Exhaust Gas Temperature and NO_x After-treatment Performance of Euro 6 Passenger Cars

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Introduction

Pollution affect air quality of cities around the world. With the objective to constrain this problem, new homologation procedures have been introduced for a long time. In Europe, the real driving emissions (RDE) tests by means of portable emissions measurement systems (PEMS) has the potential to assess emissions in a more realistic driving with a more robust framework (Hooftman et al., 2018). They also could be used to find gaps in emission models and to increase knowledge of transportation pollution phenomena.

Operating temperatures of aftertreatment systems are relevant to their performance, which is crucial for urban air quality. During cold start, which mainly occurs in urban (Weiss et al., 2017), cool combustion conditions of internal combustion engine (ICE) limit exhaust gas temperatures, so thermal heat transfer to aftertreatment systems is reduced (Chan and Hoang, 2000; Roberts et al., 2014). Aftertreatments need an initial stage of warming-up until reach the optimal operating temperatures, and they also could be affected by conditions of cooling down.

Engine gas recirculation (EGR) has been widespread used to control NO_x emissions. Depending on the application, it could be complemented with after-treatment technologies as: three-way catalyst (TWC), lean-NO_x trap (LNT) or selective catalytic reduction (SCR). Although SCR has shown high efficiency reducing NO_x emissions in diesel vehicles, it is affected by low operating temperatures produced by stop periods (v < 1 km h^{-1}) and low engine loads (Weiss et al., 2011). In the same way, long engine-off periods (engine speed < 50 rpm) of hybrid vehicles could affect to the performance of their TWC systems (Koltsakis et al., 2011).

In light of these considerations, this study aims to show the association between the exhaust gas temperature at tailpipe and the NO_x reduction performance of aftertreatment systems installed in different Euro 6 passenger cars. For this objective, cold start emissions were analysed from real driving tests during engine warming-up in a unique close loop urban route. In addition, RDE tests were performed to correlate the exhaust gas temperatures with the performance of NO_x aftertreatments. The tested fleet represent the most common fuel / powertrain / aftertreatment architectures in the market.

Methods

Driving routes and tests

Three types of tests were performed: cold start (CS), hot-running (HR) and RDE tests. The CS and HR tests had the same driving conditions in an urban route, which consisted in a close loop around Universidad Politécnica de Madrid (UPM) South Campus, as shown in Fig 1a. CS test complied with (EU) 1151/2017 requirements for cold start testing, and it included the first five minutes (t ≤ 5 min) of driving, with the inclusion of 15 seconds of idling at the start. HR test covered the consecutive five minutes to CS test (i.e., 5 < t ≤ 10 min). Then, the vehicles performed several hot-start RDE tests in a unique route, which covers some areas of Madrid city (Spain) and its surroundings. These tests complied with main RDE regulations of (EU) 1151/2017 and the main characteristics can be seen in Table 1. To avoid driving style influence on the tests, they were carried out by one professional driver, and they were done on weekdays. Figure 1 shows the trace of the routes.

In order to observe the vehicle's uninterrupted warm-up behaviour in urban conditions for CS and HR tests, long stop periods were minimized. Therefore, the CS and HR testing route had no traffic lights or heavy congestion, where vehicles equipped with stop-start system would spend much of the time with the engine off. This public route included several crosswalks with speed reducers instead. The main parameters that describe the tested routes are shown in Table 1, and the number of tests performed per vehicle are shown in Table 2.

a)
b)

Figure 1. Test routes a) route of cold start (CS) and hot-running (HR) tests b) route of RDE tests

Table 1: Tested routes parameters

	Cold start (CS)	Hot-running (HR)	RDE			
			Entire test	Urban	Rural	Motorway
Testing time [min]	5	5	101.2 (4.2)	60.8 (3.5)	26.3 (1.0)	14.2 (1.1)
Distance [km]	2.12 (0.23)	2.57 (0.17)	76.5	23.2	28.8	24.5
Average speed [km h^{-1}]	25.5 (2.7)	30.8 (2.0)	45.4 (1.8)	23.0 (1.3)	65.9 (2.3)	104.2 (6.5)
RPA [m s^{-2}]	0.22 (0.03)	0.21 (0.04)	0.19 (0.01)	0.25 (0.03)	0.19 (0.01)	0.13 (0.01)

Table shows mean and (standard deviation) of performed tests

Test vehicles

The tested fleet was composed of five modern (2016-2017) Euro 6b sport utility vehicles (SUV) fuelled by gasoline or diesel, with different NO_x aftertreatment systems. Also, one gasoline hybrid electric vehicle (HEV) was tested. Their characteristics are shown in Table 2.

