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Accelerometer-based SOC estimation methodology for combustion control applied to Gasoline Compression Ignition

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Accelerometer-based SOC estimation methodology for combustion control applied to Gasoline Compression Ignition

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Abstract. The European Community's recent decision to suspend the marketing of cars with conventional fossil-fueled internal combustion engines from 2035 requires new solutions, based on carbon-neutral technologies, that ensure equivalent performances in terms of reliability, trip autonomy, refueling times and end-of-life disposal of components compared to those of current gasoline or diesel cars. The use of bio-fuels and hydrogen, which can be obtained by renewable energy sources, coupled with high-efficiency combustion methodologies might allow to reach the carbon neutrality of transports (net-zero carbon dioxide emissions) even using the well-known internal combustion engine technology. Bearing this in mind, experiments were carried out on compression ignited engines running on gasoline (GCI) with a high thermal efficiency which, in the future, could be easily adapted to run on a bio-fuel. Despite the well-reported benefits of GCI engines in terms of efficiency and pollutant emissions, combustion instability hinders the diffusion of these engines for industrial applications. A possible solution to stabilize GCI combustion is the use of multiple injections strategies, typically composed by 2 early injected fuel jests followed by the main injection. The heat released by the combustion of the earlier fuel jets allows to reduce the ignition delay of the main injection, directly affecting both delivered torque and center of combustion. As a result, to properly manage GCI engines, a stable and reliable combustion of the pre-injections is mandatory. In this paper, an estimation methodology of the start of combustion (SOC) position, based on the analysis of the signal coming from an accelerometer sensor mounted on the engine block, is presented (the optimal sensor positioning is also discussed). A strong correlation between the SOC calculated from the accelerometer and that obtained from the analysis of the rate of heat release (RoHR) was identified. As a result, the estimated SOC could be used to feedback an adaptive closed-loop combustion control algorithm, suitable to improve the stability of the whole combustion process.

1. Introduction

The automotive industry is currently undergoing rapid transformation driven by a need for finding carbon-neutral technologies and to further mitigate regulated ambient air pollutants. In this scenario, zero-emissions (no carbon dioxide production) vehicles, such as Battery Electric Vehicles (BEVs) [1] and Fuel Cell Electric Vehicles (FCEVs) [2], are considered the most suitable technical solutions achieving the target fixed by the European community. However, the limited trip autonomy, reliability, long refueling times and high costs of end-of-life disposal of the components represent the main obstacles for a wide diffusion of the zero-emission vehicles [3-5].

As a result, over the last decades, several approaches were studied to limit pollutants production of internal combustion engines (ICE), which are considered the most reliable technology for automotive applications. A wide literature reports advantages in the field of pollutants reduction and efficiency performing Low Temperature Combustions (LTC) in ICE with respect to conventional combustion approaches [6,7]. Typically based on compression ignition, LTCs are characterized by high thermal efficiency mainly because are run under unthrottled conditions. On the other hand, since the air-fuel mixture auto-ignites spontaneously, realizing stable and safe combustions represents the main challenge for the management of such combustion methodologies. Based on the compression ignition of a fully homogeneous air-fuel mixture, the most studied LTC technique is Homogeneous Charge Compression Ignition (HCCI) combustion [7]. Despite its great potential in terms of pollutants reduction and fuel consumption, the HCCI combustion process is characterized by high impulsiveness and low controllability because it is fully chemically driven, which limits its applicability at a very small range [8-10].

One of the most suitable approaches to overcome HCCI limitations is Gasoline Compression Ignition combustion (GCI). Many researchers have demonstrated the strength of GCI combustion especially regarding its controllability [11,12] (compared to others LTC) which is promoted by using high-pressure direct injections. Furthermore, unthrottled conditions and very lean air-fuel mixture of GCI are responsible for the considerable reductions in pollutants and fuel consumption compared to conventional diesel combustion (CDC) [13-16]. Moreover, running GCI using bio-fuels with net-zero carbon dioxide emission [17] would represent a very promising solutions as well as FCEVs and BEVs, with the advantages of being based on a well-known and reliable technology such as ICE.

As for CDC, the use of a sequence of fuel jets, typically made by pilot (very small amount of fuel injected) and main (considerable amount of fuel) injections, allows to manage the heat released during combustion. Due to the absence of an external device which starts the combustion, the energy released by the small amount of fuel introduced with pilot injections plays a crucial role on the whole combustion management. As a matter of fact, the rise of in-cylinder pressure and temperature generated by the fuel injected with pilot injections (chemically driven by nature) allows to reduce the ignition delay of the following injection which burns in stratified conditions, thus generating a smoother combustion shape [18-20]. However, since the first fuel jets burns as an HCCI combustion, a proper injection strategy management is mandatory to guarantee safety GCI combustion which provides the delivered torque with a defined center of combustion (CA50).

Despite the use of low reactivity fuels with high volatility, such as gasoline or gasoline-like bio-fuels, significantly limits the pollutants production, especially particulate matter and unburned hydrocarbons [15,21-23], their different ignition dynamic strongly affects combustion stability. A lot of works report that, given a set of injection parameters, the longer ignition delay of low reactivity fuels (compared to standard diesel fuel) might lead a poor combustion of the first injection especially when GCI is run in cold operating conditions and generate a very retarded center of combustion (inefficient combustion) or misfire [19,24-26]. As a result, an extremely accurate injection management, particularly pilot injections, represents the key factor to assure stable GCI combustion over the whole engine operating range. Several works in literature show that it is possible to increase the GCI operating range by using a model-based injection strategy management aimed to predict the ignition delay of the pilot injections [27-32]. However, an accurate feed-forward prediction of the angular position at which the fuel introduced with the first injection starts burning (SOC) still represents the main challenge in the field of developing robust control strategies. Bearing this in mind, to improve the reliability of the injection strategy controller, it is often added a feedback contribution able to collect information about the previous combustion process and to adjust dynamically the injections.

For ICEs, the most common sensor which provides combustion feedback is the in-cylinder pressure sensor. However, pressure sensors on-board installation is still uncommon, mainly due to problems related to their reliability and cost. To overcome these, over the past years, several remote combustion sensing methodologies were developed to extract information about the combustion process, such as SOC, CA50, within the engine cycle through the real-time processing of signals coming from low-cost sensors (such as speed sensors or accelerometers) mounted on the engine [33-39]. One of the most studied approaches for the combustion indexes estimation is based on a accelerometer sensor [33,37-42] which has shown a reliable correlation between engine block vibrations and the way in which the energy release process takes place in the combustion chamber.

