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DESIGN OF A VALVE CAM TO OPTIMIZE THE VOLUMETRIC EFFICIENCY OF A SPARK COMBUSTION ENGINE

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Abstract. *The energetic efficiency is a priority for worldwide automotive industry. In Brazil, the INOVAR-AUTO and ROTA2030 programs establish vehicular energetic efficiency criteria in order to determine the vehicle taxation, which is pushing OEMs to design more efficient powertrains. For urban applications, the vehicle works most of the time in low speeds and short distances, then the typical engine should be a small displacement aspirated engine. It is fundamental for such machines the optimization of volumetric efficiency at rated speeds. In this work, a 1D simulation model was designed, improved and then correlated to a flex fuel engine. After that, this model was applied as auxiliary tool to simulate the combination of variables from an experiment generated by Response Surface Methodology (RSM), which resulted in a response surface that allowed a better understanding of the interaction between the main parameters and the achievement of an optimal operational point. The obtained results proved that the purpose of this work was achieved*.

Keywords: *Energetic Efficiency. Volumetric Efficiency. Otto Cycle Engine.*

1. INTRODUCTION

Reduce fuel consumption and CO2 emissions of the internal combustion engines is currently the biggest challenge of automotive industry. For compact vehicles worldwide, the best cost compromise is the propulsion through aspirated spark-ignition engines, where depending on emission regulations of the market sale, can be merged with hybrid or electric solutions.

In Brazil, former INOVAR-AUTO and now the ROTA 2030 programs, establish energy efficiency as a criterion for vehicle taxation. This criterion is driving the evolution in search of more efficient vehicle powertrains, the trend points out to optimized three-cylinder engines instead of the previous four-cylinder engines generation.

The purpose of this paper is to present a case study for optimization of the volumetric efficiency of a three-cylinder engine in urban conditions. This will be achieved through the sensitivity analysis of the parameters of the valve train system with the application of the surface response methodology (RSM) tool.

The optimization is translated into the expectation of increased torques at the most frequent regimes occurring during city cycles. Considering that in powertrain designs, the gearshift normally is limited to 3000 rpm in saw tooth diagrams the goal is a minimum gain of 1.5% at this speed with the commitment to cause the lowest impact at power range, evaluated at 6000 rpm. The admissible loss of torque is limited to a magnitude less than or equal to the torque gain at 3000 rpm.

A secondary goal is to find out through the RSM the correlation between input variables with the output engine torque.

2. VALVETRAIN VOLUMETRIC EFFICIENCY

The volumetric efficiency has a direct relation to available torque and, is defined (De Nicolao et al.,1996) as a parameter for efficiency analysis of an air pumping system and as one of the most applied parameters to characterize an Internal Combustion Engine (ICE).

The geometries of intake and exhaust systems rely among the most influent parameters of the volumetric efficiency (Heywood, 1988), therefore its fine tuning and phasing are fundamental for an optimized engine.

Adjusting the opening and closing time of the intake valve (Koo and Bae, 2000), it was limited the reverse flow of the cylinder to the intake manifold allowing significant gain of available torque at high speeds thru the delay of inlet valve closing draining the residual gas from the combustion. However, such strategy had a negative impact at low speeds.

A study of intake valve parameters impact in the volumetric efficiency of a single-cylinder four-stroke combustion engine (Parvate-Patil et al., 2003), concluded that, the valve opening phase was the most significant parameter compared to the valve lift variation. In this paper the intake valve variables, opening angle (AA_ADM), valve lift (L_ADM) and cam opening angular section (Perm_ADM) will be evaluated.

3. EXPERIMENTAL EVALUTION

As explained in Introduction, the RSM tool will be applied to evaluate variables interaction. However, it is required a second tool to simulate the engine response for such combinations. For this purpose, a 1D model under GT-Power® was chosen.

Similar works have proven the potential of this strategy of combined tools to assess engine performance, one in particular (Ahmadi, 2007) demonstrated the potential of Genetic Algorithms as a design optimization tool of an intake system and valve timing, also applying GT-Power® to simulate engine response.

3.1 1D Simulation Model

The continuous improvement in computer-aided models is resulting in good convergence with physical systems they simulate. Therefore, its application for scientific purposes is increasingly widespread.

For flow simulations the best tools are the three-dimensional Computational Fluid Dynamics (3D-CFD) models. However, given the difficulties to simulate such complex systems, 1D simulations become interesting solutions.

