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Comparison of Knock Indexes Based on CFD Analysis

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Abstract

Recent trends in gasoline engines, such as downsizing, downspeeding and the increase of the compression ratio make knocking combustions a serious limiting factor for engine performance.

A detailed analysis of knocking events can help improving the engine performance and diagnostic strategies. An effective way is to use advanced 3D Computational Fluid Dynamics (CFD) simulation for the analysis and prediction of the combustion process. The effects of Cycle to Cycle Variation (CCV) on knocking combustions are taken into account, maintaining a RANS (Reynolds Averaged Navier-Stokes) CFD approach, while representing a complex running condition, where knock intensity changes from cycle to cycle. The focus of the numerical methodology is the statistical evaluation of the local air-to-fuel and turbulence distribution at the spark plugs and their correlation with the variability of the initial stages of combustion.

CFD simulations have been used to reproduce knock effect on the cylinder pressure trace. For this purpose, the CFD model has been validated, proving its ability to predict the combustion evolution with respect to SA variations, from non-knocking up to heavy knocking conditions.

The pressure traces simulated by the CFD model are then used to evaluate cylinder pressure-based knock indexes. Since the model is able to output other knock intensity tracers, such as the mass of fuel burned in knocking mode, or the local heat transferred to the piston, knock indexes based on the cylinder pressure trace can be related to parameters only available in a simulation environment, that are likely to be more representative of the actual knock intensity, with respect to the local pressure trace for the sensor position. The possibility of simulating hundredths of engine cycle allows using the methodology to compare the indexes quality (correlation with actual knock intensity) on a statistical base.

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Keywords: Knock, Simulation, CFD, Sensor position

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1. Introduction

The knock phenomenon is not entirely deterministic: knock tendency is obviously related to compression ratio, spark advance, inlet temperature, etc., but a stochastic component is also present, leading to both knocking and non-knocking engine cycles for the same running condition [1].

Both the deterministic and stochastic elements must be taken into account by the simulation setup, in order to be representative of measurements based on the cylinder pressure signal: knock intensity evaluations are often based on the statistical analysis of many engine cycles, thus a multi-cycle simulation is mandatory to fulfill the objective of the present analysis.

The modeling of Cycle-to-Cycle Variation plays a crucial role in the simulation of combustion on a multi-cycle basis: the imposition of a change in the combustion evolution allows simulating CCV effects, but it has to be based on actual engine behavior, in order for the model to be predictive. Different approaches are possible for the generation of CCV: from simple models based on the Monte Carlo approach [2], to two-zone thermodynamic models combined with flame propagation sub-models [3], from 1D/0D simulation methodologies fed by experimental and numerical (3D) data for the perturbation [4], to analysis based on the Large Eddy Simulations (LES) [5-8]. Other interesting contributions can be found in [9-12].

In a previous work [13], the authors simulated the effects of changes in mixture composition on CCV. The relationship between the variability of IMEP and the fluctuation of local mixture air index (lambda) was clearly showed in the work of Ikeda et al. [14].

In [15, 16] the authors used a RANS methodology for the evaluation of the combustion instabilities based on the mixture composition at the spark plug, simulating the combustion characteristics, including the knock tendency. In [16] the simulation results are used to compare knocking combustions measurable effects (e.g., local pressure at the transducer) with other factors, representative of the phenomena actually taking place in the combustion chamber.

A selection of significant knock intensity tracers both in terms of cause (instantaneous fuel burning rate) and effects (local pressure and heat transfer on the piston surface) has been carried out in order to assess the cylinder pressure signal sensitivity to the phenomenon. Three different knock indexes based on the cylinder pressure signal have then been compared to the knock intensity tracers.

As suggested in [16], based on analysis of the literature concerning knock damages, several outputs of the CFD simulation can be associated to different damage mechanisms, and then used as a reference for knock intensity. Local pressure on the piston surface, local heat flux transferred to the piston, mass of fuel burned in knocking mode and instantaneous burning rate are available outputs of the CFD simulation that can be considered representative of actual knock intensity. The three knock intensity indexes use only the information pertaining to the (simulated) cylinder pressure trace: their comparison with damages-related outputs of the simulation allows assessing how sensitive they are to the phenomenon that has to be detected.

