ADVANCED STRATEGIES FOR INVESTIGATION OF INTERNAL COMBUSTION ENGINE

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Abstract. Due to several pressing matters like the drastic reduction in pollutant emissions and fuel consumption, as well as the need to increase the thermal efficiency, the research in the field of internal combustion engines running on conventional and unconventional fuels must use the newest investigation capabilities that can aid in overcoming these challenges. Currently there are many in-engine solutions that appear as promising in the development of future engines: dual fuel solutions (supplied to the engine cylinder either as blends or separately), a more precise control of the combustion in order to reach lower in-cylinder peak temperatures, compression ignition of gasoline or alcohols etc. and all these require sophisticated investigation methods. Even though, in the past years, a clear transition towards simulation could be noticed, the experimental part of the development process cannot be neglected just yet and one must combine the two methods in order to obtain progress. To this end, this paper presents novel investigations methods used in the TESTECOCEL laboratory (Testing laboratory for internal combustion engines that run on biofuels) of the Department of Automotive and Transports from the Technical University of Cluj-Napoca as well as some obtained results (through simulation and experimental).

Key words: investigation, research engine, laboratory, visualization, combustion, pollutant emissions.

1. INTRODUCTION

Investigating internal combustion engines allows researchers to achieve a higher level of understanding, to know how they operate and to correlate their performances with fuel economy, pollution level and carbon footprint. Environmental conditions, correlated with limited natural reserves, are leading internal-combustion-engine research towards the investigation and improvement of fuel efficiency and reduction of carbon footprint. Blending fuels, thus realizing the so-called dual-fuel combustion mode, is thought to be a promising trend [2, 3, 4, 5].

The homologation cycles of vehicles for private passenger transportation or for light duty applications considers a cold start from ambient temperature. Therefore, to show the effect of a faster oil heating during the homologation cycle on the fuel consumption [3] controlled test conditions like in a laboratory, are required. Mofijur

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et al. [7] analyzed the effects of a mixture of biodiesel, alcohol and diesel on engine performance and emission parameters of a diesel engine. Most of the researchers reported that adding ethanol into biodiesel-diesel blend in diesel engines significantly reduce HC, PM, NO_x and smoke emissions but slightly increase fuel consumption, all of which can be analyzed in a Laboratory test.

Other researches [2, 4, 6, 8, 10] are focused: on investigating the gaseous and particulate emissions of a 4-cyclinder natural-aspirated direct-injection diesel engine fueled with different mixed concentrations of biodiesel and diesel fuel, the effect of engine operating parameters, including the engine speed and engine load (air/fuel ratio), the particulate nanostructure and oxidative reactivity when the engine is operated with WCO (waste cooking oil) biodiesel, the performance and emission characteristics of a Dual fuel engine, with an EGR (Exhaust Gas Recirculation) system, operated with Diesel as primary fuel and ignition source and LPG as secondary fuel, the vehicle thermal management during the cold-start phase which has been driven by a desire to improve both engine and overall vehicle engine efficiency. All the mentioned tests can be performed in a specialized laboratory in safe and controlled conditions where the repeatability can be ensured. Other tests and articles that were analyzed [9, 11, 12, 13, 14] underline the importance of a certified laboratory to satisfy the current testing needs.

2. METHODOLOGY AND EQUIPMENT

In the TESTECOCEL laboratory (Testing laboratory for internal combustion engines that run on biofuels) of the Automotive Engineering and Transport Department researchers have the possibility to test internal combustion engines by using the testing infrastructure presented in Fig. 1.

The control of the Laboratory is done using the PUMA Open software application package which is also the main automation system that facilitates the control and management of all the sub-systems integrated in the test cell. Data acquisition from the sensors is done with the aid of the FEM (Front End Modules), which represent a specific interface for high precision measurement recordings of command and control parameters, for applications in the Laboratory.

The DynoRoad 202 dynamometer is an asynchronous AC machine equipped with a converter power module IGBT (Insulated Gate Bipolar Transistor) for direct connection to main voltage and to the power module, which uses a hybrid interface that facilitates control over engine torque and speed. The main specifications of the dynamometer are presented in Table 1. The most common and easy to use control configuration is speed/alpha (speed of the dyno and throttle position of the engine).

The setup of the laboratory (with respect to the maximum torque, power and speed of the dynamometer) allows the testing of engines with medium power.