For combustion engine emulation, there are one-dimensional (1D-CFD) software which simulate the average properties of the flow. These application-optimized models have the advantage of minimizing error potentials through interfaces that better emulated the occurring phenomenon. On the other hand, it is important to emphasize that the flow average properties do not consider perturbations such as geometric punctual defects, variation of roughness in parts of an element, temperature gradient in a single element, abrupt section variation, among others. It makes obligatory an assessment to the physical object of study.

In a similar work (Silvestri et al., 1994), the WAVE® simulation code was applied to the General Motors Quad 4 engine to study its performance and induction system acoustics. Results demonstrated the ability of the simulation to provide accurate predictions.

In a paper (Ahmadi, 2007) to design intake and exhaust valve timing, a GT-Power® 1D model was applied to support Multi Objective Genetic Algorithm optimization, it allowed in the first step to reach maximum volumetric efficiency at high and medium speeds simultaneously, while in the second case intake and exhaust valve timing were optimized in each engine speed. The GT-Power® model is presented in Fig. 1.

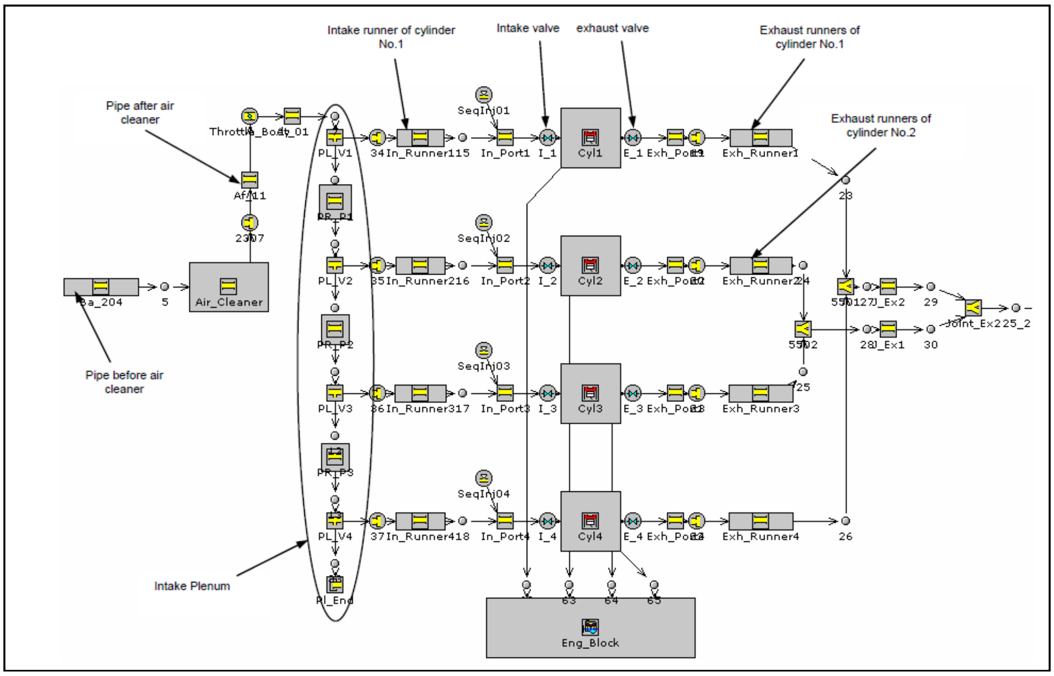

Figure 1. Four cylinder internal combustion engine 1D-simulation model
Ahmadi, 2007

3.2 Response Surface Method (RSM)

The RSM is explained (Montgomery, 2005) as a collection of mathematical and statistics tools useful for modeling and analyzing problems in which the response of interest is influenced by several variables and the goal is to optimize the response.

In most problems (Bradley, 2007), the response function curve is unknown and to develop an approximation, RSM first analyzes the convergence to a first-degree polynomial, but if curvature is detected the adjustment is a second-degree polynomial. The method used to determine the coefficients of the variables and convergence of the function is the least squares method and, from this interpolated curve, the response is generated as presented in Fig. 2. Therefore, the RSM is relevant for scientific studies.