2. Experimental Setup

The engine under analysis is a Ducati-high performance unit, whose characteristics and running conditions are reported in Tab. 1. In order to increase the volumetric efficiency at high engine speed, a wide intake valve opening duration has been chosen, which makes the actual compression ratio lower than the geometric value. However, due to the ram and pressure waves tuning effects knocking combustions can happen even at high engine speed.

The engine was tested on the test bench equipped with cylinder pressure transducers. The pressure traces of 300 engine cycles have been recorded for each engine operating point. A spark advance sweep has been carried out shifting the combustion phase (MFB50) from 7 deg ATDC to 23 deg ATDC: the sweep allows assessing the model ability to represent the combustion sensitivity to SA in terms of performance (IMEP), combustion phase (MFB50) and knock intensity (MAPO). Only the highest knock intensity condition has been analyzed for the correlation of pressure data referring to the transducer position and the piston surface.

The indicating parameters have been extracted by filtering the pressure signal with a butterworth zero-delay low pass filter at 2.5kHz for IMEP and a butterworth band-pass filter between 3 kHz and 40kHz for the high frequency parameters.

Table 1. engine characteristics.

Manufacturer, number of cylinders	Ducati, 2 cylinders
IVO	4°BTDC→58°ATDC
EVO	58°BBDC→7°ATDC
Bore [mm]	106
Stroke [mm]	67.9
Compression ratio	12.5
Operating point	WOT@8500 rpm
Lambda	0.83
Spark Advance	24→36°
MFB50	7°→23°

3. CFD Simulations

The simulation is based on a multi-step methodology for the correct reconstruction of mixture distribution in the chamber [17]. The open valve phase of the engine has been simulated by the 3D CFD FIREv2011 (AVL) code, where the overall physics involved in the injection process is evaluated and validated.
The combustion simulation (closed valve simulation) is executed by means of KIVA3D and all the main models implemented are deeply described in [18] and listed in Table 2

Table 2. KIVA Models used

Description	Model
Combustion	Extended Coherent Flamelet
Knock	Two Steps Tabulated Chemistry (based on Cantera Results)
Ignition	Lagrangian ignition model [19]
Thermal law at the wall	Modified Han and Reitz

An effective way to simulate the cycle by cycle variation of a spark ignition engine is based on a forced perturbation of the combustion evolution, with particular emphasis on the early kernel development. The methodology of perturbation used in the presented approach is not based on a simple relationship between the perturbation strength and the amplitude of results, but it is founded on the spatial characterization of the mixture and turbulence at the spark plug[15-16].

The flamelet combustion model has been tuned in order to correctly represent the actual average behavior. Due to the cycle by cycle variability of SI engines all the pressure traces of the experimental data are widely scattered, representing very different combustion characteristics: as explained in [19], the cycles representing the average behavior are those showing combustion phase (MFB50) similar to the average.

4. Heat Exchange Model

In a previous work [20] the authors showed how a knocking event can cause a considerable increase of heat exchange with the walls. The higher thermal load can be closely related to a damage risk estimation.

To quantify the knock severity, the authors proposed to use the subtraction between the Net Cumulative Heat Release of cycles selected respectively by higher and lower pressure oscillations (MAPO). This difference should represent the increase of heat flux related to waves oscillating in the combustion chamber due to detonation. The index was created by a selective choice of pressure traces with the same combustion phase (MFB50), because of its influence on heat flux.

In the actual work a new knock index based on the estimation of wall heat is presented. The index should not be dependent on the high frequency content of the pressure trace, but it should ground on a direct evaluation of the wall heat flux. One of the most used model for the prediction of engine wall heat flux is the Woschni model [21]. It makes an estimation of the convection coefficient 'h' based on pressure, velocity and temperature inside the combustion chamber. The expression of eq. (4) comes from a direct correlation of Nusselt and Reynolds numbers.

$$h = C_1 \cdot p^{0.8} \cdot u^{0.8} \cdot D^{-0.2} \cdot T^{-0.53} \tag{4}$$

where, C_1 is a constant, p is the cylinder pressure, D is the cylinder Bore and T is the Temperature in the chamber.

