A Comparison Between Combustion Phase Indicators for Optimal Spark Timing

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The closed-loop control of internal combustion engine spark timing may be accomplished by means of a combustion phase indicator, i.e., a parameter, derived from in-cylinder pressure analysis, whose variation is mainly referable to combustion phase shift and assumes a fixed reference value under optimal spark timing operation. The aim of the present work is a comparison between different combustion phase indicators, focusing on the performance attainable by a feedback spark timing control, which uses the indicator as pilot variable. An extensive experimental investigation has been carried out, verifying the relationship between indicators' optimal values and the main engine running parameters: engine speed, load, and mixture strength. Moreover, assessment on the effect of the most common pressure measurement problems (which are mainly related to pressure referencing, sampling resolution, top dead center determination, and cycle-by-cycle variations) on the indicators' values and on the performance attainable by the spark timing control is included. The results of the comparison point out two indicators as the most suitable: the location of pressure peak and the location of maximum heat release rate. The latter, not available in literature, has been introduced by the author as an alternative to the 50% of mass fraction burned. [DOI: 10.1115/1.2939012]

Introduction

Modern spark ignition engines must meet both rising fuel cost and CO_2 reduction policy by increasing as much as possible energy conversion efficiency; as is known, one of the key parameters for engine performance is spark advance, which is normally controlled in open loop by means of tables stored in the ECU. These tables are drawn up during the ECU calibration process, trying to obtain the maximum output (maximum brake torque, MBT) on the engine test bed for different speed and load conditions; some other tables account for spark advance change due to variation in air and coolant temperature, and absolute pressure. The ECU calibration becomes therefore a time consuming phase, which, however, does not guarantee to obtain always the best performances for the whole engine life: The stored tables, in fact, cannot consider all the possible operative conditions, and, moreover, optimal spark timing can also strongly depend on air humidity, engine wear, and fuel properties [1,2]; for these reasons, a closed-loop control on spark advance, capable to maximize the engine output for every engine operative condition, is preferable; it can also be employed to realize a cost effective calibration process, quickly reaching the best spark timing value. Many techniques are proposed in literature for spark advance feedback control, and most of them make use of the in-cylinder pressure history to obtain the feedback variable. Sometimes, the cylinder pressure is reconstructed by means of analysis performed on another variable, for example, engine speed fluctuation or block vibration, but as far as the spark timing control is concerned, the cylinder pressure analysis remains a fundamental step. The most of these techniques rest on a single parameter derived from in-cylinder pressure, which almost assumes a fixed value under MBT timing: Such parameters are called combustion phase indicators, since their variation is mainly referable to combustion phase shift. The work here presented aims at making a comparison between five combustion phase indicators, to evaluate their qualities and weakness as pilot variables for MBT spark timing control.

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Combustion Phase Indicators

This section gives a general outline of the five combustion phase indicators here taken into consideration:

(1) location of pressure peak (LPP)
(2) location of maximum pressure rise (LMPR)
(3) location of 50% of mass fraction burned (MFB50)
(4) location of maximum heat release rate (LMHR)
(5) value of relative pressure ratio 10 crank angle degree ATDC (PRM10)

Location of Pressure Peak (LPP). According to this criterion, spark advance is set to its best value when the pressure peak is found to be 14–16 crank angle degrees (CAD) after top dead center (ATDC), apart from engine speed and load, and from other variables. This is one of the most encountered combustion phase indicators in literature [1,3–7], and requires pressure sampling at least for 30 deg ATDC (see Fig. 1). The set point value is 14–16 crank angle degrees ATDC, and, as for all the other indicators, has been determined empirically and has not yet been theoretically explained.

Location of Maximum Pressure Rise (LMPR). Cook et al. in 1947 [8] showed that under optimal spark advance, the maximum pressure rise occurs about 3 deg ATDC. Rarely encountered in literature among the combustion phase indicators, its evaluation requires pressure sampling in the interval ± 20 deg around top dead center (TDC).

Location of 50% of Mass Fraction Burned (MFB50). It is well known to internal combustion engine researchers that in-cylinder pressure allows the evaluation of the fuel MFB [9–14]: This can be accomplished following the procedure proposed by Rassweiler and Withrow, simple yet reliable, or by means of thermodynamic analysis, which instead requires to know wall heat transfer law. According to this criterion, spark timing is set to the best value when MFB reaches 50% about 9 deg ATDC [15,16].

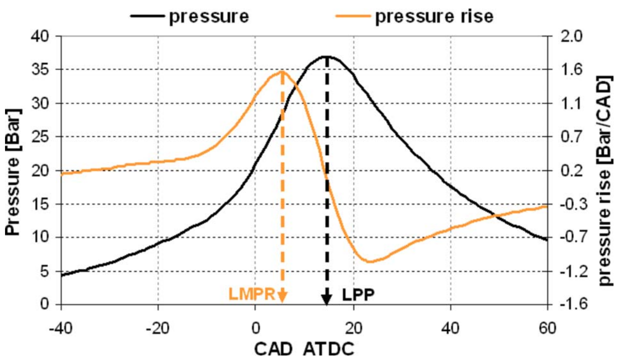

Fig. 1 In-cylinder pressure and its derivative, 2500 rpm—IMEP 6 bar (LPP and LMPR are shown)

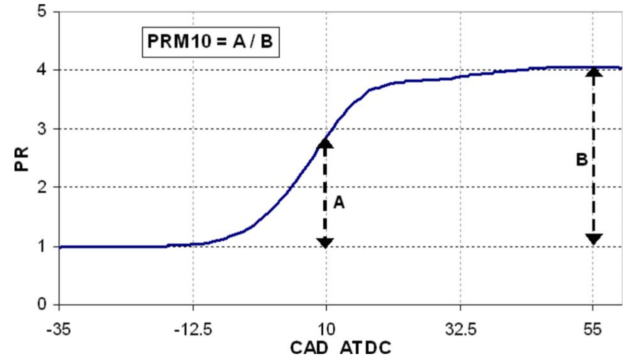

Fig. 3 PR as function of CAD: the indicator PRM10 is the ratio between A (PR10) and B (PR55)

Compared to LPP and LMPR, this indicator requires a greater amount of calculus and data to sample: In-cylinder pressure must be acquired during almost the whole compression and expansion strokes. Moreover, unlike LPP and LMPR, absolute pressure values are needed for a correct MFB50 evaluation.

Location of Maximum Heat Release Rate (LMHR). This parameter has not been found in literature among the combustion phase indicators; Pipitone and Beccari, who introduced this indicator in a previous work [17], considered it a valid alternative to MFB50, since it presents similar features, with a lower sensitivity to pressure measurement errors. If the MFB is expressed by the Wiebe function,

$$\text{MFB} = 1 - e^{-aX^{(m+1)}} \tag{1}$$

where X represents the fractional combustion angle, and a and m are constants, the position X_{MHR} at which the MHR rate occurs can be evaluated setting the second derivative to zero; this gives

$$X_{\text{MHR}} = a^{-1/(m+1)} m^{1/(m+1)} (m+1)^{-1/(m+1)} \tag{2}$$

Now, setting $X = X_{\text{MHR}}$ into Eq. (1), the MFB at the MHR rate moment MFB_{MHR} is found as follows:

$$\text{MFB}_{\text{MHR}} = 1 - e^{-m/(m+1)} \tag{3}$$

As can be seen, it exclusively depends on the constant m, which both literature and experimental results showed to be about 2; this gives $\text{MFB}_{\text{MHR}} = 0.49$.

It is so explained the reason why LMHR and MFB50 share nearly the same values (see Fig. 2).

The author of the present work introduced the parameter LMHR for a comparison with MFB50: its evaluation does not require any extra calculus effort, since MFB is normally obtained by integration, and it is less prone to errors due to bad pressure referencing or measurement. Naturally, its set point value should be near to that of MFB50, i.e., about 9 deg ATDC with optimal spark timing.