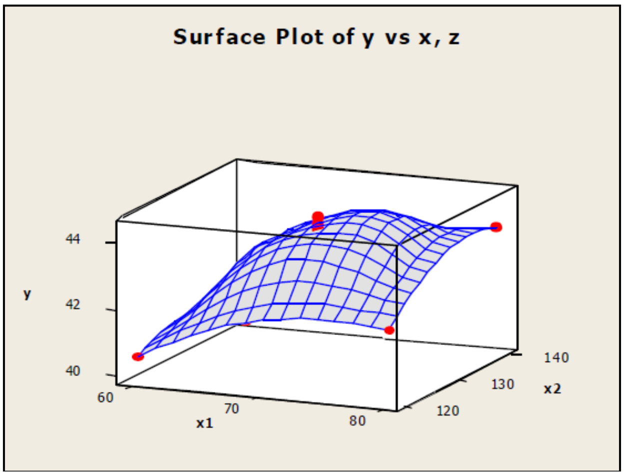

Figure 2. RSM output chart for two variables system
Bradley, 2007

This tool is indicated when the knowledge of the significant variables in the studied function is previously known, but it has as a restriction the need for the data to be continuous.

For each variable, the input data are the two boundaries, which are the inferior limit of the cube (MIN CUBE), coded in the RSM as -1, and superior limit of the cube (MAX CUBE), coded as 1. This allows determining the variable study average (CENTRAL POINT). Based on the relation of central point with limits additionally to experiment set-up such as full or half design, statistical software generates the equivalent alpha value.

The alpha value is applied to allow the system rotationality, orthogonality and is the factor to generate points extrapolated beyond the cube, called AXIAL POINTS, which allow determine the variables curvature.

The RSM can be summarized (Elbah et al., 2016) in three major parts: the first one the experimental design to determine the values of the factors on which the experiments are conducted and collected, then the empirical modeling to approximate relationships (response curve) between responses and factors and finally, the optimization to find the best response value based on the empirical model.

4. STUDY CASE

The object of study is a three-cylinder engine, 4 stroke, 1.2l, 12 valves. The input data may be found in related dissertation (Scandura, 2017), main data are described in Tab.1.

Table 1. Study case input data.

Description	Unity	Parameter
Engine outlet temperature	[°C]	90
Engine oil temperature	[°C]	110
Bore / stroke	[mm]	75 x 90.5
compression ratio	[-]	12.5:1
Fuel	[-]	Hydrous ethanol
Intake valve diameter	[mm]	27
Exhaust valve diameter	[mm]	24.5

4.1 Engine Model Assessment

The engine model was assessed with engine data, resulting in a difference of 3% at 3000 rpm and 1.9% at 6000 rpm. Differences up to 6% are considered acceptable for numerical simulation models of this nature as mentioned in other papers (Bertoncini, 2014). Then, the study reference torque are respectively 111.3 Nm at 3000 rpm and 94.6 Nm at 6000 rpm.

A polynomial mathematical model (Dudley, 1948) presented in Eq. (1) was applied to generate cam profiles according to different combination of the chosen variables and then compared to the original cam profile. In the sequence, the original cam and its equivalent polynomial generated were simulated in the same engine model. Results have shown very good agreement with a maximal difference of 1.2% in the engine rotations of the study case. Therefore, the new cam profile should be considered validated.

$$s = h.\left[1 - 1.641.\left(\frac{\theta}{\beta}\right)^{2} + 3.609.\left(\frac{\theta}{\beta}\right)^{10} - 4.375.\left(\frac{\theta}{\beta}\right)^{12} + 1.406.\left(\frac{\theta}{\beta}\right)^{14}\right] \quad (1)$$

Where
h – desired maximal cam lift
s – actual cam lift
θ – incremental angular displacement
β – half of desired cam opening angular section

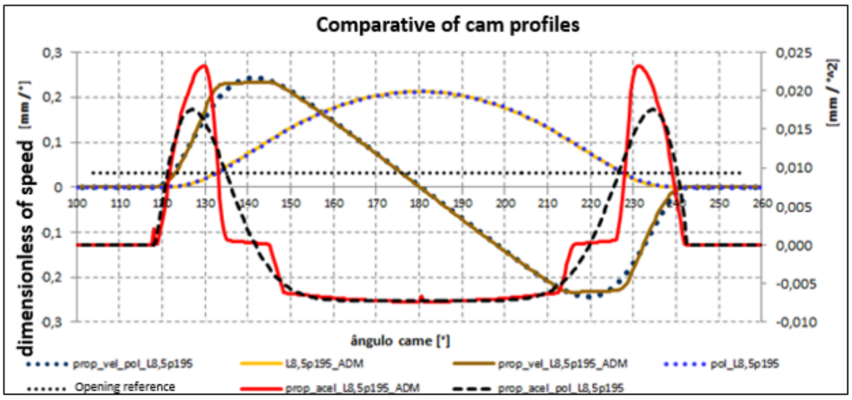

Figure 3. Comparison of original cam profile and profile generated by the proposed mathematical model
Scandura, 2017

