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Ethanol charge stratification in supercharged spark-ignition low-displacement engines: An approach to energy efficiency

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Abstract. Due to the challenges encountered by the automotive industry in developing solutions to reduce carbon emissions and harmful gases, engines that consume fuels from renewable sources are a good alternative. In this context, applying technologies that increase the energy efficiency of engines and still contribute to the reduction of emissions is strongly desirable, to the point of being a research line of the route 2030 program of the federal government in Brazil. The present work presents results obtained in research within this thematic line, using as a base a supercharged low-displacement engine, with direct injection of ethanol in homogeneous and stratified charges. A brief review of the state of the art that guides the research will be presented, followed by all the methodology and equipment used to obtain the results. For the study, engines present in the Brazilian market are used, which use the technologies studied, always powered by ethanol as fuel. The engines used are the EA211 MPI and the EA211 TSI, equipped with Bosch programmable engine control centers (ECU), which will be used for experimental validation of simulated data in computational tools such as ETAS ASCET for the production of codes and ETAS INCA used for ECU development, testing, validation and calibration. The simulation of the overall operation of the engine is carried out by the AVL Boost and AVL Fire software, where flow, combustion and performance conditions are simulated. As a result, control strategies and operation maps are presented for different conditions, varying parameters such as lambda, fuel pressure, compressor pressure, EGR adjustment and fuel composition. In addition to performance and energy efficiency studies, NO_x emissions will be estimated using the Zeldovich mechanism and other combustion substances by chemical kinetics. For validation of the results, measurements of emissions using a NAPRO automotive gas analyzer will be used. At the end, it is intended to indicate limitations and propose engineering solutions for increasing energy efficiency in low-displacement engines, associated with the adequacy of emissions to current legislation.

Keywords: Stratified ethanol injection, Internal combustion engines, Engine control strategy.

1. INTRODUCTION

Since the invention of internal combustion engines in the 19th century, their evolution has been continuous, aiming to improve performance and durability in the automotive industry. Nowadays, as environmental awareness becomes a global imperative, the pursuit of engine improvement goes hand in hand with environmental concerns. Reducing pollutant emissions, decreasing fossil fuel consumption, and adopting more sustainable alternatives have become primary objectives in research and development of new automotive technologies. In this context, new approaches have gained prominence, promoting optimization of energy efficiency without compromising environmental balance.

The combination of supercharging and stratified charge has shown promising results in achieving higher energy efficiency in internal combustion engines. Studies such as Bui *et al.* (2019) and LanzaNova *et al.* (2019) have investigated the effects of these technologies on engine performance. Supercharging, through increased charge pressure, allows for a larger quantity of air and fuel to be introduced into the combustion chamber, resulting in better combustion and utilization of available energy. In turn, stratified charge enables the formation of a highly homogeneous air-fuel mixture near the spark plug, facilitating ignition and improving combustion.

Furthermore, the use of these technologies combined with ethanol as a fuel has also shown promise in achieving better efficiency. In this context, the study conducted by da Costa *et al.* (2018) investigated stratified combustion with ethanol in a low-displacement spark-ignition engine. The results showed a significant increase in the fuel conversion of the engine,

with a reduction in nitrogen oxides and hydrocarbon emissions.

Another strategy to improve energy efficiency is highlighted in the study by Nora *et al.* (2018), which investigated the performance and combustion characteristics of a supercharged two-stroke direct injection engine fueled with gasoline and ethanol. The research demonstrated that the supercharging system significantly increased the engine power, leading to improved performance at low loads. Additionally, the use of ethanol as a fuel proved beneficial, resulting in lower specific fuel consumption and reduced pollutant emissions.

The study by Santos *et al.* (2019) analyzed the combustion in a spark-ignition engine with a pre-chamber ignition system using ethanol and hydrogen as fuels. The results indicated that the combination of charge stratification and ethanol use resulted in improved combustion, with a decrease in the production of harmful substances to the environment.

Similarly, the article by Bui *et al.* (2019) showed that fuel mixture stratification, achieved through dual injection, allowed for better mixture preparation, resulting in more complete combustion. Moreover, the high octane rating of ethanol played a fundamental role in preventing detonation and enabled operation at higher compression ratios, contributing to higher engine performance.

In summary, these studies highlight the importance of technologies such as charge stratification, the use of ethanol as a fuel, and supercharging in achieving better energy efficiency in internal combustion engines. These approaches provide optimized combustion, reduce pollutant emissions, and contribute to the transition to a more sustainable automotive industry. Ongoing research and development in this field are essential to drive the evolution of engines and promote a future with more efficient and environmentally friendly vehicles.

