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ACCURACY OF DIESEL ENGINE PERFORMANCE PREDICTION - NUMERICAL VERSUS EXPERIMENTAL

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Abstract: *The paper presents two performance characteristics of diesel engines in the process of design for a vehicular use - effective power and torque curves, at full load, versus speed. A comparison is done between a numerical prediction indicated in literature and experimental data enclosed in engine certification standards. For two types of engines manufactured in series, it was assessed the accuracy of the numerical predictions of power and torque during air induction system evolution, from naturally aspirated to turbocharging and, finally, to charge air intercooling. Discussions are made on the best fit and accuracy, showing that the polynomial prediction for design purposes is still reliable.*

Key words: *diesel engine, power prediction, numerical model accuracy.*

1. Introduction

Among the most important internal combustion engine characteristics issued by vehicle manufacturers are full load torque and power versus the whole range of rotational speeds. Torque and power are two related engine outputs, power being proportional with the product of torque and speed.

The magnitude and profile of torque and power curves are of paramount importance in the process of fitting engine with gear box and vehicle dynamics.The plotting of these curves can be performed on dynamometric test bench, involving time and costs.

An alternative solution to experiments which saves resources is to find numerical predictions with a sound accuracy.

According to engine fundamentals [5], torque is proportional to mean effective pressure, p_{me}, while power is proportional to engine speed n and p_{me}. Mean effective pressure is proportional to indicated efficiency, η_i, mechanical efficiency, η_m, volumetric efficiency, η_v, and air-fuel ratio, AFR, all these measures being dependent with the speed; the simultaneous effects of those factors affect the profiles of the characteristics.

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The shapes of torque and power as presented in Figure 1 are similar to real heavy duty diesel engines. To the maximum value of the torque, M_{max}, corresponds the speed, n_{Mmax}, and to the rated power, P_n, corresponds rated speed, n_n. When the engine operates in the low end area and the road resistance increases, the engine speed decreases and the torque drops and engine stalls.

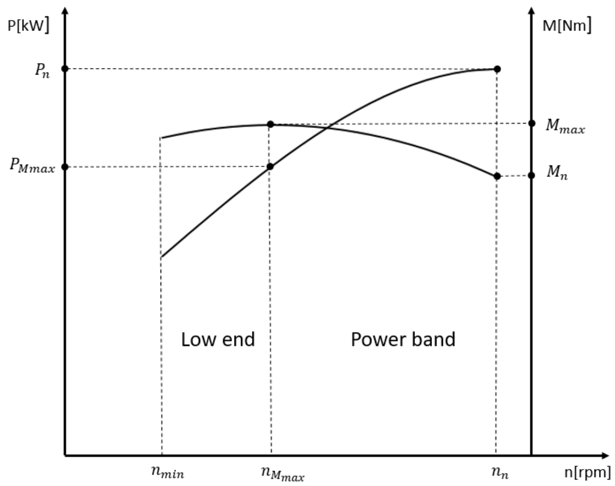

Fig. 1. *Full load torque and power versus speed characteristics* (*adapted from* [7])

So, low end area implies an unstable torque, being recommended to have higher torques values to mantain stability [3]. In the power band situated between n_{Mmax} and n_n when the road resistance increases, the engine speed is reduced and the output torque will increase to compensate the change in road load, so that area has a stable torque. For diesel engines the maximum power becomes the rated power and the fuel flow rate is adjusted by means of keeping the injection pump rack blocked on the maximum fuel flow position.

The energy relation between engine and vehicle was based on engine elasticity coefficient, *c,* which represents the ratio between maximum torque engine speed, n_{Max}, and rated power speed, n_n:

$$c = \frac{n_{Mmax}}{n_n}. \tag{1}$$

For diesel engines typical values of *c* (Eq. (1)) ranges within 0.55-0.75, the lower ones being correlated with higher elasticity, thus meaning a broader vehicle speed range for the same gear ratio [2]. Research work literature on engine power prediction indicates polynomial functions as the ones with the best fit with experiments. Crolla in [2] indicates that engine power characteristics can be represented by a cubic expression in function of engine speed:

$$P(n) = d \cdot n^3 + e \cdot n^2 + f \cdot n + g. \tag{2}$$

The constants *d, e, f, g* from Eq. (2) can be deduced from conditions imposed on P_n and M_{max}. It is also mentioned that the order of parabola can be increased by using other known points from experiments.