One of the most critical issue of eq. (4) is the estimation of convective velocity 'u'. Eq. (5) is the expression proposed by Woschni:

$$u = C_2 u_p + C_3 \frac{V_s T_r}{p_r V_r}(p - p_0) \tag{5}$$

where C_2=6.18 during scavenging and C_2=2.28 during compression, combustion and expansion, C_3=0 during scavenging and compression and $C_3=3.24\cdot 10^{-3}$ during combustion and expansion, u_p is the average piston speed, Vs the swept volume, T_r, p_r and V_r the temperature, cylinder pressure and cylinder volume at a reference state, p_0 the cylinder pressure during motored operation.

The second term of eq (5) represents the increase of convective velocity at the wall because of the rapid expansion of the burned mixture. The Woschni model constants are calibrated by means of a direct comparison with results coming from KIVA 3D simulations. The target of calibration is the KIVA evolution of wall heat transfer in the chamber on a crank angle basis, with the constraints of correctly matching the final heat exchanged at EVO. Figure 1 shows the results for a cycle with low fuel mass involved in auto-ignition condition. The main trends of heat flux are well caught (blue line), but the peak of heat flux is underestimated. The wall heat model implemented in KIVA can be used as reference to validate new 0D models: it has a modified version of Han and Reitz model, calibrated in order to correctly represent the experimental pressure traces.

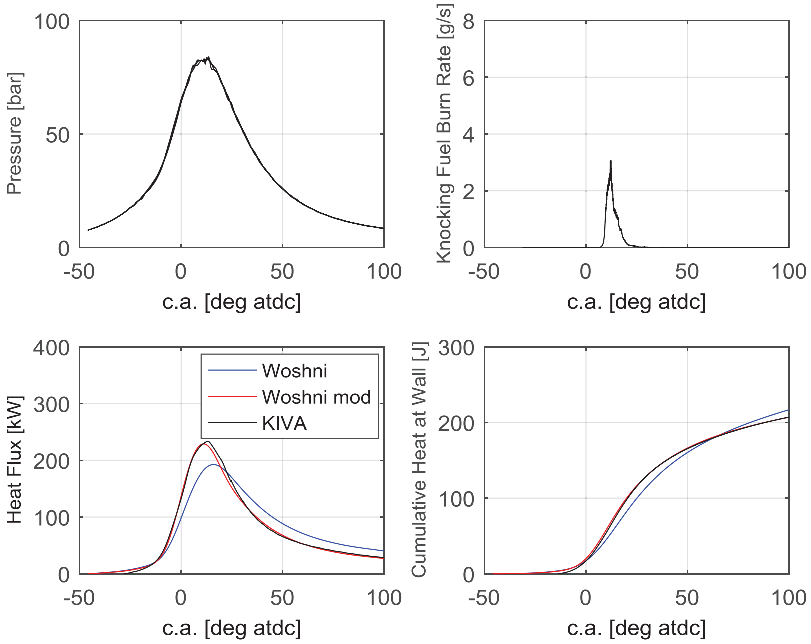

Figure 1: Pressure, fuel burning in auto-ignition mode, wall heat flux and cumulative heat to the wall for a light knocking cycle

In order to guarantee a better fitting of the 3D simulation results with the 0D model, the authors propose a modification of Woschni correlation. The velocity representative of the expansion of burned mass is no longer related to the difference of pressure between a regular cycle and a motored one, but is directly correlated to the velocity of the reaction rate. Eq. (6) show the modified definition of the convective velocity.

$$u = u_p \left(C_2 + C_3 \frac{D^3}{V_s} \frac{ROHR_{NET}}{Jmax/_{\Delta\vartheta}} \right) \tag{6}$$

Where, $ROHR_{NET}$ is the Net Rate of Heat Release, D is the bore, Jmax is the estimation of the maximum energy that can be burned in the chamber according to mixture composition, $\vartheta\Delta$ is the angular interval between Intake Valve Closing (IVC) and Exhaust Valve Opening (EVO).

