Air Pollution and Noise Emissions of a Euro5 Diesel Car in Different Testing Environments

D. SIANO, M. A. COSTAGLIOLA, M. A. PANZA, M. V. PRATI
Istituto Motori - CNR
Via Marconi, 4 80125 Napoli
ITALY
d.siano@im.cnr.it http://www.im.cnr.it

Abstract: - This paper presents results of an experimental investigation on a Diesel car, complying with Euro 5 standard, in two testing environments: in laboratory with car installed on a chassis dynamometer bench and on a track. Car was instrumented with a set of sensors for the assessment of NOx emissions, as well as for the evaluation of interior sound quality. Tests were performed in type-approval driving cycle and steady-state conditions, ranging from 10 to 130 km/h. Vehicle emissive behavior was analyzed in function of ambient conditions and engine parameters. At the same time, acoustic signals coming from pressure measurements acquired inside car cabin in correspondence of passengers' ears, were properly processed in terms of quality of the noise. Some of the most commonly used parameters for sound quality analysis were considered, in order to assess the influence of the different testing environments and the vehicle operating conditions on the acoustic comfort perceived by car's occupants. In the work, air and noise emissions data are jointly analyzed and discussed. The analysis will be preparatory for the development of an overall quality index (encompassing both polluting and noise emissions), which may be useful to evaluate the environmental quality of a vehicle and in aiding policy makers in a variety of urban context.

Key-Words: - Diesel Car, Air Pollution, Noise, Testing Environment, Vehicle Environmental Quality.

1 Introduction

In the last years, it was generally assessed that vehicle testing performed in laboratory to measure pollution from road transport suffers of some limits which could create results greatly different from real behavior of vehicles [1]. Among these limits there are the ambient parameters (temperature and humidity) usually very different from those prescribed by EU legislation during type-approval laboratory tests. For example, cold start emissions are measured in laboratory after a vehicle conditioning at 23 degC for at least 6 hours [2]. This condition should be very different from what usually happens before vehicle starting in real use. Thermal condition before cold start greatly influences the duration of warm-up phase and as consequence the amount of pollutant emissions and fuel consumption [3].

Also for vehicle acoustics, even if increasingly advanced test facilities are now available which allow a very realistic drive operation of automobiles on the roller test bench, the simulation of real acoustic and vibration measurements inside the vehicle represents a still difficult task to achieve. The noise inside a vehicle is complex by nature and in mostly originates from (a) the engine and powertrain, (b) road excitation, and (c) aerodynamic excitation [4]. The contribution of aerodynamic noise is not much relevant at moderate speeds and even at high speeds it rarely becomes a dominant sources. Hence, it is possible to state that most of the noise which is heard by the car occupants consists of a random background noise (mainly originating from road surfaces) and various discrete frequency components (originating from the engine) [5] which are superimposed on the background noise. The random background noise can be regarded as one of the main factor controlling the loudness of the internal noise, and at the same time the most difficult contribution to simulate in laboratory conditions, due to its strict dependency on the random roughness characteristics of the road surfaces [6].

For this reason, an experimental campaign was carried out in order to study vehicle exhaust pollution and noise emissions over laboratory and track tests. Track testing has the great advantage to allow the execution of same driving cycles carried out in the laboratory on the chassis-dynamometer. In other words, the comparison between the two environments is made with the same kinematics.

Interior noise emissions were analyzed highlighting, in particular, the vehicle interior sound quality characteristics, considering that these latter could induce positive or negative physiological and psychological effects on car occupants [7].

Only recently the scientific literature has started to study the associations of both environmental noise and air pollution with health [8], [9]. Only few studies tried to summarize the human exposure to these two factors into one parameter.

The simultaneous monitoring of both vehicle exhaust emissions and sound quality inside passenger compartment finally could lead to foresee the possibility of defining a vehicle overall quality index, capable of assessing the environmental quality of a vehicle and rank its impact on human health.

The "GREEN VEHICLE index" is also an issue of EU Horizon 2020 call, that describes the index capable of orienting eco-conscious consumer choice [10].

2 Experimental Set-up

Pollutant exhaust emissions and interior noise were measured over laboratory and track tests. In laboratory, driving cycles were carried out on the chassis dynamometer which simulates vehicle inertia, aerodynamic and rolling resistance.