This work discusses a non-intrusive SOC estimation methodology based on an accelerometer sensor for GCI combustion. With the aim of developing and validating the presented estimation algorithm, experimental tests have been carried out on a specifically modified 1.3L light-duty turbocharged diesel engine able to run GCI combustion in different engine conditions. Different engine operating conditions have been tested verifying the limits of the estimation methodology, mainly related to the quality of the accelerometer signal [37,41,42]. To improve the signal-to-noise ratio [37,41], a sensitivity analysis on the accelerometer positioning has been conducted finding the best sensor position on the engine block.

2. Experimental Setup

The experimental activity has been performed on a 1.3L, 4-cylinder, turbocharged, compression ignited engine installed in a test cell. The main technical characteristics of the engine under study are summarized in Table 1.

Table 1. Engine technical characteristics.

Displacement Volume [cc]	Maximum Torque [Nm]	Maximum Power [kW]	Injection System	Bore [mm]	Stroke [mm]	Compression Ratio	Architecture
1248	200 @ 1500 rpm	70 @ 3800 rpm	Common Rail	69.6	82	16.8	L4, 4 valves per cylinder

The considered engine is equipped with a variable geometry turbine actuator (VGT), suitable to manage the intake pressure, and a high-pressure exhaust gas recirculation (EGR) system, which recirculates exhaust gas to the intake manifold. It is important to highlight that GCI combustion typically works with high EGR rates to limit pollutants [15,18], and its impact on the ignition delay (and consequently on SOC) is remarkable. Previous works made by the authors demonstrated that to make stable and reliable GCI combustion, a very strong first combustion stage (related to the combustion of the pilot injections) is mandatory even using high EGR rates [13,20]. As a result, during the whole experimental activity the EGR system has been turned off mainly because its effects on the first combustion stage is negligible in terms of energy released, and consequently on the signal-to-noise ratio. The injection system used for gasoline injection is the standard Common-Rail Multi-Jet high-pressure system with 4 solenoid injectors, center-mounted, one for each cylinder. This system allows to perform high-pressure multiple injections needed to properly control the GCI combustion process, typically composed by two pilot injections (very small quantities) followed by the main injection (bigger part of the fuel injected in the engine cycle).

As documented in literature [18-21,27], GCI combustion needs high boost pressure and intake temperature to promote the gasoline autoignition. This aspect becomes crucial especially during cranking, idle or at low loads when the exhaust gas energy is not enough to drive the turbocharger reaching the target value of boost pressure. To overcome this problem, the standard intake line has been modified adding a roots blower (S/C, Eaton Compressor M24) upstream the dynamic compressor. The volumetric compressor is driven by an electric motor (5.5 kW and maximum rotational speed equal to 3000 rpm) controlled by the engine control unit (ECU) to assure the gasoline autoignition even during the cranking phase of the engine. Once the engine overcomes the cranking stage and exhaust gas energy is enough to drive the centrifugal compressor, the external supercharger is switched off and by-passed. Consequently, the boost pressure will be directly controlled with the VGT, replaying the standard layout of the engine.

Many works show that also intake temperature plays a crucial role in GCI combustion stability [19,21,22]. For these reasons, to accurately control the intake air temperature, a high temperature diathermic oil thermoregulation unit (TEMPCO T-REG HCE 609/15-O) has been installed in the middle between the centrifugal compressor and the intake manifold. The intake air management system allowed to guarantee a proper air temperature in any engine operating conditions, which was also beneficial to stabilize the combustion process in cold-start conditions. Figure 1 shows the integration of these two components and the complete experimental setup of the engine in the test cell.

