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EVALUATION OF ENGINE PERFORMANCE CORRECTED TO RATING STANDARDS

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Abstract: *The paper presents an evaluation of dissimilar standard correction factors imposed to road vehicle engine performances. The standards referred are ISO 1585, BS AU 141a, DIN 70020 and SAE 1349. The influence of atmospheric conditions (pressure, temperature and humidity) on performance declaration is assessed for a naturally aspirated diesel engine based on dynamometric bench testing. Some comments were made on the relation between gross and net power and on the admitted limits of correction factors.*

Key words: *internal combustion engine, power rating, correction factors.*

1. Introduction

The operation of internal combustion engines (ICE) depends on many design and functional variables, as well as environmental conditions, mainly atmospheric pressure, temperature and humidity. This set of ambient parameters depends on weather and region and cannot be controlled by engine management. The contribution of ambient conditions on the engine performance decreases in this order: pressure, temperature and humidity. The literature reported that by changing atmospheric conditions the engine air intake is affected and, further, volumetric efficiency, air fuel ratio, indicated and mechanical efficiencies [4], thus leading to significant changes in power, torque and fuel consumption. In order to assess performance and compare engines among them, certification procedures imposes standard atmospheric conditions; as this fact cannot be met due to the placement of the test laboratories worldwide at different altitudes and climates, correction factors have been adopted. For road vehicle engines, the highest influence on performance is produced by air density, ρ, and volumetric efficiency, η_v, [2], being sensible to pressure and temperature variation, yielding for engine effective power, P_e, the following general correction factor, C_f:

$$C_f = \frac{P_{es}}{P_e} = \frac{\rho_s}{\rho} \cdot \frac{\eta_{vs}}{\eta_v}, \tag{1}$$

with subscript *s* for corrected values, P_e - measured power, P_{es} - corrected power

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according to standard s, ρ - measured air density, ρ_s - air density in standard conditions. According to the ideal gas equation, density varies as function of pressure and reversedly, as function of temperature, while volumetric efficiency depends only on temperature; finally the correction factor is expressed as:

$$C_f = \frac{P_{es}}{P_e} = \frac{p_s}{p} \cdot \left(\frac{T}{T_s}\right)^{1-m}. \tag{2}$$

The coefficient *m* was experimentally measured, having dissimilar values in power rating standards; for example *m* = 0.5 for spark engines and *m* = 0.35 for compression ignition engines. Higher air humidity affects the volumetric efficiency, reducing the dry air fraction and finally the engine power. As humidity influence is very small, it was accepted to take it into account by correcting the pressure ratio from Equation (2):

$$C_f = \frac{p_s - p_{vs}}{p - p_v}\left(\frac{T}{T_s}\right)^{1-m}, \tag{3}$$

with p_v - ambient water vapor partial pressure and p_{vs} - standard water vapor partial pressure.

Experimental investigations have been reported both on road vehicles and airplanes, the latter being confronted with a wider range of atmospheric conditions; simulation of unmanned aerial vehicle operation fitted with a naturally aspirated diesel engine have been investigated in [5], confirming the dominant role of pressure; similarly the research work [8] reported data from two stroke spark ignition engine used in drones.

References [9], [10] have analyzed the influence of the atmospheric conditions on the performance of the spark-ignition engine passenger car, on the road, at different altitudes, by means of acceleration time, finding which standard, from DIN, SAE, JIS and ISO, is the closest to experimental data. An ANN (Artificial Neural Networks) and regression approach was used in order to find the influence of pressure, temperature, humidity and speed on power and specific fuel consumption of a naturally aspirated spark engine [6]. Closer to dynamometric test facilities, the study [3] was focused on standard correction factors and their effect on measurement repeatability applied to passenger car spark engine; similarly, in the paper [7] has been investigated heavy duty diesel engine performance measured in different atmospheric conditions and different auxiliaries.