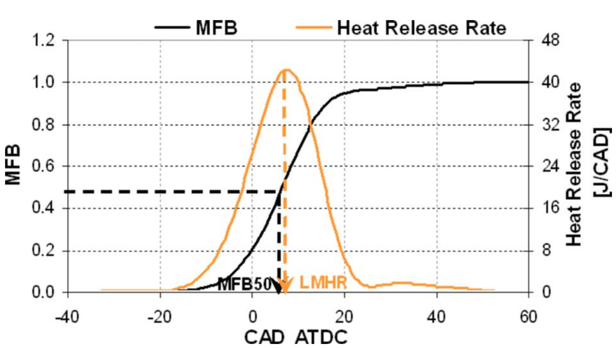

Fig. 2 MFB and heat release rate, 2500 rpm, 6 bar BMEP (MFB50 and LMHR are shown)

Value of Relative Pressure Ratio 10 Crank Angle Degree ATDC (PRM10). Also this indicator was proposed [18] as an alternative to the MFB50; Matekunas et al., in fact, defined it as

$$\text{PRM10} = \frac{\text{PR}(10) - 1}{\text{PR}(55) - 1} \tag{4}$$

being $\text{PR}(\theta)$ the pressure ratio between the measured *fired pressure* and the evaluated *motored pressure* θ deg ATDC (generally PR values stay between 1 and 4, see Fig. 3).

Under MBT spark timing, the relative pressure ratio PRM10 should assume the value 0.55, quite similar to MFB50, which should reach its 50% around 9 deg ATDC. The ratio between *measured* and *motored pressure* (the latter calculated using a polytropic law) in effect follows the concept proposed by Rassweiler and Withrow, i.e., the heat released by combustion is closely related to the pressure rise besides the compression effect. The advantage in the use of the PRM10 instead of MFB50 theoretically relies on the easier calculation and fewer data to sample: four points should be enough, two taken during compression stroke for polytropic index evaluation and the other two taken 10 and 55 CAD ATDC. As a matter of fact, measurement noise and signal referencing (absolute pressure values are needed) may require the pressure sampling for a great part of the compression stroke to correctly evaluate the expansion polytropic coefficient [19,20]. Moreover, since the expansion polytropic index is often different from the compression one, both of them should be used: This requires a complete pressure sampling during expansion stroke, and makes PRM almost equal to MFB. Unlike all the other indicators, PRM10 is a dimensionless number between 0 and 1, and decreases with a forward shifting of the combustion.

It could be argued that the indicated mean effective pressure (IMEP) could be the most valid parameter for optimal spark timing control, since it represents the total amount of energy received by the piston during a whole cycle. The author compared the spark timing control achievable using IMEP rather than torque (which means BMEP) and found great differences, as showed in Fig. 4 and Table 1. It can be clearly seen that the maximum IMEP spark advance may be quite different from the MBT spark timing. This is due to mechanical efficiency, which can vary strongly with IMEP and has a great influence on the real engine output, that is, BMEP. Using the experimental data collected for this work, the performance differences due to IMEP driven spark timing have been calculated for each operative condition: The maximum differences in terms of spark advance and performance loss are reported in Table 1.

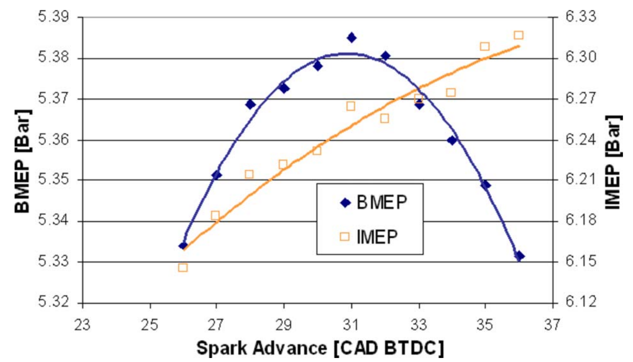

Fig. 4 BMEP and IMEP as a function of spark advance 3500 rpm, $\lambda=0.95$

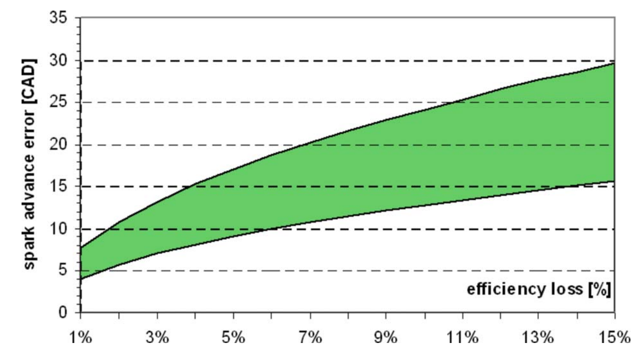

Fig. 5 Percentage efficiency loss due to bad spark advance setting (1500 to 3500 rpm, 3 bar and 6 bar BMEP)

Experimental Investigation

The comparison between the five combustion phase indicators required the acquisition of pressure cycles with varying spark advance for different operative conditions, so as to evaluate their capacity to pilot the spark advance control and to assess any possible relationship between indicators and the fundamental engine parameters. The experimental tests have been carried out on an internal combustion engine test bench using a Renault four cylinder in-line 1598 cm^3 16 V multipoint spark ignition engine connected to a Schenck eddy current dynamometer managed by means of a Borghi & Saveri control module DCU2000. The engine was equipped with an AVL GU13Z-24 piezoelectric pressure transducer, flush mounted in the combustion chamber by means of its spark plug adaptor ZF42, and a 360 pulse per revolution optical encoder was used to clock the analog acquisition with a resolution of 1 crank angle degree. The data were collected through a National Instrument 6062 DAQ card, a 12 bit resolution data acquisition board with 500 kHz maximum sampling frequency, using the LABVIEW software.

As mentioned before, absolute pressure values are necessary for a correct evaluation of MFB and PRM10 (LMHR, as shown further, is almost insensitive to pressure bias errors); this required the use of a referencing procedure of the uncooled pressure transducer signal. The two most suitable referencing techniques are [19,20] the manifold absolute pressure (MAP) based and the polytropic index based. The first method assumes that mean in-cylinder pressure around the inlet stroke BDC is equal to manifold absolute pressure: this requires the use of a MAP sensor, which is commonly integrated in modern spark ignition engine management system. The second method instead forces the compression polytropic index to a fixed value, which should lie between 1.28 and 1.32. In the tests performed, in-cylinder pressure was referenced by means of the manifold absolute pressure measured by a piezoresistive sensor; assessment on the influence of the referencing technique is, however, reported below.

To remove unwanted noise from the pressure signal, a fourth order Butterworth low-pass filter with zero phase shift (this is an essential prerequisite) and cutting frequency set to 1/9 of the sampling frequency was used, while cycle-by-cycle variations, which strongly affect indicators' measurement, were overcome computing an averaged pressure cycle obtained from a matrix of 50 consecutive pressure cycles recorded at fixed spark advance, engine speed, load, and air-to-fuel ratio (A/F). Spark timing was then varied around the MBT value by means of a Walbro TDD computer controlled ECU for every engine operative condition. The tests were performed with engine speed ranging from 1500 rpm to 3500 rpm, while engine loads were kept to about 3 bar and 6 bar BMEP, so as to evaluate load dependences without causing knocking to occur. Moreover, to check for any mixture strength dependence, the engine was fed with different A/F ratios, setting lambda to 0.88, 0.95, 1.00, 1.05, and 1.10.

The test performed permitted first of all a better understanding of the efficiency loss due to a bad spark timing management: the graph in Fig. 5, traced by means of all the experimental data acquired, shows that a 1% loss can be caused by a spark advance error of 4 deg, while a 10 deg error can cause up to a 6% loss. These results can help us to assess the allowable spark advance error with respect to optimal value: accepting, for example, a 0.2% loss in torque, extrapolation from the lower bound in Fig. 5 shows that spark advance should remain in the range of ± 1.8 deg from the optimal value.

