Coupled Engine–Fuel System Optimization for Energy Performance and Emission Control under High-Altitude Operating Conditions

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Abstract: Improving fuel efficiency and reducing emissions in spark-ignition engines, especially under high-altitude conditions, requires a comprehensive understanding of the complex interplay between engine architecture and fuel properties. This study critically examines the exhaust emissions and fuel performance of BT and SC vehicles using two gasoline types, EX and EC, selected via a statistically robust sampling method based on the characterization of Ecuador's spark-ignition vehicle fleet. Experimental evaluations were conducted at 2,500 meters above sea level, utilizing dynamometer tests with the IM 240 driving cycle integrated into the vehicle inspection and maintenance system to quantify emissions of carbon monoxide, hydrocarbons, and nitrogen oxides. A factorial experimental design and Response Surface Methodology were employed to assess the effects of engine displacement, compression ratio, and fuel composition, modeling both nonlinearities and interactions through second-order polynomials. Results reveal that vehicle-specific factors, particularly displacement and compression ratio, are the predominant determinants of fuel consumption and emission profiles. Both the use of oxygenated biofuels such as EC gasoline significantly reduced incomplete combustion byproducts CO and HC, though NOx emissions exhibited a complex response, highlighting a non-linear relationship dependent on both fuel and operational context. In addition, statistical analysis demonstrated significant differences primarily attributable to vehicle type, with fuel type and their interaction also contributing. It was important to emphasize These findings underscore that optimizing both combustion settings and fuel formulation is essential to achieving substantial gains in efficiency and emissions control, particularly in the challenging context of high-altitude operation. Finally, the study provides analytical evidence that targeted strategies—incorporating advanced engine calibration and tailored fuel blends—are critical for meeting stringent environmental standards without compromising energy performance and offers a framework for future research and policy in sustainable mobility.

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1. Introduction

Private transportation has driven the expansion of vehicle fleets worldwide, prompting governments to implement mobility management, planning, and control measures for these modes. These vehicles operate with spark-ignition engines that convert chemical energy into mechanical energy through a combustion process [1-2]. When these engines run, they release pollutants into the air, which creates serious problems for both the planet and people's health around the world [3]. To address this, governments have put strict rules in place to limit emissions. This has pushed companies and researchers to develop better engines, cleaner fuels, and new technologies that help reduce pollution while keeping engines efficient [4]. Many researchers have also looked into using alternative fuels, like biodiesel blends and bio-oils, to see how they affect engine performance and emissions. Often, these studies use experiments to find the best balance between fuel consumption and cleaner exhaust gases [5-6].

Vehicular emissions constitute one of the main problems of atmospheric pollution, which is why several studies have been developed to control and reduce them. Pollutant gases are controlled according to the use of catalysts, whose role is more important in low engine regimes. Consequently, higher fuel consumption and greater gas pollution are observed. The environmental impact of these emissions is evident in the environment and in human health [7-8]. Regarding the gasolines marketed at the national level, there are three types: Super, Extra, and Ecopais . The latter is classified as a biofuel because it contains 5% ethanol from sugarcane [9]. Two of these fuel types, Ecopais and Extra, are the most demanded in the country due to their low cost [10 -12].

This commitment highlights the global need to explore and implement alternative fuel strategies. One option is to increase the use of biofuels, which have shown great promise in reducing gas emissions and supporting sustainable development in transportation [13-14]. When these engines operate, they release pollutants into the air. This poses serious issues for both the planet and people's health worldwide. In response, governments have established strict rules to limit emissions. This has driven companies and researchers to create better engines, cleaner fuels, and new technologies that reduce pollution while keeping engines efficient. Many researchers have also investigated using alternative fuels, such as biodiesel blends and bio-oils, to examine their effects on engine performance and emissions. Often, these studies conduct experiments to determine the best balance between fuel consumption and cleaner exhaust gases.

Likewise, recent studies in high-altitude regions have shown that the age of the vehicle fleet and variations in fuel octane rating act as critical variables that significantly influence the concentration of polluting gases [15]. Moreover, current empirical evidence highlights that the atmospheric oxygen deficit characteristic of these regions significantly alters combustion stoichiometry, thereby necessitating specific calibration adjustments to mitigate the elevated HC and CO output observed in legacy fleet technologies [15-17]. Furthermore, recent research suggests that elevated altitudes exacerbate these stoichiometric imbalances, leading to a progressive increase in carbon dioxide emissions as combustion efficiency consistently declines [16].

Regulations for controlling and reducing vehicular emissions apply to terrestrial mobile sources with more than three wheels that use fossil fuels, establishing permissible limits for pollutant emissions without compromising vehicle performance, to preserve human, animal, and plant life, as well as the environment [18-19]. Excessive concentrations of exhaust gases from internal combustion engines result from inadequate maintenance, malfunctions in the electronic fuel injection system, poor fuel quality, and atmospheric parameters that vehicle systems cannot control due to technological limitations or failures [20].