The main objective of the present paper is to evaluate the influence of atmospheric factors and accessories fitted during engine tests according to DIN, BS, ISO and SAE power rating standards; the research area is limited to naturally aspirated diesel engine for which the data in the literature is scarce. The results include the assessment of three performance parameters, at full load engine operation mode: power, torque and specific fuel consumption. The novelty of the research work is the analysis of real gases behavior in the engine with the experimental data, in the variable conditions of the atmosphere (pressure, temperature, humidity).

2. Power Correction Factors

The evolution of power correction standards for automotive ICE was briefly presented in [7] being stressed the importance of three factors which make the difference: the exponent m in Equations (2), (3), fuel flow correction with a motor factor and engine accessories during tests.

DIN 70020-4 [12] is a German standard issued by German automotive industry. The reference atmospheric conditions are considered for dry air, p_s = 101325 Pa and T_s = 293 K, neglecting humidity. The coefficient m = 0.5 was adopted, yielding the correction factor:

$$C_f = \frac{P_{es}}{P_e} = \frac{101325}{p} \cdot \left(\frac{T}{293}\right)^{0.5}. \tag{4}$$

BS AU 141 a [11] is a British standard with similar reference condition as DIN: dry air, p_s = 101325 Pa and T_s = 293 K. It included the influence of fuel flow, the correction factor being directly read from a nomogram (Figure 1).

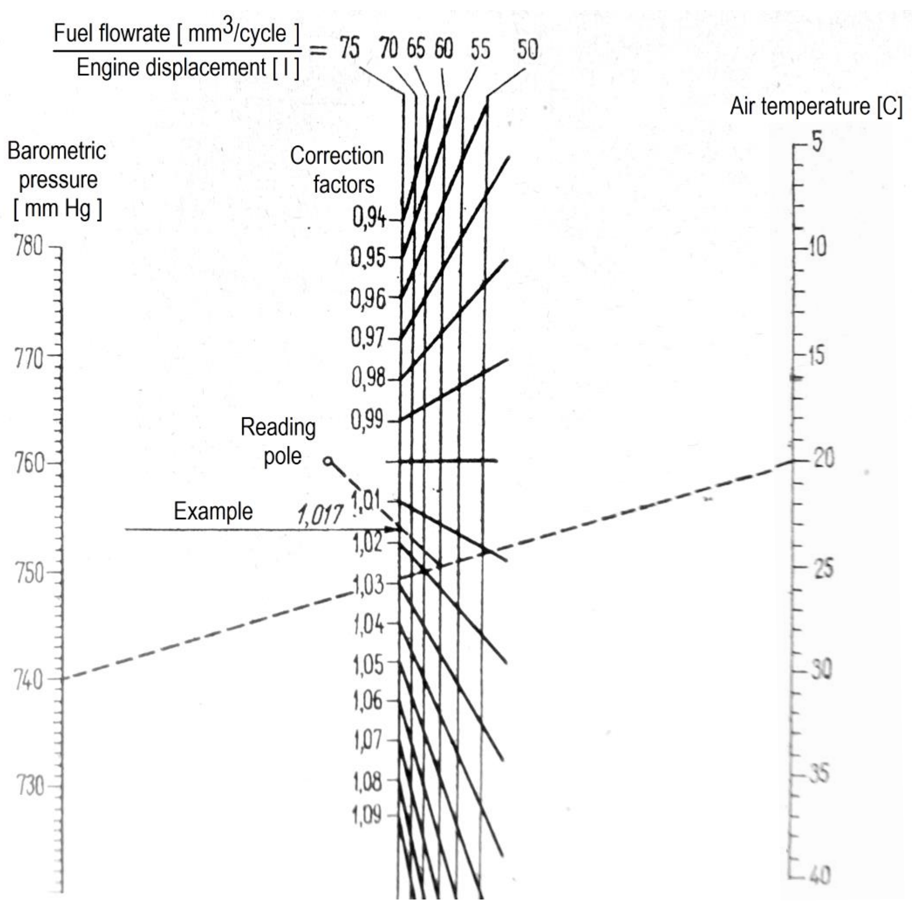

Fig. 1. *BS AU 141 a - Correction factor nomogram* [1]

ISO 1585 [14] is an international standard adopted by many countries; European Union issued ECE Regulation no. 85 which is equivalent to ISO 1585. The reference atmospheric conditions are p_s = 1 bar, T_s = 298 K and p_{vs} = 0.010 bar. The correction factor is admitted in the range of pressure 0.8-1 bar and temperature 288-308 K.

