban hot driving, indicating that the reduction of NO_x in the catalytic converter employing HC as the oxidant may not occur entirely because HC emissions of NGVs mainly consist of methane, a powerful greenhouse gas that has a less pronounced catalytic oxidation activity. Besides, pronounced emissions of HC and also ammonia together with low emissions of NO_x in high load and dynamic real-world rural and motorway driving indicate occasional fuel-rich combustion. The often low-end engine control systems used for NGVs until now and the fact that lambda sensors are cross-sensitive to methane are assumed to be responsible for this observation. In contrast, neither cold start nor hot emissions of carbon monoxide (CO) and non-methane hydrocarbons (NMHC) are critical. A comparison to sample emissions of 26 Euro-4 gasoline vehicles confirms these findings and also highlights benefits in CO_2 emissions for the considered NGVs of around 21% for the Euro-4 sample and 33% for the Euro-5 vehicle.

It can be concluded that modern NGVs demonstrate their CO_2 emission reduction potential compared to gasoline vehicles under real-world driving conditions with mostly improved pollutant emission levels. However, certain fuel-specific developments in the fields of engine control and exhaust aftertreatment are still to be undertaken to achieve best possible pollutant emission performance of NGVs.

INTRODUCTION

The need to reduce CO_2 along with pollutant emissions caused by individual mobility has become a predominant task in the development efforts of vehicle manufacturers, also because of specific CO_2 vehicle emission legislation such as in Europe (1). Varied powertrain concepts aiming at meeting these requirements are therefore subsequently entering the market and one promising short-term approach represent natural gas powered vehicles (NGVs) that use compressed natural gas (CNG) as engine fuel (2). Its lower carbon content per unit energy allows reducing CO_2 emissions significantly. Another advantage represents the fact that reliable and approved technical solutions for energy conversion and exhaust aftertreatment can be employed with minor specific adaptations to this fuel. Further, the possibility of employing methane gas from renewable sources is feasible and established for these vehicles without considerable additional technical constraints, leading to major reduction in the environmental impact of NGVs regarding greenhouse gas emissions.

Given this, it is of great interest to estimate the effective CO_2 and pollutant emission performance of modern NGVs under real-world driving conditions. The present study addresses to this topic and reports the outcomes of an experimental investigation on a chassis dynamometer test bench with 13 in-use NGVs of certification category Euro-4 and Euro-5 including the statutory cycle for Europe and two real-world driving cycles for cars. The results obtained for CO_2 and both regulated and non-regulated pollutant emissions in real-world hot and cold-start driving conditions are discussed in detail and compared to sample emissions of Euro-4 vehicles to highlight the respective differences in vehicle emission performance.

METHODOLOGY

NGV Sample

The main characteristics of the 13 in-use NGVs selected for the test series are summarized in Table 1. This selection has been chosen in order to match a representative vehicle sample within the registered Swiss vehicle fleet and is based on the respective vehicle registration database at the time of the investigation. 12 vehicles conform to certification category Euro-4 and one vehicle to certification category Euro-5. Out of this Euro-4 sample, 10 vehicles represent an original equipment manufacturer (OEM) completion and the other two correspond to a retrofit and OEM-retrofit completion. In addition, 5 of the OEM completions of the Euro-4 sample (vehicles 1, 2, 3, 6 and 12) are monovalent, i.e. they feature a maximum gasoline tank volume of 15 liters and operate exclusively in CNG mode except cold start at low ambient temperature. The state-of-the-art Euro-5 (vehicle 13) follows the same operation regime although being characterized as bivalent. All vehicles are of course equipped with three-way catalytic converters (TWCs) to aftertreat the exhaust.