In figure (1) the red line is the result of the wall heat model here presented (Woschni Mod, red) compared versus 3D KIVA simulation (black) and versus the original Woschni model (blue). It is possible to appreciate the good reconstruction of the evolution of the flux at the wall. The overall heat exchanged at IVC is perfectly in line with KIVA together with phase of the peak flux.

Figure (2) represents the scenario of a severe knocking cycle. The modified model well represents the evolution of heat flux up to the beginning of the abnormal combustion. This result is intrinsic in the definition of the model, because the increase of convective velocity related of pressure waves are filtered out by the low frequency content of the pressure trace. This takes to an underestimation of heat flux in case of knocking events. This behavior can be used for the definition of a knock index, sensitive to the heat flux underestimation caused by knocking combustions.

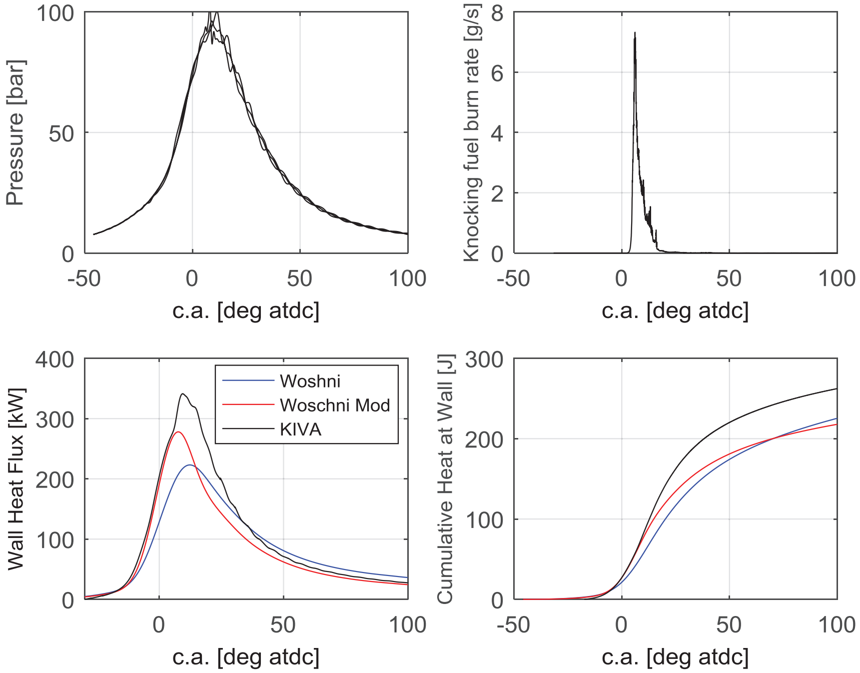

Figure 2: Pressure, fuel burning rate in auto-ignition mode, wall heat flux and cumulative Heat to the wall for a heavy knocking cycle.

5. CFD Model Output Analysis

The results of the CFD simulation have been used to assess the ability of different knock indexes to represent knock intensity. Several CFD simulation outputs can be used as reference knock intensity tracers, while knock indexes are evaluated based on the simulated cylinder pressure trace referring to the pressure sensor position. In the present work the Mass of Fuel burned in Knocking Mode (MFKM), the fuel Burning Rate in Knocking Mode (BRKM), the Local Heat transferred to the Walls (LHW), the Local Peak Heat Flux (LPHF) and the Local Maximum Amplitude of Pressure Oscillations (LMAPO) have been used as reference knock intensity tracers. The first two describe the phenomenon from the point of view of the combustion evolution: they inherently describe the global conditions in the chamber. The others describe the effects on the piston surface: the local parameters are evaluated as the maximum value of Heat, Flux and Pressure oscillations on the most stressed piston cell.

Knock indexes defined using the pressure trace are usually based on the high frequency content of the signal: the Mean Amplitude of the Pressure Oscillations (MAPO) and the Mean Absolute Value of the Pressure Oscillations (MAVPO) have been used for the analysis.

$$\boldsymbol{MAPO = max\left(\left|p_{fi}\right|\right)_{i=1}^{i=N}} \tag{7}$$

$$\boldsymbol{MAVPO = \frac{1}{N}\sum_{i=1}^{i=N}\left|p_{fi}\right|} \tag{8}$$

As regards the MAVPO, in order to increase its sensitivity, a dynamic window has been used: firstly, the sum of pressure samples is carried out on a fixed angular window, then, only the portion of the signal corresponding to the range 10%-90% of the sum is considered for the index definition. This approach allows rejecting non-significant portions of the pressure signal (e.g., before knock happens).