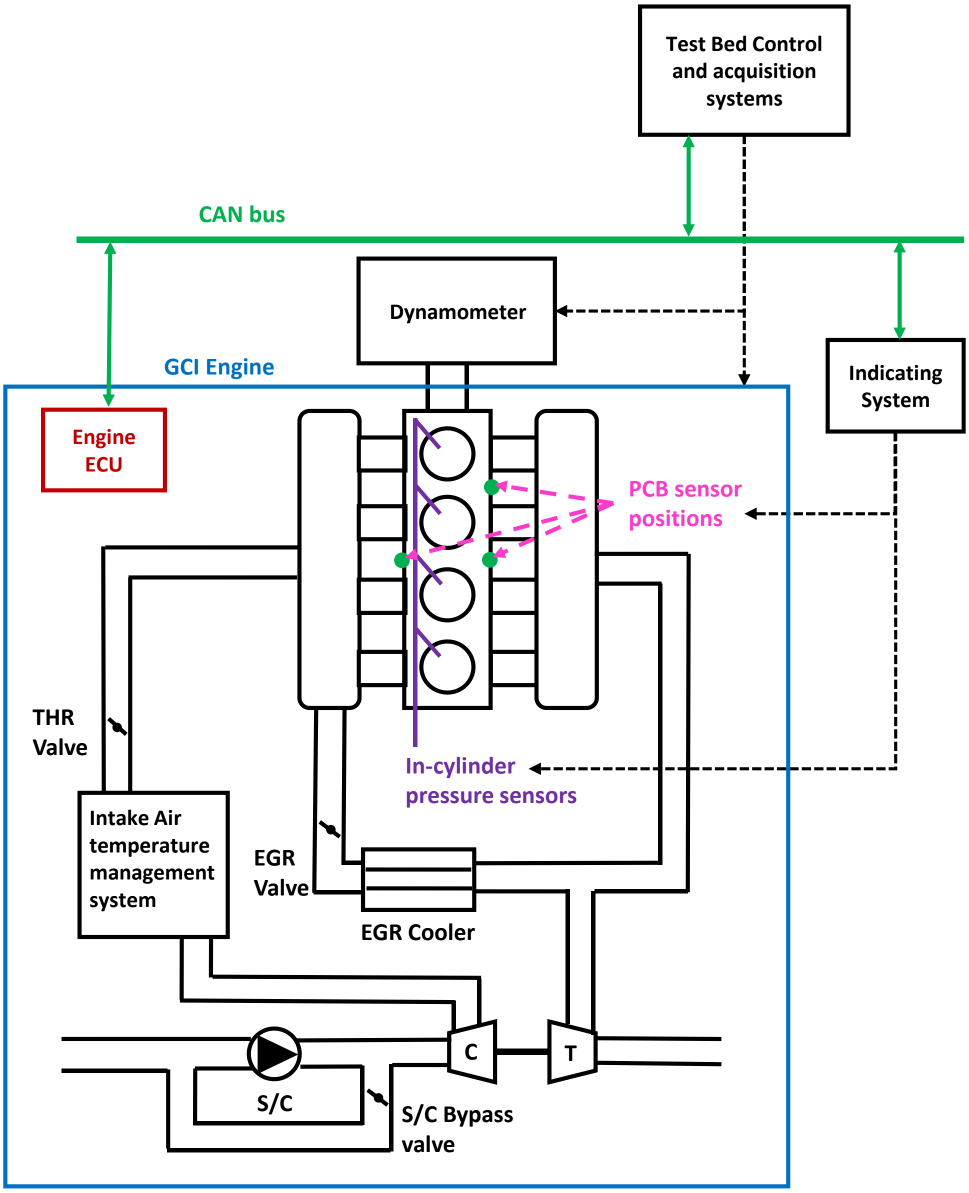


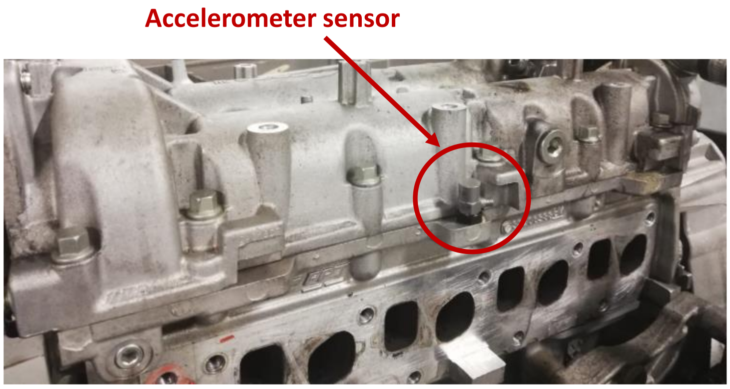
Figure 1. Scheme of the developed GCI engine and control system layout.

Since the management of GCI combustion needs complex control strategies, very far from those used in standard applications, the engine was equipped with a fully programmable electronic control unit (ECU), SPARK by Alma Automotive. By using this open ECU, based on National Instruments hardware and programmable via LabView software, it was possible to manage the engine and all the subsystems (VGT, EGR, TEMPCO, S/C) with a huge number of degrees of freedom stabilizing the gasoline autoignition and, consequently, the overall combustion process.

Besides standard sensors which are acquired by the open ECU (as usual in standard application), the engine has been also equipped with pressure and temperature sensors placed on intake and exhaust pipes. All the additional sensors have been acquired and logged by the test bench control system. Moreover, to study in detail the GCI process, the 4 cylinders have been equipped with in-cylinder pressure sensors (AVL GH14P, one per cylinder), acquired at 200 kHz and real-time analyzed by the indicating system to calculate the main combustion indexes such as indicated mean effective pressure (IMEP), CA50, SOC, pressure peak value and location. By using the information provided by the indicating system and sent to the open ECU via CAN bus, a specifically developed closed-loop combustion controller (and implemented in SPARK) allowed to stabilize the engine at each tested speed and load. Figure 1 also shows the control systems and test cell communication layout developed to properly manage GCI combustion.

The last sensor applied to the engine is a high-resolution accelerometer sensor (PCB Piezotronics 353B51) mounted through a threated connection on the engine, Figure 2. During the whole experimental activity, the accelerometer sensor has been acquired at high frequency 200 kHz by the indicating system providing the data needed to accurately estimate the SOC.

a)



b)

Figure 2. PCB sensor (a) and its placement on the engine (b)

3. Results and Discussion

a) Accelerometer-based SOC methodology

As previously described, GCI combustion proved to be an effective way to increase the thermal efficiency and reduce pollutants of the ICE. However, to make GCI combustion stable and controllable, very complex control strategies are needed. As a matter of fact, it was demonstrated that GCI controllability is achievable by using a multiple injections pattern, which is needed to generate a proper rate of heat release shape during the combustion (typically composed by two combustion stages) avoiding the limits of a purely chemical driven process, such as HCCI. The energy released during the first combustion stage holds the main characteristics of a typical chemical driven process, i.e., very short duration with high rate of heat released.

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Many works in literature show that such combustion shape can be easy detectable by using an accelerometer mainly because it generates a remarkable vibration which propagates through the engine block [39-41]. Cylinder pressure and accelerometer signal typically show high coherence in the frequency range usually associated to the combustion process, i.e., for frequencies lower than 4 kHz [36,40,41]. The highest coherence values occur at the engine firing frequency and its multiples, indicating that the firing frequency and its harmonics dominate the response of the engine structure and the response captured by both cylinder pressure transducer and accelerometer. Moreover, it was demonstrated that the accelerometer signal in many cases can be easy correlated with the derivative of the rate of heat release RoHRD [42], calculated through the well-known Equation 1 from the in-cylinder pressure signal where $\gamma = \frac{c_p}{c_v}$ is the specific heat ratio [42].

$$RoHRD = \frac{d}{d\theta}\left(\frac{\gamma}{\gamma-1}pdV + \frac{1}{\gamma-1}Vdp\right) \tag{1}$$

Previous results demonstrate that engine block acceleration is usually correlated with cylinder pressure first derivative, except for the delay between the signals, that corresponds to the time delay existing between the combustion event and the moment in which the effect is captured by the acceleration transducer [36]. Considering conventional gasoline combustion process, the highest accelerometer peak is typically correlated to the start of the combustion position (SOC), while the following zero-crossing provides information about the angular location of in-cylinder pressure peak. Therefore, during this work, the SOC has been considered as the RoHRD peak near the TDC, while the pressure peak angular position can not be detected mainly because of the shape of the GCI combustion.