Contemporary research has evolved from static laboratory tests to the evaluation of Real Driving Emissions, driven by the "Dieselgate" context [21]. This research analyzes the synergistic vehicle-fuel interaction using the dynamic IM240 method to establish predictive models that guide specific calibration and co-optimization strategies for high-altitude environments.

2. Methodology

The present experimental investigation comprises two principal phases. The first phase involved determining volumetric emission concentrations through a gas analyzer, coupled with fuel consumption measurements. The second phase involved estimating emission factors utilizing Ecopais and Extra gasolines. The tests were performed with specialized equipment at the Technology Transfer Center for Training and Research in Vehicular Emissions Control laboratory, in Quito, under the following environmental conditions: average altitude of 2500 m above sea level, average temperature of 20 °C, atmospheric pressure of 732 hPa, and relative humidity of 40% [19]. The experimental procedures considered these parameters. Regulatory standards are essential for assessing the permissible limits of vehicle-emitted gases, and thus for calculating emission factors, derived from the volumetric concentrations obtained via the standard driving cycle and associated fuel consumption [22]. Furthermore, the calibration of gas analyzers remains a critical prerequisite for these assessments, thereby ensuring that sensors operate within established standard operating procedures to maintain data precision [23].

2.1 Vehicle Assignment

Once the analysis of the last five years was completed for selecting the vehicles to study, furthermore, Table 1 describes the technical specifications of each vehicle; Prior to the tests, the vehicles underwent adequate maintenance to ensure accurate measurements. This meticulous preparation aimed to minimize extraneous variables and establish a reliable baseline for evaluating fuel performance and emissions.

Table 1. Technical specifications of BT and SC vehicles

Model / Version	**BT-50 CD / 4x2 (BT)**	**S-CROSS / 4x2 (SC)**
Type	PICK UP	SUV
Year	2020	2022
VIN	8LFUNY02GCMD04702	TSMYA22SXJM569783
Engine Model	F2E SOHC-8V	DOHC MPFI
Displacement / Number of Cylinders	2.2 L / 4 cilindros	1.6 L / 4 cilindros
Power	99.3 HP@5000 rpm	118 HP a 6000 rpm
Torque	164 Nm@2000 rpm	156 Nm a 4400 rpm
Compression Ratio	8.6:1	11:1
Drive	Rear	Front
Tire Designation	215/75 R15	215/60 R16

2.2 IM240 Dynamic Test Method

The IM240 is an American Inspection and Maintenance driving cycle recommended by the US EPA for emission testing of in-use light-duty vehicles, ensuring compliance with regulatory quality standards by regulating pollutant emissions into the environment [9]. Performed on a warm engine to unify procedures across tests, this protocol incorporates acceleration and deceleration maneuvers along a predetermined trajectory—unlike constant-speed tests—to better simulate real-world transient conditions, while enabling accurate fuel economy and emissions assessments [24]. Applied to used vehicles, the brief 240-second test, derived from selected segments of the FTP-75 cycle and representing a 3.1 km route with a maximum speed of 91.2 km/h and average speed of 47.3 km/h, has been widely employed for emissions certification and fuel economy testing of light-duty vehicles in the United States [24- 25]. During the test, all exhaust gases produced by the mobile source are collected—typically via constant volume sampling systems—to determine their total mass, providing robust data for precise emission factor calculations under varying speeds and loads [25]. This standardized procedure offers a reliable assessment of emission characteristics under simulated transient driving conditions, which is particularly advantageous in challenging environments like high-altitude locations where reduced oxygen impairs combustion and elevates hazardous discharges [16, 24]. Additionally, the test evaluates dynamic properties, such as effective power calculated during full-fuel-dose accelerations across multiple iterations for data robustness [25].

Once the vehicle is installed on the chassis dynamometer, a high-precision gas analyzer, such as the MAHA MGT5 equipped with valid calibration certificates, is connected to ensure accurate real-time, continuous measurements of exhaust gas components [23, 26]. Subsequently, the driving conditions specified by the IM240 cycle protocol are precisely followed using specialized software, and recorded data are saved in a calculation template for further analysis of pollutant gases from gasoline mobile sources, as shown in Figure 1.To capture the inherent variability of on-road operations, the experimental protocol utilizes the IM240 dynamic cycle, a 240-second transient trajectory derived from the initial segments of the FTP-75 standard. Commencing from a state of rest, the vehicle undergoes a sequence of progressive accelerations and decelerations guided by real-time software cursors to replicate authentic urban stopping patterns and highway transitions [14]. Executing this protocol on a thermally stabilized engine ensures the reproducibility of measurements while accurately reflecting the "metabolic" response of the vehicle to diverse driving environments—ranging from congested city centers to rural pathways—even under the restrictive oxygen partial pressures typical of high-altitude regions. Fuel economy metrics are rigorously quantified through a multidimensional analysis of vehicle mass, volumetric fuel flow, and effective work performed, typically normalized to L/100 km [27]. This high level of precision is essential for deriving mass-based emission factors, which convert raw volumetric concentrations into useful data about the vehicle's environmental impact. As a result, the detailed simulation of different engine loads and rotational speeds enables a thorough assessment of important exhaust components, such as carbon dioxide and nitrogen oxides. This detailed characterization is crucial for understanding the environmental footprint of vehicle technologies that operate under the specific thermodynamic conditions of high-altitude ecosystems [28].