A third index has been introduced, based on the difference between the expected heat released by the combustion, the estimated heat transferred to the walls, based on the modified Woschni model, and the net heat release:

$$\boldsymbol{DQ = Q_{ch} - Q_{net} - Q_{wall}} \tag{9}$$

The total heat released by the combustion can be evaluated estimating the mass of air trapped in the cylinder and the combustion efficiency: for the cycles where knock does not occur, the modified Woschni model accurately estimates the heat transferred to the walls, as reported in Figure 1, thus ΔQ will have small values. For knocking cycles the model underestimates the heat transferred to the walls (Figure 2), thus ΔQ will increase accordingly.

MAPO and MAVPO are sensitive to the sensor position, thus three different sensor positions have been considered: position 1 corresponds to the spark plug location (center of the chamber), while position 2 and 3 are on the opposite side of the chambers, between intake and exhaust valves.

Figure 3 shows correlation plots between knock indexes based on the pressure trace analysis (DQ, MAPO, MAVPO) and two knock tracers available from the CFD simulation (MBKM, LMAPO): the first one (MBKM) is representative of the process on a global scale, while the second (LMAPO) describes the effect, on a local scale. It is evident that DQ is better correlated with MBKM, while MAPO and MAVPO are better correlated with LMAPO. It is also very important to notice that DQ is almost independent from the sensor position, while both MAVPO and MAPO strongly depend on the position. This is due to the fact that DQ is not influenced by the high frequency content of the signal: the non-homogeneities in the pressure chamber enhancing local effects are related to fast heat release, preventing an homogeneous pressure increase propagation within the cylinder.

The complete evaluation of the correlation between the three knock indexes with the five knock tracers is summarized in Table 3: it is evident how the index DQ is the only one showing a high correlation coefficient with the amount of fuel burned in knocking mode, with almost no influence of the sensor position on the results. The correlation coefficient is still high with the burning rate in knocking mode, while it decreases to low values as the knock intensity tracer assumes local significance. Indexes based on the high-frequency content of the cylinder pressure signal have high correlation with local phenomena: the correlation coefficient and the indexes absolute values, however, strongly depend on the sensor position, as Figure 3 shows.

The independence of the DQ index from the sensor position makes it suitable to set the threshold for other indexes: when this task cannot be based on experience (for example, when major changes are carried out on the engine, or when the sensor position changes), it can be set using DQ. For example, figure 3 shows that the threshold on MAPO could be placed in the range of 10 bar (corresponding to a value of 100J for DQ).