In this context, the purpose of this study is to investigate ways to increase the efficiency of internal combustion engines through the application of technologies such as stratified direct injection and supercharging. Consequently, the development of these approaches will contribute to the creation of more efficient and sustainable automotive propulsion solutions.

2. Materials and methods

The fuel consumption can be obtained by determining the volume of air admitted by the engine. For this, the parameters obtained from the original electronic control unit of the tested vehicles were used, such as the intake manifold temperature, intake manifold pressure, and the lambda value commanded by the control unit. These parameters allow determining a consumption curve for each engine speed range. Finally, data from the power and torque graphs of the engine were cross-referenced to obtain the specific fuel consumption curve. The (Eq.1) provides the adapted equation for the model, considering the direct value of rotation per second rps to obtain consumption of air \dot{m}_{ar} ,

$$\dot{m}_{ar} = rps \cdot \frac{p_1 \cdot V_d}{R \cdot T_1} \quad (1)$$

The displacement volume of engine is represented by V_d in m^3 ; The density of air $\rho(T)$ is a function of temperature and it can be defined by $\frac{p_0}{RT}$ in $[kg/m^3]$.

The density of the mixture was calculated using (Eq.2), where M_m represents the mass of mixture, R_f the mass fraction of fuel, R_a the mass fraction of air, ρ_f the fuel density, and ρ_a the air density.

$$\rho_m = \frac{M_m}{\frac{M_m \cdot R_f}{\rho_f} + \frac{M_m \cdot R_a}{\rho_a}} \quad (2)$$

To calculate the volumetric efficiency e_V (Eq.7) we used \dot{m}_e to mass flow of mixture, N to engine rotation and x to number of engine strokes divided for 2.

$$e_V = \frac{\dot{m}_e}{\rho_m \cdot V_d \cdot N \cdot x} \quad (3)$$

The effective power \dot{W}_e (Eq.4), that means the power developed by the engine shaft, can be represented by

$$\dot{W}_e = T \cdot \Omega \quad (4)$$

where T represents torque [N.m] and Ω represents angular velocity [rad/s]. The specific fuel consumption on break ($bsfc$) equation 5, is the ratio between fuel consumption and effective power. In other words, it is a parameter of the engine's thermal efficiency in converting fuel into work (Brunelli, 2009).

$$bsfc = \frac{\dot{m}_f}{\dot{W}_e} \quad (5)$$

in which \dot{m}_f is the mass flow rate of fuel [kg/h] Directly obtained by the measuring system.

To calculate the time of injection (T_i) was used the follow equation (Eq.6)

$$T_i = \frac{\rho_0 \left(\frac{p_1}{p_0}\right) \left(\frac{T_0}{T_1}\right) V_d e_v}{\dot{V}_i n_i (A/F)} \quad (6)$$

The volumetric efficiency was measured using Equation 7, while the engine efficiency can be calculated using Equation 8.

$$e_v = \frac{\dot{m}_e}{\rho_m V_d N_e} \quad (7)$$

$$\eta = \frac{1}{b_{sfc} \cdot LHV} \quad (8)$$

where LHV stands for Low Heating Value and represents the amount of energy contained per unit mass of the fuel.

2.1 Vehicles used

Three test runs were conducted for each vehicle to evaluate the experiment's repeatability. The tests involved using a Volkswagen Up! equipped with an EA211 MPI engine and another Volkswagen Up! with an EA211 TSI engine. The manufacturer-provided data is shown in the following table 1. In both cases, the engines were fueled with ethanol, and the measurement conditions were adjusted according to ABNT 1585 standard, utilizing temperature, humidity, and atmospheric pressure sensors from the weather station of the Dynomite measurement system.

