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# Experimental Evaluation of CO and $CO_2$ Emissions and Thermal Parameters in a Baja Off-Road Vehicle Equipped with a Stationary Engine

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**ABSTRACT**
This study experimentally evaluates pollutant emissions and thermal-operational parameters of a stationary gasoline engine installed in a Baja off-road vehicle. Using a Testo 310-II portable gas analyzer, concentrations of carbon monoxide (CO), carbon dioxide ($CO_2$), and oxygen ($O_2$) were measured under six engine speeds. Exhaust temperature (TF), relative air intake (qA), excess air factor (lambda, $\lambda$), and engine efficiency (REN) were also recorded. Polynomial fitting was applied to identify behavioral trends and correlations. Results showed an inverse relationship between engine speed and CO emissions, indicating more complete combustion at higher RPM. In contrast, $CO_2$ increased with speed, reinforcing improved combustion efficiency. Both $\lambda$ and $O_2$ decreased as load increased, suggesting richer mixtures under higher thermal demand. qA increased proportionally with engine speed, evidencing enhanced volumetric filling at high RPM. The combined behavior of thermal parameters and efficiency supports combustion diagnosis under realistic off-road operating conditions. Findings were compared with international studies and aligned with Brazilian environmental regulations, emphasizing the environmental importance of low-power stationary engines used in small vehicles. This work contributes to understanding emission patterns in Baja-type engines and provides insights for future monitoring strategies and emission control policies in non-urban transport applications.
***Keywords* -** Internal Combustion Engine, Baja Off-Road Vehicle, Gaseous Emissions, Thermal Efficiency, Air-Fuel Ratio

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## I. INTRODUCTION

Several international studies have highlighted the impact of vehicle emissions on urban air quality and public health. Sharma et al. (2020) [1] conducted a large-scale analysis of 181 vehicles in the National Capital Region of Delhi, revealing that many automobiles exceed legal emission limits for CO, $CO_2$, and HC. Pollution was attributed to the aging of the fleet, population growth, and rapid urbanization. The authors advocate the urgent need for stricter public policies, incentives for alternative fuels, and improvements in public transportation.

Habib et al. (2017) [2] investigated CO, $CO_2$ and $NO_x$ emissions from four-wheeled vehicles using real-time exhaust measurements. The study showed that diesel vehicles have higher $NO_x$ emissions, while gasoline-powered vehicles release more CO. CNG vehicles had the lowest emission rates for all pollutants. The authors recommend expanding the use of CNG and electric vehicles, in addition to continuous monitoring based on real measurements.

Habib and Jaiprakash (2018) then complemented these findings by analyzing emissions from light vehicles on different types of roads and at different speeds. They found that $NO_x$ emissions remain a challenge in diesel vehicles, while CO emissions are predominant in gasoline vehicles. The study highlights the influence of speed and acceleration on emissions, reinforcing the need for policies that consider real urban driving conditions.

Mei et al. (2021) [4], using a Portable Emissions Measurement System (PEMS), characterized CO, HC, and $NO_x$ emissions in urban, suburban, and highway routes. They concluded that urban roads generate higher emissions due to heavy traffic and frequent stops. CO and HC stand out at low speeds and accelerations, while $NO_x$ increases at speeds above 40 km/h.

Yang et al. (2020) [5], when studying Euro 6b vehicles powered by gasoline and diesel in France, showed that, although gasoline vehicles emit less $NO_x$, their emissions of CO, $CO_2$ and THC are higher, especially during cold starts. Diesel vehicles, on the other hand, despite emitting less $CO_2$, continue to be significant sources of $NO_x$. Both groups presented emission levels above the legal limits under certain operating conditions, pointing to limitations of the regulations when applied to real conditions.

Taken together, these studies reinforce that, although technological advances have significantly reduced some emissions, challenges persist, especially in urban environments. The use of data obtained under real-world conditions is essential to validate technologies, inform public policies and guide more effective future regulations.

In this work, an experimental study was carried out on a Baja off-road vehicle , equipped with a stationary engine, to analyze gas emissions at different rotation speeds. This type of platform is widely used in academic environments because it allows greater control of experimental variables and simulates real engine stress conditions, without interference from urban traffic. The adopted methodology allowed the direct measurement of critical parameters, such as CO, $CO_2$, $\lambda$, $O_2$, REN, TF and qA, providing reliable and repeatable data in the laboratory. Recent studies confirm the correlation between gas temperature and engine operating speeds [6].

