DOI: 10.61782/fa.2023.1120

MULTI-DOMAIN EVALUATION OF A LATEST GENERATION COMBUSTION ENGINE: FOCUSING ON SOUND QUALITY PERCEPTION

Nicolò Salamone[1,3*] **Claudio Colangeli**[1] **Fabio Bianciardi**[1] **Karl Janssens**[1]
Stefano d'Ambrosio[2] **Alessandro Mancarella**[2] **Wim Desmet**[3,4]
[1] RTD Test Division, Siemens Industry Software NV, Heverlee, Belgium
[2] Energy Department, Politecnico di Torino, Italy
[3] Department of Mechanical Engineering, KU Leuven, Belgium
[4] DMMS Core lab, Flanders Make, Heverlee, Belgium

ABSTRACT

Compression ignition engines still account for the larger share of traction architectures for low to high duty commercial vehicles. The combustion noise has always been one of the main drawbacks of this technology caused by the quasi-instantaneous burning of the premixed charge in the cylinders, which generates high pressure derivatives. The calibration levers associated with the fuel injection and the intake charge systems can be exploited with the aim of reducing the combustion noise, by trading-off with other efficiency and exhaust emission targets. In this paper, the effect of some calibration parameters has been investigated with a focus on the acoustic perception of the combustion phenomena. An experimental campaign has been executed on a modern Euro 6 Diesel engine mounted on an engine test bed, realizing a multi-domain assessment, by measuring vibro-acoustic and performance quantities within the complete operational envelope. Regression models are applied to correlate calibration levers and psychoacoustic metrics. The tested engine has been finally virtually incorporated on a full vehicle assembly through an NVH simulator to render the dynamic operations of the engine inside the modeled vehicle system, aiming at multi-objective evaluation along a simulated emission driving cycle.

Keywords: *psychoacoustic, sound synthesis, NVH driving simulator.*

1. INTRODUCTION

Calibration levers refer to engine control parameters that influence the combustion process and consequently affect both the efficiency of the mechanical conversion and the chemical products of the combustion. Defined as physical quantities, these parameters determine the position, or more generally, the behavior of certain actuators and controllable sub-systems. In modern diesel engine, the fuel injection pattern and the intake charge composition are generally the two main aspects the calibration procedure focuses on. The targets can be different according to the application of the powertrain to be calibrated. In the automotive sector, the key challenges are certainly the improvement of engine performance, and the reduction of fuel consumption and pollutant emissions. Another, not secondary, target is the noise level which must comply with certain standards. In the engine calibration process this is usually tackled by introducing combustion noise indexes, estimated from in-cylinder pressures signals [1], and by setting limits for certain critical working conditions. However, noise indexes are not able to capture the variations in terms of sound perception of different engine operations. In this sense, an extended test campaign has been executed in an engine

---

[*] ***Corresponding author***: nicolo.salamone@siemens.com.

testbed, including NVH instrumentation, specifically to evaluate the effect of different calibration parameters.

2. EXPERIMENTAL SETUP

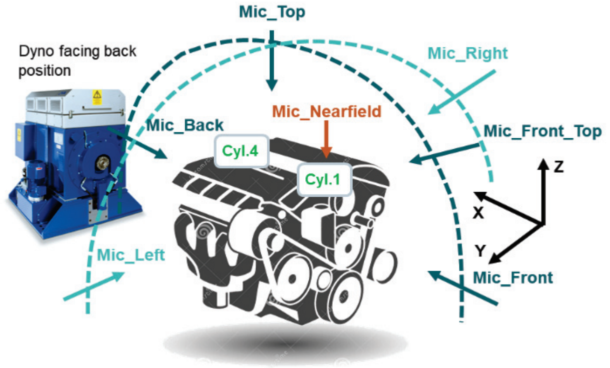


Figure 1. Engine test bed schematic set-up with microphone positions.