Table 2: Characteristics of tested vehicles

ID	Fuel	Fuel injection type	NO_x control	Stop-start system	CS / HR tests	RDE tests
G-DI	Gasoline	Direct injection (stratified air fuel mixture)	TWC	√ (off)[a]	1	3
G-HEV	Gasoline	Port-fuel injection (PFI)	TWC	X[b]	3	5
D-SCR	Diesel	Common rail	EGR + SCR	√	2	5
D-LNT	Diesel	Common rail	EGR + LNT	√	2	5
D-EGR	Diesel	Common rail	EGR	√	2	5

[a] Stop-start system was deactivated during the test
[b] Hybrid system acts as stop-start system.

Measurement system

The MIVECO-PEMS was developed and validated by the Universidad Politécnica de Madrid in (Fonseca González, 2012). For this measurement campaign, the system was simplified to reduce its weight and size. NO_x concentration was directly measured, and CO_2 was estimated using carbon balance method by means of lambda value measured by the PEMS. This system was also used in the study of high instantaneous NO_x emissions in (Mera et al., 2019), with a sample frequency of 10 Hz. The PEMS consists of exhaust flow meter (EFM), NO_x exhaust gas analyser, exhaust gas temperature sensors, a global positioning system (GPS), and a weather station for recording ambient temperature and humidity. Additionally, PEMS records data from vehicle's on-board diagnosis (OBD) port. The MIVECO-PEMS measures exhaust gas concentration of NO_x by means of a Horiba Mexa 720 ceramic zirconium sensor. The EFM is a differential pressure Pitot tube type, which is detailed in (Fonseca González et al., 2016). The exhaust gas temperature was measured at the exhaust flow meter by means of K-type thermocouples. Approximately 190 kg were added to the mass of the vehicle, including the PEMS system, the driver, the co-driver and the batteries as power source for PEMS. The recorded data was checked and synchronized in the postprocessing stage.

Emission factors

The raw distance-specific emission factors (in mg NO_x km^{-1}) for section *i*, and from vehicle *j*, were computed as:

$$EF_{i,j} = \frac{m_{i,j}}{s_{i,j}} \quad (1)$$

where *m* is the mass NO_x emission (in mg NO_x) produced during distance *s* (in km).

Results and Discussion

Cold start and exhaust gas temperature profile

CS and HR tests were performed under the same urban testing conditions; therefore, they are directly comparable. As shown Table 2, CS and HR tests had average speed and RPA similar to the RDE urban section values. Additionally, these values are in line with RDE regulation, which establishes an average speed between 15 to 40 km h^{-1}, and a maximum of 60 km h^{-1} speed limit for urban section.

One exhaust gas temperature profile per vehicle is shown in Figure 2. All vehicles evidence a growing temperature pattern during CS and HR driving. As it was said before, stop periods were minimized during CS and HR tests, so a constant warm-up profile is reflected, except for HEV vehicle. Hybrid vehicle shows a saw profile due to combustion engine-off periods which represented 61 % of CS and HR testing time. It implies less warming-up time of TWC aftertreatment, so aftertreatment light-off temperature could take more time to be reached. Also, long engine-off periods could yield to TWC cooling, with the reduction of performance depending of its thermal energy management.

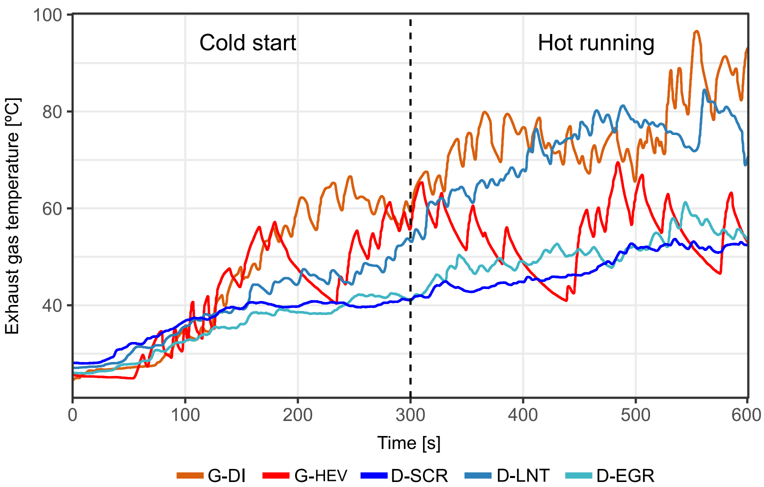

Figure 2. Exhaust gas temperature profiles during cold start (CS) and hot-running (HR) tests.