## II. METHODOLOGY

The study was conducted on a Baja-type off-road vehicle (Fig.1a), equipped with a 10 HP Briggs & Stratton stationary engine (Fig.1b), single-cylinder, and powered by regular gasoline. This type of vehicle is widely used in academic settings because it allows controlled testing of mechanical and thermal systems, with easy access to components for instrumentation and analysis purposes.

To assess gaseous emissions, a Testo 310-II combustion gas analyzer, calibrated according to the manufacturer's specifications, was used. This equipment allows direct measurement of the volumetric concentration of carbon monoxide (CO) and carbon dioxide ($CO_2$) in the exhaust gases. Measurements were performed with the analyzer probe positioned directly in the engine exhaust, after stabilization of the selected rotation speed. Readings were recorded in parts per million (ppm) for CO and in percentage (%) for $CO_2$. The reliability of portable analyzers such as the Testo 310-II was highlighted by Zhou et al. (2021) in applications with small engines.

(a)

(b)

Fig. 1. Academic Baja-type off-road vehicle Briggs & Stratton 10 HP Gasoline Engine

The engine speeds were manually adjusted on a test bench, based on the reading of a digital tachometer. For each regime (140, 380, 820, 1500, 2660 and 3200 RPM), the gases were analyzed after approximately 30 seconds of stabilization. For greater precision, three measurements were performed per point, adopting the average as a representative value.

In addition to CO and $CO_2$ concentrations, auxiliary parameters such as residual oxygen concentration ($O_2$), lambda factor ($\lambda$), exhaust gas temperature (TF), estimated thermal efficiency (REN) and relative air quantity (qA) were also determined,

based on the analyzer's own internal calculation functions and formulas applied from the measured data. Recent studies confirm the correlation between gas temperature and engine operating speeds [6].
All data were organized in spreadsheets and subjected to statistical analysis, including second-order polynomial adjustment and calculation of Pearson's correlation coefficient, aiming to identify trends and relationships between the monitored parameters and the engine rotation speeds. The results were subsequently compared with values found in the international literature.
The fuel was purchased at a gas station in the city of Cachoeiro de Itapemirim-ES, Brazil. The detection of exhaust gases was done using a probe, which when inserted into the engine exhaust directs the flow of gases. After the engine speed stabilized, a detection time of 2 minutes was stipulated for each measurement, performing three repetitions at low and high speed and the value adopted will be the average value.
The engine speed was measured using a digital tachometer model TDV100, manufactured by Vonder.

### 2.1 Dilution Factor and CO corrected

Dilution can occur due to uncontrolled air entering the exhaust pipe, usually due to leaks or sealing failures. This dilution reduces the measured values of carbon monoxide (CO) and carbon dioxide ($CO_2$), since the ambient air introduced dilutes the concentration of gases actually emitted by the engine.
For gasoline engines in good working order, the sum of the volumetric contents of CO and $CO_2$ in the exhaust gases should be close to 15%, considering complete combustion. When this sum is lower than this value, it is assumed that there is false air intake, characterizing dilution. Although this phenomenon indicates the presence of unburned air in the system, it does not directly quantify its proportion [8]. According to Brazilian legislation, as established by CONAMA, the maximum dilution allowed for vehicle approval is 6% [9].
In addition, the correction factor (CF) is used to estimate the actual value of CO emitted, compensating for the effects of dilution. This factor is calculated based on the ratio 15 / (CO + $CO_2$). The logic behind this calculation is that all the carbon present in the fuel must be converted to $CO_2$ or CO; therefore, their sum should be close to 15%. The lower this sum, the greater the dilution, and therefore the higher the correction factor.
Corrected CO is obtained by multiplying measured CO by the correction factor. This variable represents a more accurate estimate of the actual CO concentration emitted by the engine, especially in the presence of leaks. When corrected CO > measured CO, this is a clear indication of dilution and therefore false air entry into the exhaust system.

## III. RESULTS AND DISCUSSIONS

Internal combustion engines remain one of the main technologies used for energy conversion in transportation systems, power generation and industrial machinery. Their operation is based on the controlled burning of fossil or alternative fuels, releasing thermal energy that is transformed into mechanical work. However, this process also generates gaseous byproducts — such as carbon monoxide (CO), carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$), unburned hydrocarbons (HC) and particulate matter — with significant implications for system efficiency and the environment [10].