no.	make	model	empty mass	displ.	rated power	mileage	cert. cat.	comple-tion	super-charging
	[-]	[-]	[kg]	[cm^3]	[kW]	[km]	[-]	[-]	[-]
1	VW	Touran	1640	1984	80	2814	Euro-4	OEM	no
2	Opel	Zafira 1.6 CNG	1590	1598	69	4404	Euro-4	OEM	no
3	VW	Caddy	1642	1984	80	32429	Euro-4	OEM	no
4	Volvo	V70 CNG	1591	2435	103	47709	Euro-4	retrofit	no
5	Fiat	Punto 1.2 Bipower	1025	1242	44	23426	Euro-4	OEM	no
6	Opel	Combo C16CNG	1395	1598	71	39459	Euro-4	OEM	no
7	VW	Golf Variant Bifuel	1434	1984	85	93344	Euro-4	OEM	no
8	Citroën	C3 1.4i	1014	1360	54	11300	Euro-4	OEM-retrofit	no
9	Mercedes Benz	E 200 NGT	1690	1796	120	44192	Euro-4	OEM	compr.
10	Fiat	Multipla 1.6Bipower	1470	1596	65	46401	Euro-4	OEM	no
11	Mercedes Benz	B 170 NGT	1440	2034	85	21154	Euro-4	OEM	no
12	Opel	Zafira B16T CNG	1660	1598	110	8988	Euro-4	OEM	turbo-charged
13	VW	Passat Ecofuel	1537	1390	110	5296	Euro-5	OEM	twin-charged

Table 1. Main characteristics of the considered vehicle sample; displ.: displacement, cert. cat.: certification category, compr.: compressor.

The engines of vehicles 9, 12 and 13 include a form of supercharging in order to compensate possible charge losses due to port injection of CNG and to fully exploit the fuel characteristics of CNG with its higher knock resistance compared to gasoline. Besides, no particular servicing was carried out before the test runs except a general vehicle function check.

Experimental Program

Several driving cycles were employed in the test series in order to determine the CO_2 and pollutant emission performance of the selected NGVs. The statutory cold-start driving cycle for Europe (3) was included, as well as the real-world Common Artemis Driving Cycle (CADC) and the repetitive real-world Inrets Urbain Fluid Court (IUFC15) cycle. The warm-start cycle CADC was derived from car driving behavior studies within the ARTEMIS research program (4), and its cycle sections represent European real-world urban, rural and motorway driving behavior for cars (5). The cold-start cycle IUFC15 was developed within the same research program and is suitable for investigating the effect of cold start on vehicle pollutant and CO_2 emissions because it consists of 15 repetitions of a short representative European real-world urban driving pattern (6) equally divided in three sections.

Experimental Setup

Figure 1 shows the overall experimental setup employed for the test series. The exhaust was sampled with a Constant Volume Sampling (CVS) system. Exhaust emissions of CO_2 and regulated pollutants were measured according to the statutory procedure specified in Council Directive 70/220/EEC (3) of storing a sample of diluted exhaust in a tedlar gas sampling bag and analyzing its content offline after completion of the test run. Time-resolved measurements of CO_2 and raw exhaust pollutants emissions were also performed, correcting the resulting signal traces with respect to time delay due to the length of the sample lines. Adequate exhaust gas analyzers as specified by Council Directive 70/220/EEC (3) were employed for regulated pollutants and CO_2 in both cases and selected time-resolved unregulated pollutants were detected with a chemical ionization mass spectrometer (CI-MS).