Exhaust gases were collected and diluted by a Constant Volume Sampler (CVS) system. CO, CO_2, THC, NOx concentrations were measured by a gas analyzer (Horiba Mexa 7200H). Moreover, a smart NOx sensor (Continental) was installed on the raw exhaust for comparative measurements. An OBD interface was used to acquire main engine parameters such as engine revolutions, intake air flow, EGR rate, intake air temperature, vehicle speed. Particle Number (PN) was measured by using a condensation particle counter (TSI-CPC) installed on the dilution tunnel. CPC counts particles with diameter from 20 nm to 1 μm.

Noise measurements were carried out by equipping car cabin with eight microphones (ICP Class 1 pressure sensors), located at the height of driver and front/rear passengers ears' position, as shown in Fig. 1. Acoustic signals were recorded at a sampling rate of 40960 Hz by using an LMS SCADAS multi-channel acquisition system which allows to trigger them with the engine rotational speed signal. Collected data were then properly processed in LMS Test.Lab software.

On track, vehicle was instrumented with the smart NOx sensor, the ECU interface and a home-made driver aid in order to display and save speed trace of different driving cycles to be performed.

The interior noise acquisition set-up was unchanged for on-road tests. In this latter case, acoustic data were also triggered with the GPS signal in addition to the tachometer one.

On board instrumentation was powered by a couple of batteries (12V) and an inverter AC/DC.

In order to avoid measurement errors, in both testing environments, noise acquisitions were carried out being careful that car windows were closed and air conditioning system turned off. During on-road tests the sound radiated by the vehicle to the outside contributed to the inside noise only by reflections from the road surface, thanks to the absence of sound reflecting objects in the proximity of the track site. Moreover on the test day the weather was sunny and windless.

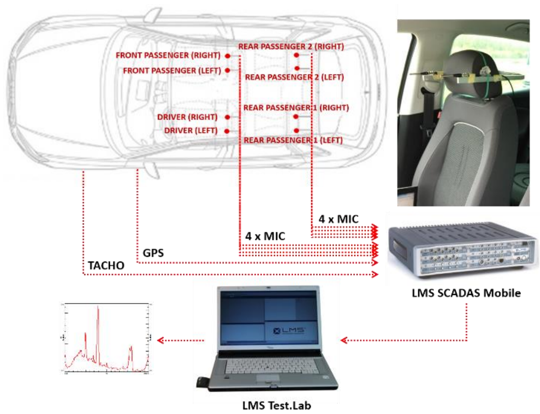


Fig. 1: Interior noise acquisition set-up.

2.1 Vehicle

Table 1 summarizes main vehicle characteristics. Experimental vehicle is a diesel passenger car (category M1), Euro 5b compliant. Diesel oxidation catalyst (DOC) is used to oxidize CO and THC whereas Exhaust Gas Recirculation (EGR) to reduce NOx formation in the compression ignition engine. Moreover an active Diesel Particulate Filter (DPF) removes particulate from the exhaust stream.

At the start of the experimental activity vehicle odometer was 3300 km.

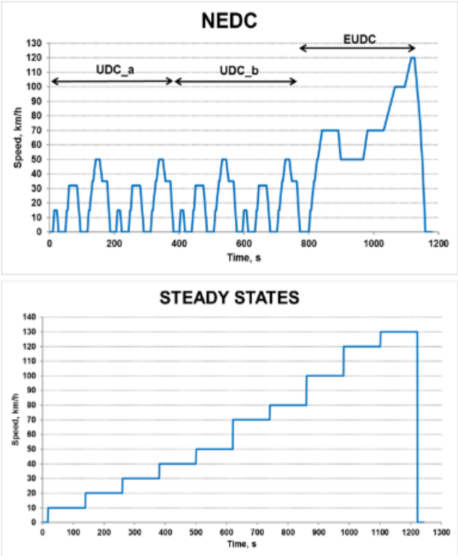
Displaced volume, cc	1461
Maximum power, kW	55
Maximum speed, km/h	170
Transmission	Manual, 5^{th} gear
Inertia, kg	1130
Road load coefficients F0/F1/F2, N/ N/(km/h)/N/(km/h)^2	57.128/0.5287/ 0,0289
Type approval stage	Euro 5b
After-treatment systems	DOC+EGR+ DPF

Table 1: Vehicle characteristics.