It includes both the influence of atmospheric factor f_a and engine factor f_m. The atmospheric factor can have dissimilar exponents m. For naturally aspirated compression-ignition engines:

$$f_a = \left(\frac{99}{p_s}\right)\left(\frac{T}{298}\right)^{0.7}, \tag{5}$$

$$f_m = 0.036q - 1.14, \tag{6}$$

$$q = \frac{120000 \cdot m_f}{V_d \cdot n}. \tag{7}$$

The variable q in Eq. (6) represents fuel flow expressed in milligram per cycle and per liter of total swept volume (mg/(L·cycle) and the measures in Eq. (7) are Z -120000 for four stroke engine, m_f - fuel flow rate [g/s], V_d - total swept volume in litres and n - engine speed [min^{-1}].

Finally, the correction factor is:

$$C_f = (f_a)^{f_m}. \tag{8}$$

SAE J 1349 [15] is the net power rating standard issued by Society of Automotive Engineers (U.S.A.).

The reference atmospheric conditions are identical to those of ISO 1585, as well as the Equations (5-7).

The correction factor includes, additionally, the influence of fuel properties by factor F_f, with ρ_f fuel density at 15 °C in kg/L, S viscosity sensitivity coefficient, V_0 - fuel kinematic viscosity at 40 °C, in mm²/s:

$$C_f = (f_a)^{f_m} \cdot F_f, \tag{9}$$

$$F_f = \left(1 + 0.7 \cdot \frac{0.85 - \rho_f}{\rho_f}\right)\left(\frac{1 + \frac{S}{V_0}}{1 + \frac{S}{2.6}}\right). \tag{10}$$

3. Engine Testing

For the test it has been selected a naturally aspirated engine, which, according to literature [1], [2], [4], [5], is more sensitive to air density variation when operating at high altitudes. The four - stroke, commercial vehicle MAN D0824 diesel engine having the main characteristics presented in Table 1, was tested on a dc-300 kW dynamometric test bench at Road Vehicle Institute - INAR Brașov [13].

Engine characteristics Table 1

Engine type	**Diesel**
Cylinder configuration	4 in-line
Bore x Stroke [mm]	108 x 125
Total displacement [L]	4.58
Compression ratio	17 : 1
Rated power [kW]	75
Rated speed [rpm]	2600
Maximum torque [N·m]	310
Maximum torque speed [rpm]	1600

The engine was instrumented to measure temperature of the cooling liquid, oil, and exhaust gas; pressure was measured for oil, air, and exhaust gas and flow rates of air and fuel; it was equipped with an in-line injection pump, fitted with timing and speed regulator, fan mounted on the crankshaft, unloaded compressor, air filter and exhaust duct of the test bench. The dynamometric tests included two types of tests: fan power curves and full-load speed characteristics. The fan power curves have been plotted as the difference of engine power fitted with fan and without fan. The full load speed characteristics indicate the variation of the torque, power, hourly fuel consumption and specific fuel consumption with engine speed, when the condition of maximum load was fixed by setting the rack of the fuel injection pump at the extreme position.

The accuracy of the instruments were for torque ±0.5% measured value, for speed ±0.2% measured value, for fuel flow rate ±1% measured value, inlet air temperature ±0.5 °C, air and exhaust pressures ±0.1 kPa. During tests, the atmospheric pressure was 95 kPa, water vapor pressure p_{vs}=1kPa and temperature T = 289 K.

The lower values of atmospheric pressure during the tests are explained by the altitude of 650 m of the location of experiments.

4. Interpretation of Results

In order to assess the influence of the auxiliaries on engine power, which differentiate the gross and net power, the engine was tested with and without fan.

Figure 2 illustrates the contribution of the continuously driven fan, which consumes engine power.