The experimental data which are shown in the following sections have been collected from a test campaign conducted on a 2.3-liter, four-stroke diesel engine, adopted for modern Euro 6 light-duty commercial vehicles. The engine was installed on a dyno testbed at the ICE Advanced Laboratory located in Politecnico di Torino. The engine specifications and geometrical properties are shown in Table 1. The acoustic responses from the engine were measured with 7 ½" microphones placed at different distances around the engine (Figure 1): for sake of simplicity, only the "front-top" microphone, which is 0.65 m distant from the closest engine edge, has been considered in this study. To measure the in-cylinder pressure in all four cylinders of the engine, high-frequency piezoelectric transducers were utilized. These relative in-cylinder pressure signals were referenced with an absolute pressure sensor installed in the intake manifold. A crankshaft-driven encoder with a 0.1 crank angle degree resolution was used to track the revolution speed and the crank angle position. The above-mentioned signals were acquired by a SCADAS Mobile using Simcenter Testlab 2206. In addition, a fuel flowrate measurement system was used to record the engine fuel consumption, while an exhaust gas analyzer was used to measure the concentrations of gaseous emissions at the engine outlet. The engine-out soot emissions were measured with a smoke meter. The tested engine is coupled with a cradle-mounted AC dynamometer with nominal torque and power ratings of 525 Nm and 220 kW, respectively. Both steady-state and transient tests have been performed changing selected calibration levers to study their effects with a multi-physical approach.

Table 1. Main technical characteristics of the tested Euro 6 engine.

N. cylinders	4
Displacement	2.3 l
Broke\stroke	88 mm / 94 mm
Compression ratio	16.3:1
Valves per cylinder	4
Max power	102 kW
Max Torque	400 Nm
Turbocharger	Single stage VGT
EGR circuit	Short-route water cooled

3. EFFECT OF CALIBRATION LEVERS ON NVH

The noise radiated by internal combustion engines is a combination of different contributions. Traditionally acoustic sources from engines are categorized in three groups: combustion, mechanical and gasdynamic. The focus of this paper is to study the effect of the calibration levers on the perception of the combustion contribution, considering that these parameters primarily affect the combustion evolution. To separate the combustion and the mechanical contributions from the overall engine noise, the Wiener filtering technique has been applied [2, 3]. In addition to the primary objective of breaking down the combustion from the mechanical noise, with this approach it is also possible to filter out the contributions coming from other acoustic sources in the testbed (testbed ventilation and conditioning unit, measurement systems, dynamometer, etc.). The method is based on the existence of coherence between the contribution x(t) of a measured signal y(t) and a reference signal r(t) and the uncorrelation between the same reference and the other noise contribution b(t) (Figure 2). The combustion related noise is defined as the noise that is coherent with the reference in-cylinder pressure. The transmissibility functions h(t) are generated among the four in-cylinder pressure traces and the acoustic target(s).

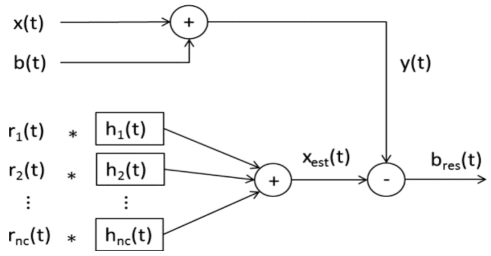


Figure 2. Schematic of the Wiener filtering.

The total combustion related noise is the sum of each in-cylinder pressure signal contribution. Once the combustion contribution is isolated, sound quality metrics can be calculated from the extracted contribution. Figure 3 shows the effect of changing the relative air-fuel ratio (i.e., lambda) measured at the exhaust, by acting on the exhaust gas recirculation (EGR) valve, on key psychoacoustic quantities. Since higher EGR rates increase the ignition delay and reduce the premixed phase of the combustion [4], which is responsible for higher peaks in the first derivative of in-cylinder pressure, the engine is expected to have a smoother and less noisy operation. This is confirmed by the lower overall levels and Loudness (ISO 532-1) at lower relative air/fuel ratio. An EGR rate variation also results in changes of Sharpness (DIN45692) and Tone-to-noise ratio (ECMA-74).