Table 1. Engine Specifications

	EA211 TSI	EA211 MPI
Displacement	999cm ³	999cm ³
Cylinder diameter	74.5mm	74.5mm
Piston stroke	76.4mm	76.4mm
Number of cylinders	3 in-line	3 in-line
Valves per cylinder	2	2
Compression ratio	10.5:1	10.5:1
Fuel injection system	Side-mounted Air-Guided Direct Fuel Injection	Port Fuel Injection
Maximum rated power	78.3kW(ethanol)@5000RPM	61kW(ethanol)@6350RPM
Maximum rated torque	168 Nm @ 1500 RPM	102 Nm @ 3000 RPM
Injection pressure	50-250 MPa	0.3 MPa
Ignition order	1-2-3	1-2-3
Variable valve timing range	50° on intake, 40° on exhaust	50° on intake, 40° on exhaust
Maximum boost pressure	100 kPa	NA
Engine operating temperature	87°C at head, 105°C at block	87°C at head, 105°C at block

2.2 Chassis Dynamometer

To gather vehicle performance curves, a 2WD (two-wheel drive) chassis dynamometer was utilized, featuring a set of four low-inertia rollers with a 12-inch diameter. It is equipped with an advanced eddy current absorber, an overdrive controller, and an S-beam load cell for precise measurements. Data acquisition was carried out using a DYNomite data acquisition system (DAQ) and DYNO-MAX PRO software, offering automatic load control and a 3-channel data set. This configuration allows for repeated testing, enabling multiple measurements and increasing sample accuracy. The measurement system has a resolution of 5%, and data can be exported as CSV tables for further analysis.

2.3 Tests procedures

Prior to the evaluation, vehicles equipped with 1.0L, 3-cylinder MPI and TSI engines were fueled with Brazilian Ethanol fuel (E100). Subsequently, the vehicles were positioned on a dynamometer with their front drive wheels placed on the rollers. Care was taken to ensure proper alignment of the vehicle on the equipment. The vehicles were securely fastened using four anchor points on the ground—two at the front and two at the back. Four ratchet straps were employed to crisscross the vehicle (forming an "X") at the front and rear, effectively preventing lateral forces that could compromise safety during the test. Following the calibration of parameters on the computer, such as gear ratio, atmosphere temperature and pressure of the environment tested, the engine cubic capacity. After setting the parameters, the vehicle was ready to undergo testing in order to obtain the torque and power curves.

To measure fuel consumption, an OBDII (On-board diagnostics II) reading device was utilized. This device received and transformed data from the vehicle's central system into a data table. Upon completion of these preliminary steps, the tests were conducted, and the resulting data was stored for subsequent analysis and calculations.

3. Results

The results obtained for the EA211 TSI engine are presented below, in Figure 1, indicating maximum power values of 103.7 hp (77.3 kW) with a margin of error of approximately 1.2 hp, and torque of 17.3 kgf.m (179.4 Nm) with a margin of error of approximately 0.9 kgf.m.

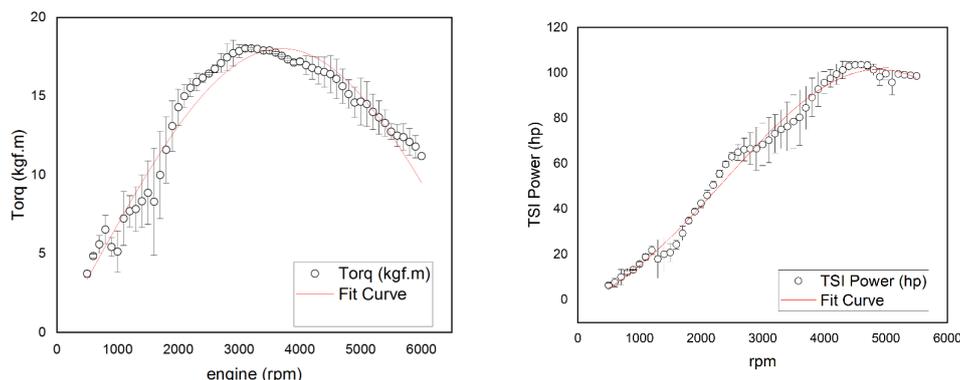


Figure 1. TSI Power in full load.

The results obtained for the EA211 MPI engine are presented below, in Figure 2, indicating maximum power values of 65 hp (48.5 kW) with a margin of error of approximately 1.2 hp, and torque of 9 kgf.m (88.25 Nm) with a margin of error of approximately 0.9 kgf.m.