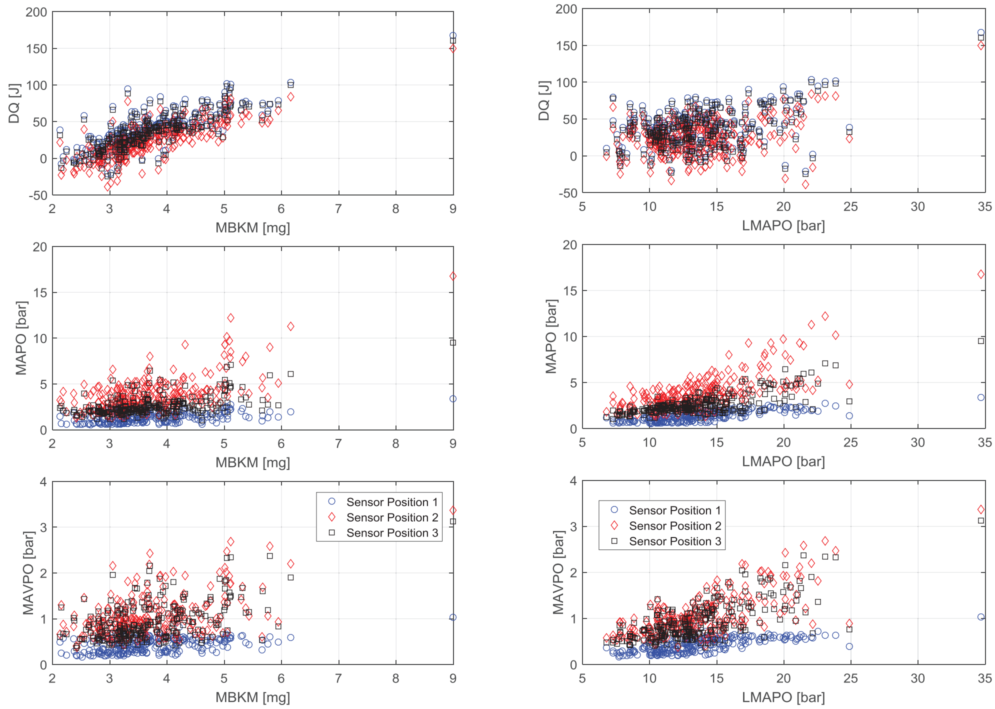

Figure 3: correlation plots for knock indexes (evaluated using three different sensor positions) with CFD simulation outputs

Table 3. Correlation Coefficients for DQ, MAPO, MAVPO

Index	Sensor Position	MFKM	BRKM	LHV	LPHF	LMAPO
DQ	1	0.792	0.760	0.489	0.534	0.393
	2	0.797	0.732	0.448	0.495	0.341
	3	0.793	0.764	0.497	0.548	0.402
MAPO	1	0.397	0.751	0.758	0.858	0.733
	2	0.629	0.844	0.672	0.730	0.731
	3	0.537	0.749	0.666	0.713	0.738
MAVPO	1	0.412	0.751	0.773	0.879	0.686
	2	0.475	0.702	0.637	0.683	0.725
	3	0.500	0.727	0.640	0.716	0.700

6. Conclusions

The paper presents a correlation analysis between knock Indexes based on the cylinder pressure trace, and knock intensity tracers evaluated by means of a CFD simulation. The pressure traces are also simulated by the CFD model, and they refer to different sensor positions. The tracers are representative of both global and local facets of the knocking combustion. An index (DQ) based on the increase of the heat transferred to the walls caused by the knocking combustion has been introduced: the index is grounded on a modified Woschni model, that shows very good agreement with the CFD simulation results, when knock does not occur. The index values are independent of the sensor position, and show good correlation with global knock intensity tracers, but it is not well correlated with other tracers: the use of this knock index can help improving the robustness of knock diagnosis carried out with indexes using the high-frequency content of the cylinder pressure signal.

References

[1] Heywood J. B. “Internal combustion engine fundamentals”. New York: McGraw-Hill; 1988.

[2] Kim, K. and Ghandhi, J., “A Simple Model of Cyclic Variation,” SAE Technical Paper 2012-32-0003, 2012, doi:10.4271/2012-32-0003.

[3] Dai, W., Trigui, N., and Lu, Y., “Modeling of Cyclic Variations in Spark-Ignition Engines,” SAE Technical Paper 2000-012036, 2000, doi:10.4271/2000-01-2036.

[4] Vitek, O., Macek, J., Poetsch, C., and Tatschl, R., “Modeling Cycle-to-Cycle Variations in 0-D/1-D Simulation by Means of Combustion Model Parameter Perturbations based on Statistics of Cycle-Resolved Data”, SAE Int. J. Engines 6(2):1075-1098, 2013, doi:10.4271/2013-01-1314.

[5] Tatschl, R., Bogensperger, M., Pavlovic, Z., Priesching, P. et al., “LES Simulation of Flame Propagation in a Direct- Injection SI-Engine to Identify the Causes of Cycle-to- Cycle Combustion Variations,” SAE Technical Paper 201301-1084, 2013, doi:10.4271/2013-01-1084.

[6] Vitek, O., Macek, J., Tatschl, R., Pavlovic, Z. et al., “LES Simulation of Direct Injection SI-Engine In-Cylinder Flow,” SAE Technical Paper 2012-01-0138, 2012, doi:10.4271/2012-01-0138.