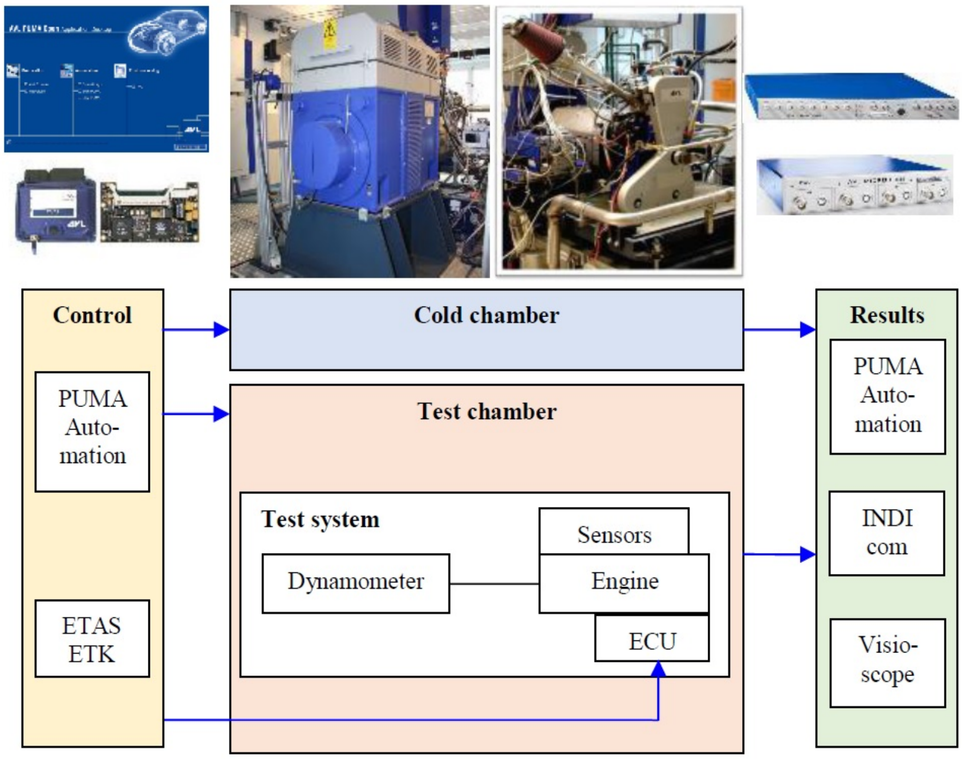


Fig. 1 – Information flow and control in the Laboratory.

High power engines can be tested as well, but only in the lower speed and power range (for emissions purposes).

Table 1

Technical specifications of the DynoRoad 202 dynamometer

Performances in generator mode	*Value*	*M.U.*
Nominal torque	525	[Nm]
Nominal power	220	[kW]
Maximum speed	12 000	[rpm]
Performances in motor mode	*Value*	*M.U.*
Nominal torque	473	[Nm]
Nominal power	198	[kW]
Maximum speed	12 000	[rpm]

One of the engines that was intensively tested is the AVL 5402 SCRED (Single Cylinder Research Engine Diesel), which is presented in Fig. 1. Being destined for research, the engine has a special configuration. Its main technical characteristics are presented Table 2. The ECU of the engine has an open architecture, so the engine can be tested either via parameter mode (where all the parameters are controlled by the user) or via map mode (where the engine operates according to the ECU predefined maps, whereas the user controls the throttle position).

Table 2

Technical characteristics of the AVL 5402 engine

Parameter	*Value*	*M.U.*
Bore	85	[mm]
Stroke	90	[mm]
Con-Rod length	138	[mm]
Compression Ratio	17.5	[-]
Displacement	510.7	[cm^3]
Injector Holes	8	[-]
Rail Pressure	1800	[bar]

The engine is fitted with an in-cylinder pressure transducer, with intake and exhaust temperature and pressure sensors, oxygen sensor, in-cylinder image capture hardware and others. The desired temperature for the lubricating oil and coolant are ensured by using the AVL 577 conditioning device.

3. EXPERIMENTAL RESULTS

As an example of the laboratory capabilities, in Table 3 are given values measured using the in-cylinder pressure transducer for tests done at various operating points.