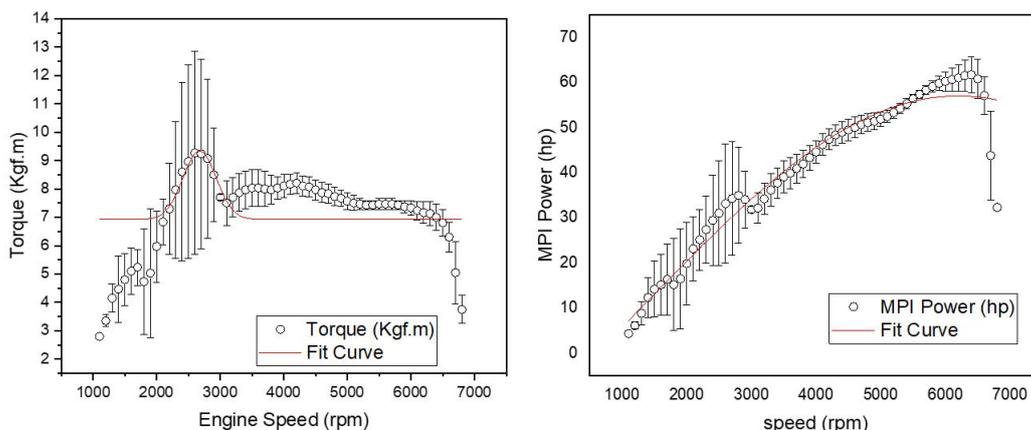


Figure 2. MPI Power in full load.

The specific consumption allows the comparison of the efficiency of completely different engines. I.e, how much fuel is spent per power generated per time and is expressed by kg/kWh. The graph in Figure 3 in question shows a comparison between the TSI (blue line) and MPI (orange line) engines.

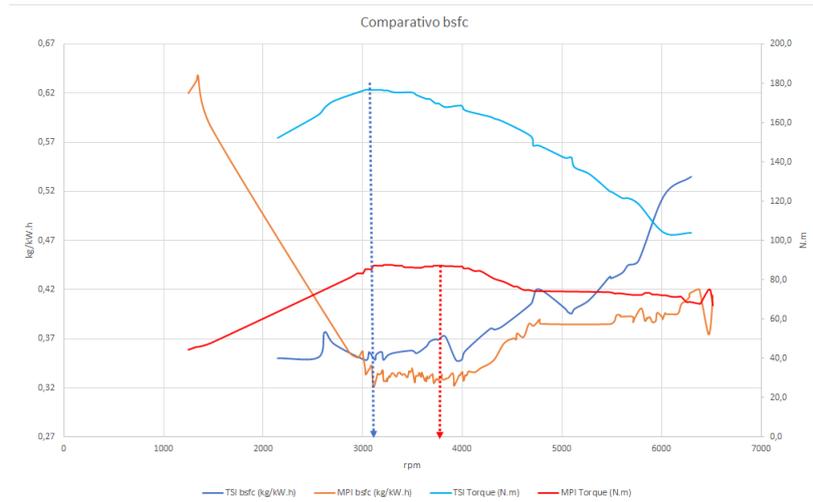


Figure 3. Comparative specific fuel consumption obtained at full load on a chassis dynamometer using vehicles equipped with EA211 MPI and EA211 TSI engines.

In Figure 3, it can be observed that the TSI engine demonstrates improved specific consumption in the maximum torque region spanning from 2000 to 3000 rpm. During this range, the TSI engine consumes 0.38 kg/kW.h and achieves an overall efficiency of 35% when fueled with ethanol. On the other hand, the multi-point injection engine (EA211 MPI) exhibits in the same region, a specific consumption of 0.39 kg/kW.h and an overall efficiency of 32%.

The power delivery of the TSI engine is significantly higher compared to the MPI engine due to important technological changes such as supercharging and direct fuel injection. By analyzing the graph in Figure 4, it is possible to observe the significant difference in behavior between the engines. This change in behavior also results in increased fuel consumption, which is considerably higher in the TSI engine compared to the MPI engine. In the maximum power region, the TSI engine delivers 77.3 kW with a bsfc of 0.39 kg/kW.h and an efficiency of 35%. On the other hand, the MPI engine delivers 50 kW with a bsfc of 0.37 kg/kW.h and an efficiency of 36%.

For the motor performance comparison, Figure 3 presents the torque and power data generated by the motors. It can be seen, in blue, that the TSI engine has higher levels of torque in all speed ranges and consequently higher levels of power. Performance results is shown by Figure 4.