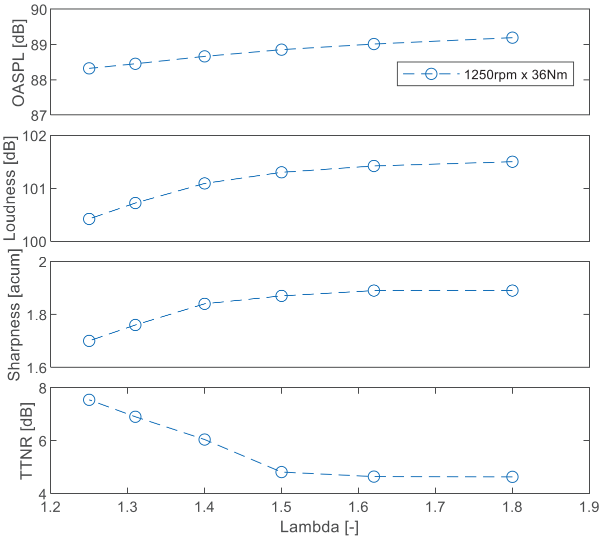


Figure 3. Sound quality metrics change by sweeping EGR rate on a specific steady-state condition. OASPL: OverAll Sound Pressure Level, TTNR: Tone-To-Noise Ratio.

Since the EGR technology is mainly used to limit the formation of nitrogen oxides (NOx) during the combustion process [4], it is of paramount importance to evaluate the acoustic perception together with the effect on the exhaust emission products. In addition to the mentioned NOx, which contribute to the formation of "photochemical smog," the other most significant pollutant emission in diesel engines is particulate matter (PM). Particulate matter refers to any substance in the exhaust of an internal combustion engine that can be captured on a sampling filter medium at 52°C [5]. Figure 4 shows how the Tone-to-noise ratio evolves along the classical trade-off NOx-PM characteristic curve for three different engine working points. The Tone-to-noise ratio sensibility to the EGR rates seems to change with the working conditions, with the mentioned psychoacoustic metric that shows to be more affected by lambda variations at lower engine speeds and loads.

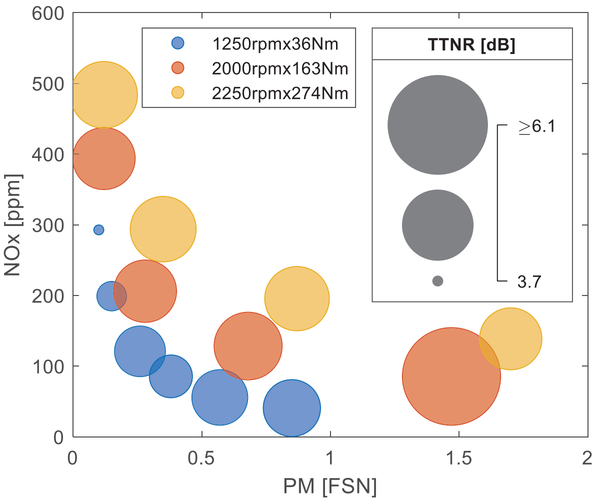


Figure 4. Tone-to-noise-ratio evaluated on EGR trade-offs for three different working points. ppm: Parts Per Million, FSN: Filter Smoke Number.

4. CORRELATION BETWEEN CALIBRATION SETTINGS AND SOUND QUALITY

A pure statistical approach is proposed for modeling psycho-acoustic metrics based on selected calibration levers or quantities resulted from the calibration process. This approach highlights the influence of the control setting on the perceived sound and enables possible future optimization in terms of acoustic perception. An example is shown in Figure 5 where an acceptable estimation of Loudness has been obtained using a quadratic function of rotational speed (n), fuel injected quantity (q_b), start of the main injection (SOI), relative air/fuel ratio (λ), rail and boost pressures (p_{rail}, p_{boost}) and pilot injected quantities (q_{pil1}, q_{pil2}), as follows:

$$Loudness = \gamma_0 + \gamma_1 n + \gamma_2 q_b + \gamma_3 SOI + \gamma_4 q_{pil1} + \\ + \gamma_5 \lambda + \gamma_6 {p_{rail}}^2 + \gamma_7 {p_{boost}}^2 + \gamma_8 {q_{pil2}}^2 \quad (1)$$

which results in a coefficient of determination R^2= 0.893 and a root mean square error $RMSE$ = 1.565 dB. The input data are steady-state points across the whole engine map and several EGR sweeps for selected working points. The set of variables has been selected among the ECU levers that should mostly affect the combustion development and first derivative of the in-cylinder pressure. Similar regression models were obtained to estimate other sound quality metrics.