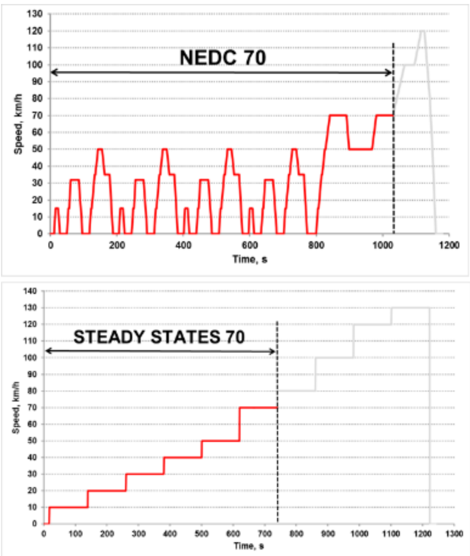
2.2 Driving Cycles

Laboratory testing involved the execution of type-approval and constant speed driving cycles (Fig. 2(a)). Type approval NEDC was carried out in cold and warm start condition. Cold start occurred after 8 hr of vehicle stop inside the laboratory held at 23degC. Warm start occurred at oil temperature higher than 80degC.

Constant speed tests from 10 to 130 km/h were also carried out.



(a)



(b)

Fig. 2: (a) Laboratory driving cycles; (b) Track driving cycles.

Track testing involved same driving cycles. Due to track geometry was not possible to overcome the maximum speed of 70 km/h. For this reason NEDC driving cycle and constant speed tests were driven up to this maximum speed, as shown in Fig. 2(b). In the following NEDC 70 will be used to indicate track driving cycle.

3 Results

3.1 Exhaust pollutant emissions

Vehicle emissions measured over the cold start NEDC driving cycle carried out in laboratory confirm that it complies with type approval limits. Table 2 reports the comparison between emissions and standard limit. In particular, Table reports emission factors of CO, NOx, THC and NOx sum, CO_2, particulate matter PM, particle number PN and fuel consumption, which is estimated by carbon balance of exhaust species.

	NEDC cold	Euro 5 limit
CO, g/km (*standard deviation*)	0.09 (*0.004*)	0.5
NOx, g/km	0.177 (*0.03*)	0.18
THC+NOx, g/km	0.185 (*0.028*)	0.23
CO_2, g/km	107.7 (*11.0*)	
PM, mg/km	0.36 (-)	0.5
PN, pt/km	$1.94*10^{11}$	$6*10^{11}$
Fuel consumption, l/100km	4.07 (*0.42*)	

Table 2: Emissions over NEDC cold.

CO and THC emissions are measurable only during cold start phase, i.e. during light-off of the oxidation catalyst. After DOC activation, CO and THC emissions are close to zero. For this reason only NOx and CO_2 emissions will be discussed during warm driving cycles.

Engine tuning of this vehicle realizes a different EGR rate on cold and warm driving cycles. In particular, over cold start NEDC the EGR rate ranges between 10 and 15%, allowing the NOx to comply with Euro 5 standard limit. When the same driving cycle is performed in warm condition, the EGR rate falls to almost zero and as consequence NOx emissions greatly increase.

Exhaust NOx and CO_2 emissions over NEDC warm and constant speed driving cycles were deeply analyzed.

CO_2 emissions are presented as a function of the average speed in Fig. 3. Data, referred to laboratory tests, are grouped in transients and steady states. Transient points are the urban and extra-urban modules on NEDC warm driving cycles whereas steady-states are the single point of constant speed test. Minimum values of CO_2 are registered in the range of 80-100 km/h. The highest ones, instead, occur at low speeds. In general, a 2^{nd} order polynomial trend well interpolates data points (R^2=0.8).

Same trend is visible for PN emissions (Fig. 4). Due to the great difference in measured values, plot is semi logarithmic. Up to 100 km/h, PN emissions are very low. They range between 10^9 and 10^{10} particles/km. High speed tests, instead, are characterized by an increment of two orders of magnitude of PN emissions. In these cases, PN exceeds also Euro 5 limit of $6*10^{11}$ particles/km.

In Fig. 5, NOx emissions are presented. In this case, track results are available in addition to laboratory ones. It is possible to observe a reduction of NOx emissions when increasing the average speed. When moving from 20 km/h to 120 km/h, NOx emissions reduce of almost 50% [11].