The typical result of one complete spark sweep test with constant speed, load, and A/F ratio is represented in Fig. 6: here, engine torque and combustion phase indicators are plotted against spark advance. Two immediate simple observations can be drawn: engine torque exhibits a square-law dependence on spark advance (a good second order polynomial regression was confirmed by every test), while all the indicators change linearly with spark advance (a narrow linear correlation was found for every operative conditions), which is a desirable feature for the pilot variable of a feedback control. Table 2 resumes both the mean slope and the mean intercept values found for each indicator, together with their coefficient of variation (COV) (i.e., ratio between standard deviation and mean value). As is shown, MFB50 and LMHR revealed to be more sensitive to spark advance change than LMPR

Table 1 Performance loss due to maximum IMEP spark timing

	Maximum differences
Spark advance	25 deg
BMEP loss	0.87 bar
BMEP % loss	16.8%

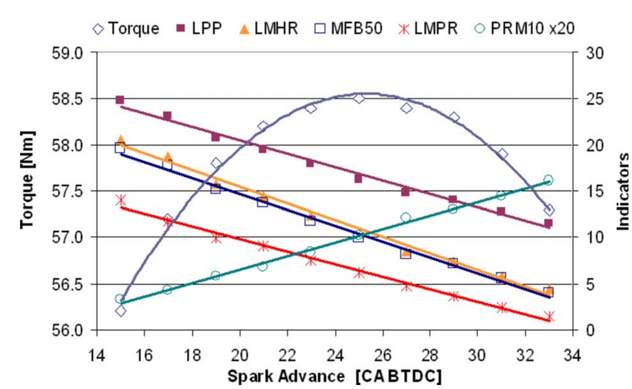

Fig. 6 Engine torque and combustion phase indicators as a function of spark timing (1500 rpm, $\lambda=1.1$)

Table 2 Indicators' slope and intercept (mean values)

	Slope		Intercept	
	Mean	COV (%)	Mean	COV (%)
LMPR	−0.662	21.3	23.14	13.4
LPP	−0.725	15.6	35.87	7.5
PRM10	0.0387	21.7	−0.535	26.0
MFB50	−0.905	11.4	34.51	11.3
LMHR	−0.920	12.4	35.26	11.2

and LPP. Naturally, from the point of view of a feedback control, a higher sensitiveness of the pilot variable to the controlled variable is desirable, so as to obtain a fast response. It is worthwhile to mention that the linear regression coefficients in Table 2 are mean values evaluated over all the tests, with a certain dispersion, as pointed out by the COV. However, even considering every single test, the above mentioned relation between the slope coefficients remains true. These linear regression coefficients can also be used to model the indicators' behavior as function of spark advance in the feedback controller development. As mentioned above, the PRM10 is the only indicator that exhibits a positive slope with respect to spark advance. The spark advance for MBT (for example, 25 CAD BTDC in Fig. 6) was then assessed to find the corresponding optimal value for each of the indicators. This procedure was followed for every operative condition, thus obtaining indicators' mean optimal values and their variation range (i.e., the difference between the maximum and the minimum value encountered): In Table 3, the overall results are resumed together with those obtained with stoichiometric mixture.

The ideal pilot variable of a feedback spark timing control system should depend exclusively on spark advance; for this reason, the author verified any possible correlation between each indicator optimal value and the most important running parameters, such as engine speed, load, and mixture strength. The graphs in Fig. 7 show the measured optimal values for each of the indicators with varying engine speed, two load conditions, and stoichiometric mixture: As can be seen, and confirmed by closer examinations, engine speed has a certain influence on every indicator in the higher load case, while for the lower load case a clear relationship with engine speed can be found only for LMPR and PRM10; the latter, moreover, is the only one that showed a quadratic dependence.

Assessment on the effect of engine load shows a feeble influence on the indicators' optimal values; the indicator, which exhibits the highest dependence from engine load, is LMPR, as after all is pointed out by the graphs of Fig. 7: Here, a sort of separation occurs between the medium and the low load points. A negligible influence was found on the other indicators, which can be then considered independent of engine load.

The data recorded at different A/F permitted also to evaluate the influence of mixture strength on the combustion phase indicators: As pointed out by the left graphs in Fig. 8, all of them showed a certain dependence on A/F at low engine speed and medium load; as can be seen, in these operative conditions, all the angle based indicators (LPP, LMPR, MFB50, and LMHR) increase with increasing A/F up to stoichiometric mixture, then start decreasing. The PRM10, instead, due to its definition (see Eq. (4)), showed a reverse behavior. At the lower loads or higher engine speed, the dependence on mixture composition almost disappear, as shown in the right graphs of Fig. 8. It must be noted, however, that mixture composition changes have a negligible effect on the indicators' set point values, as attested by the results in Table 3: In fact, the variation ranges and the optimal values obtained at stoichiometric mixture do not differ significantly from those obtained considering also the test performed with different A/F values. Therefore, mixture strength can be considered to have no importance for a feedback spark timing control driven by combustion phase indicators.

Some differences arise from the comparison of the range of variation of Table 3: LPP values moved in a 3.6 deg wide band, i.e., remained in the range of ± 1.8 deg from the mean optimal value of 14.7; MFB50, LMHR, and LMPR instead were characterized by a wider dispersion around the mean optimal value (about ± 2.5 deg). Such a simple comparison cannot be made with PRM10, since it is not expressed in degrees. The real effect of the dispersion range, however, should be evaluated on the basis of the spark advance errors it induce or rather on the efficiency loss it can cause. In fact, if spark advance is controlled so as to set the indicator's value to its set point while for a particular operative condition the best combustion phase requires instead to set the indicator's value at the edge of the variation range, there will be a certain spark advance error with respect to optimal condition, which, in turn, will cause a loss in engine efficiency. To quantify this maximum combustion efficiency loss, the author calculated the spark advance errors using the narrow linear correlations found between each indicator and the spark timing for all the operative conditions tested, supposing to run the engine with maximum indicator's error, while the quadratic correlation between spark timing and torque permitted to calculate the efficiency loss related to each spark advance error: It was then found (see Fig. 9) that LMPR could cause a loss of about 5%, with a spark advance error of more than 8 deg with respect to the MBT condition. PRM10 resulted to cause a lower maximum efficiency loss (around 1.5%), with a spark advance error of 5 deg, while LPP, MFB50, and LMHR proved the best performances with a maximum spark advance error of 4 deg and an efficiency loss of about 1% in the worst condition.

Naturally, the difference between the indicator's optimal value and reference value is maximum only in a few cases, while in all the other cases the indicator's optimal values lie in between the variation band; therefore, for each of the operative condition tested, the efficiency loss due to the spark timing error that a feedback control would cause when driven by indicators' set point values has also been calculated. The results, represented in Fig. 10, show that LMPR would cause the highest spark timing error (up to 8 deg) with an efficiency loss of 1.1%, while the use of the other indicators would allow remaining in the range of 3.5 deg from optimal spark timing, causing a torque loss always under 0.3%.