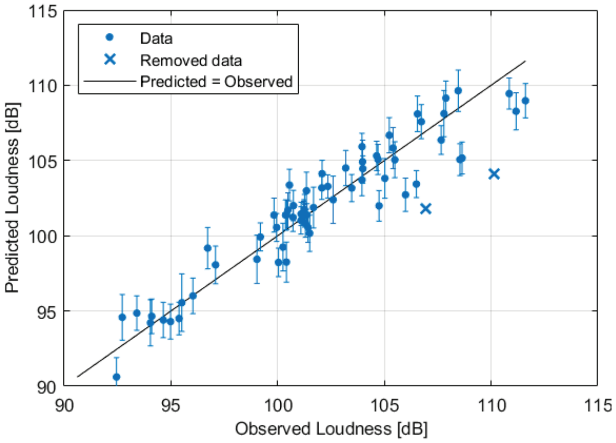
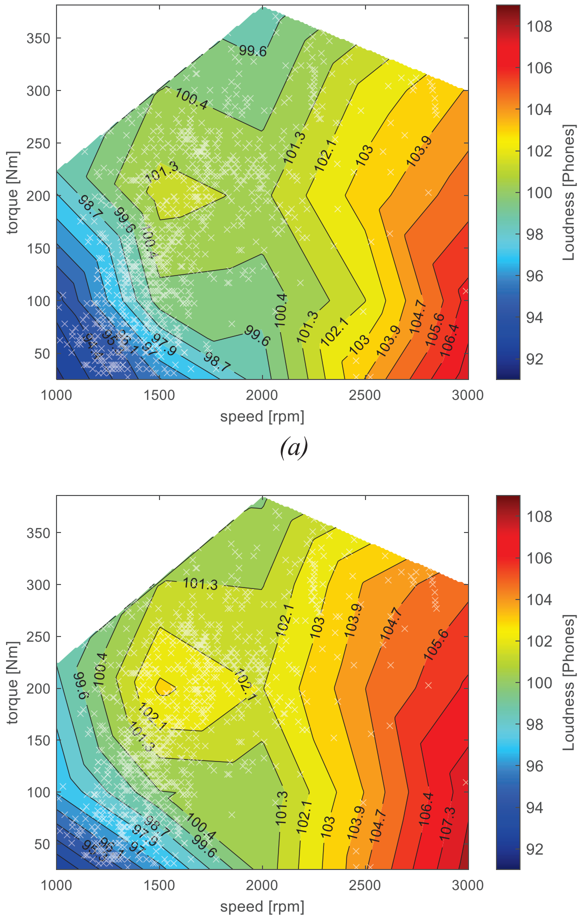


Figure 5. predicted vs. observed Loudness, where the prediction is obtained by eq. 1

5. SOUND QUALITY IMPLICATIONS OF DIFFERENT CALIBRATIONS OBESRVED WITH NVH SIMULATOR OVER WLTP CYCLE

The experimental information described so far has been obtained executing acoustic tests at fixed speed-torque points or sweeping through these points linearly varying the speed or torque (examples of sound quality metrics obtained from these tests are shown in Figure 6). In this paragraph we show how this database has allowed to perform a comparative sound quality study on simulated scenarios adopting an NVH Simulator [6, 7]. For this purpose, the available experimental information has been encoded to create NVH models of the tested engine at different proposed calibrations. This has allowed to perform an order-based synthesis [8] of the sound emitted by the engine under different calibration conditions during a simulated WLTP driving (Figure 7). By doing so, we can observe sound quality implications of the different calibration levers under more dynamic maneuvers and at the same time correlate the NVH behavior of the engine with its emission and performance attributes. Hereafter is shown an example of comparison between two calibrations: (a) baseline and (b) alternative SOI (Start Of Injection). As shown in Figure 7 this comparison highlights an increase in Loudness of calibration (b) relative to (a). While this is already observable in the Loudness maps obtained on the controlled maneuvers performed during the calibration process, the study of the same Loudness parameter along a simulated driving cycle enables to better pinpoint the most affected regions and assess the severity of this difference in NVH performance.



(a)

(b)

Figure 6. Loudness map of the emitted noise under two different calibration conditions: *(a)* baseline; *(b)* alternative SOI, with the main injection advanced from 2 to 10 °CA depending on speed-torque regions. Calibration (b) results in an increase in Loudness in high RPM regions. White

crosses represent the working points of the WLTP driving cycle for the reference light-duty commercial vehicle.