NO_x Emission factors

As shown in Figure 3, for the cold start test (CS) none of the tested vehicles could meet Euro 6 limits. The performance of G-HEV and D-SCR aftertreatment systems at CS was the most affected, being observed that CS emission factors are higher than HR and RDE emission factors; however, their RDE emissions comply with Euro 6 NO_x limits. The CS emission factors of G-HEV and D-SCR were 5.5- and 2.8-times Euro 6 limits, respectively. Curiously, the emissions from cold start tests of SCR and EGR-only diesel vehicles were the same (223 mg NO_x km^{-1}).

The vehicles G-DI, D-LNT and D-EGR show opposite patterns to G-HEV and D-SCR in the emission factor values. Firstly, they increase their emission factors in the following order: CS-HR-RDE. Secondly, none of their average RDE emissions complied with Euro 6 limits, which reflects the general performance of those vehicles. They surpassed in 6.0, 7.4- and 9.0-times Euro 6 limit, for G-DI, D-LNT and D-EGR vehicles, respectively.

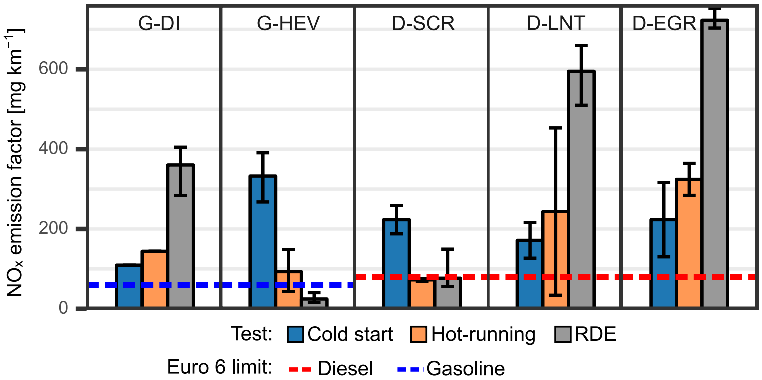

Figure 3. Average emission factors of cold start (CS), hot-running (HR) and RDE tests. Error segments represents maximum and minimum tests values.

Comparing CS and HR tests, it is remarkable the fast reduction of CS emissions of G-HEV and D-SCR. CS emissions were reduced in 72 % and 68% by G-HEV and D-SCR, respectively. Thus, their HR emissions resulted near to Euro 6 limits in the time expected by European regulation, namely 5 minutes. It means that light-off temperature of TWC and SCR was reached within these test periods. On the contrary, the other vehicles showed HR emission factors slightly higher than CS.

Exhaust gas temperature and NO_x emissions

In this study, stop periods were only relevant in urban section of RDE tests, and they were similar for all vehicles, namely 28% (s.d 3%). On the other hand, motorway stop periods were negligible. Due to the action of stop-start, engine-off periods are directly correlated to stop periods. However, it is not always the case of HEV vehicles, where hybrid system controls combustion engine switching-on by its complex strategy for energy storage/demand. Also, stop-start system of G-DI vehicle was intentionally deactivated to measure the exhaust gas temperature without the cooling down effect of TWC produced by that system. In this way, the opposite stop-start behaviours of HEV and G-DI could be contrasted.

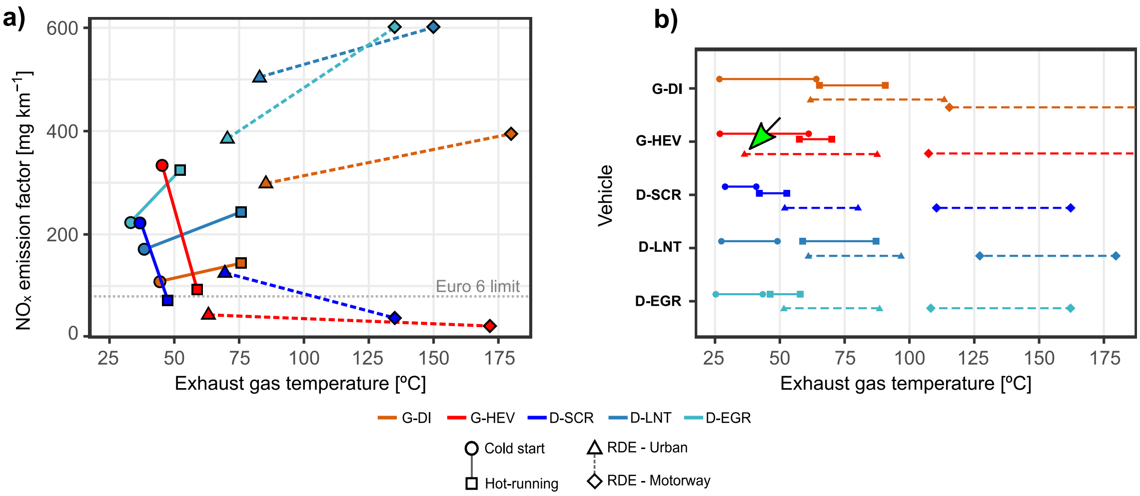

Figure 4. Exhaust gas temperatures for each vehicle and test, engine-off periods were not taken into consideration a) raw distance-specific emission factors and average exhaust gas temperature b) endpoints of horizontal lines represent 5th and 95th percentiles of test.