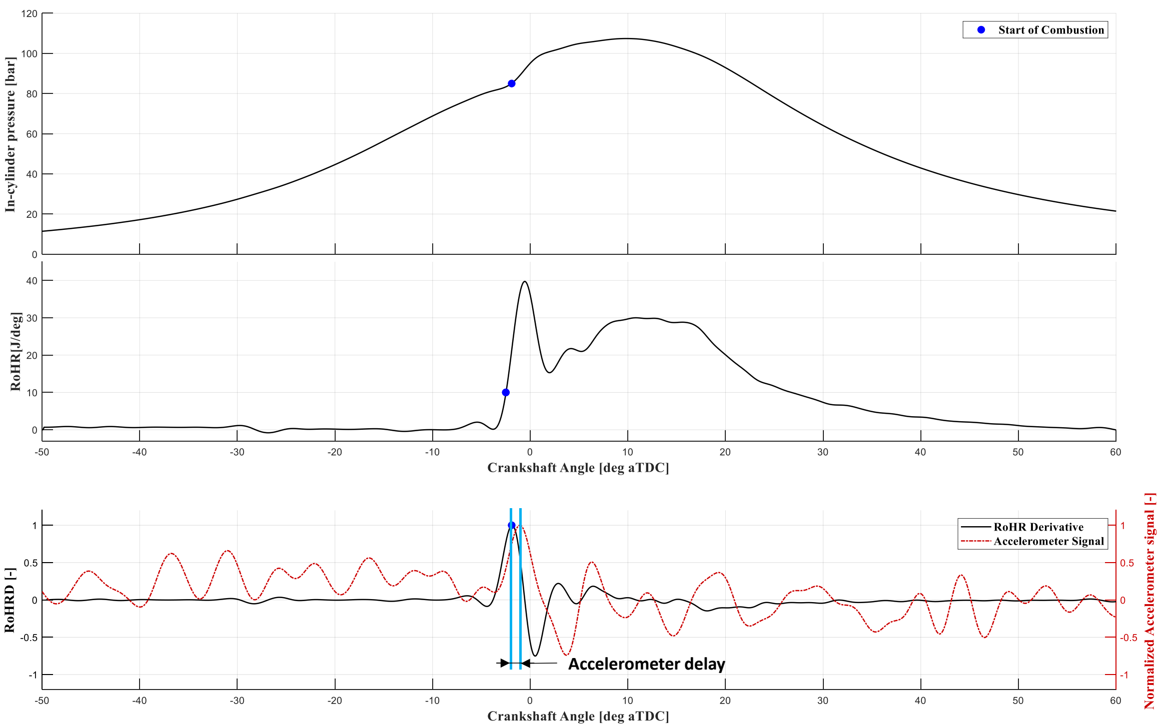

Figure 3. Normalized RoHRD and Normalized Accelerometer signal

Due to the typical shape of GCI combustion, only the premixed combustion stage generates a remarkable engine block vibration because it releases a big amount of energy in a short time. The following combustion stage, characterized by smoother heat release, generates very low vibration which could be confused with the mechanical vibration of the engine or, in the worst case, with the propagation tail of the oscillation generated by the previous combustion stage. As a result, for GCI combustion only the SOC can be effectively detected and then, to make a more reliable SOC estimation, the developed methodology considers the RoHR derivative. Figure 3 reports the RoHR derivative and engine block acceleration (all normalized with respect to their maximum values), confirming a very good accordance also in GCI operating mode.

The methodology reported in this work, is based on filtering the acquired accelerometer signal using a bandpass filter with cutoff frequencies equal to 0.3 kHz and 2.5 kHz. Then, the filtered signal is resampled in the angular domain and properly windowed around the top dead center (TDC) of each cylinder. Finally, the algorithm automatically detects, for each cylinder, the major peak of the windowed signal, whose angular position provides a reliable SOC estimation. It is important to point out that, due to the velocity of vibration propagation on the engine block, the time delay of the accelerometer signal have to be characterized offline cylinder-by-cylinder at each engine sensor position.

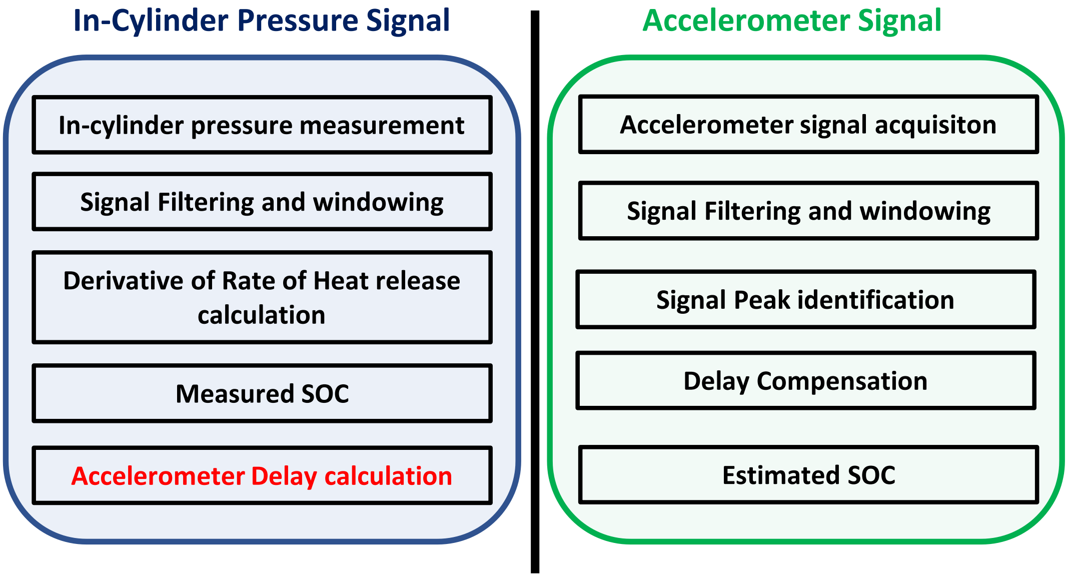

Figure 4. Signal processing and manipulation for the in-cylinder pressure and accelerometer signals

To calculate the accelerometer delay and obtain the measured SOC, needed to validate the output of the presented methodology, the above-described signal processing (filtering) was applied also to the in-cylinder pressure signal. Then, the RoHRD was calculated, and the accelerometer delay was characterized as time delay between the first peak of the two signals (RoHRD and accelerometer signal) during the combustion. As reported in literature, the vibration propagation on the engine block depends on sensor positioning and engine speed [36-41]. Since during the validation of the estimation methodology the position of the sensor was fixed, the signals delay was considered only as a function of the engine speed, which increases rising the engine speed. All the steps performed on the in-cylinder pressure signal and on the accelerometer signal for the SOC estimation are reported in Figure 4.