Table 3

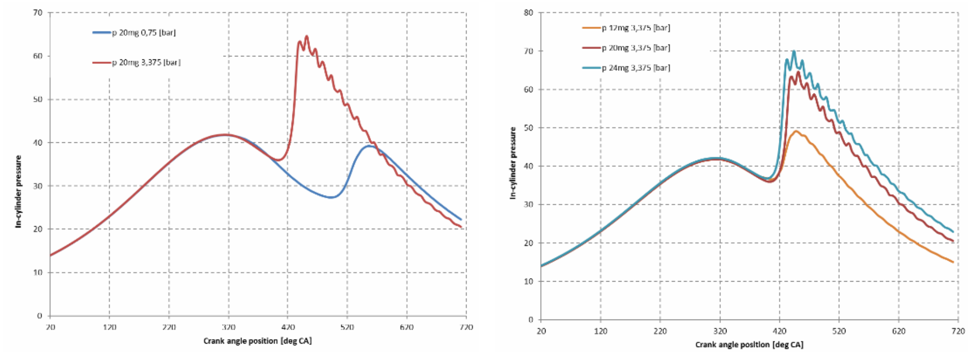
Injection parameters

Test	Notation	Main injection		Pilot injection		Max. pressure
		Quantity	Timing	Quantity	Timing	
		[mg]	[°CA]	[mg]	[°CA]	[bar]
1	20mg 0,75	20	0,75	-	-	41,736
2	20mg 3,375	20	3,375		-	64,589
3	20mg 3,375 1,5mg 7,5	20	3,375	1,5	7,5	70,754
4	20mg 3,375 1,5mg 23,5	20	3,375	1,5	23,5	66,58
5	24mg 3,375	20	3,375	-	-	70,079
6	12mg 3,375	12	3,375	-	-	49,1

During the tests, the engine speed was kept constant at 1 500 [min^{-1}] and the properties of the injection were modified as follows:

- tests 1 and 2 were done to underline influences of the injection advance on engine operation. For this purpose, the fuel quantity was kept constant, while the injection timing was changed from 0,75 to 3,375 [°CA];
- tests 2, 5 and 6 were done to underline influences of the injected quantity on engine operation. For this purpose, the injection advance was kept constant, while the injection quantity was varied;
- tests 2, 3 and 4 were done to show the importance of the pilot injection with respect to effective power and in-cylinder pressure.

All the result graphs are shown in Figs. 2 and 3.



a) b)

Fig. 2 – In-cylinder pressure versus crank angle position for a) tests 1 and 2; b) tests 2, 5, and 6.

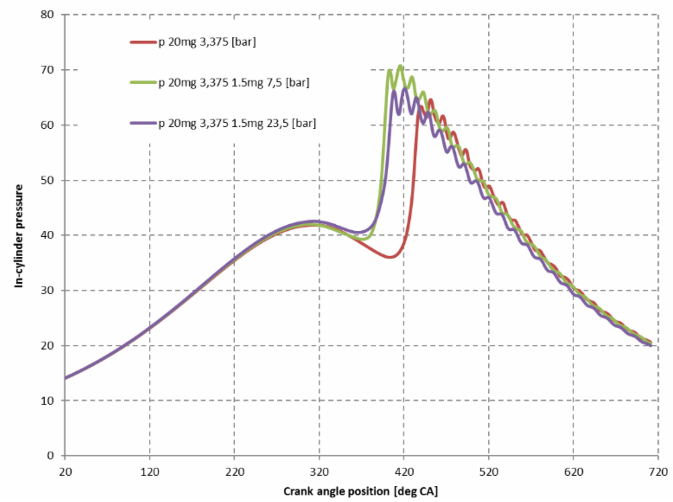


Fig. 3 – In cylinder pressure *versus* crank angle position for tests 2, 3 and 4.

Even if experimental investigations are a vital and indispensable tool of research they cannot provide access for the user in all the required areas or processes. As a result, simulations are equally important in understanding the phenomenon that takes place inside an internal combustion engine. However, simulation models must be validated before they can be used (see Fig. 4).

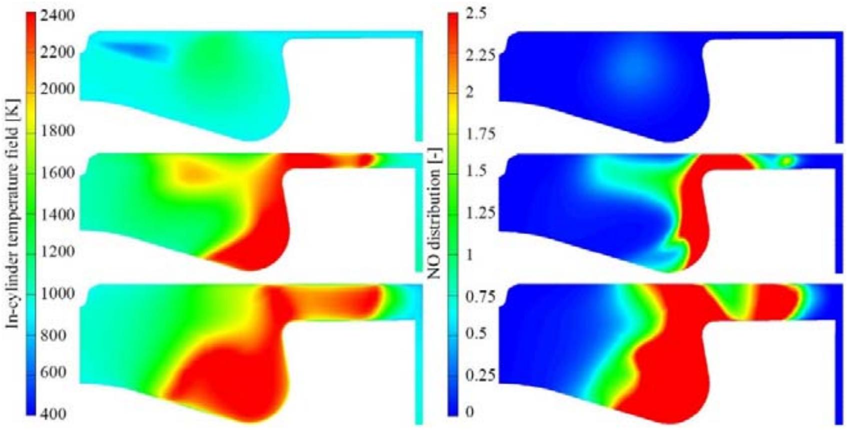


Fig. 4 – Validation of a simulation model (Diesel engine, 1 500 [min^{-1}], 2 [mg] pilot and 19 [mg] main).