Other research works refer to a polynomial function, called Lederman equation; Repcic et al. in [8] evaluates the full load power versus speed with Lederman equation described by formula (3), to compare tractive effort gearbox curves when a race car runs on two different tracks:

$$P(n) = P_n \left[\left(\frac{n}{n_n} \right) + \left(\frac{n}{n_n} \right)^2 - \left(\frac{n}{n_n} \right)^3 \right]. \quad (3)$$

Also Grzelka in [4], investigating on-board diagnosis system capacity of approximation of engine calculated torque and power in function of speed by means of a polynomial Equation, referred to Lederman formula to generate the theoretic engine power, as reference.

Grunwald in [5] describes the full load engine relative speed characteristics indicating a similar Equation with (3):

$$P(n) = P_n \left[a\left(\frac{n}{n_n} \right) + b\left(\frac{n}{n_n} \right)^2 - c\left(\frac{n}{n_n} \right)^3 \right], \quad (4)$$

with *a*, *b*, *c,* coefficients equal to unit for spark engine and a = 0.5, b = 1.5 and c = 1 for diesel engine with unitary combustion chambers.

Mărdărescu et al. thoroughly explained in [7] polynomial power and torque equations, similar to Lederman equations (3), (4) having coefficient calculations based on elasticity coefficient, *c*; for different type of applications, knowing engine manufacturer data, error analysis indicated fair values.

Reference [10] intended to analyze the torque and the power output in dependency on engine speed in order to generate an automated design tool for data mining, based on experimental data for correlations with displacement volume, stroke, number of cylinders; some emergent techniques such as Support Vector Machines are applied for engine calibration [9] and Artificial Neural Networks [6] for sensitivity analysis of engine performance.

The aims of this paper are to evaluate the fit of polynomial prediction with experimental data of diesel engines in terms of full load power and torque curves over speed, to take into account the changes of technologies in engine induction system which may affect the predictions and to update prediction equations for a better accuracy.

2. Numerical Model

The numerical model considered in this paper is a classical predictor described in [7] and it has the purpose to replace the real measurements, when is possible and needed, and to predict the engine power and torque curves based on the given formulas (5) and (6), the terms α_1, α_2 and α_3 ((Eq. (7), (8), (9)) being characteristics which are depending exclusively by the coefficient of elasticity *c*:

$$P(n) = P_n\left[\alpha_1\left(\frac{n}{n_n}\right) + \alpha_2\left(\frac{n}{n_n}\right)^2 + \alpha_3\left(\frac{n}{n_n}\right)^3\right], \tag{5}$$

$$M(n) = M_n\left[\alpha_1 + \alpha_2\left(\frac{n}{n_n}\right) + \alpha_3\left(\frac{n}{n_n}\right)^2\right], \tag{6}$$

$$\alpha_1 = \frac{3-4c}{2(1-c)}, \tag{7}$$

$$\alpha_2 = \frac{2c}{2(1-c)}, \tag{8}$$

$$\alpha_3 = \frac{-1}{2(1-c)}. \tag{9}$$

3. Engine Data Collection

Two engine models were tested, both manufactured at Motoare AB company (Brașov, Romania) being provided to power trucks and buses. The basic engine formulas were six-cylinder, naturally-aspirated direct injection diesel and codifications are D2156 and 797-05, with the main engine specifications presented in Table 1 [1].

Engine family characteristics Table 1

Engine type	D2156	797-05
Bore x Stroke [mm]	121 x 150	102 x 112
Total displacement [l]	10.35	5.5
Compression ratio	17:1	18:1

Those engine models evolved in time, the natural aspiration being replaced by turbocharging and then by turbocharging with intercooling of charged air.

This evolution was motivated by the general tendency of increasing engine power per cylinder, as a result of aspiration of a higher mass air flowrates within the engine.