Table 2. GCI operating conditions during the calibration of SOC estimation with accelerometer signal

Engine Speed [rpm]	IMEP [bar]	CA50 [deg aTDC]	Boost Pressure [barA]	Intake Temperature [°C]	Exhaust Pressure [mbarA]	Gasoline Pressure [bar]	Soi Pil [deg bTDC]	Soi Pre [deg bTDC]
2000	12	12	2	THigh - 79	1.9	PrailScan - 350:900	32	18
2000	12	12	2	TLow - 54	2.2	PrailScan - 350:900	32	18
2000	12	12	2.1-1.8	TLow - 54	3.5-3.3	500	34	20
2000	12	12	2.1-1.8	THigh - 79	3.5-3.3	500	34	20
2000	14	12	2.1-1.8	TLow - 54	3.5-3.3	500	35	21
2000	14	12	2.1-1.8	THigh - 79	3.5-3.3	500	35	21

Once the accelerometer signal processing algorithm is defined, the correlation between measured and estimated SOC was obtained and verified running the GCI engine at 2000 rpm (a constant time delay was applied) changing the control parameters which typically affect the SOC positioning. Table 2 summarizes the operating conditions tested to calibrate the measured and estimated SOC correlation. By looking at Figure 5 it clearly arises the strong correlation (1-to-1 values correlation) between SOC position evaluated through in-cylinder pressure (SOC ROHR) and accelerometer signals (SOC ACC) for the cylinder 3 after compensating the time delay (100 consecutive engine cycles for each condition were considered). It is important to point out that, especially for engine conditions characterized by low temperature, which causes the retard of the ignition phase, the reliability of the SOC estimation decreases. The following section discuss the aspects which can compromise the reliability of the SOC detection through an accelerometer sensor.

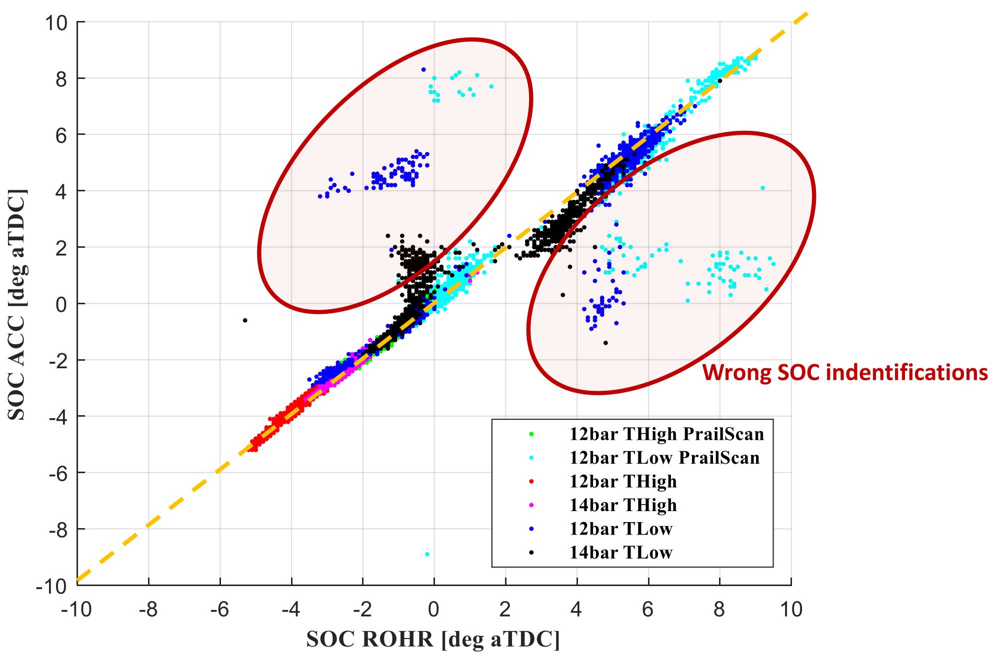

Figure 5. Comparison between measured SOC (SOC ROHR) and estimated SOC through the accelerometer (SOC ACC) running the engine in GCI mode

b) Performance assessment of the Accelerometer based-SOC estimation methodology: Effect of combustion shape

As mentioned before, in GCI combustion, the SOC is mainly related to the premixed combustion stage efficiency. As a result, lowering the intake temperature, the ignition delay of the pilot injections (responsible of the first combustion stage) will increase modifying the whole RoHR shape. Figure 6 shows the RoHR with the engine running at the same condition run (2000 rpm – 12 bar IMEP) but at different intake temperatures. By looking at the RoHR traces, the remarkable differences on the first combustion stage explains the worsening on the SOC detection by the accelerometer: the high temperature condition, Figure 6a, shows two separated combustion stages, with a significant portion of energy released in the first part; on the contrary, decreasing the intake temperature, Figure 6b, the typical GCI dual stage combustion collapses in only one phenomenon. The reduction of the premixed combustion peak is the main cause of wrong SOC detections reported in Figure 5. Moreover, the high cycle to cycle variability generated by the low efficiency of the first combustion stage might led to wrong SOC identification because of the very low signal-to-noise ratio. As a result, since during this work the SOC estimation has been performed using only one accelerometer sensor (the position has not been optimized), the wrong identification located below the correlation reported in Figure 5 might be related to the mechanical noise of the engine which can be confused with the block vibration of a poor combustion stage.

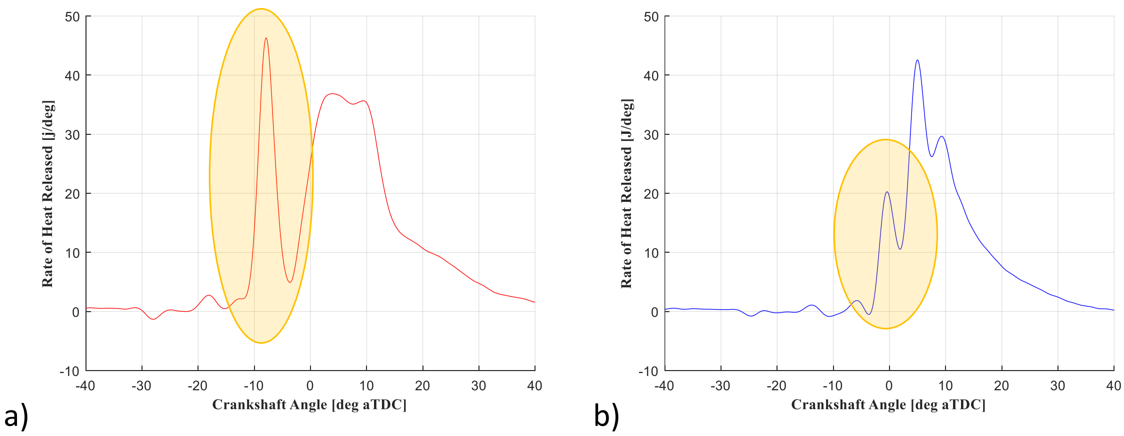

Figure 6. Comparison between RoHR of the GCI combustion performed with two different intake temperature, a) high intake air temperature, b) low intake air temperature.

c) Performance assessment of the Accelerometer based-SOC estimation methodology: Cylinder-to-cylinder estimation accuracy

Despite it was demonstrated that SOC position can be effectively obtained through the analysis of the accelerometer signal, due to the different propagation of vibrations through the engine block, the accuracy of the presented estimation methodology is strongly affected by the sensor positioning [34]. As a matter of fact, the sensitivity to vibrations changes cylinder-to-cylinder mainly because the distance between the sensor and the cylinders are different.