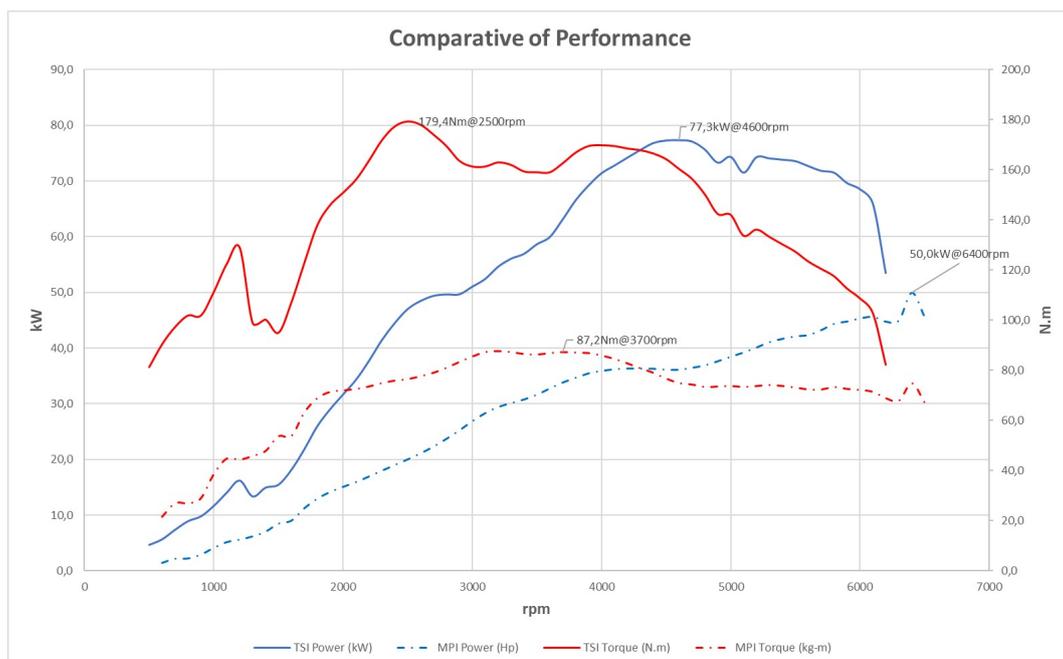


Figure 4. Performance comparison between the EA211 TSI and EA211 MPI engines, both with a displacement of 1 liter and fueled with hydrated ethanol.

It is also important to note that the TSI engine has its maximum torque, as well as its maximum power, presented at

a speed significantly lower than that of the MPI engine. Note also that the TSI engine has a performance of 175 N.m of torque at 3000 Rpm while the MPI engine has a maximum torque of 90 N.m at 3500 Rpm, a difference of approximately 1.95 times. In the comparison of power, the TSI engine has 75 kW of power at a speed of approximately 4000 Rpm, while the MPI engine has a maximum power at a speed above 6000 Rpm of approximately 45 kW, thus making the TSI engine 1.66 times more powerful in the engine performance comparison.

Figure 5 shows that there is a good similarity of the points of torque, power and specific consumption simulated through numerical models, with the real data obtained in a Roller dynamometer of the operation of the vehicles used. Thus validating the numerical model.

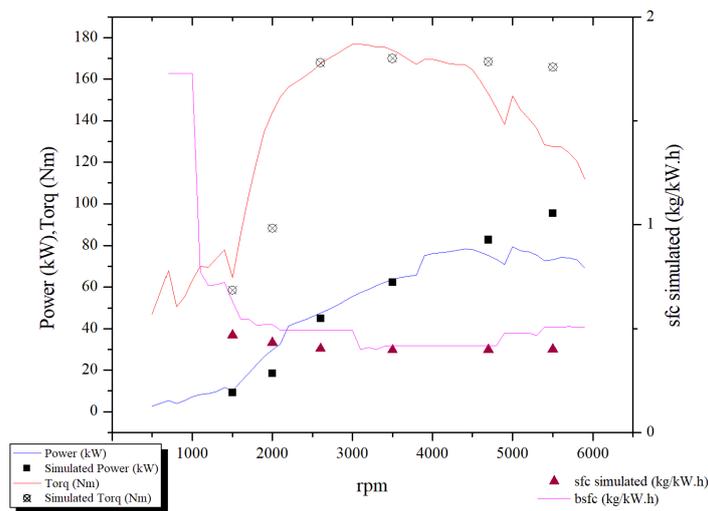


Figure 5. Performance comparison between the real and simulated for the EA211 TSI engine.

Figure 6 presents the energy balance of the engines analyzed in this work. It was expected that the TSI engine would have a higher efficiency in relation to exhaust, in this case 6 percent higher, as the turbo is responsible for reusing part of the energy that would be wasted. For mechanical efficiency, the TSI engine features variable valve timing both at the inlet and outlet of gases, thus causing greater mechanical loss. For the cooling efficiencies and for the cycle, the TSI presented a low, since it is a turbo powered vehicle without the presence of the inter cooler, this causes the admitted air to heat up, making it less dense and consequently less efficient.