The data included in Tables 2 and 3 belong from engine catalogue [1] and vehicle manufacturer catalogue [11]. The performances of all tested engines were corrected according to DIN 70020 standard [12].

D2156 engine family characteristics Table 2

Version	D2156HMN8 Naturally aspirated	D2156MTN8 Turbocharged	D2156MTN8R Turbocharged and intercooled
Rated power [kW]	160	190	205
Rated speed [rpm]	2200	2200	2100
Maximum torque [Nm]	760	901	1037
Max. torque speed [rpm]	1500	1400	1400
Elasticity, *c*	0.68	0.63	0.66

797 engine family characteristics Table 3

Version	797-05 Naturally aspirated	798-05 Turbocharged	798-05R Turbocharged and intercooled
Rated power [kW]	99	110	125
Rated speed [rpm]	2900	2800	2600
Maximum torque [Nm]	353	424	534
Max. torque speed [rpm]	1900	1900	1700
Elasticity, *c*	0.65	0.67	0.65

4. Data Processing and Interpretation of Results

By applying numerical analysis according to Eqs. (5-9) and plotting experimental engine data, the comparative curves were generated in Figure 2. The significance of the subscripts are m - from measured, meaning experimental data and t - from theoretical equations, expressed by Mărdărescu et al. model, as described in reference [7]; the solid lines describe the theoretic power and torque and the dotted line the experimental ones.

The graphs on the left side of Figure 2 represent 797 engine family and the ones on the right side represent the family D2156.

From top to bottom, the images correspond to time evolution of the engine, from naturally aspirated engine, to turbocharged engine and, then, to turbocharged and intercooled solution.

It can be noticed that for all the six engines, the experimental curves do not exceed the predicted ones, showing a predominance of the model.

The fit of the polynomial prediction with experimental data of diesel engines in terms of full load power and torque curves over speed was evaluated using mean relative deviation, having as reference the experimental values of torque and power.

For 797 engine family, the mean relative deviation was 6.15% for naturally aspirated engine (797-05), 1.63% for turbocharged engine (798-05) and 11.3% for turbocharged and intercooled one (798-05R).