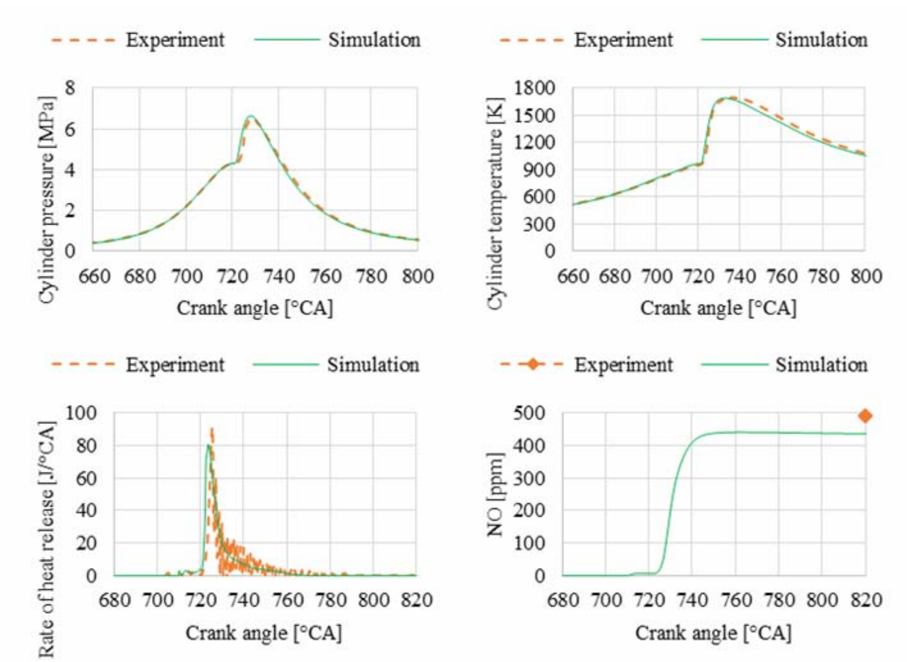
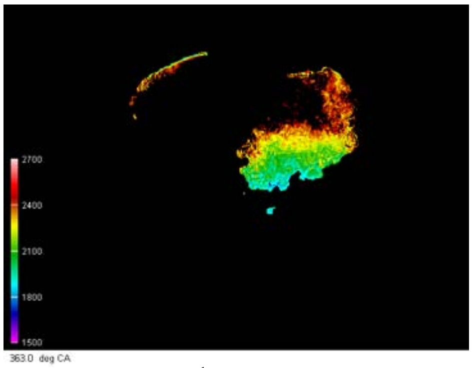


Fig. 5 – Temperature and NO_x distribution fields inside the combustion chamber (Diesel engine, 1 500 [min^{-1}], 2 [mg] pilot and 19 [mg] main) [1].

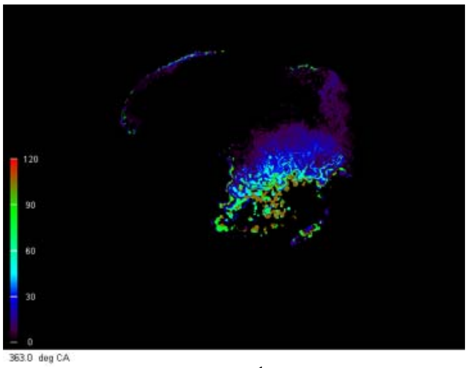
With the aid of numeric simulation, one can also determine the distribution fields inside the cylinder for fuel, temperature, pollutant emissions etc. In Figure 5 a NO_x (nitric oxides) distribution field versus in-cylinder temperature is presented.

Temperature is one of the most important factors in the NO_x formation process. Knowing its values in every point of the combustion chamber can help identify the causes that lead to NO_x formation as well as possible improvement paths.

a) 2 000 [min^{-1}] 1,75 [mg] 10 [mg]

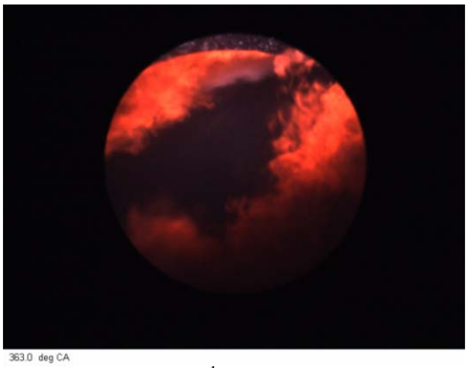


b) 2 000 [min^{-1}] 1,75 [mg] 10 [mg]



c) 2 000 [min^{-1}] 1,75 [mg] 10 [mg]

d) 1 000 [min^{-1}] 10 [mg]