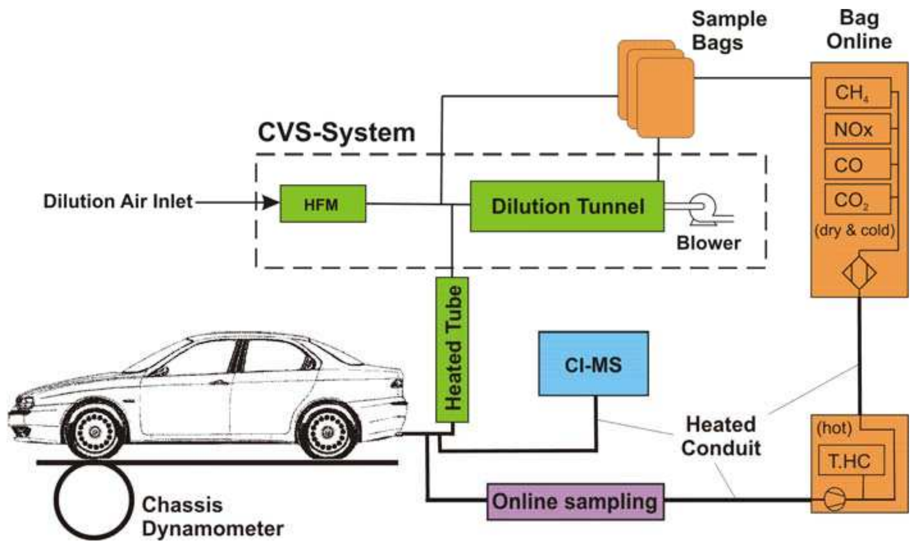

Figure 1. Schematic diagram of the test setup; HFM: hot-film air-mass flow meter; CVS: constant volume sampling; CI-MS: chemical ionization mass spectrometer.

The chassis dynamometer and its settings were applied according to the provisions of Council Directive 70/220/EEC (3). The driving resistance of the vehicle was simulated using the respective coast-down data provided by the manufacturer and the inertia settings were set at empty vehicle mass plus 100 kg payload. The test cell ambient conditions were set to 23°C temperature and 50% relative air humidity. All vehicles were operated with commercial CNG.

RESULTS

The test results obtained for the present NGVs in the different driving cycles discussed below are reproduced in sample emissions of the 12 Euro-4 NGVs on one hand (NGV-E4) and single vehicle emissions of the Euro-5 NGV on the other hand (NGV-E5) in order to highlight the possible improvements that can be expected from state-of-the-art completions of NGV powertrains. In Addition, sample emissions of a Euro-4 gasoline vehicle sample (G-E4) are included for comparison reasons that were recorded in earlier experimental investigations (7,8) but applying the same determination methodology.

The main characteristics of the two samples are summarized in Table 2. They differ from each other because of the larger variation of the latter needed to be reflected by the G-E4 sample to achieve in-use representativeness, resulting in lower average empty mass and higher average displacement, power and mileage for G-E4 together with larger variance than NGV-E4.

	empty mass [kg]	displ. [cm^3]	power [kW]	mileage [km]
NGV-E4	1466	1767	83.7	31302
G-E4	1277	1946	102.8	54889

Table 2. Main sample characteristics of the NGV-E4 and G-E4 vehicle sample; displ.: displacement.

Statutory Pollutant Emission Performance

The emission limit compliance of the measured NGVs in the statutory driving cycle NEDC is acceptable, having only two vehicles failing hydrocarbon (HC) emission limits and showing less spread in emissions with regard to G-E4, see Figure 2. Considerably lower sample emission levels of the NGVs compared to G-E4 can be stated for emissions of carbon monoxide (CO), nitrogen oxides (NO_x) and particularly of non-methane hydrocarbons (NMHC), because HC emissions of NGVs almost entirely consist of methane. The observed differences in sample pollutant emissions are assumed to be mainly caused by the less aged catalytic converters of some NGVs thanks to their lower mileage (9) in contrast to G-E4. Also, the larger variance in vehicle sample characteristics of G-E4 leads to the given wider spread in pollutant emissions.