The characterization of these gases is essential to optimize energy performance and control atmospheric emissions. Parameters such as CO and $CO_2$ provide direct indications of combustion efficiency — with CO being associated with incomplete combustion and $CO_2$ with the total combustion of the carbon present in the fuel [11]. The residual oxygen ($O_2$) content in the gases reveals the proportion of excess or deficient air, which, together with the lambda factor ( $\lambda$ ), allows us to infer the mixture condition (rich or lean) in the combustion process [12].

Exhaust gas temperature (ET) is related to combustion intensity and engine thermal load, and is an indicator of volumetric efficiency and operating point. Thermal efficiency (REN) expresses the efficiency with which chemical energy is converted into useful work, being impacted by factors such asrotation, compression ratio and mixture composition [13]. Recent studies confirm the correlation between gas temperature and engine operating regimes [6].

Furthermore, the relative quantity of air (qA) and the lambda factor itself are crucial for the control of modern electronic injection systems, enabling dynamic adjustments for different operational objectives, such as economy, power, and environmental compliance. As highlighted by Arantes et al. (2011) [14], gas analysis allows the identification of emission patterns and the proposal of more efficient control strategies. As discussed by Morris et al. (2020) [15], control of the air- fuel mixture by electronic strategies is essential to mitigate emissions under real conditions.

In this way, monitoring and integrated analysis of these parameters allows us to understand combustion quality and guide the development of cleaner and more efficient technologies. A deep understanding of these phenomena is essential for future automotive engineering and for advancing environmental policies .

Fig.2 presents the polynomial fit to experimental carbon monoxide (CO) emission data as a function of engine speed (RPM). The observed behavior indicates an initial trend of increasing emissions up to a certain speed, followed by a reduction at higher speeds, reflecting a possible improvement in combustion efficiency.

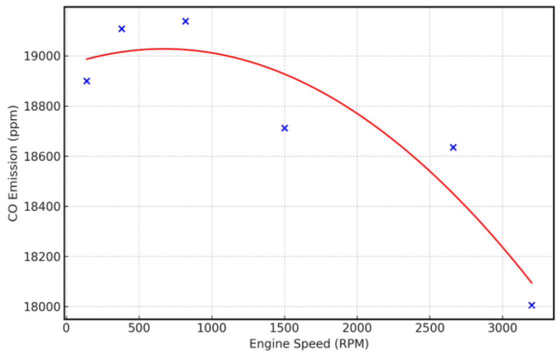


Fig. 2. Relationship between revolutions per minute (RPM) and carbon monoxide (CO) emissions, expressed in parts per million (ppm).

This behavior is consistent with the results found by Arantes et al. (2011) [14], who analyzed agricultural engines and observed that increasing load and rotation speed led to a reduction in CO emissions, due to improved combustion efficiency. According to the authors, the engine operating speed has a more significant influence on emissions than the type of fuel used.

Similarly, Oliveira et al. (2021) [16] found that increasing rotation speed results in a higher temperature in the combustion chamber, which favors the oxidation of CO into $CO_2$, thus reducing its concentration in the exhaust gases.

Such evidence reinforces the importance of operational control of engines — especially rotation — as an effective strategy for mitigating the emission of atmospheric pollutants.

Nonlinear behavior is observed, with a slight increase in emission up to approximately 820 RPM, followed by a downward trend as the rotations increase. The red curve represents the second-degree polynomial fit applied to the experimental data, evidencing an inflection point characteristic of this behavior.

The adjusted model indicates that, at higher rotation speeds, there is a reduction in CO emissions, which may be related to the improvement in combustion efficiency. These results suggest that engine speed control may be a relevant variable in mitigating atmospheric pollutant emissions, especially in automotive systems.

During the experimental tests, carbon monoxide (CO) emissions were quantified in their diluted form, indicated by µCO (Fig.3). This procedure consists of the controlled dilution of exhaust gases with ambient air or inert gas, a technique widely used in emissions analysis to simulate real atmospheric conditions and ensure the stability and safety of measurements.

Dilution allows:

- Avoid saturation of analytical sensors;
- Reduce interference due to condensation or high concentration of compounds;
- Increase data reproducibility;
- Facilitate comparison with normative standards and scientific literature.

As pointed out by Braga (2010) [11] , the measurement of diluted CO is also related to the control of the air-fuel ratio (λ), with rich mixtures — with less oxygen availability — tending to increase the formation of CO. In the present study, the concentrations of µCO showed a decreasing behavior with the increase in rotations, which suggests an improvement in combustion efficiency and a higher oxidation rate of CO to $CO_2$ at higher operating regimes.