Moreover, emissions measured in laboratory result generally higher than those measured on track [12]. This is mainly due to different cooling modes. On track, in fact, engine temperatures are lower than those measured in laboratory, besides during laboratory tests a variable speed blower was used for vehicle cooling. As confirmation of this, Fig. 6 reports NOx emissions as a function of the intake air temperature. This parameter is acquired from OBD.

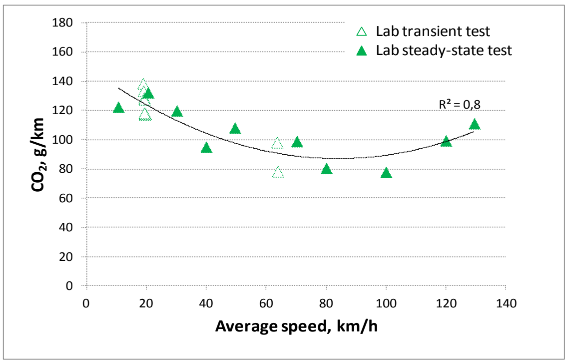


Fig. 3: CO_2 emissions as a function of the average speed.

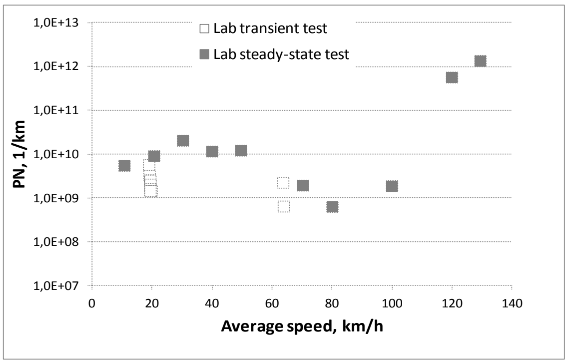


Fig. 4: PN emissions as a function of the average speed.

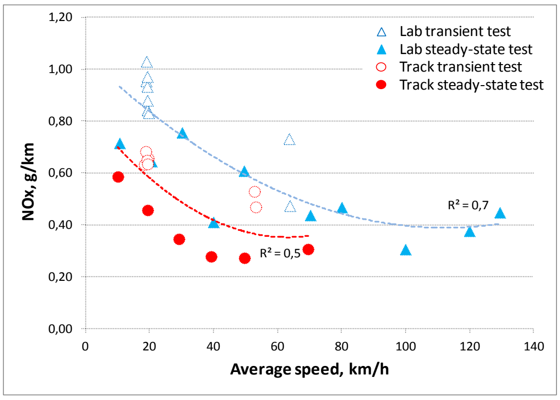


Fig. 5: NOx emissions as a function of the average speed.

It is evident that there is an increasing trend when intake temperature increases [13]. The direct influence of temperature is explained by the mechanism of NOx formation over warm driving cycles carried out with this vehicle. It was, in fact, already observed the exclusion of EGR during warm transient and steady-state tests. This means that NOx formation depend on peak combustion temperature inside the engine. It increases when intake air temperature increases involving an increasing of NOx emissions.

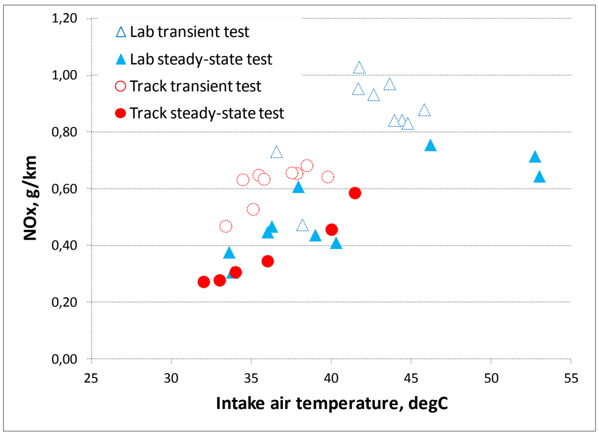


Fig. 6: NOx emissions as a function of the intake air temperature.

Fig. 6 also highlights that temperatures measured on track were lower than those measured in laboratory.

3.2 Interior noise emissions

Acoustic measurements inside car cabin, in addition to be processed in terms of frequency spectra and overall levels, were accurately elaborated in terms of some of the most common sound quality metrics widely used in automotive industry [14].