Table 3 Indicators', optimal values and dispersion range

	LMPR	LPP	PRM10	MFB50	LMHR
			Stoichiometric mixture values		
Optimal value	4.1	14.7	0.58	8.0	8.2
Variation range	±2.4	±1.7	±0.11	±2.3	±2.3
			Global values		
Optimal value	4.0	14.7	0.58	7.9	8.2
Variation range	±2.6	±1.8	±0.12	±2.5	±2.5

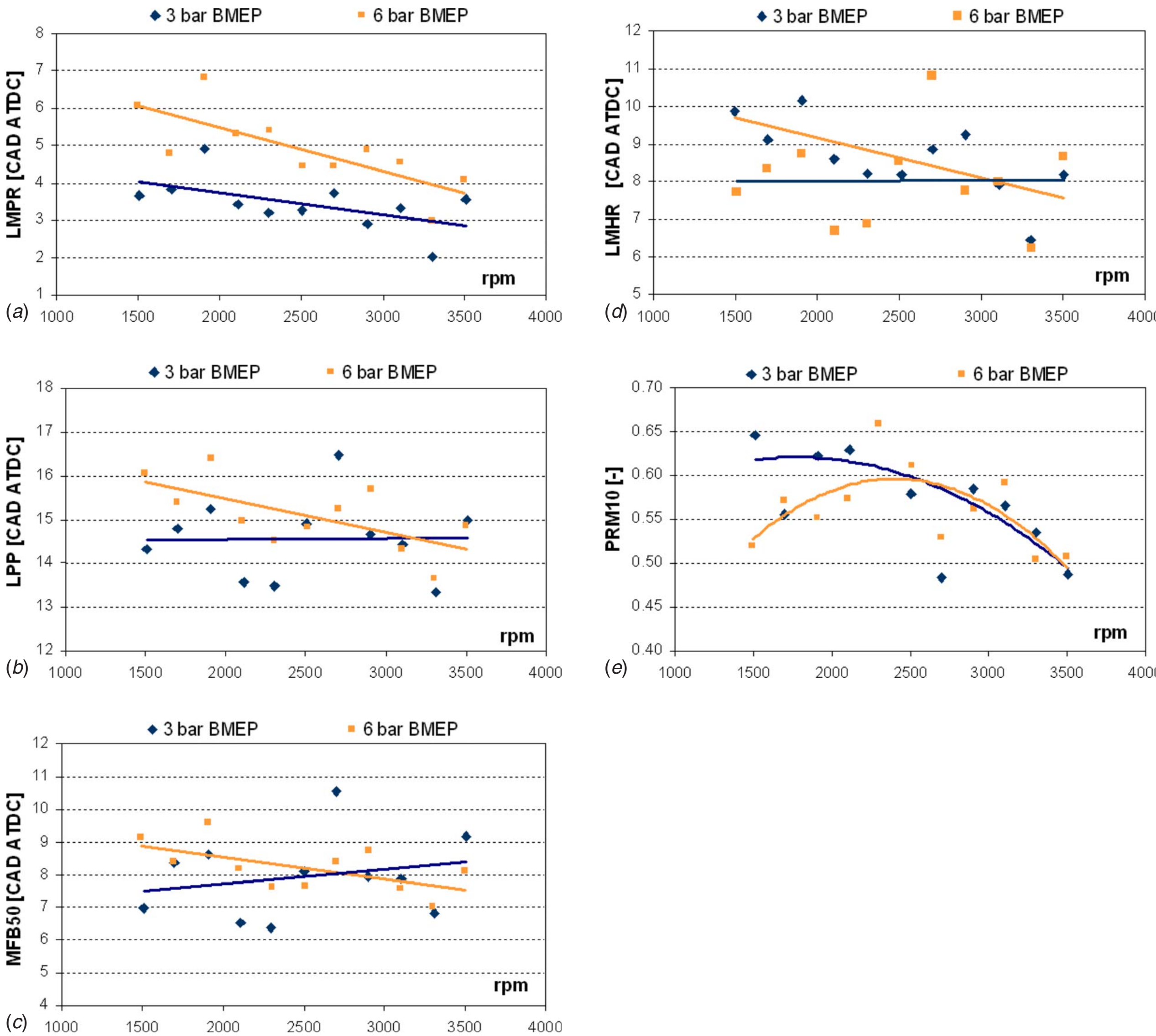

Fig. 7 Indicators versus engine speed (stoichiometric mixture, 3 bar and 6 bar BMEP)

As regards the LMHR, the results presented up to this point (Tables 2 and 3, figures from 7–10) revealed that this parameter can be considered a good combustion phase indicator for MBT spark timing control, since it is characterized by a set point value, which is almost independent of engine speed and load, and exhibits the same behavior of MFB50 with respect to mixture strength; moreover, its variation range is equal to those found for MFB50 and LMPR. It has been proposed as an alternative to MFB50 and proved to have comparable characteristics and performances: The close resemblance between MFB50 and LMHR is further shown in Fig. 11: Here, LMHR values are reported against MFB50 for every operative condition tested.

Measurement Problems and Evaluation Errors

All the five combustion phase indicators here taken into consideration derive from in-cylinder pressure analysis. Therefore, their evaluation and, hence, the performance attainable by the spark timing control could present some inaccuracy due to pressure measurement problems, which are mainly related to sensor performances, pressure referencing, pressure sampling resolution, TDC determination, and cycle-by-cycle variations. As regards the pressure sensor, for example, it is well known that the output signal of a piezoelectric transducer can carry a bias error, due to thermal sensitivity shift (long term drift) or to deformation stresses; this may lead to an erroneous evaluation of the indicator [19,20] and consequently to poor spark timing control.

Obviously, the indicators merely based on the phase of the pressure signal, i.e., LPP and LMPR, are free from this problem; the other three indicators, instead, revealed a different sensitivity to pressure bias error: Figure 12(*a*) shows the highest induced evaluation errors found on LMHR, MFB50, and PRM10; as can be seen, a bias error on pressure values has a stronger impact on MFB50 (nearly 2 deg) than on LMHR (less than 0.5). The effective comparison between the three indicators must be, however, made only on the base of the induced spark advance error: Fig. 12(*b*) shows that PRM10 caused up to 8 deg deviations from optimal spark timing, while LMHR maintained the best performance with spark timing errors lower than 1 deg. Therefore, the use of PRM10 can seriously damage the control performance, while LMHR demonstrated to be almost insensitive to pressure bias errors.

When absolute pressure values are needed, a referencing procedure on sensor signal output is often required. As previously mentioned, during the tests, the inlet manifold technique was used, which is mainly recommended when low engine speeds are investigated. According to this method, in-cylinder pressure, when