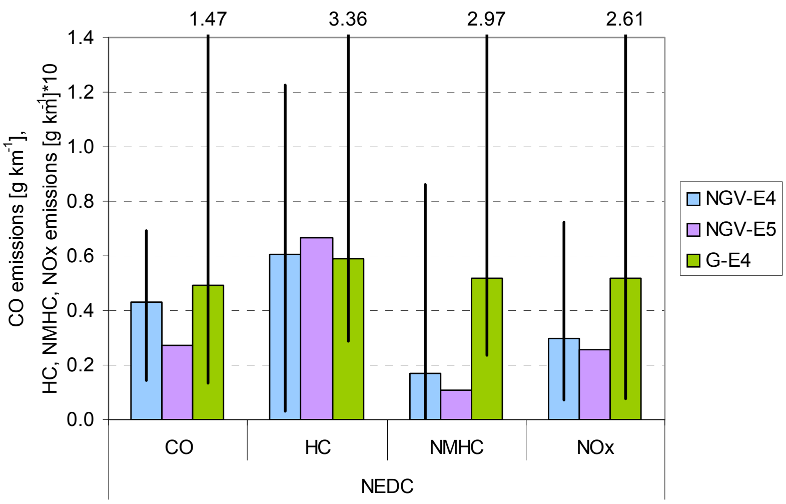

Figure 2. Average sample emissions of regulated pollutants in the cycle NEDC; error bars represent maximum and minimum sample emissions.

Real-World Hot Pollutant Emission Performance

Figure 3 shows the outcomes regarding NGV pollutant emissions in the warm-start real-world driving cycle CADC. The lower CO emission levels of NGVs compared to G-E4 observed in the cycle NEDC is confirmed, especially for NGV-E5, demonstrating the emission reduction potential for CO of state-of-the-art NGV powertrains. Low NO_x emission levels can also be stated except in urban driving conditions, where similar emission levels like G-E4 are detected together with a larger spread in emissions. This behavior is linked to the equivalent HC emission performance observed in that cycle section: it appears that not all the NO_x

formed under stoichiometric combustion conditions can be oxidized in the catalytic converter with the respective amount of resulting HC because it mainly consists of methane, which typically has a less pronounced catalytic oxidation activity (9,10,11). Besides, the high HC emissions of some NGVs recorded in the more demanding rural and especially motorway cycle sections of the CADC combined with low NO_x emissions indicate occasional fuel-rich combustion. A possible reason for this insufficient fuel management in such high load and dynamic operating conditions can be found in the often low-end engine control systems implemented in these vehicles up to now, especially when they do not accurately compensate the cross-sensitivity of the exhaust gas oxygen sensor to methane. Also note that the pronounced NMHC emissions of the NGV-E4 sample in the motorway cycle section are only caused by excessive emissions of a single vehicle and may rather constitute an exceptional occurrence.