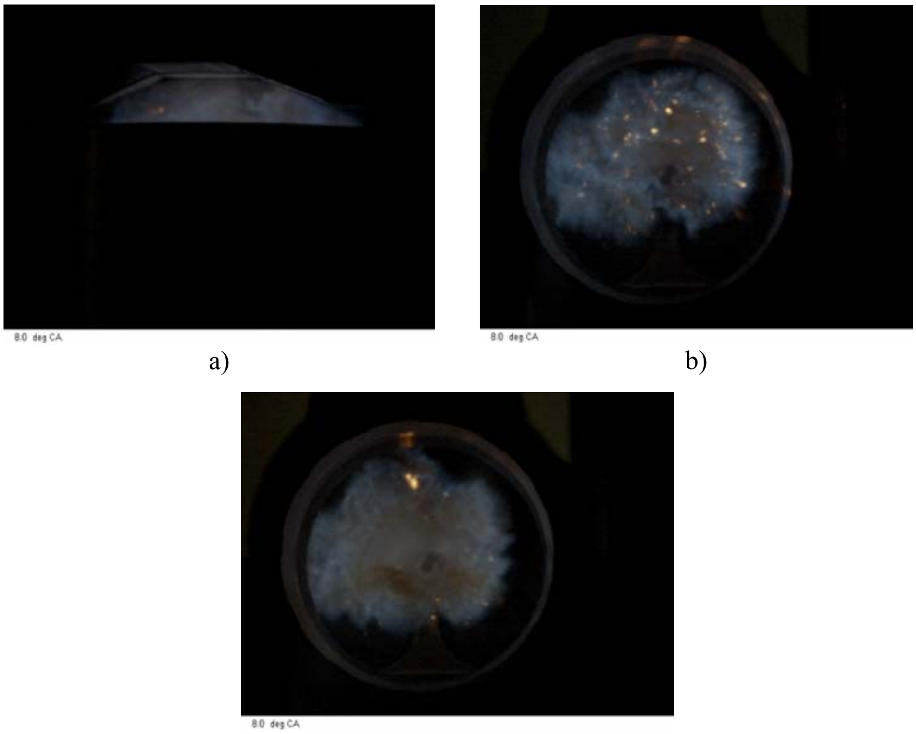
e) 1 000 [min^{-1}] 1,75 [mg] 10 [mg]

f) 1 000 [min^{-1}] 1,75 [mg] 15 [mg]

Fig. 6 – In cylinder flame recordings inside the SCRED 5402 engine.

On the same AVL 5 402 engine, the operator can gain optical access in the combustion chamber using the endoscopic camera and the AVL Visioscope system, which allows investigations of the injection and combustion processes with respect to fuel, temperature and pollutant distribution. This can also help with investigations regarding the mechanical movement of the engine mobile components (piston-rod assembly). The system incorporates a top image recording technology in the field of internal combustion engines, as well as an image processing software for data analysis.

Measurements made using the Visioscope system are presented in Fig. 6, for different speeds and various injection properties but at the same crank angle: 363 [°CA], with 360 being the top dead center (TDC) at the end of the compression stroke. Using the post-processing Thermal Vision Software, the images can be analyzed to highlight the soot nucleus formation areas and the temperature spectrum inside the combustion chamber. Figure 6a shows the flame inside the cylinder at 363 [°CA], for an engine speed of 2 000 [min^{-1}], a pilot injection of 1,75 [mg] injected with 20 [°CA] BTDC (Before Top Dead Center) and a main injection of 10 [mg] injected at 3,375 [°CA] BTDC. Figures 6b and 6c show the same image processed using the Thermal Vision Software. Figure 6d shows the flame inside the cylinder for a speed of 1000 [min^{-1}], with no pilot injection and a main injection of 10 [mg] injected at 3,375 [°CA] BTDC. Figures 6e and 6f show the flame inside the cylinder for different injection quantities, namely 10 [mg] and 15 [mg], but with the same injection timing of 3,375 [°CA] BTDC.



a) b) c)

Fig. 7 – In cylinder recordings for the gasoline 5 403 engine: a) side view inside the combustion chamber; b) through-piston view of the combustion chamber first recording; c) through-piston view of the combustion chamber second recording

Due to the special build of the SCRED 5 402 engine, it can be converted into a gasoline engine (designated 5 403) with port fuel injection. This engine can be equipped with a transparent liner and piston, thus allowing the recording of the flame development inside the cylinder. An example of such recordings is presented in Fig. 7. Figures 7b and 7c represent the same recording but during different cycles, thus showing the repeatability of the test. All SCRE 5403 recordings were done at 1 500 [min^{-1}].

The PUMA Open Automation system also controls what happens inside the cold chamber. Here, all the components (engine, fuel, battery, etc.) can be tested at temperatures as low as –30 [ºC] and analyzed for startup, using different fuels. Such a test was performed on a 1,5 [l] Diesel engine from Renault (designated K9K). During the test the pollutant emissions were measured using the Sesam FTIR System. The AVL Sesam FTIR pollutant emissions measuring system contains the hardware and software components for evaluation and analysis of different chemical components of the exhaust gases. This system is based on the Fourier transformation infrared spectroscopy (FTIR), a method that activates the direct measurements in real time for detailed investigations of transient processes which take place in the internal combustion engines. Results obtained with this equipment during the tests with the Renault K9K engine are presented in Figs. 8–11. The measurements were done starting from different temperatures (0, –5 and –20 [ºC]) for classic diesel fuel (M) and for a mixture of 50% diesel and 50% biodiesel (B) obtained through transesterification of rapeseed oil.