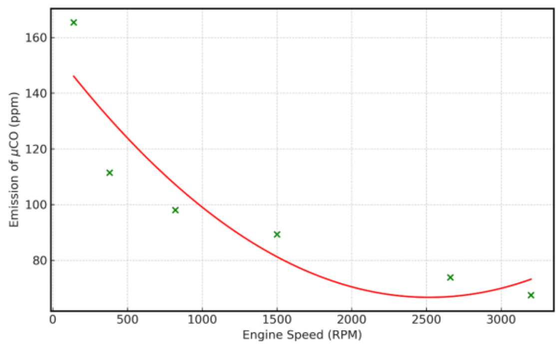


Fig. 3. Carbon monoxide (µCO) emission, in ppm, as a function of engine speed (RPM)

The data indicate a decreasing trend in diluted CO emissions as engine speeds increase, highlighting a possible improvement in combustion efficiency at higher engine speeds. This behavior can be attributed to factors such as:

· Increased combustion temperature at high speeds, favoring the oxidation of CO into $CO_2$;

· Greater efficiency of the air-fuel mixture (lower λ rich ratio), promoting more complete combustion;

· Reduction in partial combustion time , with less formation of intermediate species.

This pattern is consistent with the results of Gomes et al. (2017) [10], who demonstrated that diesel engines operating at higher temperatures present lower CO emissions, and with Braga (2010) [11], who demonstrated the direct dependence of CO on the control of the air-fuel mixture (λ ratio).The data obtained for carbon dioxide ($CO_2$) emissions, expressed as a percentage, as a function of engine speed (RPM), demonstrated a clearly increasing trend, as shown in Fig.4:

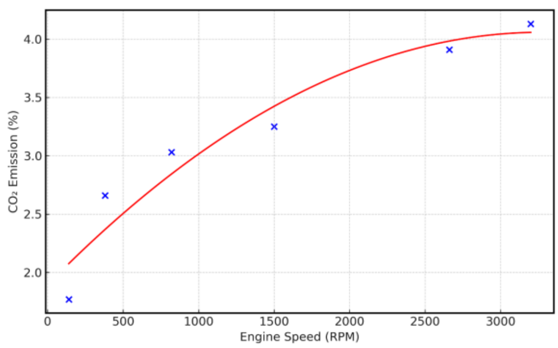


Fig. 4. Carbon dioxide ($CO_2$ ) emission, in % (v/v), as a function of engine speed (RPM)

This correlation suggests that as engine speed increases, combustion efficiency improves. This is because the oxidation of carbon in the fuel becomes more complete, resulting in increased production of $CO_2$ – the desired end product of ideal combustion.

Furthermore, this behavior is often accompanied by the reduction of intermediate species, such as carbon monoxide (CO), as observed in the µCO emission data, which reinforces the greater thermal efficiency at high operating regimes.

However, increased $CO_2$ emissions also indicate greater release of greenhouse gases, which requires attention to environmental impact. Strategies such as the use of biofuels or post-treatment systems may be viable alternatives to mitigate this effect. Müller et al. (2022) [17] also observed that higher rotations tend to increase $CO_2$ emissions due to greater combustion efficiency.

These observations are in agreement with the studies, which demonstrate that higher rotations and temperatures favor the conversion of CO into $CO_2$, reflecting cleaner and more efficient combustion [11,14].

Several international studies corroborate the positive correlation between engine speed and carbon dioxide ($CO_2$) emissions, reinforcing the experimental observations obtained in this work.

Kim et al. (2024), when analyzing emissions in maritime vessels, observed that the increase in engine speed is directly associated with the increase in $CO_2$ emissions. According to the authors, this is due to the higher fuel consumption and the consequent more complete combustion under high operating loads [12].

Similar results were obtained in a study, which investigated the effect of bioethanol blends on emissions in internal combustion engines. It was identified that higher engine speeds led to increased $CO_2$ emissions, especially with blends containing bioethanol, demonstrating more efficient combustion [18].

Finally, Senecal and Reitz (2015) address the influence of the operating regime on emissions in their review of reactivity controlled combustion (RCCI). The authors point out that, although high rotation tends to increase $CO_2$ due to greater efficiency, strategies such as RCCI can mitigate this effect, promoting cleaner emissions [13].

These studies reinforce the direct relationship between increased rotation and increased $CO_2$

emissions, indicating that combustion efficiency, although desirable from an energy point of view, must be accompanied by technological solutions that minimize adverse environmental impacts.