As a matter of fact, the A-weighted sound pressure level (SPL) is not adequate to provide information about the level of sound annoyance or pleasantness in passenger compartment. In order to objectively assess the acoustical comfort of a vehicle interior, different psychoacoustics-based indices are rather used. In this work, in particular, Loudness, Sharpness and Articulation Index psychoacoustic metrics were calculated and carefully analyzed over the investigated driving cycles, for each measurement location inside car cabin. All these metrics reflect the perception character of human auditory systems. Briefly:

- Loudness is related to the magnitude of sounds taking into account the filtering characteristics of human auditory sense in time and frequency domains.
- Sharpness sensation is a measure of the proportion of the high frequency content of a sound and can be regarded as an indication of tone colour.
- Articulation Index (AI) is a measure of degree of speech privacy or intelligibility and represents, for a given noise condition, the proportion of the normal speech signal that is available to a listener for conveying speech intelligibility. The reduction of speech intelligibility in an environment can cause annoyance.

Among all the methods developed to numerically quantify acoustical stimuli, the ISO 532B method [15], i.e. the Zwicker model, was adopted to compute loudness levels, since it has been proven to be a very effective and accurate method for sound quality prediction in automotive engineering.

Considering the recording positions for interior noise and the vehicle working conditions (steady-states as well as urban and extra-urban modules of NEDC), the above mentioned metrics were extracted from a total of 104 noise signals referred to laboratory test and 72 noise signals referred to track test.

As sound quality analysis of vehicle interior was carried out in parallel to exhaust pollutant evaluation, results will be show below in a similar way to those referred to vehicle air emissions.

Average values of each metric over all the measurement locations inside cabin are considered. Loudness, Sharpness and Articulation Index are plotted against average speed in Figg. 7-8-9. Also in this case, as for exhaust NOx emissions, data are grouped in transient and steady states referred to both laboratory and track tests.

As it is possible to note in Fig. 7, Loudness level tends to rise when increasing the average speed in both testing environments. A 2nd order polynomial trend seems to well interpolate laboratory as well as track data points (R^2=0.94 and R^2=0.97 respectively). Besides, starting from 30 km/h, levels measured on the track result higher than those measured in laboratory. A possible reason could be found in the rougher road surfaces of the track, which produce much higher road excitation than that produced by the wheels on roller in laboratory at the same average speed. As consequence, this may result in a greater loudness of internal noise, depending also on the vibrational and acoustical behavior of the car body. For a better comprehension, the frequency spectra of noise measured at driver left ear position, when driving the car at 40 km/h in the two different testing environments, are compared in Fig. 8.

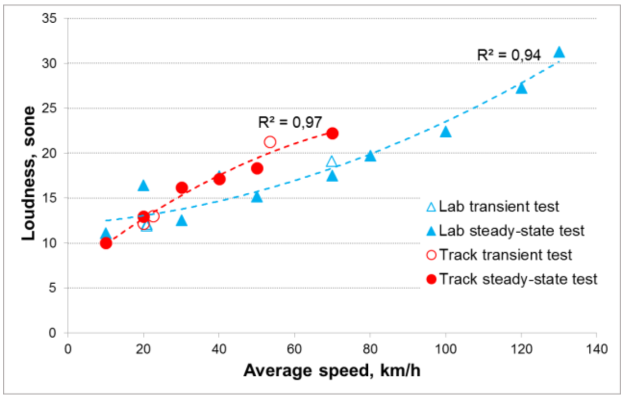


Fig. 7: Loudness level as a function of the average speed

Since a slight difference between average engine rotational speeds is present, the two noise spectra can be compared with sufficient accuracy.

Various peak responses at frequencies corresponding to wheel and engine harmonics are clearly noticeable, indicating that various resonances of the car system are excited by engine and wheel harmonics. As the dynamic characteristics of the vehicle structure as well as the acoustic resonances of the car cavity are uniquely defined for both testing conditions, the higher amplitudes of individual resonances measured over the track most likely depend on the larger magnitude of the wheel harmonic excitation level on the track rather than in laboratory. This is evident especially within the 25-70 Hz low frequency region and produces less intense effects also in the 80-150 Hz frequency band.

In Fig. 9 Sharpness trends as a function of average vehicle speed are reported. In this case a 3rd order polynomial equation is necessary to well interpolate both laboratory and track data points (R^2=0.67 and R^2=0.97 respectively).