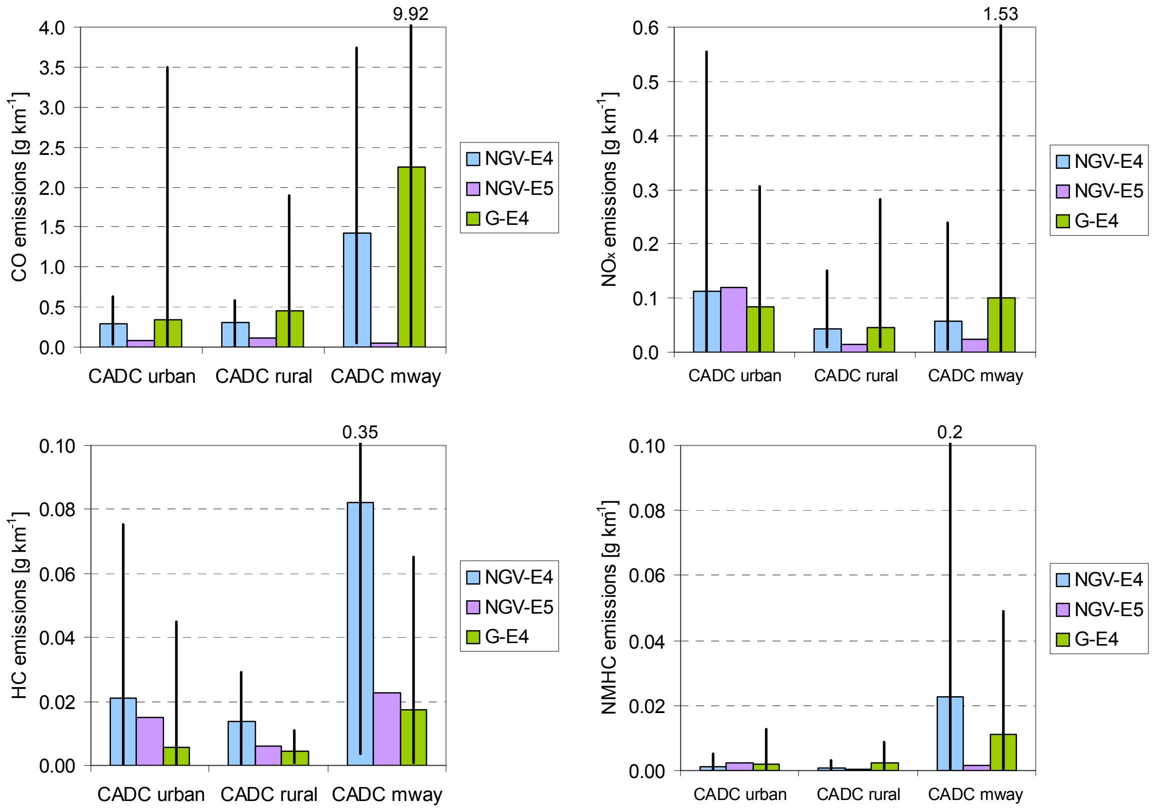

Figure 3. Average sample emissions of regulated pollutants in the cycle CADC; error bars represent maximum and minimum sample emissions.

Cold-Start Real-World Emission Performance

The results from the repetitive urban real-world driving cycle IUFC15 suitable for investigating cold start effects on vehicle pollutant emissions are given in Figure 4. Again, a considerably better CO emission performance can be stated for the NGV-E4 sample compared to G-E4 that is topped by the very low CO emissions of NVG-E5. Similar sample emissions are detected for NO_x and HC in the cold started cycle section, but remarkably higher emissions of the latter appear for NGVs in the last two cycle sections where catalyst light-off already occurred. The same behavior than in the CADC urban cycle section is assumed to be responsible for it, i.e. that not all of the HC can be used as oxidant to catalytically reduce NO_x in the catalytic converter because it mainly consists of methane that does not easily oxidize catalytically (9,10,11). Besides, most of the NMHC emissions in the first section of the IUFC15 of sample NGV-E4 are caused by the respective vehicles carrying out cold start in gasoline mode.