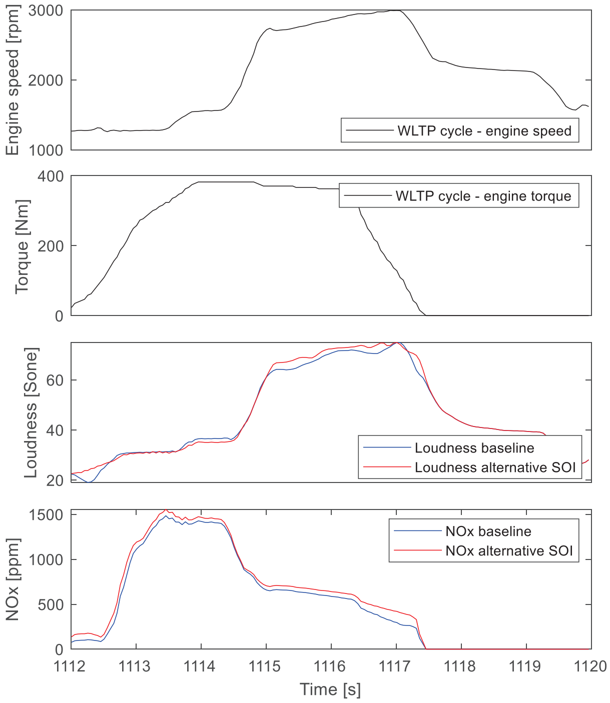


Figure 7. An 8s zoomed fragment of the driving cycle where it is observed that a larger Loudness is obtained by the "alternative SOI" calibration in specific operating conditions.

6. CONCLUSIONS

In this paper, the relations between selected calibration parameters and psychoacoustic metrics, which express the human perception of sounds, have been researched by testing a EURO 6 diesel engine for light-duty commercial applications. The study specifically focuses on the combustion contribution as the most affected by the mentioned parameters. After performing a breakdown of the total noise recorded by microphones in the engine testbed, the combustion noise was used to calculate the sound metrics. The effect of the exhaust gas recirculation has been assessed with a multi-domain approach, observing sound quality aspects together with other key performance indicators (e.g., exhaust emissions). Relations among levers and sound quality metrics were explored through linear regression models that show promising statistical results. Finally, two different calibration sets have been compared using an NVH simulator, reproducing a simulated driving cycle. This approach aims at assessing the sound quality in more complex scenarios that include transient dynamic operations. The comparison shows differences in Loudness in specific sections of a simulated WLTP cycle.

7. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support and contribution of the European Commission with the Marie Sklodowska Curie program through ETN ECO DRIVE project n. GA 858018.

8. REFERENCES

[1] I. Jung, J. Jin, H. So, C. Nam, and K. Won: "An advanced method for developing combustion noise through the analysis of diesel combustion," SAE Int. Journal of Engines, Vol. 6, No. 2, pp. 1379-1385.

[2] F. Bianciardi, K. Janssens, K. Gryllias, S. Delvecchio, et al., "Assessment of combustion mechanical noise separation techniques on a V8 engine," SAE Technical Paper 2017-01-1846, 2017

[3] Q. Leclere, J. Drouet, E. Parizet. "Extraction and analysis of diesel engine combustion noise", Pitesti, Romania. 2011.

[4] N. Ladommatos, S. Abdelhalim, H. Zhao, "The effects of exhaust gas recirculation on diesel combustion and emissions.", International Journal of Engine Research, Vol. 1, No. 1, pp. 107-126.

[5] D.B. Kittelson, "Engines and Nanoparticles: A Review", J. Aerosol Sci., Vol. 5/6 (29), pp. 575-588

[6] F. Bianciardi, N. Salamone, C. Colangeli, J. Ortega Almirón, et al., "NVH prediction and real-time auralization for virtually assembled vehicles: an overview of the technology," SAE Technical Paper 2023-01-1091, 2023.

[7] P. Mordillat, C. Colangeli, F. Di Tommaso and L. Britte, "Sound Simulator for Hybrid Vehicle NVH Development". Proc. of the *SIA* simulation numérique, 2021.

[8] M. Adams, and P. van de Ponseele. "Sound Quality Equivalent Modeling for Virtual Car Sound Synthesis." SAE Transactions, vol. 110, 2001, pp. 1906–12.