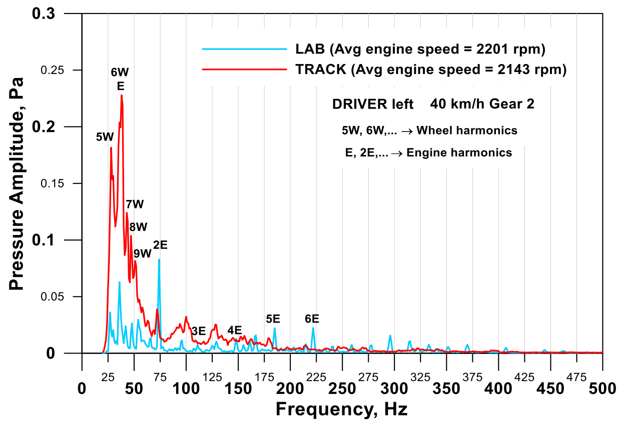


Fig. 8: Noise spectra inside car at driver left ear location at 40 km/h in laboratory and track testing conditions.

Different trends are now observed. While Sharpness in laboratory conditions slightly increases with increasing the average speed, a reduction is observed instead in track conditions. Moreover, Sharpness values in laboratory are higher than those obtained over the track from 30 km/h on. This results in a different sensation of interior sound in laboratory conditions due to the greater proportion of high frequency content of the measured noise, which produce a more annoying feeling especially at the highest average speed (100-130 km/h).

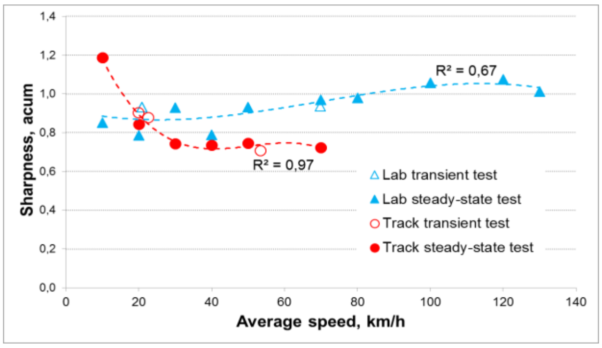


Fig. 9: Sharpness as a function of the average speed.

Articulation Index trend can be finally observed in Fig. 10. In both testing conditions, as expected, the metric falls down with increasing the average speed. It is interesting to note how the AI values over the track are always higher, except at 10 km/h, than those detected in laboratory, indicating an overall lower annoyance level of the interior sound when driving the car on the road. Accordingly, considering previous results obtained over the track, a reduction of Sharpness may exert a greater influence on the improving of pleasantness sensation, more than an increment of the Loudness level can worsen the quality of the perceived noise.

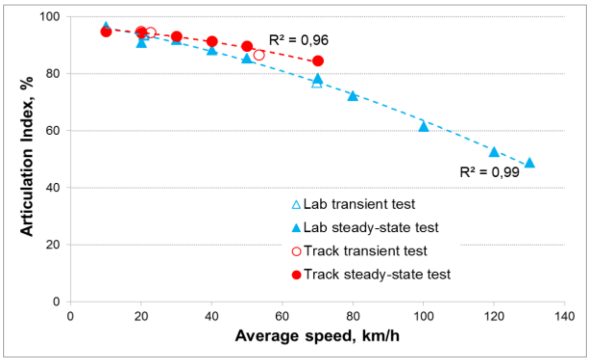


Fig. 10: Articulation Index as a function of the average speed.

4 Discussion and conclusion

In conclusion, by comparing pollution and noise emissions results in the two testing environments, some important remarks emerge.

Most critical gas pollutants of the tested vehicle are NOx and PN. Besides both are lower than Euro 5 standard limit over type-approval driving cycle, sensible increasing is monitored outside of legislative boundaries.

PN is influenced by vehicle speed and load. PN emissions, in fact, show an increasing for speed higher than 100 km/h: they increase of almost two orders of magnitude compared with emissions measured at lower speeds.

NOx are greatly influenced by temperature. Low ambient temperature together with a better engine cooling of track tests justify lower NOx emissions compared to laboratory ones. Moreover, in laboratory warm start is the dominant factor which involves an increasing of NOx production.

Tests in laboratory for the assessment of the vehicle internal acoustic comfort have been proven to present some limits, which can be summarized as follows.