The latest equipment installed in the Laboratory is the AVL InMotion system which allows the computer simulation (using the IPG CarMaker software) of a vehicle traveling on a specified road (implemented directly in the software or imported from Google Earth), following certain maneuvers and with a well-defined driver.

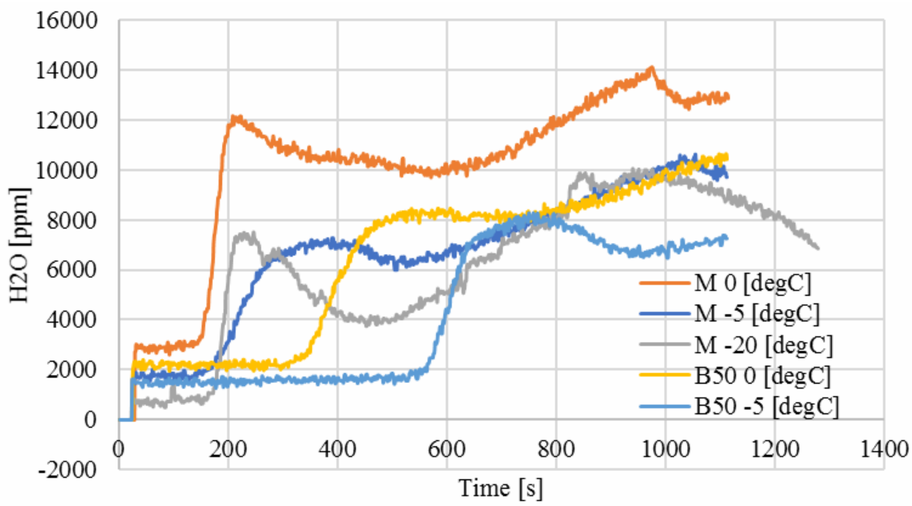


Fig. 8 – H_2O emissions for the five measurements [8].

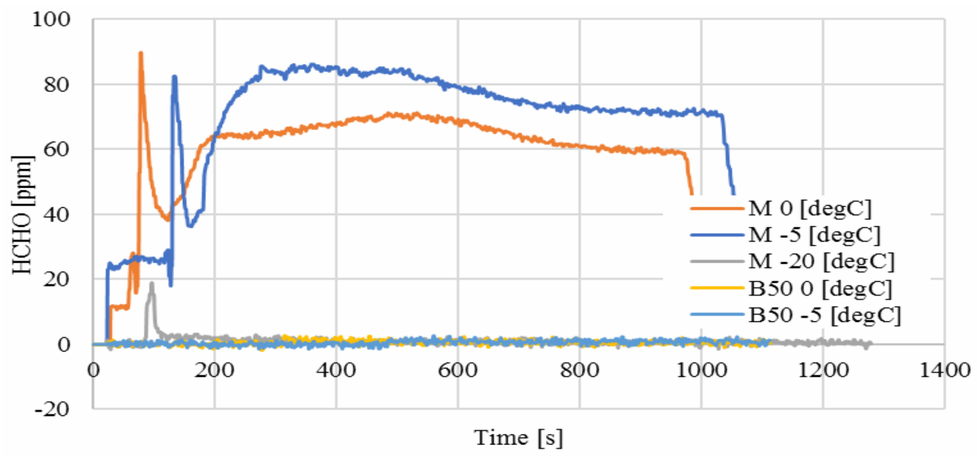


Fig. 9 – HCHO emissions for the five measurements [8].

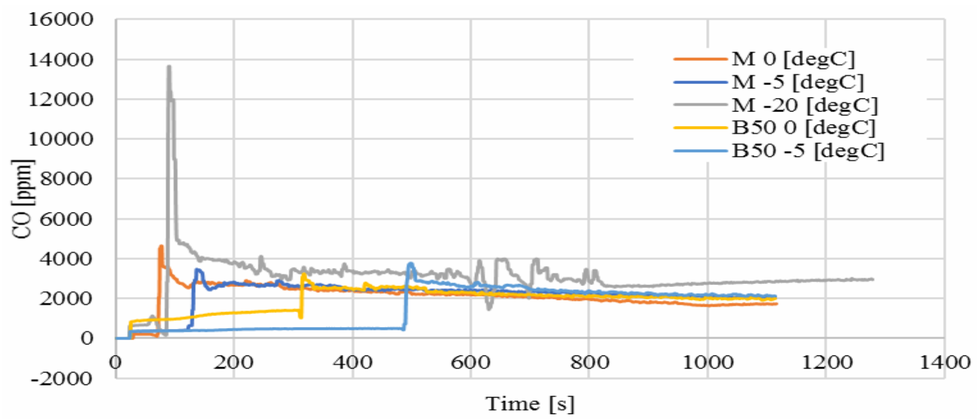


Fig. 10 – CO emissions for the five measurements [8].