[7] Fontanesi, S., Paltrinieri, S., Tiberi, A., and D'Adamo, A., “LES Multi-cycle Analysis of a High Performance GDI Engine,” SAE Technical Paper 2013-01-1080, 2013, doi:10.4271/2013-01-1080.

[8] Vermorel, O., Richard, S., Colin, O., Angelberger, C., Benkenida, A., and Veynante, D., 2009. “Towards the understanding of cyclic variability in a spark ignited engine using multi-cycle les”. Combustion and Flame, 156(8), pp. 1525-1541.

[9] Chakravarthy, K., Wagner, R., and Daw, S., “On the Use of Thermodynamic Modeling for Predicting Cycle-to-Cycle Variations in a SI Engine under Lean Conditions,” SAE Technical Paper 2005-01-3802, 2005, doi:10.4271/200501-3802.

[10] Mehrani, P. and Watson, H., “Modeling the Effects of Mixture Composition on Cyclic Variability,” SAE Technical Paper 2007-01-0672, 2007, doi:10.4271/2007-01-0672.

[11] Czarnigowski, J., “A Simple Method of Analysis and Modeling of Cycle-to-Cycle Variation of Engine Work - the Example of Indicated Pressure,” SAE Technical Paper 2007-01-2079, 2007, doi:10.4271/2007-01-2079.

[12] Choi, S., Lim, J., Ki, M., Min, K. et al., “Analysis of Cyclic Variation and the Effect of Fuel Stratification on Combustion Stability in a Port Fuel Injection (PFI) CAI Engine,” SAE Technical Paper 2009-01-0670, 2009, doi:10.4271/200901-0670.

[13] Forte, C., Bianchi, G. M., Corti, E., and Fantoni, S., 2008. “Combined experimental and numerical analysis of the influence of air-to-fuel ratio on cyclic variation of high performance engines”. ASME ICEF 2008-1668.

[14] Ikeda, Y., Nishiyama, A., Kim, S., Takeuchi, A., Wilnklhofer, E., and Baritaud, T., 2006. “Cyclic variation of local a/f (lambda) and mixture quality in si engine using local cheminuminescence”. 7th International Symposium in Internal Combustion Diagnostics.

[15] Forte, C., Corti, E., Bianchi, G., Falfari, S. et al., "A RANS CFD 3D Methodology for the Evaluation of the Effects of Cycle By Cycle Variation on Knock Tendency of a High Performance Spark Ignition Engine," SAE Technical Paper 2014-01-1223, 2014, doi:10.4271/2014-01-1223.

[16] Corti, E., Forte, C., Bianchi, G., and Moro, D., "Relating Knocking Combustions Effects to Measurable Data," SAE Int. J. Engines 8(5):2133-2144, 2015, doi:10.4271/2015-24-2429.

[17] Forte, C., Bianchi, G. M., and Corti, E.,2012, “Multicycle simulation of the mixture formation process of a PFI gasoline engine”, SAE Technical Paper 2011-01-2463, DOI: 10.4271/2011-01-2463

[18] Forte, C., Corti, E., and Bianchi, G. M., 2010. “Combined experimental and numerical analysis of knock in spark ignition engines”. ASME ICEF09-14102, pp. 473-488.

[19] Forte, C., Bianchi, G. M., and Corti, E., 2010. “Validation of a lagrangian ignition model in si engine simulations”. ASME ICEF2010-35159, pp. 859-871.

[20] Corti, E., Forte, C.,2010, “Combination of in-cylinder pressure signal analysis and CFD simulation for knock detection purposes”, SAE International Journal of Engines Volume 2, Issue 2, 2010, Pages 368-380, DOI: 10.4271/2009-24-0019

[21] Woschni, G., “A Universally Applicable Equation for the Instantaneous Heat Transfer Coefficient in the Internal Combustion Engine,” SAE Technical Paper 670931, 1967, doi:10.4271/670931.

[22] Cavina N., Po G., Poggio L., "Ion Current Based Spark Advance Management for Maximum Torque Production and Knock Control". In: Proceedings of the 8th Biennial ASME Conference on Engineering Systems Design and Analysis. Torino, Italy, July 4-7 2006, NEW YORK: ASME International, 2006, ISBN: 0-7918-3779-3.