As function of exhaust gas temperature, measured at the external exhaust flow meter, Figure 4 compares CS with HR emissions and urban with motorway sections of RDE tests. Figure 4a shows that SCR and hybrid vehicles emissions were affected by temperature. Their emission factors decrease as curves go from “low” to “high” gas temperature conditions (CS → HR, urban → motorway), while the other vehicles show opposite patterns. SCR system is affected by low temperatures, and it need an activation threshold of ~200 ºC (Ntziachristos et al., 2016). TWC system also need to reach a light-off operating temperature of 250-350 ºC (Dardiotis et al., 2013). It implies that G-HEV and D-SCR vehicles, both with catalyst-type NO_x control systems, are more effective controlling NO_x emissions in motorway than urban. In urban and during cold start, low operating temperatures and low load conditions affect the performance of catalytic converters.

Surprisingly, computing engine-off periods, hybrid vehicle combustion engine works much more time in motorway (99%) than urban (26%), but emissions in urban are higher due to influence of low temperature in TWC. It reflects a better performance of G-HEV’s TWC in motorway compared with urban. As noted (Huang et al., 2019) comparing Hybrid and conventional models in a novel convoy-type RDE tests, frequent stops, restarts and low exhaust gas temperatures of HEV vehicles, reduces the performance of oxidation catalyst. The low exhaust gas temperatures in urban of hybrid vehicle (green arrow in Figure 4b), with a 5th percentile value of 29.8 ºC could be mainly attributed to additional time with combustion engine turned off by hybrid system, where convection heat transfer from exhaust gas to TWC is cut out. For G-DI and diesel vehicles (averaged), the 5th percentile of urban was 61.7 ºC and 50.6 ºC, respectively. These exhaust gas temperature values are for reference, because they were measured at exhaust flow meter of PEMS equipment.

Conclusions

This study shows the association between the exhaust gas temperature and the performance of NO_x aftertreatments installed in different Euro 6 SUV vehicles. The tested fleet contain the common architectures of modern passenger cars in the current market: fuel (diesel, gasoline), powertrain (conventional, HEV), and NO_x control system (TWC, EGR-only, LNT, SCR). The main conclusions of this work are the following:

The diesel vehicle equipped with SCR and the hybrid-electric vehicle equipped with TWC had the best real-world performance reducing NO_x emissions in RDE tests, showing their potential to comply with Euro 6 limits. Conversely, both vehicles had the worst performance during cold start owing to low operating temperatures of aftertreatment systems. SCR and TWC systems, both catalytic converters, require a minimum operating temperature, which is decisive for their optimal performance. It is also important note that both vehicles quickly reduced their emission near to Euro 6 limits after 5 minutes of CS testing time.

The gasoline vehicle with stratified air fuel mixture direct injection and the diesel vehicles with EGR-only and LNT aftertreatment were far to meet Euro 6 limits. Also, they showed a positive correlation between emission factors and the exhaust gas temperature, so their emission factors increased as tested sections went from “low” to “high” exhaust gas temperatures (i.e., CS → HR, urban → motorway). G-HEV and D-SCR vehicles showed the opposite behaviour, reducing efficiently NO_x emission at high exhaust temperature conditions, and therefore, showing a negative correlation between emission factors and average exhaust gas temperature.

For G-HEV and D-SCR vehicles, NO_x reduction efficiency in motorway is higher than urban. Stop-start system and low load in urban constrain heat transfer from exhaust gas to catalytic converters. In the case of HEV, combustion engine-off periods further restrict this heat transfer. For this reason, although its combustion engine works much more time in motorway (99%) compared with urban (26%), motorway emission factors resulted lower.

Incorrect operating temperatures of exhaust gas aftertreatments and cold start are major issues, because it led to increased emissions of NO_x and other pollutants, especially for catalytic converters. Therefore, it is important to model accurately actual emissions from vehicles in those conditions. The findings of this study suggest that emissions of HEV and SCR equipped vehicles could be sub estimated in driving cycles widely represented by urban driving. Finally, these vehicles could improve their aftertreatment thermal management to further exploit their emissions reduction potential.

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