The fan contribution ranges 0.2-2.7 kW, representing in average less than 2.5% from the measured power without fan. In the following graphics DIN correction was applied to gross powers (without fan) and ISO, BS and SAE corrections were applied to net powers (with fan). Being known the mean values of the measured powers with and without fan, it can be concluded that the difference in rating in case of DIN gross power (8.33%) yields from fan power consumption (2.43%) and from atmospheric correction (5.9%).

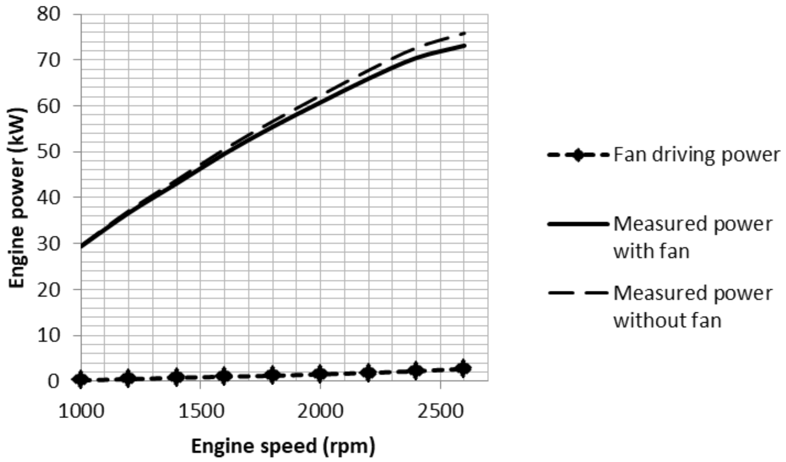

Fig. 2. *Influence of the fan on measured power*

The corrected torque values are represented in Figure 3, indicating the highest correction for DIN gross torque, which is 8.2% higher, on average, than measured torque values. A similar behavior of the same order was reported by [3] for a spark ignition engine corrected (DIN standard) and measured torque.