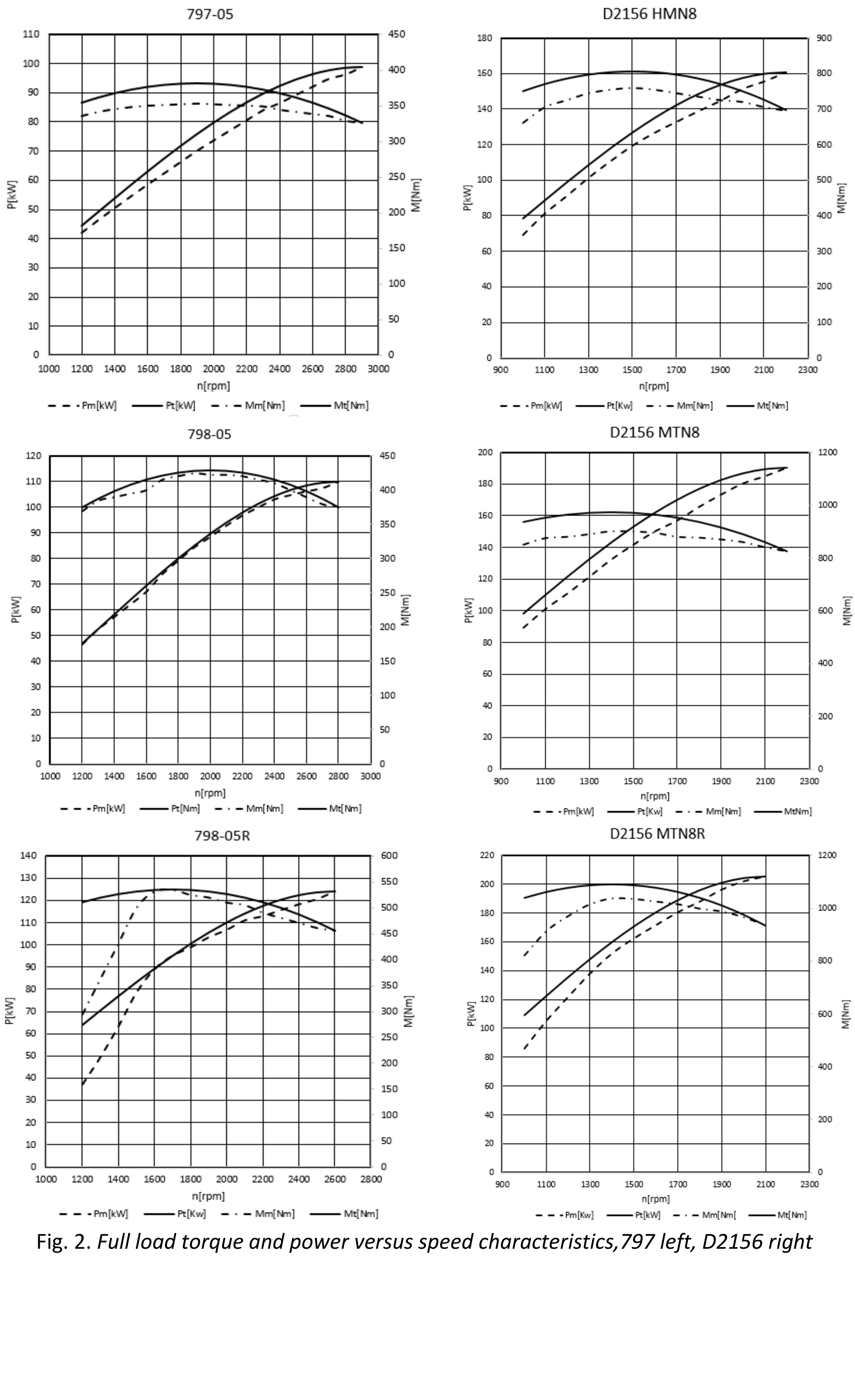

Fig. 2. *Full load torque and power versus speed characteristics,797 left, D2156 right*

For D2156 engine family, the mean relative deviation was 6.5% for naturally aspirated engine (D2156HMN8), 6.85% for turbocharged engine (D2156MTN8) and 7.45% for turbocharged and intercooled one (D2156MTN8R).

It can be observed that the highest mean relative deviations are met for the latest air induction systems, those in which the mass flowrates are increased both by turbocharging and by intercooling - 11.3% for 798-05 engine and 7.45% for D2156MTN8R engine. An explanation to that fact can be time history of the predicted model, which was issued decades before the maturity of charge air intercooling.

Nevertheless, the higher errors occur to lower speeds in low end area (Figure 1) and not in the power band, n_{Max}-n_n, which is the most frequently used speed range. The reason of the lower torque values for these engines was environmental protection legislation which has imposed smoke limits in European Union emission standard [13]; especially at low speeds, the meeting of the smoke limits has required the introduction of a fuel flowrate correction which reduces the fuel flowrate in the in-line fuel pumps according to charge air pressure, by means of LDA mechanical device, (abbreviated from German term Ladedruckabhängigkeit); as a result of its action, the torque values drops, in a similar way as in Figure 2.

By subtracting from the prediction model the values in low end area, thus meaning 1200-1600 rpm, the mean relative deviation for intercooled 798-05R engine becomes 2.5% ; similarly for D2156MTN8R engine with the subtraction of the values in the range 1000-1400 rpm, the mean relative deviation is 3.5%, showing that the prediction model error is more accurate on the limited speed range.

The aforementioned analysis includes some errors as the engine families have not kept a constant elasticity coefficient to all three versions of the engines, due to manufacturing decision makers; elasticity coefficient varied within (0.63-0.68) for 797 series and within (0.65-0.67) for D2156 series.

According to EU Regulation 85 [14], to verify the conformity of engine series production, the power is measured in two points, at the maximum torque speed and rated speed accepted for type approval. The power measured shall not differ by more than +/- 5% from declared power in homologation certifications.