4.2 RSM experiments

The limits of the study were defined based on a benchmark study, those are the input points to the RSM tool generate the axial points in full experiment, summarized in Tab. 2. They are combined to evaluate all iterations of the variables, which are afterwards simulated in the engine model. Finally, the results are returned to model for the statistical analysis in MINITAB software. For the validity of the statistical model the parameters R2 (full experiment), Pvalue and the residual error were considered. For R2 the target is equal or superior to 90%, Pvalue equal or superior to 0.05 and residual errors limited to module of 3.

Table 2. Study case variables limits.

POINTS	AA_ADM [°]	L_ADM [mm]	Perm_ADM [°]
MIN AXIAL (model generated)	-35.3	7.66	166
MIN CUBE (input)	-21	8	180
CENTRAL POINT (input)	0	8.5	200
MAX CUBE (input)	21	9	220
MAX AXIAL (model generated)	35.3	9.34	234

In the reference experiment, despite the good fit of the data to a normal distribution shown in Fig. 4, the model was considered unrepresentative due to the lack of adjustment of Pvalue, which means that the second-level model proposed by the software is not representative of the behavior of the response curve.

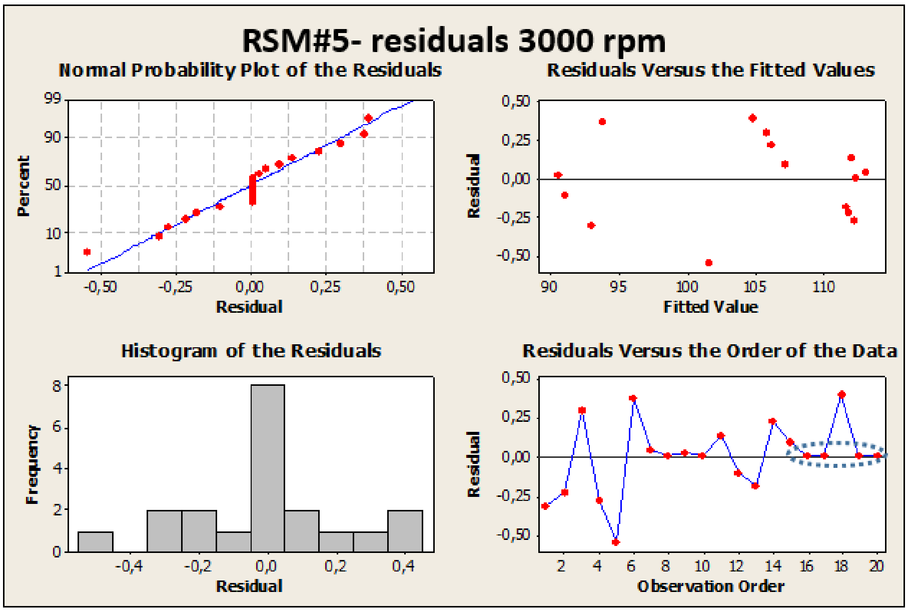

Figure 4. Analysis of residuals at rated speed 3000 rpm
Scandura, 2017

The "residual vs. order of data" chart in Fig. 4 demonstrates evidence related to this non-conformity, from iteration 16 up to 20 (except 18), the residuals are zero for those points. These data were verified and it was observed that they are the central points. It was identified as the cause of lack of adjustment of the model Pvalue.

To outline this abnormality, the proposal was to add dispersion to repeated central points. In physical experiments, central points have dispersion in-between, but in a simulated model with same input data, the output is always the same value. In order not to harm the RSM model, dispersions were inserted in the original simulated central point for the repeated central points, based standard deviation of study ranging from -100% to 100%.

The statistical revaluation finally resulted in convergence for a model adjusted to a response curve, as evidenced with Pvalue above 0.05, as shown in Fig. 5.