To better clarify this point, Figure 7 shows the SOC detection performed for each cylinder running the GCI engine at 2000 rpm with IMEP 8 bar and performing CA50 sweep from 8 to 14 deg aTDC (100 consecutive engine cycles were considered for each CA50). During this experimental activity, the gasoline injection pressure was set equal to 500 bar. Despite the unfavorable conditions for GCI combustion (very low load) [15,18], the accuracy of SOC estimation through the accelerometer (after having compensated the time delay) remains high for cylinders 2 and 3, while significantly decreases for cylinder 1 and 4. By the analysis of the results reported in Figure 7, it clearly arises that to guarantee the SOC estimation reliability using the accelerometer, the sensor positioning plays a crucial role.

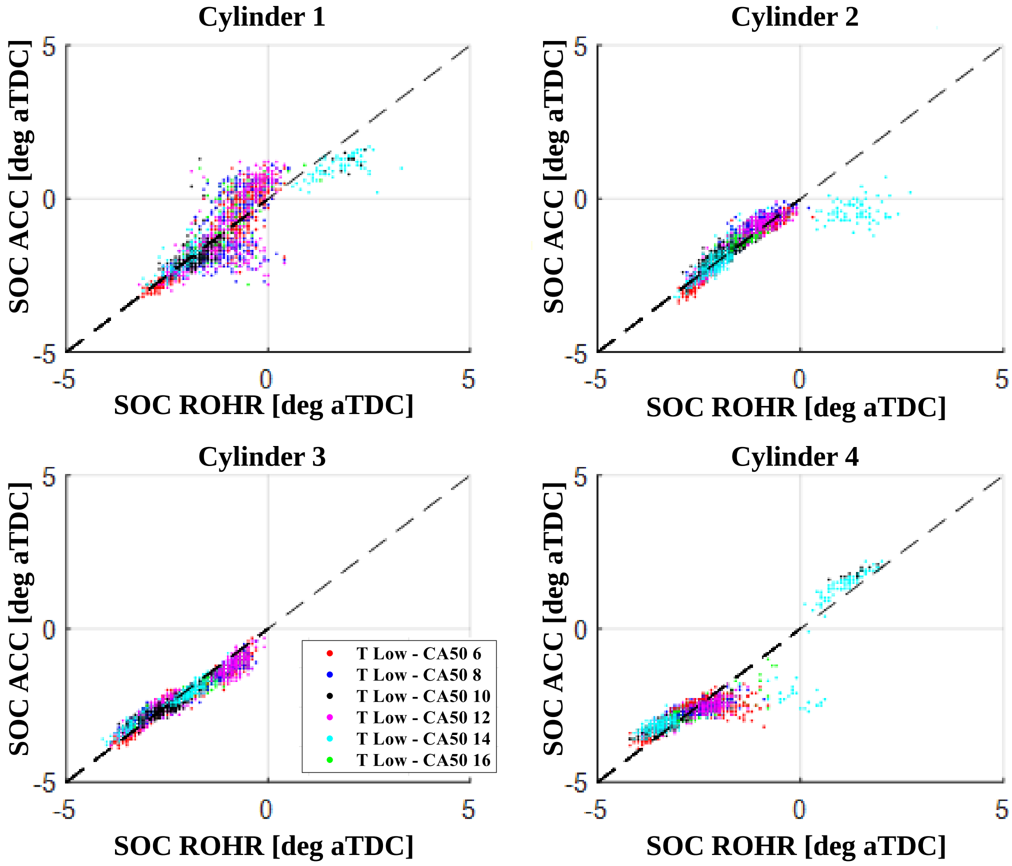

Figure 7. Cylinder-to-cylinder comparison between SOC ROHR and SOC ACC performing CA50 sweep in GCI mode at 2000 rpm and IMEP 8 bar

d) Performance assessment of the Accelerometer based-SOC estimation methodology: Effect of the sensor positioning on engine block

With the aim of finding the sensor position on the engine block which guarantee good accuracy on SOC estimation for all the cylinders, a wide experimental activity was carried out running the engine in the same conditions while changing the sensor position. Figure 8 shows the three different sensor positions considered for this activity (dummy sensors are shown): one on the intake side, Figure 8a, and two on the exhaust side of the engine, Figure 8b. The whole experimental activity was conducted using the same sensor, PCB Piezotronic 352C33, used during the development and the validation of the presented methodology. Since the literature on remote sensing techniques using accelerometer sensors demonstrated that to maximize the sensitivity on vibration the sensor must be placed on the engine block (bottom part is preferred) [40,41], the sensor positions highlighted by Figure 8 were chosen following this guideline.