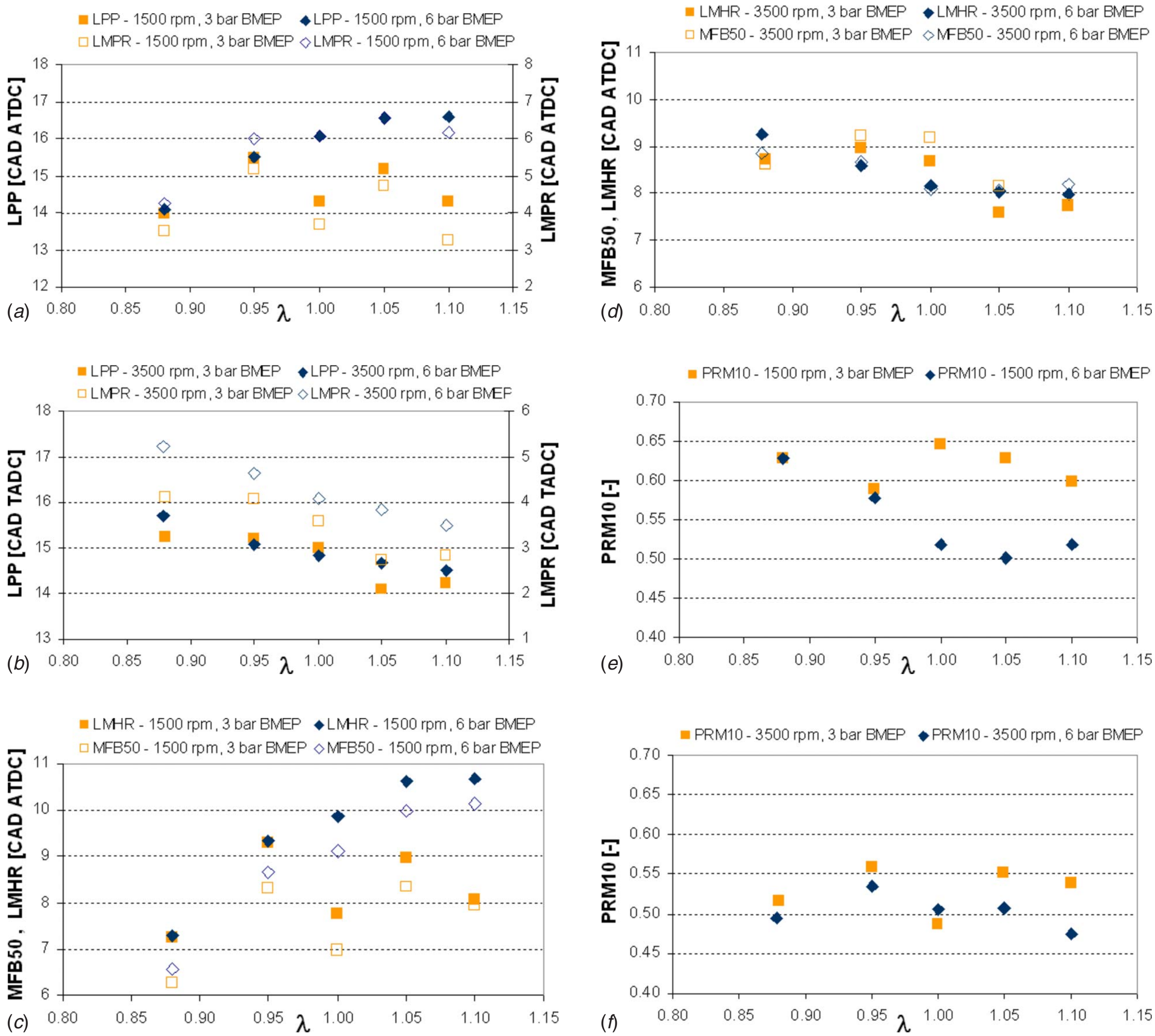

Fig. 8 Indicators versus mixture strength

piston is at intake BDC, should equal manifold absolute pressure. Generally, disturbance on sensor signal compels to use a mean in-cylinder pressure value computed at least over a 10 deg arc, which theoretically should have a symmetrical position with respect to the BDC; inertia effects of fluid flow may cause the BDC pressure to be different from manifold pressure, requiring so the forward shifting of the referencing arc: The magnitude of this shift depends naturally on engine speed and intake duct design, and this fact introduces an uncertainty on the pressure correction procedure. In Fig. 13, the maximum and mean variation in referencing pressure are represented versus the starting position of the referencing arc: As can be seen, a 20 deg shift of the arc can cause a 7 kPa pressure correction variation. When the engine is used at a high speed, above all if it is endowed with tuned intake systems, the polytropic index technique should be preferred, since inertia effect may change considerably in-cylinder pressure on the first part of the compression stroke. As an example, Fig. 14 shows, for each engine speed considered, the maximum difference in pressure correction that occurred using the two techniques on the pressure cycles recorded. It represents an uncertainty in the pressure acquisition chain that, at relatively high engine speed, can reach 20 kPa, which is anything but negligible, as remarked by the graphs in Fig. 12.

Considering that none of the two referencing methods can guarantee an absolute reliability, the difference in pressure correction obtained by the two techniques over all the operative conditions tested and with varying polytropic index was also investigated: As a result, Fig. 15 shows that this difference reached 26 kPa when using a polytropic index equal to 1.28, and 19 kPa with 1.33, which, as can be observed, is the index that best matches with the MAP based method; these polytropic index values are not exactly valid for every engine: Hence, the high differences found in pressure referencing may imply remarkable indicators' evaluation errors (as stated in Fig. 12); therefore, if a referencing procedure must be adopted, the use of indicators immune to pressure correction errors, such as LPP or LMPR, or not much affected, such as LMHR, should be preferred.

Concerning pressure sampling resolution, it is clear that the higher it is, the more precise will be the reconstruction of pressure cycle and consequently the calculation of combustion phase indicators. Actual engines, however, are not equipped with high resolution timing devices, such as encoders; usually a ring gear is employed together with an inductive or Hall effect sensor, which generates a wave form whose frequency gives the engine speed; the generated wave forms can also be used to trigger signal acquisition, but its resolution depends on the number of teeth on the

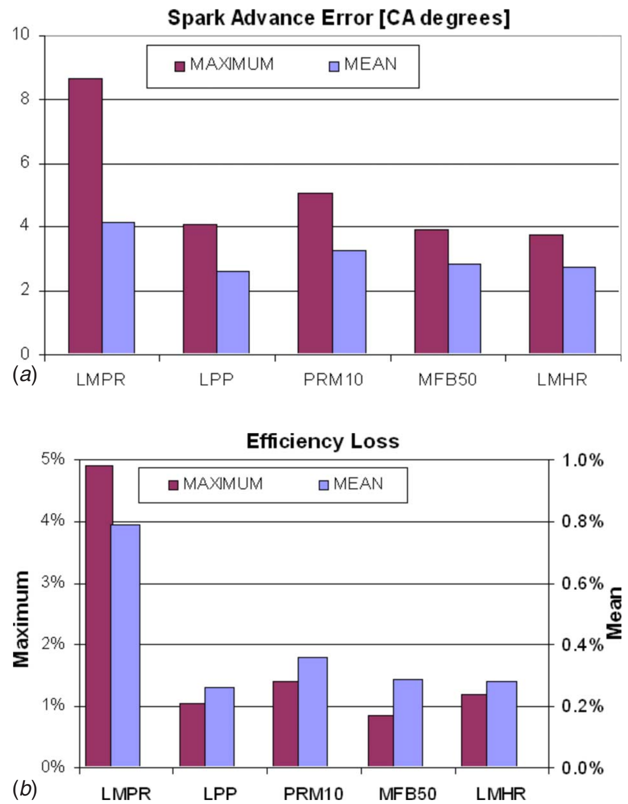

Fig. 9 (*a*) Spark advance error and (*b*) performance loss with indicators' value on the edge of the variation range

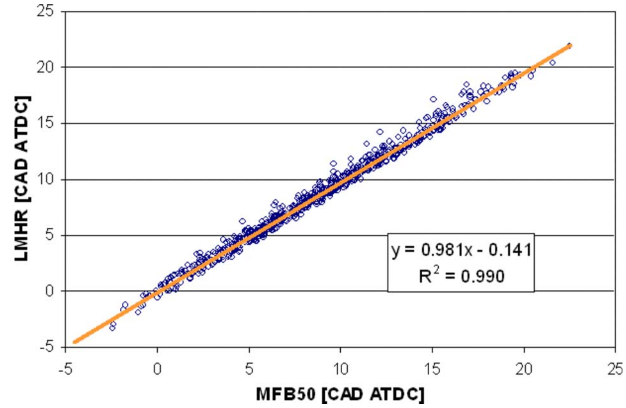

Fig. 11 LMHR versus MFB50 (all operative conditions)

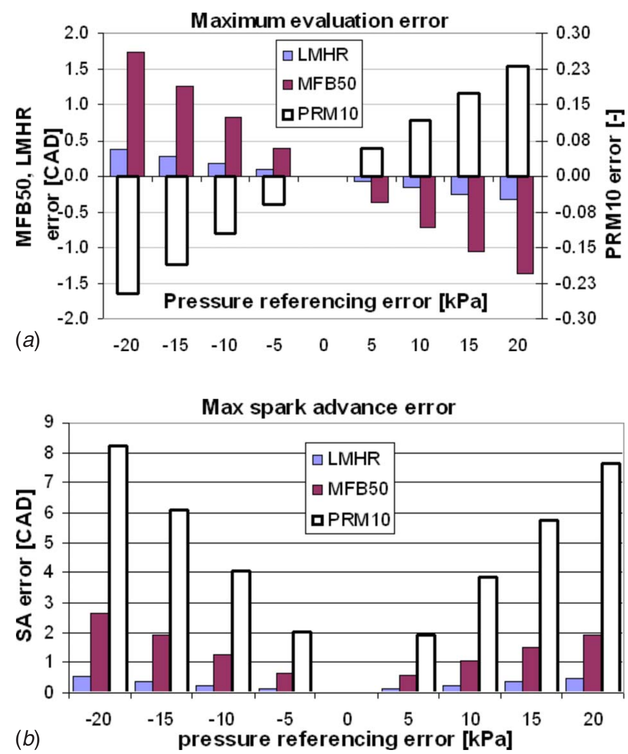

Fig. 12 (*a*) Maximum indicators' evaluation error and (*b*) maximum spark advance errors for bad pressure referencing