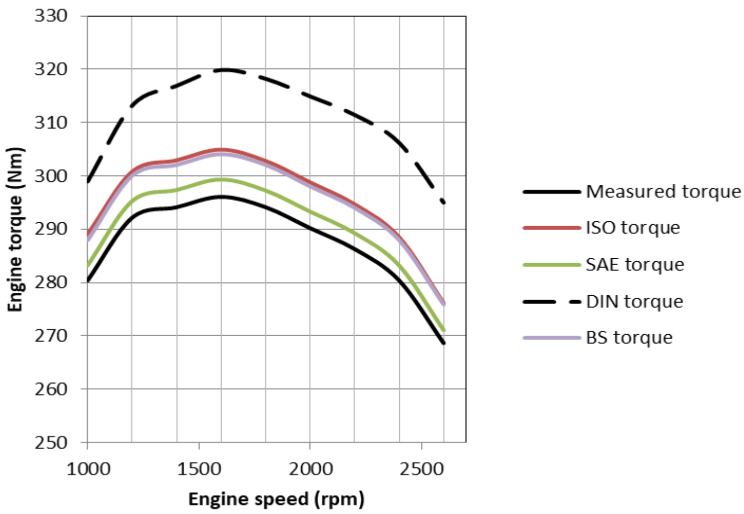

Fig. 3. *Corrected torques versus speed*

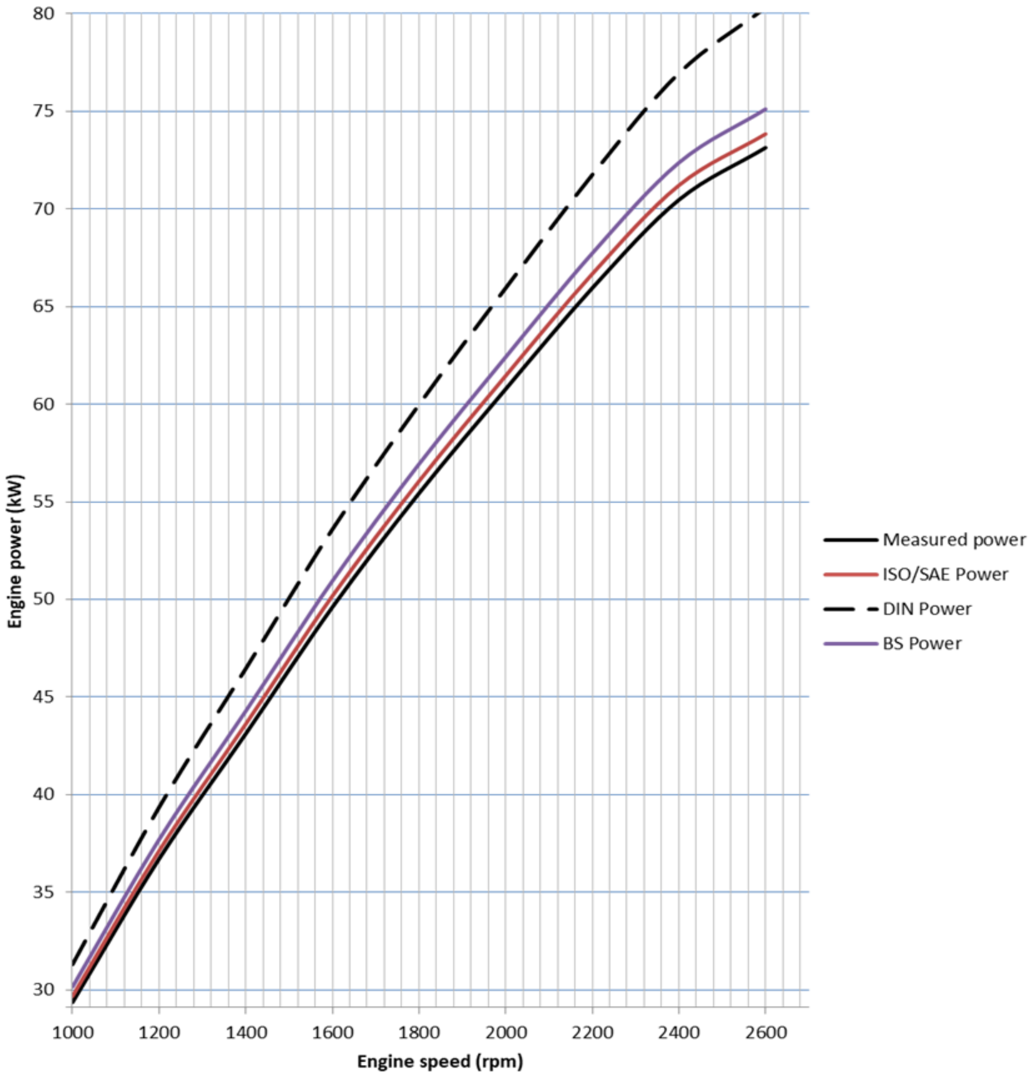

Fig. 4. *Corrected powers versus speed*

By applying the correction factors described in Chapter 2, the measured power and corrected values are represented in Figure 4. The common line ISO-SAE can be explained as the difference between corrected powers is so small that cannot be represented separately. It means that the contribution of fuel properties, (Eq. 9), in SAE standard was extremely small (F_f = 0.9995).

Reported to measured power, corrected power was 5.9% higher for DIN standard, and on average, 2.7% higher for BS, 1.094% for ISO and 1.039% for SAE.

The averaging of the correction factors for BS, ISO and SAE comes from q variable (Eq. 7) which depends on injected fuel quantity and engine speed.

The evolution of specific fuel consumption represented in Figure 5 is predictable from power correction (Figure 4) as the definition of specific fuel consumption reports hourly fuel consumption to effective power.