Fluid temperature (TF), represented in this study by the air temperature in the exhaust system, presents a strong positive correlation with increasing engine speeds (Fig.5). Experimental data reveal that, as the engine operates at higher speeds, the fluid temperature also increases, with the exception of a slight stabilization at very high speeds (3200 RPM). The calculated Pearson correlation coefficient was r = 0.95, indicating a strongly positive relationship. Recent studies confirm the correlation between gas temperature and engine operating speeds [6].

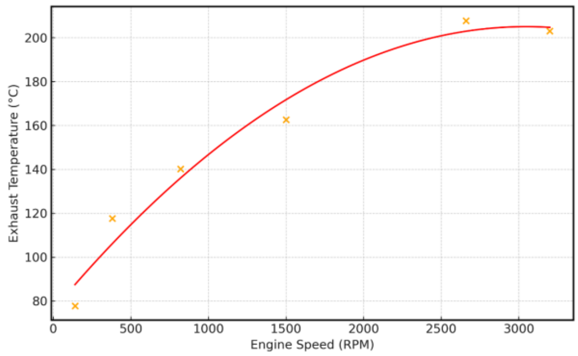


Fig. 5. Exhaust Gas Temperature at Different Rotation Speeds

This behavior is associated with the increase in energy released in the combustion chamber at high speeds, which raises the temperature of the exhaust gases. According to Kim et al. (2024) [12], this trend is typical in more intensive combustion systems, in which the greater engine load implies greater heat release. Furthermore, as pointed out by Senecal and Reitz (2015), high exhaust temperatures are indicative of more complete combustion and greater thermal efficiency. Recent studies confirm the correlation between gas temperature and engine operating regimes [6].

However, the slight drop observed in TF at 3200 RPM may be related to engine thermal control strategies, such as mixture enrichment or cooling system action, which aim to prevent overheating at extreme speeds. Braga (2010) [11] also discusses that, at very high speeds, the residence time of gases in the combustion chamber decreases, which can limit heat transfer and slightly reduce the exhaust gas temperature.

Therefore, the data confirm that fluid temperature can be used as an indirect parameter of combustion intensity, being useful in the evaluation of energy efficiency and in the thermal diagnosis of internal combustion engines.

The data obtained for the engine efficiency (REN), expressed as a percentage, as a function of the rotations (RPM) (Fig.6), reveal a decreasing trend up to approximately 2660 RPM, with a slight recovery observed at 3200 RPM. The 2nd degree polynomial fit applied to the data reflects this behavior with high fidelity. The variation indicates that the engine reaches its highest efficiency at low rotation regimes, which is characteristic of conventional internal combustion thermal systems.

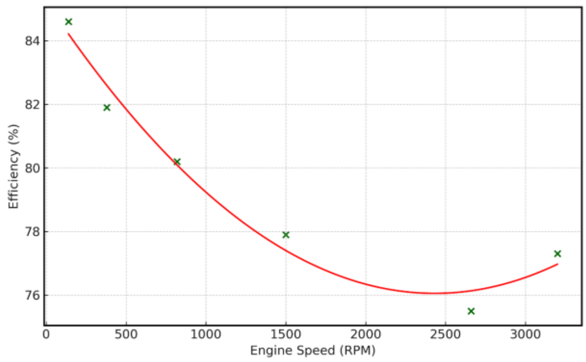


Fig. 6. Variation in efficiency (%) as a function of engine speed (RPM)

air-fuel mixture and combustion time. At high rotations, the useful combustion time is reduced, which can compromise efficiency, justifying the drop in efficiency.

On the other hand, the slight increase in REN observed at 3200 RPM may be associated with interventions in the engine's electronic control system, which adjusts parameters such as ignition advance, air-fuel mixture and injection pressure to compensate for thermal losses. Kim et al. (2024) [12] also highlight that, in vessels and heavy engines, electronic control strategies can act to maintain performance stability even in extreme rotation ranges.

Braga (2010) [11] emphasizes that Otto engines present maximum efficiency at speeds close to full load, but below peak power, reinforcing the importance of identifying the range of best energy performance for specific applications. Therefore, the experimental data presented here are consistent with the literature and highlight the importance of optimizing engine operation in speed ranges that maximize thermal and energy efficiency.