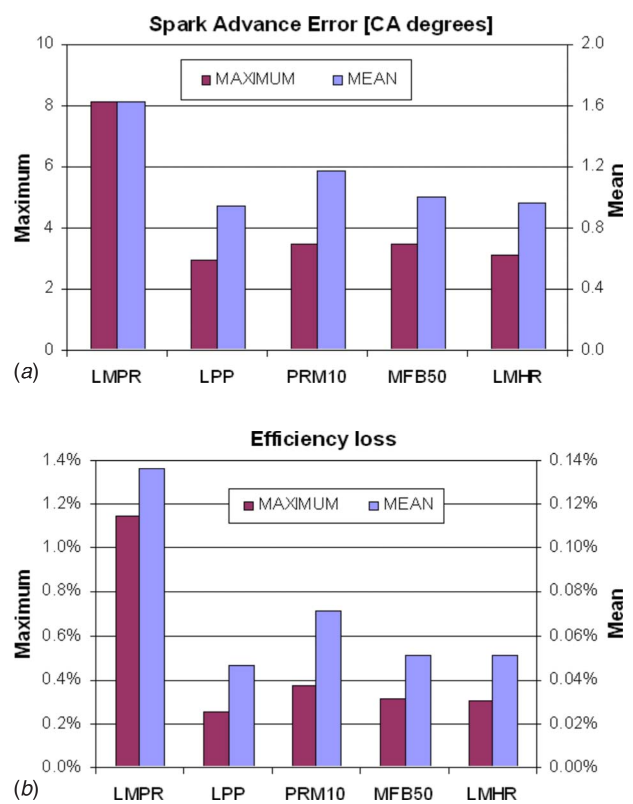

Fig. 10 (*a*) Spark advance error and (*b*) performance loss with optimal spark advance control

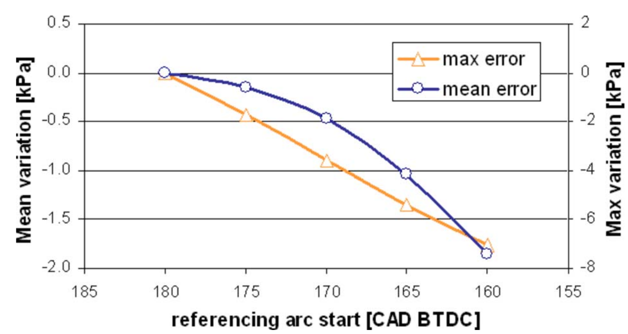

Fig. 13 Mean and maximum pressure referencing variation versus start of the referencing arc

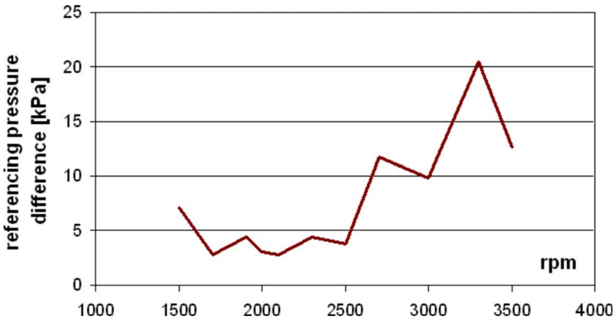

Fig. 14 Maximum pressure correction difference between "MAP" and k=1.32 referencing methods

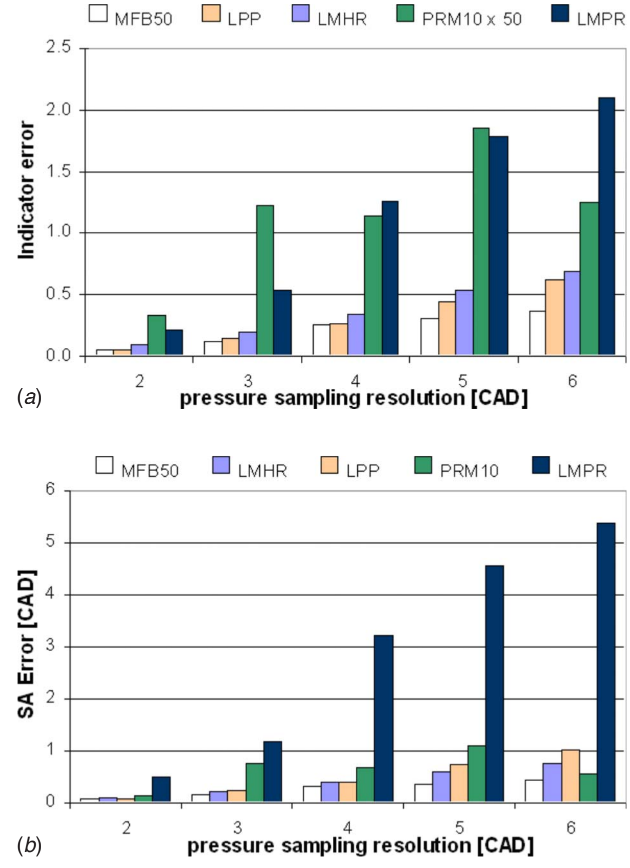

Fig. 16 (*a*) Indicators' maximum evaluation errors and (*b*) spark advance maximum errors with varying sampling resolution

ring gear: Normally these are 60, which means that the waveforms' period is 6 deg and therefore a maximum resolution of 3 deg (the distance between the positive and negative peaks of the wave form signal) can be achieved with the actual systems. It was then checked how pressure sampling resolution affects both combustion phase indicators' evaluation and the attainable spark advance control. Down sampling the recorded pressure cycles, it was possible to compare the indicators' values obtained using different sampling resolutions (from 2 deg to 6 deg) with those obtained with maximum resolution (1 deg). The results are resumed in the graphs in Fig. 16: It can be seen that the only indicator that suffers for a low sampling resolution is LMPR, showing a maximum evaluation error of 2 deg (which is nearly its variation range) together with a spark advance error of 5 deg. All the other indicators proved to well tolerate coarse sampling resolution, with spark timing errors always within 1 deg.

Another source of error in the evaluation of combustion phase indicators is represented by inaccurate TDC determination, which can be avoided only with the use of TDC position sensor (which guarantees a 0.1 deg precision) or by means of thermodynamic methods, based on engine motored pressure acquisition and analysis [21–23], whose accuracy may be lower.

In both cases, the procedure should be applied for every single engine, which could not be practicable for mass production. The importance of TDC determination is well known in terms of IMEP calculation: As can be seen in Fig. 17, the tests performed revealed an 8% IMEP evaluation error as a consequence of a wrong TDC determination of just 1 deg. The assessment of the influence of TDC position error on the combustion phase indicators' evaluation was carried out altering the phase of the pressure cycles recorded: The results shown in the left part of Fig. 18 point out that MFB50 and LMHR undergo an evaluation error higher than LPP and LMPR, which, obviously, change linearly with the TDC error.

As concern the induced spark advance error with respect to the MBT values, LMPR proved again the worst performances (10 deg error with respect to a 3 deg TDC error), while MFB50, LMHR, and LPP shown almost the same lower spark advance deviation (6–7 deg); the best result was achieved by PRM10, whose induced spark advance error followed almost linearly the TDC error.