In comparison, the EA211 TSI engine shows greater efficiency in harnessing the energy from the fuel. Consequently, it can generate more power while consuming fuel at a lower rate per hour, in the region of maximum torque.

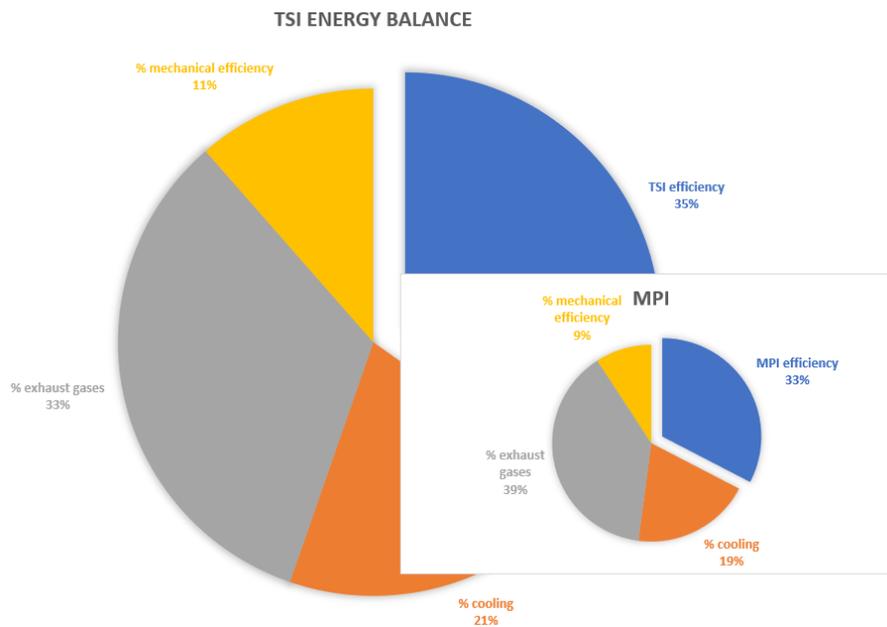


Figure 6. comparative of energy balance between the tested engines.

4. Conclusion

As can be seen in the graphs presented in the results and discussions section, which represent the tests conducted on the chassis dynamometer and the analysis of parameters provided by the electronic control unit for the indirect extraction of the specific consumption curve of EA211 engines in the indirect MPI injection version and turbocharged with TSI direct injection, it was possible to gather information and generate knowledge regarding how the technologies observed in this analysis contribute to the transformation of current engines. Thus, it is possible to downsize engines, such as 3-cylinder engines, while achieving a balance between performance and energy efficiency. Therefore, the choice of a supercharged engine with direct injection has positively influenced this scenario.

It is possible to infer from the statement that the technologies present in the VW EA211 1.0 L TSI engine, when compared to the EA211 1.0 L MPI engine, result in significant performance improvements:

- **Effective Power Increase:** The TSI engine is capable of generating a 66% increase in effective power. This means that the TSI engine delivers 66% more power than the MPI engine, which can result in better acceleration and overall performance.
- **Gain in Moment of Force (Torque):** The TSI engine also exhibits a 95% gain in moment of force (torque) in absolute values. Torque is essential for low-end power and acceleration, so this increase can lead to improved performance, especially in situations like starting from a stop or climbing hills.
- **Specific Consumption:** The TSI engine has lower specific fuel consumption, especially at typical city driving speeds. This means that it is more fuel-efficient in urban driving conditions. This improved efficiency is attributed to direct injection technology and the reuse of energy present in exhaust gases, which helps reduce fuel consumption and emissions.

In summary, the VW EA211 1.0 L TSI engine seems to offer significant advantages over the EA211 1.0 L MPI engine in terms of power, torque, and fuel efficiency. These improvements are likely due to the utilization of direct injection technology and energy recovery from exhaust gases, which are common features in modern engines aimed at achieving better performance and efficiency.

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7. RESPONSIBILITY NOTICE

The authors Túlio Costa de Oliveira, Fábio Cordeiro de Lisboa, Yago Levi Acypreste Benazio, Gabriella Reinert Tosta and Raul Fernando Sanchez Aguilar are solely responsible for the printed material included in this paper.