The lambda factor (λ) is a dimensionless quantity that expresses the ratio between the amount of air actually supplied to the engine and the amount of air required for stoichiometric combustion of the fuel. In mathematical terms, it is defined as Eq. (1):

$$\lambda = \frac{real\ air-\ fuel\ ratio}{stoichiometric\ air-\ fuel\ ratio} \quad (1)$$

This parameter allows us to assess whether the air-fuel mixture is ideal, rich or lean:

· λ = 1: stoichiometric (ideal) mixture – there is exactly the amount of air needed to burn all the fuel;

· λ > 1: lean mixture – there is excess air in relation to fuel;

· λ < 1: rich mixture – there is excess fuel and a deficiency of air.

Lambda factor control is essential in modern electronic injection systems, as it allows for the simultaneous optimization of engine performance, fuel consumption, and pollutant emissions. Rich mixtures are common at high speeds and high loads to ensure combustion chamber cooling and prevent detonation. Lean mixtures are used in low-load regimes to achieve thermal efficiency and reduce consumption. As discussed by Morris et al. (2020) , control of the air-fuel mixture by electronic strategies is essential to mitigate emissions under real-world conditions.

*Fig.7* shows the variation of the lambda factor (λ) as a function of engine speed. This parameter represents the ratio between the actual amount of air admitted and the stoichiometric amount required for complete combustion of the fuel. Graphical analysis allows identifying the rich (λ < 1), stoichiometric (λ ≈ 1) or lean (λ > 1) mixture regimes. Lourenço and Menezes (2022) [19] highlighted the influence of the air-fuel ratio on pollutant emissions in small engines.

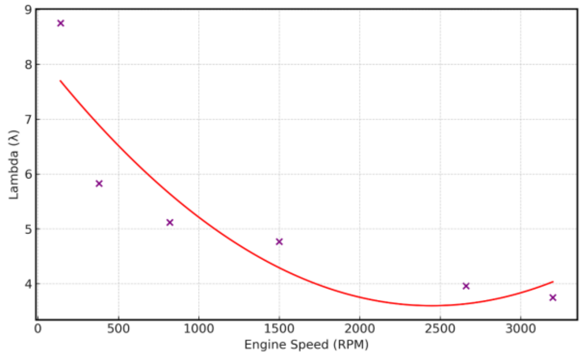


Fig. 7. Variation of the lambda factor (λ) as a function of engine speed (RPM).

The lambda factor (λ), which represents the relative air-fuel ratio, showed a decreasing trend with increasing engine speed (RPM). The data reveal that at low speeds the engine operates with an extremely lean mixture (λ > 8), while at higher speeds the mixture approaches stoichiometry, with λ around 3.75. The 2nd degree polynomial fit applied to the data demonstrated good adherence to the observed behavior.

The Pearson correlation coefficient obtained was r = -0.82, indicating a strong negative correlation between the increase in rotation and the reduction in the lambda factor. This behavior is consistent with typical engine calibration strategies, in which, to ensure performance and thermal control, the mixture tends to be enriched at high rotations (lower λ), favoring thermal dissipation and avoiding the occurrence of detonation. As discussed by Morris et al. (2020) [15], control of the air-fuel mixture by electronic strategies is essential to mitigate emissions in real conditions.

Braga (2010) [11] highlights that the presence of CO is directly associated with the lack of oxygen in the mixture, with λ being a fundamental parameter in emissions control. According to Senecal and Reitz (2015) [13], modern electronic engine management systems use lambda factor control to simultaneously optimize fuel consumption, emissions, and performance, especially in high-speed transients.

Thus, the progressive reduction of the lambda factor with increasing rotation speeds reinforces the hypothesis of intentional enrichment of the air-fuel mixture as a thermal control and combustion optimization strategy. This practice is common in Otto and Diesel cycle engines with electronic injection programmed to prioritize performance at high rotation speeds.

The quantity of air admitted (qA) represents the relative fraction of air entering the engine compared to the maximum quantity theoretically possible under ideal intake conditions. Generally expressed as a percentage (%), qA provides an estimate of the volumetric efficiency of the engine, that is, the capacity of the cylinder to suck in atmospheric air in each intake cycle. qA is influenced by variables such as engine speed, temperature, pressure, cylinder head characteristics and the presence (or not) of supercharging. High qA values indicate greater cylinder filling efficiency, being desirable to improve engine power and performance [20].

Fig.8 illustrates the variation in the quantity of air admitted (qA) as a function of engine speed. This parameter is directly related to volumetric efficiency, reflecting the use of the engine's suction capacity at different operating speeds.