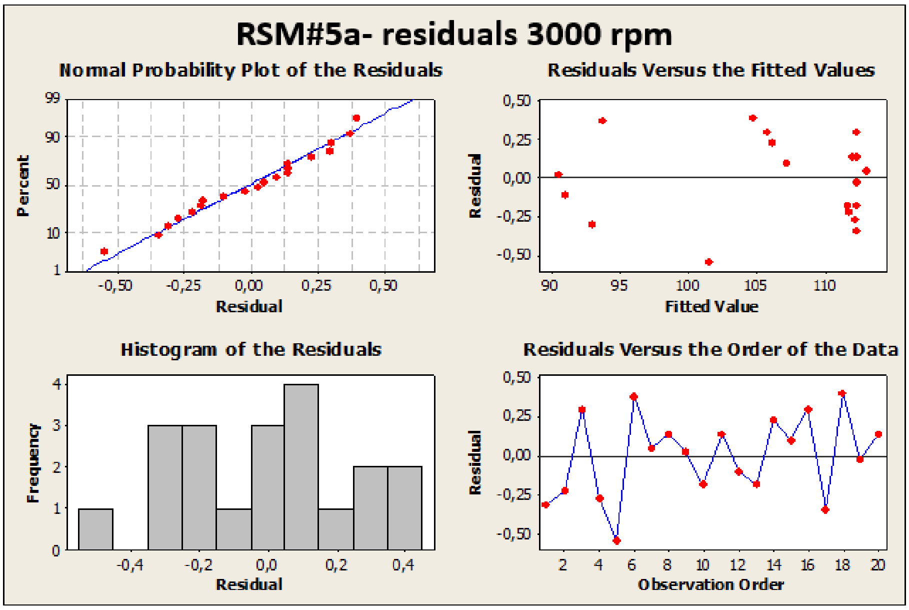

Figure 5. Analysis of residuals at rated speed 3000 rpm with corrected central points
Scandura, 2017

The statistical model is now valid, the RSM output is the response surface chart such as the one for 3000 rpm presented in Fig. 6. The chart indicates one surface interaction for each variable interaction. In this case, it is possible to observe the most significant interaction is the relation of cam opening angular section (Perm_ADM) and the valve opening angle (AA_ADM). This procedure was repeated for 6000 rpm, which resulted in similar correlations.

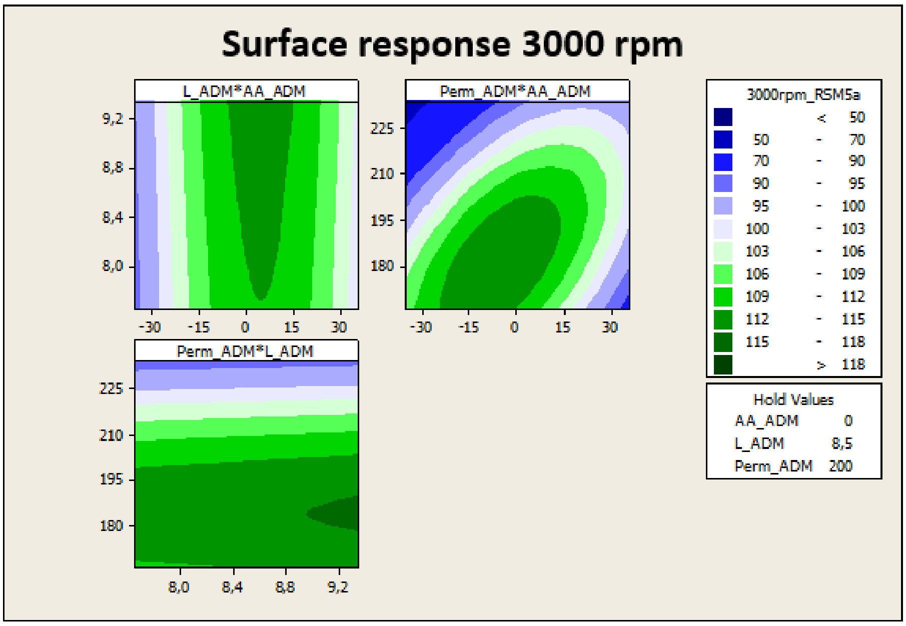

Figure 6. Analysis of residuals at rated speed 3000 rpm with corrected central points
Scandura, 2017

The other important output of RSM analysis is the polynomial equation which is expressed in coded cube factors, as explained in section 3.2. Fig. 7 demonstrates the behavior of each variable, it is possible to identify the quadratic correlation of cam opening angular section (Perm_ADM) and the valve opening angle (AA_ADM) with the output engine torque. The surprise was the weak correlation of valve lift (L_ADM) which from engine constructive point of view, its increase offers significant layout impact. The model demonstrates for this variable a linear and weak effective response.