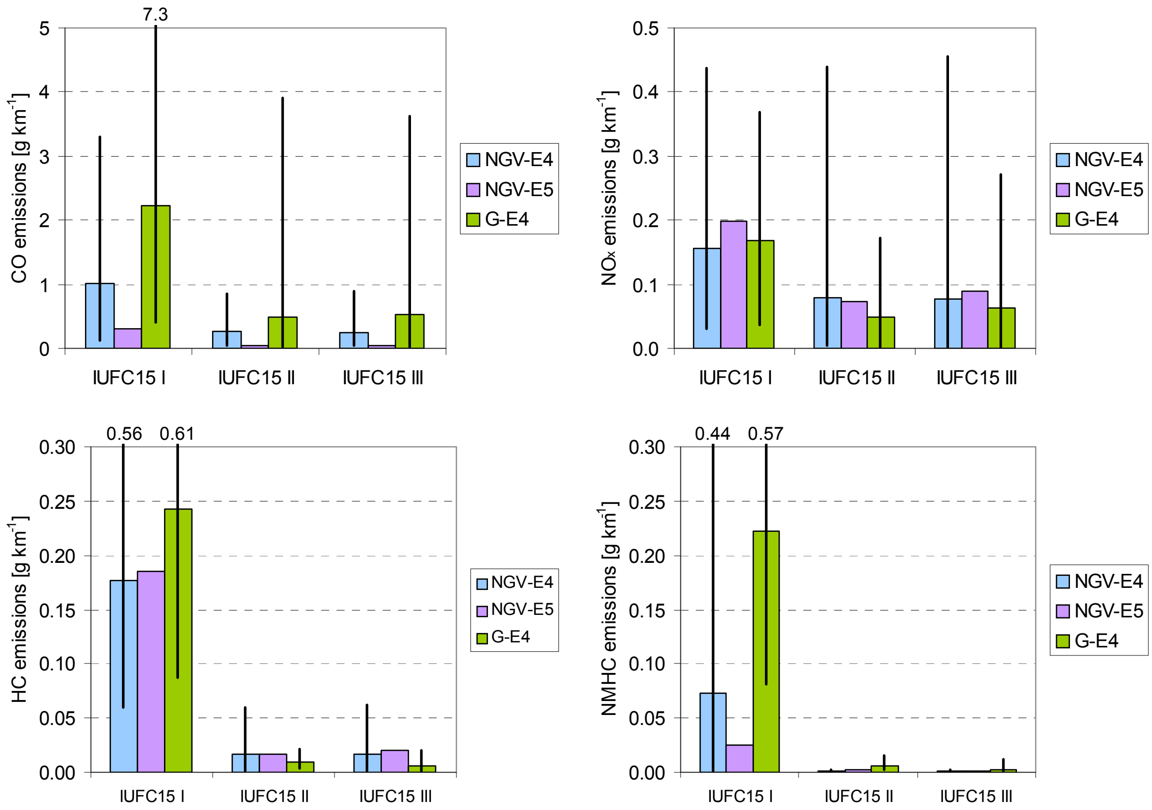

Figure 4. Average sample emissions of regulated pollutants in the cycle IUFC15; error bars represent maximum and minimum sample emissions.

These findings are confirmed by the resulting cold start extra emissions (CSEE) for the single vehicle samples given in Table 3 that are calculated from the emissions values of the single IUFC15 cycle sections based on the methodology described in (12): comparable CSEE are stated for NO_x, CSEE for CO improve broadly and CSEE for HC and particularly for NMHC are much lower for the NGVs as their hot emissions of HC are more pronounced and basically consist of methane.

	CSEE [g/cyc]			
	CO	HC	NMHC	NOx
NGV-E4	0.768	0.160	0.071	0.079
NGV-E5	0.261	0.162	0.025	0.094
G-E4	1.664	0.240	0.223	0.090

Table 3. Pollutant cold start extra emissions (CSEE) of the single vehicle samples in the driving cycle IUFC15

Non-Regulated Pollutant Emission Performance

A chemical ionization mass spectrometer has been employed in the present experimental investigation to determine possible relevant unregulated pollutant emissions of NGVs. Out of the substances considered, basically no emissions of aromatic hydrocarbon compounds like benzene or toluene could be detected, which excludes the possibility of formation in the catalytic converter as CNG barely contains such compounds. Also hardly any emissions of NO_2 were recorded in accordance to the evidence of marginal shares of NO_2 in vehicles exhaust emissions of NO_x for modern vehicles equipped with TWCs (13). In contrast, hot emissions of ammonia (NH_3) of vehicle sample NGV-E4 are relevant, see Figure 5. There, emissions of NH_3 in hot cycle sections of NGV-E4 and NGV-E5 are plotted versus the mean cycle speed in the respective cycle sections and compared to speed-dependent emission factors determined from a subsample of G-E4 within another experimental investigation (14).

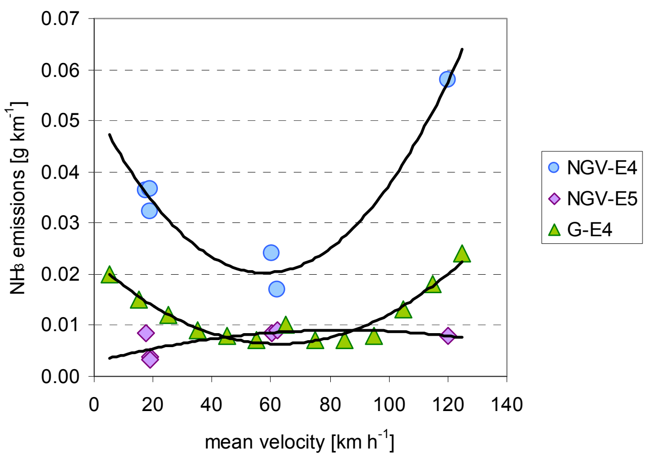

Figure 5. Hot NH_3 emissions of NGV-E4 and NGV-E5 vs. the respective mean cycle section speed together with velocity-dependent NH_3 emission factors for a subsample of G-E4 (14)