The last, but not the least, trouble in pressure measurement is related to cycle-by-cycle variations: As is known, in fact, in-cylinder pressure during the combustion phase is highly variable from one cycle to the next (see, for example, Fig. 19) due to differences in start of combustion and flame propagation speed. This high variability can seriously endanger the stability of a feedback spark timing control, as a result of the wide variations induced on the combustion phase indicators' values; for example,

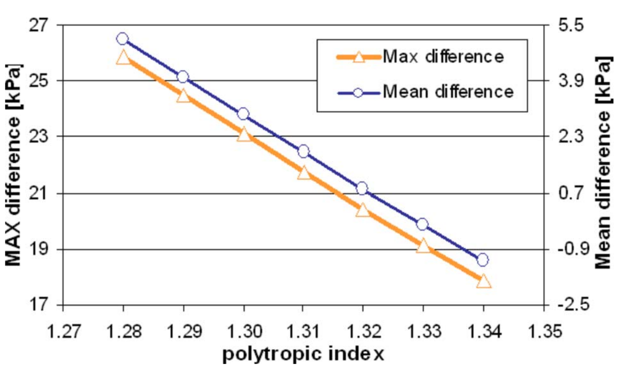

Fig. 15 Pressure correction difference between "MAP" and k referencing methods for different polytropic indices

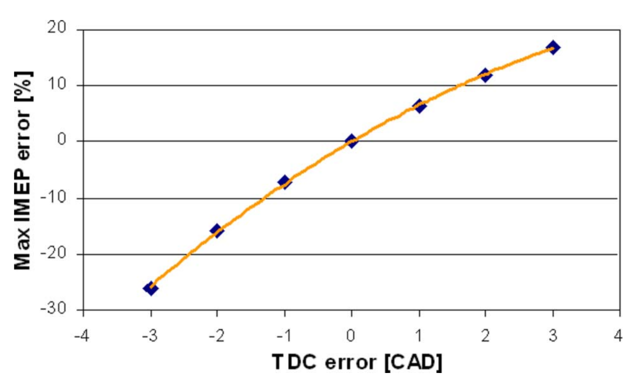

Fig. 17 IMEP evaluation error with wrong TDC reference

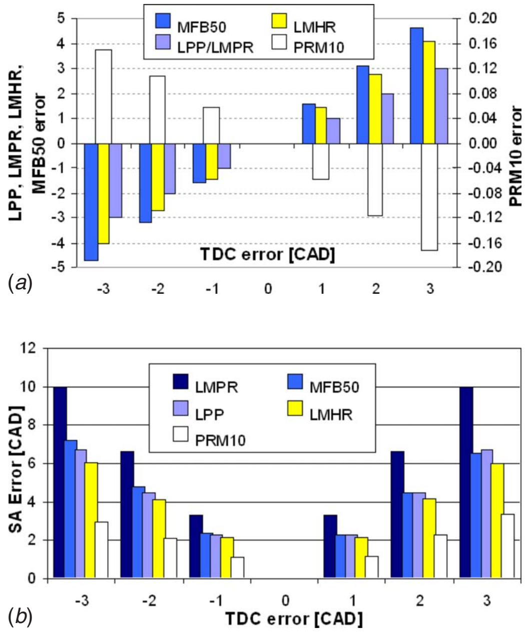

Fig. 18 (*a*) Indicators' maximum evaluation errors and (*b*) spark advance maximum deviation from MBT value as a function of TDC error

Fig. 20 shows the progress of LPP, PRM10, and MFB50 evaluated over 250 consecutive cycles with constant engine speed, load, spark timing, and A/F: As also resumed in Table 4, it can be noted that all the three indicators move in a wide variation band, whose amplitude is higher than the characteristic dispersion range of Table 3, thus obtaining a relative variation of 2.7 for PRM10 and approximately 3.6 for LPP and MFB50. Quite similar results can be obtained by the other two indicators, LMPR and LMHR.

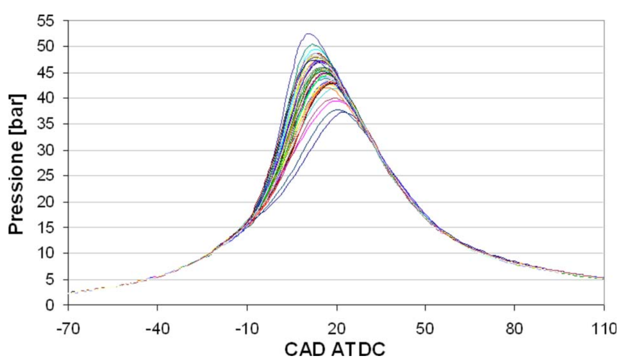

Fig. 19 In-cylinder pressure cycle-by-cycle variation: 50 consecutive cycles with constant speed, load, A/F and spark timing

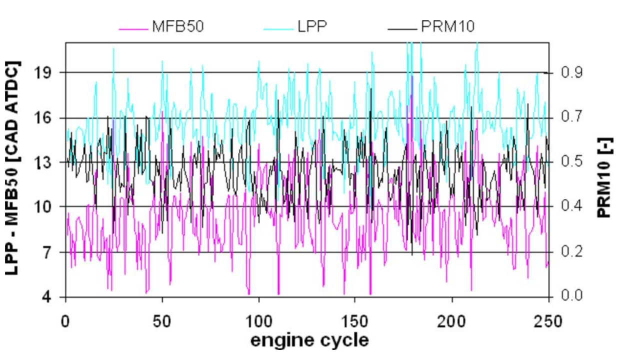

Fig. 20 Indicators cycle-by-cycle variation (3500 rpm 4.8 bar IMEP, MBT SA, $\lambda=1$)

Table 4 Indicators and consequent SA variation

	LPP	PRM10	MFB50
Variation range	±6.8	±0.33	±9.2
Rel. variation	3.7	2.7	3.6
SA variation	±9.4	±8.4	±10.1

This wide oscillation range could drive the spark timing control system (whose task is to keep indicator value to its set point) to strong, and maybe dangerous, spark advance oscillation, which can be easily evaluated using the slope coefficient of Table 2, as resumed in Table 4. To avoid spark advance oscillations as high as 20 deg (±10.1), it is safer to evaluate indicators on the base of a mean pressure cycle, computed over a certain number of pressure cycles, sufficient for a stable estimation of indicators' value. Naturally, this number of engine cycles must be as low as possible, since a high value would slow down the spark timing controller, which instead must preserve a fast response so as to follow the transient operations, which characterize the application of internal combustion engine to vehicle propulsion.

The number of engine cycles for the calculation of the mean pressure cycle can be established once the allowable indicators' fluctuation has been fixed, and this, in turn, depends on the maximum allowable spark advance oscillation around the MBT value; if a mean 0.2% efficiency loss is tolerated, the lower bound of Fig. 5 gives a maximum spark advance oscillation within the range of ±1.8 deg; by means of the slope coefficient in Table 2, the allowable indicators' range of oscillation have been calculated (see Table 5).

For the assessment of the minimum number of pressure cycles for a stable evaluation of the indicators' value, pressure matrices of 250 consecutive cycles have been recorded with engine speeds of 1800 rpm, 2500 rpm, and 3200 rpm, and two different loads: ~4 bar and 8 bar IMEPs; moreover, to test highly unstable operative conditions, a lean mixture ($\lambda=1.1$) was adopted, together with a retarded spark advance (MBT-10), thus running the engine with IMEP COV ranging from 1% to 5%.