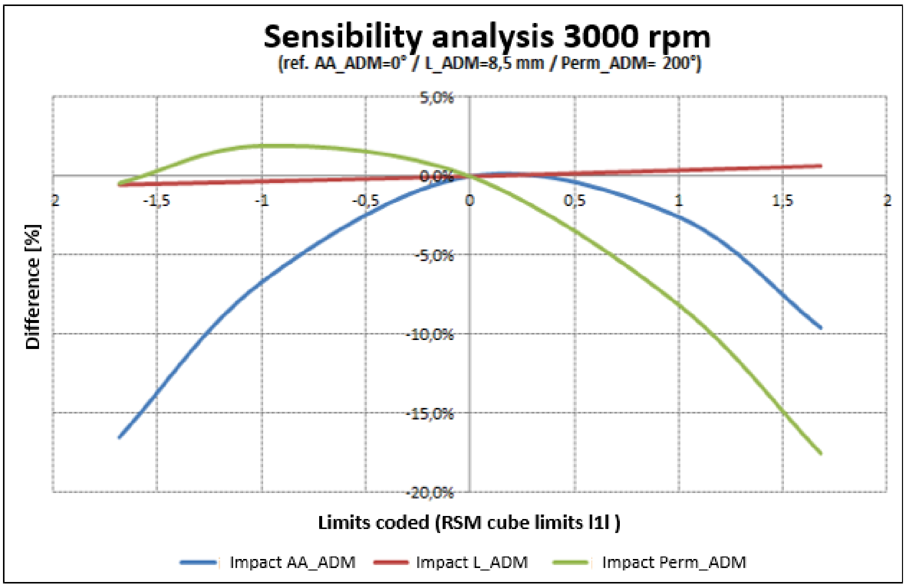

Figure 7. Analysis of residuals at rated speed 3000 rpm with corrected central points
Scandura, 2017

The identified optimal points for each speed were compared with impact to the other evaluated speed, it means evaluation at 3000 rpm assess the impact in the other rated speed of 6000 rpm. Based on it, it was proposed optimal points for both speed to meet the targets, the only variable which in this configuration with independent values was the intake open angle AA_ADM, because the engine feature Variable Valve Timing (VVT) allow it. The results are presented in Tab. 3.

Table 3. Torque prediction of RSM polynomial equation.

Optimization	AA_ADM [°]	L_ADM [mm]	Perm_ADM [°]	Torque 3000 [rpm]	Torque 6000 [rpm]
3000 rpm	-11.6	9.34	175	+3.7%	-
both speeds + opt AA_ADM 3000 rpm	-2.3	9.34	186	+3.7%	-
both speeds	-12.4	9.34	186	+2.5%	-6.7%
both speeds + opt AA_ADM 6000 rpm	-35.3	9.34	186	-	-0.7%
6000 rpm	-15.7	9.34	234	-	+0.8%

The RSM optimal values were then re-simulated in engine model confirming the goal achievement as represented in Tab. 4.

Table 4. Study case variables limits.

GT-Power engine simulation	3000 rpm	6000 rpm
Engine torque of baseline [Nm]	111.3	94.6
Engine torque of final proposal [Nm]	115.4	94.1
Difference [%]	3.70%	-0.50%

5. CONCLUSIONS

The potential of increasing in 3.7% at 3000 rpm the useful torque with small reduction of 0.5% at 6000 rpm, a regime rarely employed in urban cycles, demonstrated the effectiveness of the proposal to combine the RSM tool with the simulation software of engine for torque optimization.

To achieve such results, the boundary conditions of each variable was identified by the competitive benchmark. Running a large experiment with many variables can be much more complex and have a poorer result than a focused experiment with few variables such as the one presented.

In addition to the optimizer to identify the optimal regions that were confirmed in the GT-Power® simulation, the correlation with the response polynomial was also proved, which allows extrapolating conditions beyond the simulated ones.

The secondary objective of identifying the most significant variables and their iterations assessing the relevance of an adjustment to a linear or quadratic curve was also achieved. These conclusions would be restricted in classical methods of experiments like the DOE.

The most significant intake valve variables for both speeds are the cam opening angular section (quadratic relation) and the valve opening angle (quadratic relation). The surprise was the linear relationship of cam lift with low impact on response. The valve opening angle was considered in the strategic case study by the possibility of compensation by the phase inverter (VVT), therefore analyzes were performed through dedicated optimization studies.

Finally, the proposed strategy to add dispersion to central points for mathematical emulated models was effective and could be extended to further studies in several areas.

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