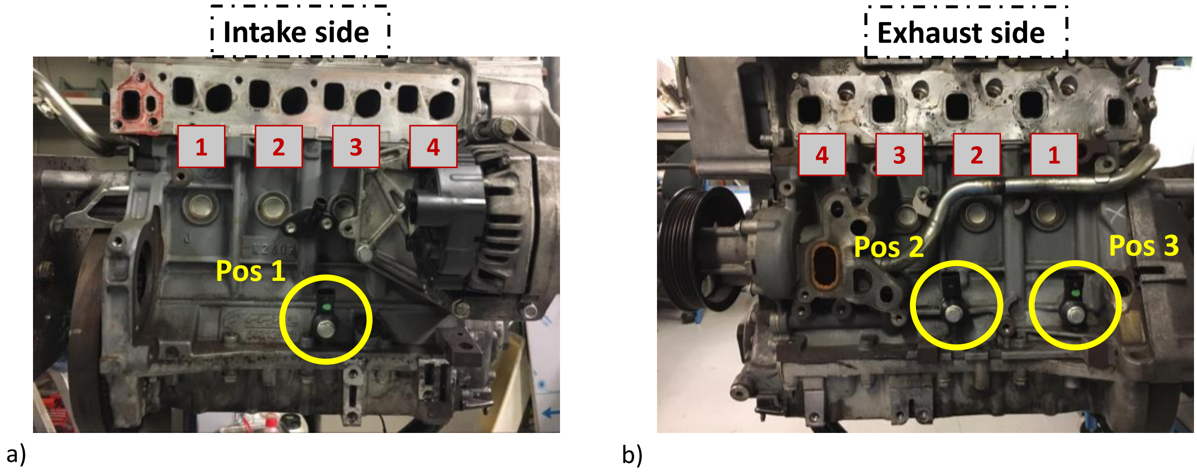

Figure 8. Different accelerometer positioning on the engine block: a) Position 1 on the intake side, b) Position 2 and 3 on the exhaust side

By using the engine calibration obtained by the authors through previous activities on the GCI engine [19,20], to evaluate the accuracy of the accelerometer-based SOC estimation methodology with different sensor positions, two different loads were tested: low load, with IMEP equal to 10 bar; high load, with IMEP equal to 14 bar. Table 3 and Table 4 summarize the engine operating conditions for the low load and high load tests respectively.

Table 3. Low-Load Engine operating conditions tested during the evaluation of the effect of sensor positioning at different engine speed on the accelerometer-based SOC estimation

Engine Speed [rpm]	IMEP [bar]	Gasoline Pressure [bar]	Boost Pressure [barA]	CA50 [deg aTDC]
2000	10	500	1.5	Sweep from 8 to 14
2250	10	700	2.0	Sweep from 8 to 14
2500	10	700	1.9	Sweep from 8 to 14
2750	10	700	2.0	Sweep from 8 to 14
3050	8	700	1.9	Sweep from 8 to 14

Table 4. High-Load Engine operating conditions tested during the evaluation of the effect of sensor positioning at different engine speed on the accelerometer-based SOC estimation

Engine Speed [rpm]	IMEP [bar]	Gasoline Pressure [bar]	Boost Pressure [barA]	CA50 [deg aTDC]
2000	14	500	1.5	Sweep from 8 to 14
2250	14	700	2.0	Sweep from 8 to 14
2500	14	700	1.9	Sweep from 8 to 14
2750	14	700	2.0	Sweep from 8 to 14
3050	10	700	1.9	Sweep from 8 to 14

As widely explained before, an increased engine speed might compromise the SOC detection mainly because of the signal-to-noise ratio worsening. As a result, to verify the impact of the engine speed on the SOC estimation accuracy through the accelerometer sensor, five different engine speed were tested: 2000, 2250, 2500, 2750 and 3050 rpm. At any selected speed, the time delays between RoHRD and accelerometer signal were identified for each cylinder and sensor position at the highest load and the most anticipated CA50 tested. Then, once identified the delays, they were applied, as a constant values, to all tests with the same engine speed. As expected, increasing the rotational speed of the engine, the time delay between the two signals increases.

To quantify the performance of the presented SOC estimation methodology and determine the best sensor positioning on the crankcase, 150 consecutive engine cycles for each condition were considered and the error between measured SOC through in-cylinder pressure signal and accelerometer was calculated. The engine cycles with the SOC angular position estimation error greater than +/- 3 degrees were considered unrecognized and, as a performance index was selected the percentage of the unrecognized cycles defined in Equation 2.

$$Unrecognized\ cycle\ \% = \frac{\text{n°cycle not recognized}}{150} * 100 \tag{2}$$

Figure 9 shows the results of the analysis on sensor positioning in different engine operating conditions. By the comparison of the reported results, it clearly arises that the position 2 can be considered the best sensor placement both in terms of accuracy and cylinder-to-cylinder variability. As a matter of fact, despite the performance of the algorithm decrease at low load (due to low signal to noise ratio generated by the low energy released in the first combustion stage and the high cycle-by-cycle variability) with the sensor in position 2, a reliable and accurate SOC estimation for all the tested engine speed can be obtained, meaning that the signal-to-noise ratio (in that position) does not strongly decreases. Furthermore, the SOC estimation by placing sensor in position 2 is almost constant with a deviation lower than 20% of unrecognized cycles (and quite accurate) for all the four cylinders. On the contrary, the results obtained with the sensor in position 1 and 3 are generally worse in terms of accuracy (high percentage of unrecognized cycles) with, in some cases, huge cylinder-to-cylinder differences.