For each of the operative conditions tested, the minimum number of engine cycles, which bring each indicator's range of oscillation under the respective limits fixed in Table 5, has been calculated: As an example, Fig. 21 shows the range of variations of LMHR, LPP, and PRM10 with respect to the number of engine cycles used for the mean pressure cycle calculation; the broken lines represent the limits of Table 5. As can be seen, in this operative condition, all three of the indicators cross their limit line within less than 25 engine cycles. The overall results, shown in Fig. 22, revealed that the evaluation of the indicators rarely requires more than 25 engine cycles; LMPR presented the highest instability, while PRM10 proved to be the most stable of the indicators; moreover, once again, LMHR performed quite similar to MFB50. The mean values of these results are summarized in Table 6. However, it must be pointed out that the results of Fig. 22 and Table 6 closely depend on the limits in Table 5, and hence on the allowable spark timing variation.

Table 5 Allowable indicators, range of variation for a maximum spark timing error of 1.8 deg from MBT value (0.2% efficiency loss)

LMPR	LPP	PRM10	MFB50	LMHR
±1.19	±1.31	±0.070	±1.63	±1.66

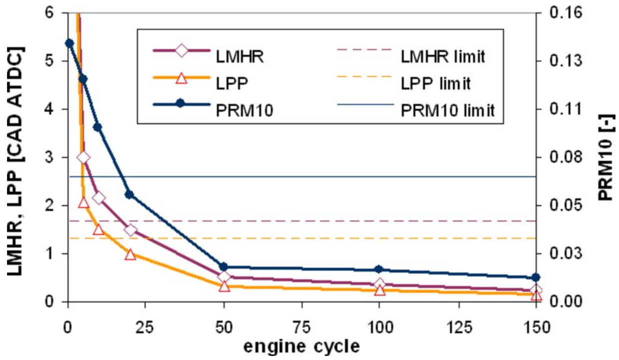

Fig. 21 Indicators' range of variation versus number of engine cycles for the mean pressure cycle calculation (3200 rpm, 3.78 bar IMEP, COV IMEP 4.9%)

Conclusions

An experimental investigation has been carried out to compare five combustion phase indicators derived from in-cylinder pressure analysis (LMPR, LPP, PRM10, MFB50, and LMHR) as pilot variables for optimal spark timing. One of the indicators (LMHR) was introduced by the author as an alternative to the MFB50, since less prone to pressure measurement error.

The dependence of the indicators' optimal values on the principal engine working parameters has been assessed: LMPR and PRM10 proved to be influenced by engine speed apart from load, while the other indicators manifested a relationship with engine speed only for the higher loads. A deeper assessment on the effect of engine speed should be carried on for the application to high speed engine (series production motorcycle engine can reach 12,000 rpm). LMPR was also found to manifest a certain dependence on engine load, while the other indicators proved to be almost insensitive; mixture strength instead was found to influence all the indicators at low engine speed and high loads, even if this influence is of scarce importance, when compared to each indicator's characteristic variation range, i.e., the difference between the maximum and the minimum optimal values. The comparison of these variation ranges revealed the first significant differences among the indicators: It was found, in fact, that the use of LMPR as a pilot variable for best spark timing can cause remarkable engine efficiency losses, while the best performances were obtained by LPP, MFB50, and LMHR. Since all the five combustion phase indicators taken into consideration derive from in-cylinder pressure analysis, the comparison included the indicators' evaluation errors, and the induced spark advance deviation from optimum, due to the most common problems in combustion chamber pressure measurement: pressure referencing, sampling resolution, TDC determination, and cycle-by-cycle variations. All these problems may induce errors on the evaluation of indicators' values, whose sum may seriously prejudice the spark timing control performances: Hence, the indicator to be used must be carefully chosen.

Pressure referencing error was found to affect the control attainable by the use of PRM10 or MFB50, while LMHR revealed to have a negligible sensitivity; LPP and LMPR instead, being based on the phase only of the pressure signal, are immune to pressure bias error. LMPR was also found to be both the only indicator to suffer for low pressure sampling resolution, and the most sensible to wrong TDC determination; in this case, LPP, LMHR, and MFB50 performed almost equally producing non-negligible deviation from optimal spark advance, while PRM10 obtained the best results, causing low spark advance errors.

Internal combustion engine cycle-by-cycle variations induce wide fluctuations on indicators' value, which, in turn, can cause a high instability in the spark timing control; it is then necessary to evaluate the indicators on the base of a mean pressure cycle. All the indicators revealed to require less than 20 engine cycles for a stable measure, being LPP and PRM10 faster than LMPR, MFB50, and LMHR.

The overall results of the comparison, which are also summarized in Table 7, point out that among the combustion phase indicators, the most suitable for MBT spark timing control is the LPP, which not only is fast and easy to calculate, but also resulted scarcely influenced by common pressure measurement errors.

If an indicator related to MFB is preferred, then LMHR should be used. The comparative tests demonstrated, in fact, that LMHR can be considered a good combustion phase indicator for MBT spark timing control, since it is characterized by a set point value, which is almost independent of engine speed and load, and exhibits the same behavior of MFB50 with respect to mixture strength; moreover, its variation range is equal to those found for MFB50

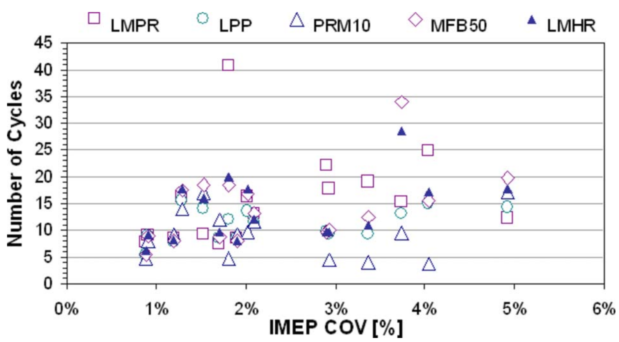

Fig. 22 Minimum number of engine cycles for stable indicators' evaluation as a function of IMEP COV

Table 6 Mean value of the minimum number of engine cycles for stable indicator evaluation

LMPR	LPP	PRM10	MFB50	LMHR
15	11	9	14	14

Table 7 Performance comparison between indicators (++ very good, + good, − bad, and −− very bad)

	LMPR	LPP	PRM10	MFB50	LMHR
Calculus and sampling effort	+	++	−	−	−
Engine speed dependence	−	+	−	+	+
Engine load dependence	−	++	++	++	++
Mixture strength dependence	+	+	+	+	+
Efficiency loss related to variation range	−−	+	+	+	+
Sensitivity to bias (or referencing) errors	++	++	−−	−	+
Sensitivity to pressure sampling resolution	−−	+	+	+	+
Sensitivity to wrong TDC determination	−−	−	+	−	−
Sensitivity to cycle-by-cycle variation	+	++	++	+	+

and LMPR, allowing a high efficiency spark timing control. It represents a valid alternative above all for its lower sensitivity to pressure bias or referencing errors, which make unnecessary the pressure measurement accuracy required by MFB50 and PRM10, thus allowing us to use cost effective pressure transducers. The cost of pressure transducers is at present the only drawback in the onboard use of combustion phase indicators; their use can be overcome if in-cylinder pressure is obtained by means of analysis performed on other quantities, such as ionization current, engine block vibration, or engine speed, whose measure is neither problematic nor expensive.

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Nomenclature

λ = air excess index $=(A/F)/(A/F)_{stoichiometric}$
A/F = air to fuel ration
ATDC = after top dead center
BDC = bottom dead center
BMEP = brake mean effective pressure
BTDC = before top dead center
CA = crank angle
CAD = crank angle degree
COV = coefficient of variation (=standard deviation/mean value)
ECU = electronic control unit
IMEP = indicated mean effective pressure
LMHR = location of maximum heat release rate
LMPR = location of maximum pressure rise
LPP = location of pressure peak
MAP = manifold absolute pressure
MBT = maximum brake torque
MFB = mass fraction burnt
MFB50 = location of 50% of mass fraction burnt
MHR = maximum heat release rate
PR = pressure ratio
PRM = pressure ratio management
PRM10 = pressure ratio management value 10 crank angle degrees ATDC
SA = spark advance
TDC = top dead center

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