Besides the manufacturing engine dispersion, there are measurement errors of torque and speed during testing on the dynamometric bench assumed to be 1%, respectively, 0.5% [15], thus leading to 1.5% measurement errors for rated power.

In order to answer to the last objective, to update prediction equations for a better accuracy, there were considered just experimental data from Figure 2.

The torque profiles are presented in Figure 3, being predicted with second and higher order of polynomial interpolation, without any links between equation coefficients as in classic model [7].

Two corresponding coefficients of determination, R^2, were indicated in Figure 3 for the second order and sixth order polynomial prediction; for the second order the coefficient of determination R^2 varied within 0.816-0.988; by rising the order of the polynome to six, R^2 coefficient was increased in the range of 0.985 - 0.999.

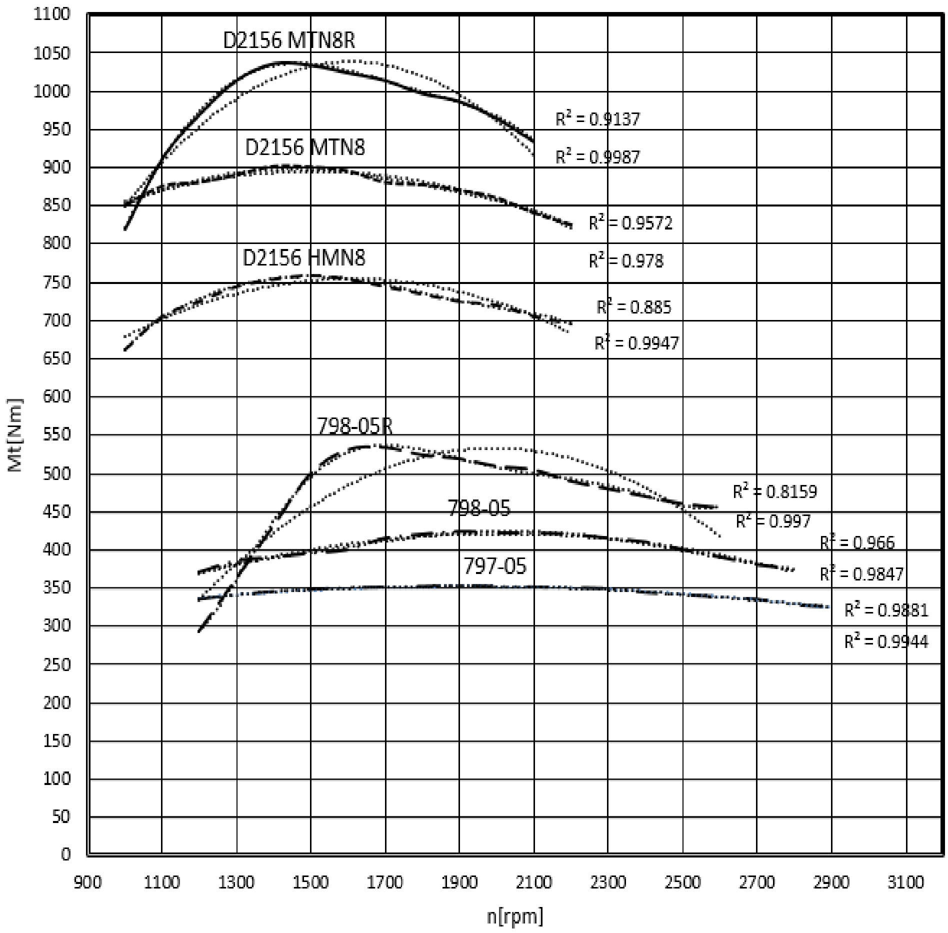

Fig. 3. *Polynomial fit of full load torque versus speed*

By comparing the two engine families, it can be observed a similarity in the profiles of the torque curves. The naturally aspirated and turbocharged versions have milder curves, while the turbocharged-intercooled engines show a more abrupt torque profiles.

The data in Figure 3 can be useful also for assessing of the gain in torque performance along with air induction technology, confirming the effectiveness of the methods.