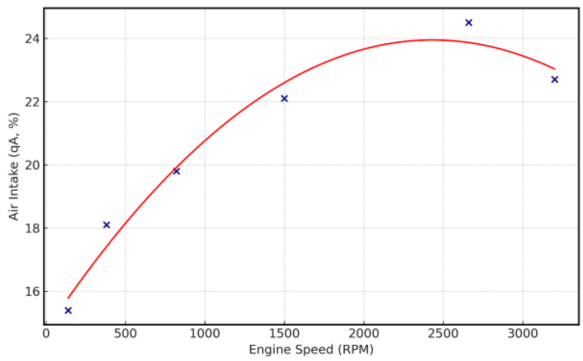


Fig. 8. Variation in the quantity of air admitted (qA, in %) as a function of engine speed (RPM).

The quantity of air admitted (qA), expressed as a relative percentage, showed a strong positive correlation with the increase in engine speed, with a Pearson correlation coefficient of r = 0.89. The data show a progressive increase in qA up to approximately 2660 RPM, followed by a slight reduction at 3200 RPM. This behavior is typical in internal combustion engines with natural intake or even with variable electronic control, reflecting the use of volumetric efficiency in different operating regimes.

The increase in qA at low and medium speeds is associated with the greater demand for power and the consequent need for air to maintain the appropriate proportion in combustion. According to Braga (2010), the amount of air admitted directly influences the formation of pollutants and the thermal efficiency of the engine, being essential to maintain an efficient mixture. Senecal and Reitz (2015) [13] point out that, at high speeds, a slight reduction in qA may occur due to the limitation of intake time and air flow dynamics, especially in engines without supercharging.

This final oscillation in the qA value can also be attributed to control strategies of the electronic control unit, which adjusts the valve opening time and injection advance to maintain the thermal and operational stability of the engine. Kim et al. (2024) [12] reinforce that, in modern systems, the variation of qA is part of a complex real-time control strategy to simultaneously meet performance, economy and emissions criteria.

*Fig.9* shows the variation in oxygen concentration ($O_2$) in exhaust gases as a function of engine speed. This parameter allows us to assess the degree to which oxygen is used in combustion and to infer the air-fuel ratio used in different operating regimes.

The oxygen concentration ($O_2$) in the exhaust gases corresponds to the amount of oxygen that was not consumed during the combustion process in the engine and that remains in the combustion products. This parameter is usually expressed as a percentage by volume (%) and serves as an indication of the air-fuel ratio of the mixture. Under conditions of complete and stoichiometric combustion, the amount of residual oxygen tends to be low, since all the oxygen is consumed in the reaction with the fuel. High $O_2$ values in the exhaust indicate the presence of lean mixtures (excess air), while lower concentrations are associated with rich mixtures (excess fuel). Measuring the $O_2$ concentration is essential for combustion diagnosis, emissions control and fine adjustment of the mixture by electronic injection control units (ECU) [21].

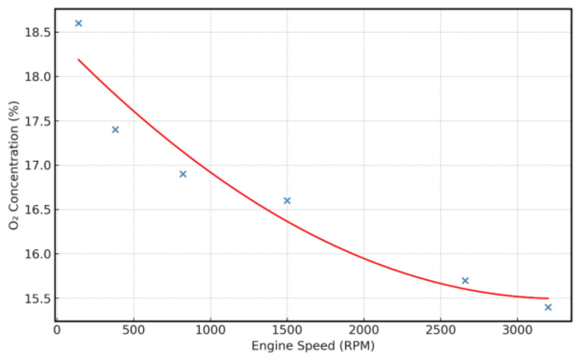


Fig. 9. Variation in oxygen concentration ($O_2$) in exhaust gases as a function of engine speed (RPM).

The oxygen concentration ($O_2$) in the exhaust gases showed a decreasing trend with increasing engine speed, as evidenced by polynomial fit to the experimental data. This behavior indicates that, as the speed increases, the oxygen available in the exhaust system decreases, which is compatible with more intense combustion and the use of richer air-fuel mixtures.

According to Braga (2010) [11], lower $O_2$ values in the exhaust suggest greater oxygen consumption in the combustion process, which may occur both due to greater energy demand and due to strategies to enrich the mixture for thermal control. In engines with electronic injection, the management of the air-fuel mixture at high speed generally aims to preserve thermal integrity and performance, which results in less excess air and, therefore, lower $O_2$ concentration in the exhaust.

Kim et al. (2024)[12] highlight that, in modern combustion engines, the reduction of $O_2$ content in the exhaust is strongly correlated with the power delivered and with the adaptation of the injection system in real time. This parameter is also used to adjust the performance of catalysts, which depend on the air-fuel ratio to promote pollutant conversion reactions.