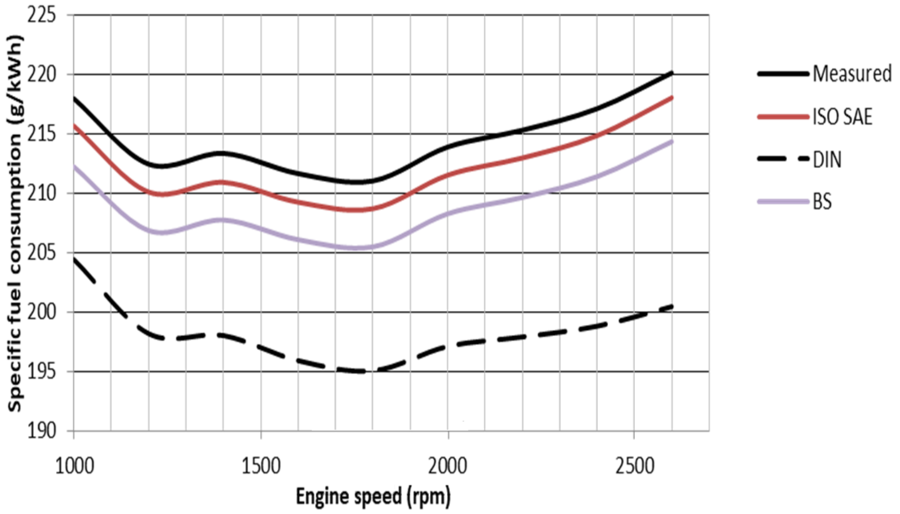

Fig. 5. *Specific fuel consumption versus speed*

The variation of performances according to standards is not so evident due to low variations of pressure and temperature towards standardized ones.

Some extreme conditions applied to the power of this engine according to ISO corrections could be interpreted (Eqs. 5-8) and illustrated in Table 2.

Engine power versus ISO atmospheric factor Table 2

Temperature	Air pressure (kPa)	f_m	Power (reported to standard power *Ps*)
298 K (25 °C)	99 kPa		*P* = *Ps*
313 K (40 °C)	99 kPa		*P* = (0.980 - 0.984) *Ps* (decreases with max. 2%)
253 K (-20 °C)	99 kPa	variable with *q*	*P* = (1.057 - 1.069) *Ps* (increase with max. 7%)
298 K (25 °C)	70 kPa (3000 m altitude)		*P* = (0.820 - 0.847) *Ps* (decreases with 15-18%)
269 K (-4 °C)	70 kPa (3000 m altitude)		*P* = (0.855 - 0.878) *Ps* (decreases with 12-15%)

The influence of pressure outweighs that of temperature, as it can be seen by comparing the last two rows of Table 2, that impact being also confirmed by study [5].

For the mean values of percentages in the brackets, it can be concluded that pressure effect on power is 13.5% and that of the temperature is 3%.

To be precise, the data from Table 2 exceeds the limits of ISO 1585 correction, which imposed ambient temperatures within 283-313 K and correction factors (Eq. 8), *Cf* = 0.9-1.1.

The influence of the humidity can be considered roughly 1% of pressure influence, knowing that for ISO and SAE standards, the reference value of water vapor pressure is p_{vs} =1 kPa and for atmospheric pressure, p_s = 100 kPa.

5. Conclusions

1. The road vehicle engine power rating legislation still includes gross and net power standards. The national standards as DIN 70020-4 and BS AU 141a became less spread and relevant. There is a tendency of convergence in the requirements of the SAE and ISO standards, along with a dominance of the same standards which are chosen to be complied by more countries worldwide.
2. In the conditions of the engine tested at 95 kPa and 16 °C the power rating tests have indicated rather high values of correction factors for DIN (1.059) and BS (1.027) standards. Smaller values have been found ISO (1.01094) and SAE (1.0104) conditions.
3. The difference between gross and net power ratings, which in this case was represented by cooling fan drive energy consumption, was less than 3%.
4. For the same ISO reference temperature, with the increase of altitude to 3000 m the power can drop to 82% of standard power. Similarly, for the same atmospheric pressure, the decrease of temperature with 29°C can increase power with 7%. Based on the analysis of the extrapolated data, according to tabulated atmospheric pressures and temperatures, it may concluded that atmospheric pressure has the dominant contribution on the power rating, approximately 80%.

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