For 797 series, by reporting to naturally aspiration values, the relative increase of mean torque was 17% for turbocharged engine and 37% for turbocharged-intercooled version.

Similarly, for D2156 series, by reporting to naturally aspiration values, the relative increase of mean torque was 20% for turbocharged engine and 34.5% for turbocharged-intercooled version.

The engine power profiles, represented in Figure 4 were predicted with a third order polynomial model, R^2, having for all the engines the values higher than 0.997, thus showing that third order polynomial prediction is accurate enough to predict power.

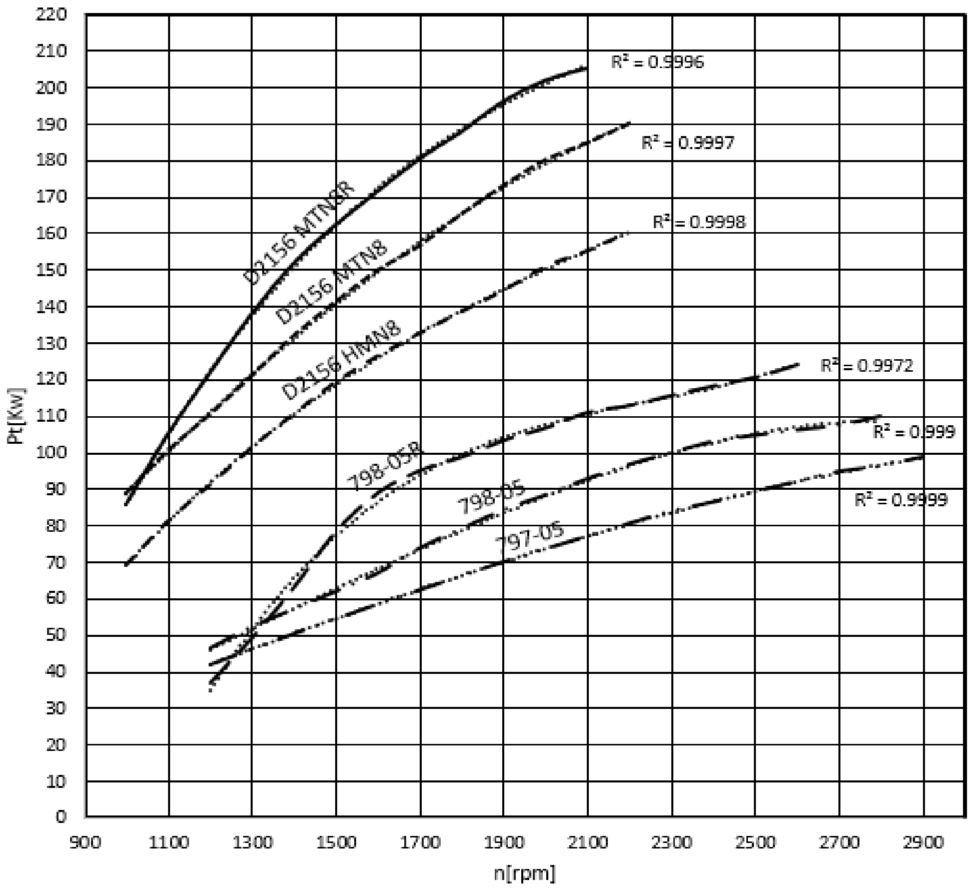

Fig. 4. *Polynomial fit of full load power versus speed*

5. Conclusions

The results of the present study assert that the engine performance model using polynomial equations defined in [7], based on elasticity coefficient, proved to be a suitable predictor for three generations of engines with different air induction technologies. Excepting the low end area of turbocharged and intercooled engine, it may be summed up that the maximum mean relative deviation between numerical and experimental power was 6.85%, value comparable with the accepted engine production dispersion (5%) and measurement errors (1.5%).

The experimental full load torque and power curves could be the best assessed with polynomial equations; the strong physical dependency between engine power and third order speed was confirmed, the best fit for the power prediction was the third order polynomial, R^2 ranging in the interval 0.997-0.999.

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