The observation of the continuous drop in $O_2$ up to 3200 RPM confirms the trend of greater use of oxygen in the combustion chamber and complements the previous analyses of lambda factor ( $\lambda$ ), REN and qA, pointing to an increasingly richer and more efficient operation at higher rotation regimes.

The analysis of the experimental parameters obtained in this study was compared with the limits established by current Brazilian legislation, mainly through the Air Pollution Control Program for Motor Vehicles (PROCONVE), coordinated by CONAMA. The PROCONVE L7 (for light vehicles) and P8 (for heavy vehicles) phases define maximum limits for emissions of carbon monoxide (CO), hydrocarbons, nitrogen oxides ($NO_x$) and particulate matter, in addition to requiring the use of on-board diagnostic (OBD) systems and tests under real conditions [22,23].

The CO and μCO emissions observed in this study showed a decreasing trend with increasing rotations, indicating greater combustion efficiency. This behavior is consistent with the limits established in phases L7 and P8, which predict values below 1.0 g/km (light vehicles) and 1.5 g/kWh (heavy vehicles) [22,23]. This performance suggests compliance with CO emission standards.

Although carbon dioxide ($CO_2$) is not yet regulated as a legal limit in Brazil, it is used as an indicator of energy efficiency and greenhouse gas emissions. The data shows an increase in $CO_2$ with RPM, which indicates more complete combustion, compatible with greater thermal efficiency.

The lambda factor ($\lambda$), although not directly regulated, is monitored by OBD systems and is directly related to the formation of CO and $NO_x$. The $\lambda$ values varied according to the rotation, indicating a transition between lean and rich mixture - expected behavior and consistent with modern electronic control strategies [22]. As discussed by Morris et al. (2020) [15], control of the air-fuel mixture by electronic strategies is essential to mitigate emissions under real conditions.

The progressive reduction in $O_2$ concentration and the increase in the amount of air (qA) allow for greater oxygen consumption in combustion, which is consistent with greater energy demand at high speeds. The fluid temperature (TF), which increases with RPM, suggests efficient thermal operation of the engine, compatible with the requirements for ideal operation of aftertreatment systems, such as catalysts.

Furthermore, CONAMA Resolution No. 418/2009 [9] establishes criteria for vehicle inspection and maintenance, with the aim of maintaining emissions within legal limits throughout the vehicle's useful life. In this context, the data presented also contribute to demonstrating thermal and emission stability throughout different operating regimes.

Therefore, the data analyzed indicate that the engine operates in accordance with the principles of current Brazilian legislation regarding combustion quality, thermal efficiency and pollutant control. These results indicate that, under real standardized test conditions, such as the FTP-75 cycle, the engine evaluated would have a strong chance of meeting the PROCONVE requirements.

## IV. CONCLUSION

The joint analysis of the measured parameters — carbon monoxide (CO and μCO), carbon dioxide ($CO_2$), residual oxygen ($O_2$), exhaust gas temperature (TF), thermal efficiency (REN), lambda factor (λ) and quantity of air admitted (qA) — reveals a panorama consistent with the thermodynamic behavior of internal combustion engines in different operating regimes.

It was observed that, with increasing rotations, there is a significant reduction in CO and μCO emissions, reflecting more efficient and complete combustion, which is also evidenced by the progressive increase in $CO_2$ emissions and gas temperature. This pattern confirms the transition of the air-fuel mixture to a richer regime at high rotations, with greater energy demand, resulting in greater oxygen consumption (decrease in $O_2$ content) and automatic adjustment of the λ factor by enriching the mixture.

Thermal efficiency, in turn, was higher at lower speeds and declined with increasing load, which is expected due to volumetric limitations, reduced combustion time and thermal losses at high speeds. The quantity of air admitted (qA) followed an upward trend to a certain extent, with a drop at higher speeds, which indicates the intake limit at extreme regimes, potentially compensated by electronic valve and injection control strategies.

These findings, when integrated, demonstrate that the engine operates with progressively greater efficiency at intermediate to high speeds, but with thermal and energy costs that justify the use of compensation strategies. Furthermore, the observed adjustments are consistent with patterns described in the literature, reinforcing the reliability of the experimental results.

Therefore, the study provides a comprehensive overview of combustion behavior in internal combustion engines, with potential application in the development of calibration strategies, energy efficiency and emission control in automotive and industrial

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