- Driving car on the chassis-dynamometer bench in laboratory does not allow to take into account the real roughness characteristics of the road surfaces, thus the influence exerted by the road exciting forces on the loudness of the internal noise cannot be accurately assessed.
- The absence of any acoustical treatment in laboratory makes the acoustic measurements affected by possible reflections of external sound field.
- The presence in the laboratory of external noise sources not referable to the vehicle (such as the speed variable blower for vehicle cooling), may cause a different frequency content of the internal acoustic signals, considerably affecting the quality of the perceived noise.

Track data indicate only a slight reduction of the speech intelligibility when increasing the average speed, which does not necessarily implies a worse quality of the perceived noise (AI values are all over 80%). The interior sound becomes progressively louder but more pleasant at the same time, since the Sharpness-related annoying sensation decreases with increasing the average speed. Therefore, driving the car over the track at ever higher speed, the reduction of NOx emissions occurs together with the improvement of the sound pleasantness sensation.

The analysis outcomes will be useful for further studies regarding the environmental quality of a vehicle. Specifically, future developments will concern the definition of a vehicle overall quality index through the employment of a multi-criteria method. The index will include all the most relevant criteria, e.g. CO_2, NOx, PN emissions, interior and exterior noise, and will be capable of assessing vehicles, supporting consumers and policy makers in their choices.

References:

[1] Khan and Frey, *Comparison of real-world and certification emission rates for light duty gasoline vehicles,* Science of The Total Environment Volumes 622–623, (2018): 790-800.

[2] Suarez-Bertoa and Astorga, *Impact of cold temperature on Euro 6 passenger car emissions*, Environmental Pollution Volume 234 (2018): 318-329.

[3] Luján, Bermúdez, Dolz, Monsalve-Serrano, *An assessment of the real-world driving gaseous emissions from a Euro 6 light-duty diesel vehicle using a portable emissions measurement system (PEMS),* Atmospheric Environment Volume 174, (2018): 112-121.

[4] Xu Wang, *Vehicle noise and vibration refinement*, Woodhead Publishing, 2010. Hardcover ISBN: 9781845694975.

[5] Siano, D., Viscardi, M., & Panza, M. A. (2016). Automotive materials: an experimental investigation of an engine bay acoustic performances. *Energy Procedia*, *101*, 598-605.

[6] Abouel-Seoud, S. A. (2015). Influence of Road Roughness Parameters on Low Frequency Interior Noise in Off-road and Mid-size Passenger Vehicles. *International Journal of Vehicle Structures & Systems*, 7(2), 71.

[7] Siano, D., & Panza, M. A. (2017). Sound quality analysis of the powertrain booming noise in a Diesel passenger car. *Energy Procedia*, *126*, 971-978.

[8] I. A. Istrate, T. Oprea, E. C. Rada, V. Torretta, *Noise and air pollution from urban traffic. The Sustainable City IX, Vol. 2, pp. 1381-1389.* WIT Transactions on Ecology and The Environment, Vol 191 (2014).

[9] Stephen A. Stansfeld, *Noise Effects on Health in the Context of Air Pollution Exposure*, Int J Environ Res Public Health. 2015 Oct; 12(10): 12735–12760.

[10] European Commission Decision C(2017)7124 of 27 October 2017. EN Horizon 2020 Work Programme 2018-2020. 11. Smart, green and integrated transport. http://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-transport_en.pdf

[11] Lozhkina and Lozhkin, *Estimation of nitrogen oxides emissions from petrol and diesel passenger cars by means of on-board monitoring: Effect of vehicle speed, vehicle technology, engine type on emission rates*, Transportation Research Part D: Transport and Environment Volume 47 (2016): 251-264.

[12] Kwon, Park, Park, Kim, Choi, Cha, *Characteristics of on-road NOx emissions from Euro 6 light-duty diesel vehicles using a portable emissions measurement system*, Science of The Total Environment Volume 576 (2017): 70-77.

[13] Luján, Climent, García-Cuevas, Moratal, *Pollutant emissions and diesel oxidation catalyst performance at low ambient temperatures in transient load conditions*, Applied Thermal Engineering Volume 129 (2018): 1527-1537.

[14] Zwicker, Eberhard, and Hugo Fastl, *Psychoacoustics: Facts and models*. Vol. 22. Springer Science & Business Media, 2013.

[15] Zwicker, Eberhard, et al. *Program for calculating loudness according to DIN 45631 (ISO 532B)*, Journal of the Acoustical Society of Japan (E) 12.1 (1991): 39-42.