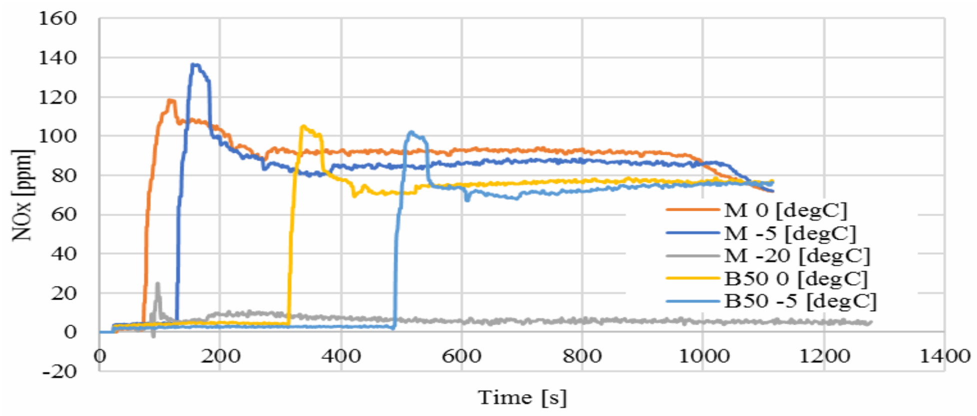
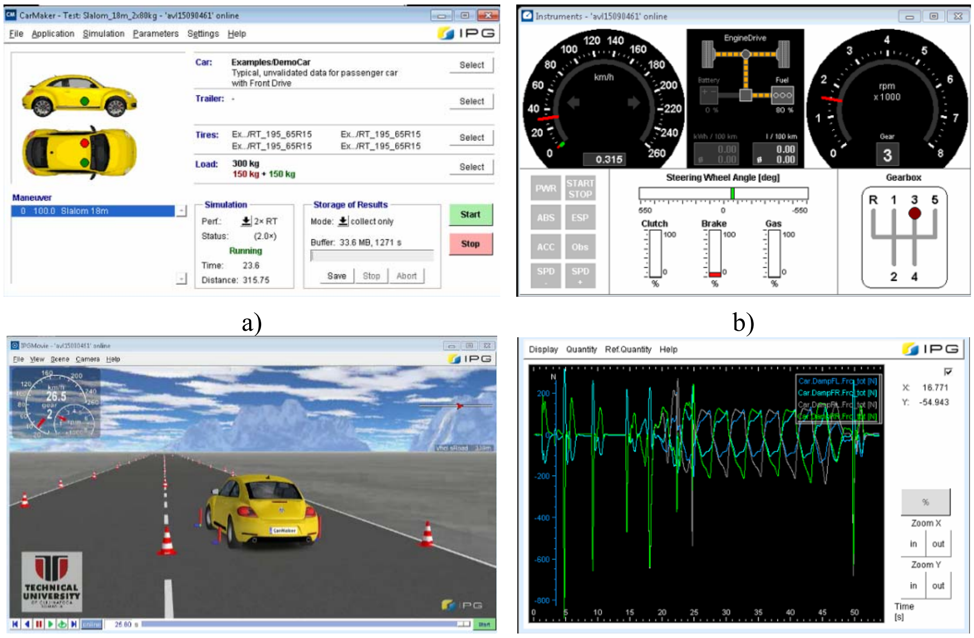


Fig. 11 – NO_x emissions for the five measurements [8].

The data that can be analyzed with this type of simulations vary depending on the purpose of the study. As a result, the system can be used for implementing new sensors on vehicles, general vehicle behavior, engine behavior, transmission analysis, suspension system analysis, brake system analysis etc.

To ensure the connection between simulation and reality, the simulated engine, or any other sub-system can be replaced with a real one and the entire system becomes a Hardware in the Loop Simulation (HIL).

The simulation presented in Fig. 12 shows the IPG CarMaker interfaces, starting with the main window (a), the instruments (b), the IPG Movie (c) and the results window (d). A simulation was made using a pre-defined vehicle, that must go through a slalom course as fast as possible, with different types of drivers: normal, defensive and aggressive. The driver settings for all situations are presented in Fig. 13.



a) b) c) d)

Fig. 12 – IPG CarMaker simulation interfaces.

The normal driver can cruise with a maximum speed of 150 km/h, a maximum longitudinal acceleration of 3 m/s^2, a maximum longitudinal deceleration of –4 m/s^2 and a corner cutting coefficient of 0.5.