The velocity-dependent NH_3 emissions of NGV-E4 are about twice the emissions of G-E4. This observation enforces the above-mentioned assumption of insufficient fuel management in certain driving situations by the low-end engine control system of some NGVs, because ammonia is almost exclusively formed in fuel-rich combustion conditions. But the overall low NH_3 emission levels of NGV-E5 indicate once more the possibility of reducing pollutant emissions when employing state-of-the-art abatement measures.

CO_2 Emission Performance

The CO_2 emissions of the NGV samples recorded in the single driving cycles are given in Figure 6 together with respective sample emissions of G-E4. Reduced CO_2 sample emissions of around 21% for NGV-E4 and even 33% for NGV-E5 compared to G-E4 can be stated in all cycle sections, although the average empty mass of the latter is articulately higher. The higher average displacement and rated power of sample G-E4 may account to this finding. Also, the wider spread in CO_2 emissions of G-E4 is clearly to be attributed to the higher variance of its sample characteristics. But the reduction potential regarding CO_2 emissions of NGV powertrains when employing CNG as engine fuel because of the lower carbon content per unit energy of CNG is evident.

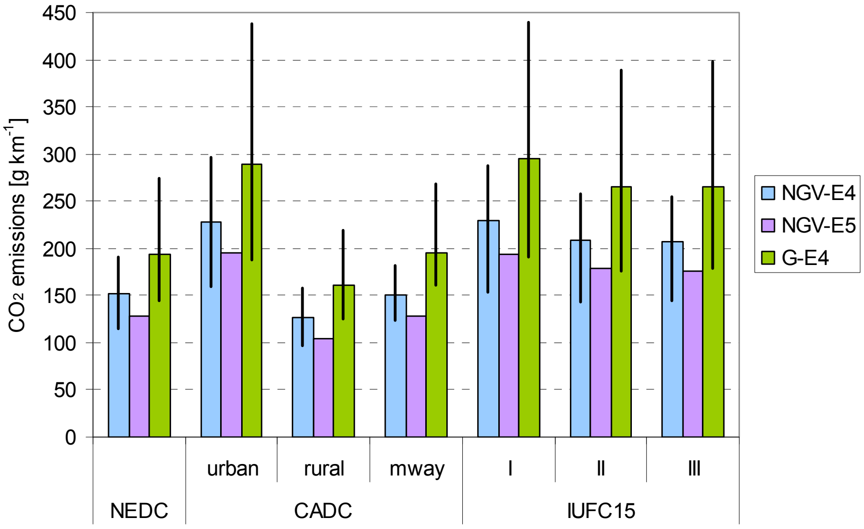

Figure 6. CO_2 sample emissions in the different driving cycles; error bars represent maximum and minimum sample emissions.

Note that even though methane features a considerable greenhouse gas equivalence factor of 25 with regard to CO_2 (15), the CO_2-equivalent NGV sample emissions of methane represent only around 0.5% of the respective CO_2 emissions. CO_2 therefore constitutes the most relevant greenhouse gas for NGVs.

CONCLUSIONS

The present experimental investigation on CO_2 and pollutant emissions of modern NGVs demonstrates their remarkable potential in reducing vehicle CO_2 emissions compared to gasoline vehicles under real-world driving conditions and highlights an improved general emission performance regarding regulated and non-regulated pollutants. However, it is also shown that further development in engine control and exhaust aftertreatment systems of NGVs is still required to fully compensate certain fuel-specific effects in order to avoid pronounced hot vehicle emissions of some pollutants, especially NO_x, methane and also ammonia.

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