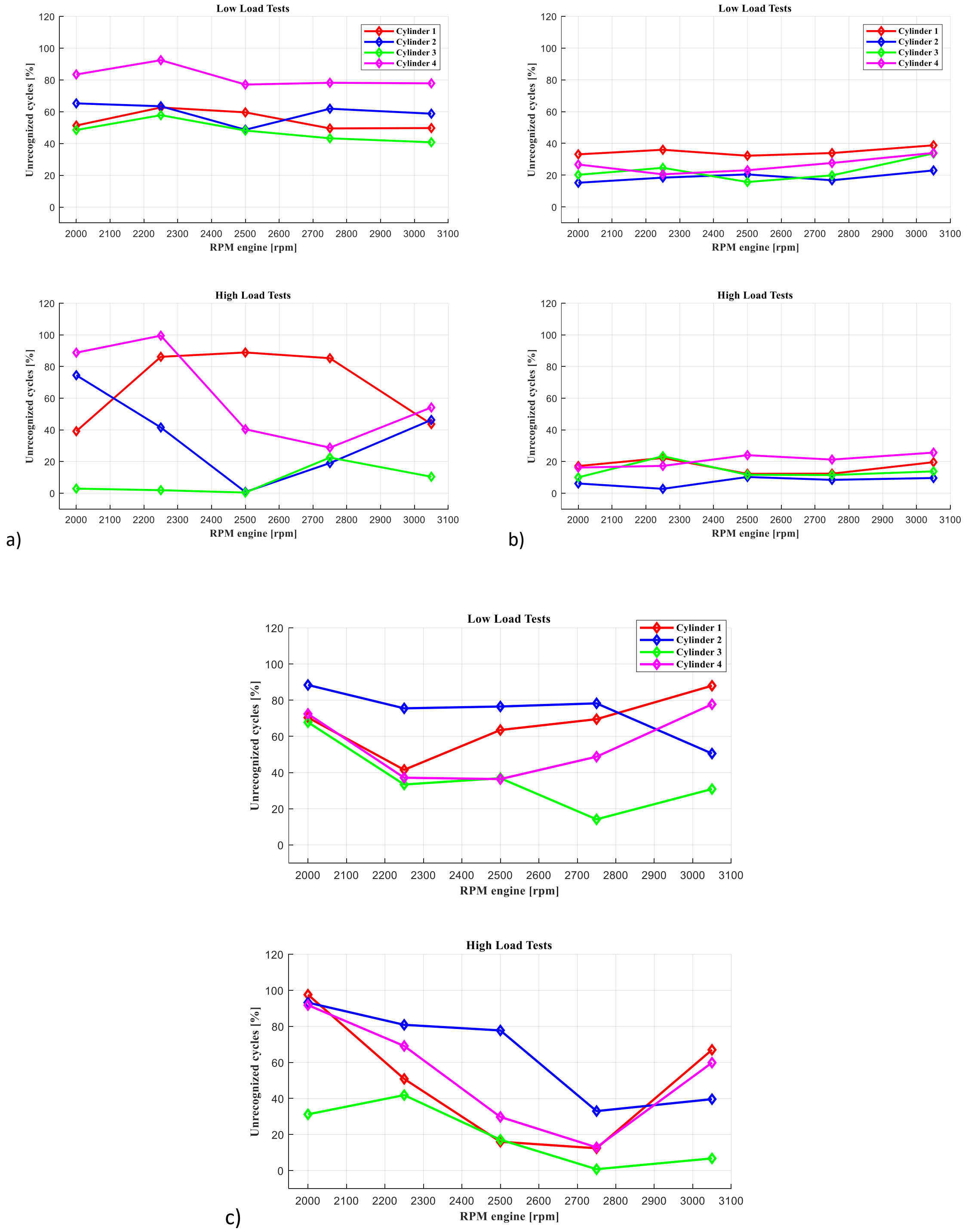

Figure 9. Accuracy of the accelerometer-based SOC detection methodology in different engine operating points and sensor positions: a) Position 1, b) Position 2 and c) Position 3 on the engine block

4. Summary/Conclusions

This work presents an estimation methodology of the start of combustion position for innovative GCI combustion. Based on the analysis of the signal coming from an accelerometer sensor mounted on the engine block, the SOC can be obtained through the deep analysis of the acquired signal. To realize the high efficiency GCI combustion, a standard light-duty compression ignited engine was modified adding a volumetric compressor and an external air conditioning system, suitable to provide the minimum level of boost pressure and intake air temperature necessary to auto-ignite the air-gasoline mixture.

The first part of the study was mainly aimed at the development of the signal processing algorithm to obtain the SOC angle from the accelerometer signal. The identification of the time delay between accelerometer signal and the Rate of Heat Release derivative, needed to compensate the vibration propagation dynamic on the engine block, was calculated by comparing the two signals in a reference engine condition. To validate the reliability of the presented methodology, the proposed algorithm was tested running the engine with different control parameters which typically affect the ignition delay, and consequently the SOC position. The reported results have shown that moving away from the typical GCI combustion shape (consisting of two combustion stages: the first like a HCCI with fast RoHR and the second very close to a conventional diffusive combustion with smoother RoHR), the accuracy of the SOC detection by the accelerometer sensor strongly decreases. However, to maximize the benefits of such advanced combustion, unusual combustion shapes (very far from the standard) have to be avoided and, therefore, these conditions do not represent an obstacle on the methodology application.

Moreover, the obtained results demonstrated that the SOC detection algorithm accuracy also depends on sensor positioning on the engine block and differs from cylinder-to-cylinder because of different signal-to-noise ratio and by how the vibrations propagate on the engine block. To identify the best sensor position which maximize the accuracy of the estimation methodology, several tests were performed running the GCI engine with different speeds and loads performing CA50 sweeps. After having compensate the time delay at each engine speed between the two signals, RoHRD and the accelerometer signal, each group of tests were repeated changing the position of the accelerometer on the engine block. Among the three different positions tested, one of them had shown good SOC estimation accuracy with a percentage of unrecognized cycles (SOC ACC error greater than +/- 3 degrees) below 20%, for all the four cylinders of the engine, proving the reliability of the presented approach.

Since the stability of the ignition phase, and consequently SOC position, plays a crucial role on the GCI combustion management, further activity is currently being performed to implement the SOC estimation in real-time as a feed-back contribution of the combustion controller, with the goal of improving the injection management strategies and, consequently, increasing the GCI engine operating range.

5. Appendix A. Uncertainties

Further information about the additional sensors used by the authors to measure:

1. In-cylinder pressure: necessary to calculate all combustion indexes (IMEP, CA50, PPRR)

Element	**Value**
Sensor Name	AVL GH14P
Measuring range	0-250 bar
Overload	300 bar
Sensitivity	15 pC/bar
Linearity	≤ ± 0.3%
Calibrated ranges	0 ... 80 bar 0 ... 150 bar 0 ... 250 bar
Natural frequency	115 kHz

2. Accelerometer sensor: necessary to evaluate the engine block vibration

Element	**Value**
Sensor Name	PCB Piezotronic 352C33
Measuring range	±490 m/s^2 pk
Sensitivity	10.2 $mV/(m/s^2)$
Linearity	≤1 %
Natural frequency	≥50 kHz

6. Definitions/Abbreviations

BEVs	Battery Electric Vehicles
CA50	Center of combustion
CAN	Controller area network
CDC	Conventional diesel combustion
C_p	Heat specific value at constant pressure
C_v	Heat specific value at constant volume
ECU	Electronic control unit
FCEVs	Fuel Cell Electric Vehicles
GCI	Gasoline Compression Ignition

HCCI	Homogeneous charge compression ignition
ICE	Internal Combustion Engines
IMEP	Indicated mean effective pressure
LTC	Low Temperature Combustion
PPRR	Peak Pressure Rise Rate
RoHR	Rate of Heat Release
RoHRD	Rate of Heat Release derivative
RPM	Revolution per minute
SOC	Start of Combustion angle
SOI Pilot	Start of Injection angle for Pilot injection
SOI Pre	Start of Injection angle for Pre injection
SOC ACC	Start of Combustion angle from accelerometer sensor
SOC ROHR	Start of Combustion angle from in-cylinder pressure sensor
TDC	Top Dead Center angle
γ	Adiabatic Index

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