The aggressive driver can cruise with a maximum speed of 250 km/h, a maximum longitudinal acceleration of 4 m/s^2, a maximum longitudinal deceleration of –6 m/s^2 and a corner cutting coefficient of 0.8 (1 is for a racing driver).

The defensive driver can cruise with a maximum speed of 100 km/h, a maximum longitudinal acceleration of 2 m/s^2, a maximum longitudinal deceleration of –2 m/s^2 and a corner cutting coefficient of 0.25.

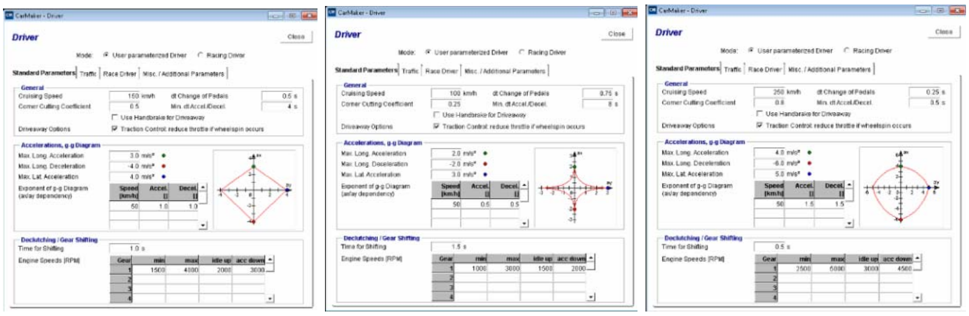


Fig. 13 – Driver settings in IPG CarMaker: a) normal driver, b) defensive driver, c) aggressive driver.

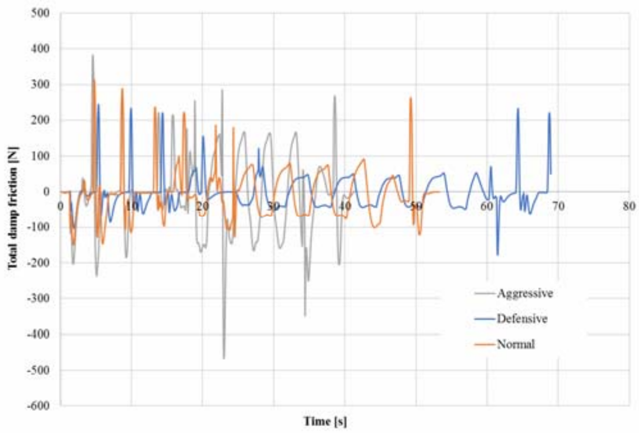


Fig. 14 – Total Damp Friction for the front left damper from IPG CarMaker
for all three types of drivers.

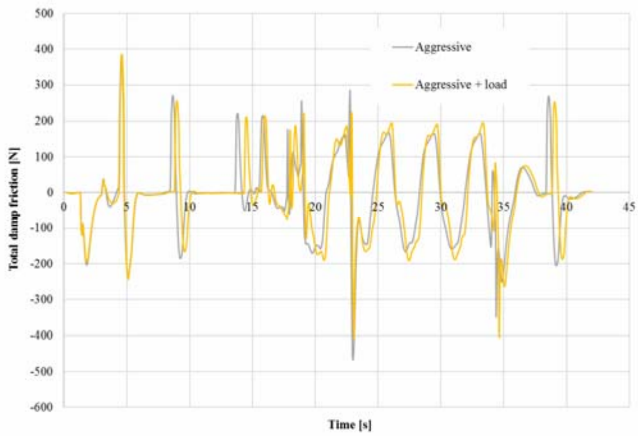


Fig. 15 – Total Damp Friction for the front left damper from IPG CarMaker
for the loaded and unloaded vehicle with an aggressive driver.

For all simulations, the driver had to go through a slalom course with 10 cones as fast as possible. The total damp friction was exported for all four wheels. The results for the front left wheel are presented in Figure 14. Figure 15 presents the same simulation, but with an additional load of 300 kg, like seen in Figure 12a.

4. CONCLUSIONS

This paper underlines the importance and the possibilities of a comprehensive ICE investigation, starting with cold start investigations, which can be done in the cold chamber (shown in figures 8 – 11), ICE simulations in AVL FIRE corroborated with real results to further the insight inside the process, as shown in figure 4 and 5, real pressure measurements to underline the effect of injection parameters like pressure, number and timing of the injections and injection quantity (figures 2 and 3), simulated driving cycles that underline the drivers influence on different vehicle behavior, but also in-cylinder recordings for gasoline and diesel engines. All these methods aid in the identification of problematic areas, or area that require improvement and in finding the proper solutions that can be implemented.

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