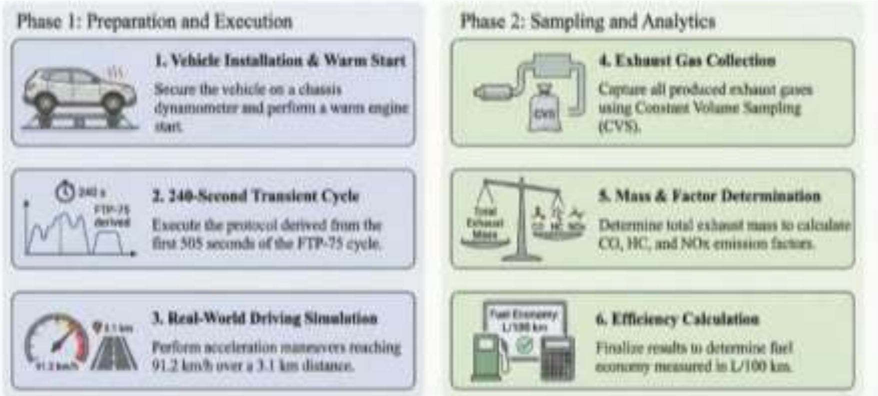


Figure 1. IM 240 Dynamic Test Cycle: Standard Procedure for Emissions and Fuel Economy

Next, the high-precision MAHA gas analyzer is described, which allows for obtaining exhaust gas results expressed as a volumetric percentage. The main characteristics of the device are detailed in Table 2. This analyzer provides real-time, continuous measurements of exhaust gas components, enabling a comprehensive assessment of emission profiles during the dynamic IM240 cycle [26].

Table 2. MAHA Gas Analyzer Specifications

Brand	MAHA				
Model	MGT5				
Type of analysis	Exhaust gases for vehicles with Otto engines (Partial flow measurement)				
Gases that can be analyzed	CO	CO2	HC	O2	Nox
Measurement range	0 – 15.00 Vol %	0 – 20.00 Vol %	0 – 2000 ppm (Hexane) 0 – 4000 ppm Propane	0 – 25.00 Vol %	0 - 5000 ppm Vol
Measurement accuracy	0.06 Vol. %	0.5 Vol. %	12 ppm vol.	0.1 Vol. %	32 - 120 ppm vol.
Measurement principle	Infrared	Infrared	Infrared	Electrochemical	Electrochemical
Measurement resolution	0.001 Vol. %	0.01 Vol. %	0.1 ppm vol.	0.01 Vol. %	1 ppm vol.
Lambda value	Indicator range: 0.500 -9.999 / Resolution: 0.001 / Calculated according to Brettschneider				
Measurement range drift	Less than ± 0.6 % of the final value of the measurement range				

We also describe the variable load dynamometer and auxiliary rollers. This equipment simulates the dynamic state of the vehicle, reproducing vehicle speeds as stipulated by the IM240 cycle [29], as shown in Table 3.

Table 3. Dynamometer specifications

Make	**MAHA**
Model	LPS 3000
Power supply	400 V / 50 Hz
Power measurement range	min. 30 kW – max. 660 kW
Traction force	max. 15 kN
Maximum speed	max. 200 km/h
Revolutions per minute (RPM)	max. 10,000 rpm
Measurement accuracy	± 2% of measured value
Standards	DIN 70020, EWG 80/1269,
Test vehicles	ISO 1585, SAE J1349 or JIS D1001
Axle load	Cars/Trucks/Vans/Buses
Minimum wheel diameter for testing	15 tons

2.3 Fuel Consumption Measurement

Fuel consumption measurement during the IM240 driving cycle is essential for deriving accurate emission factors, as the amount of emitted CO_2 is directly correlated with fuel consumption, and both CO_2 and other pollutants dilute equally in the exhaust plume [27]. This is achieved by employing an external fuel tank connected via adapters to the engine's gasoline supply lines, a precise volumetric method commonly used in chassis dynamometer testing to enhance the accuracy of fuel volume quantification relative to the distance covered, minimizing errors from vehicle tank variations or evaporation [26]. After completing the IM240 dynamic driving cycle on the chassis dynamometer, we carefully recover the remaining fuel from the external fuel tank to ensure accurate measurements. To prevent spills and keep the sample intact, we pour the fuel into an Erlenmeyer flask using a funnel. Then, we transfer it to a graduated cylinder for exact volume measurement. If we need to calibrate the recovered volume, we use a beaker for precise adjustments, returning any excess fluid to the original flask to keep the measurement controlled. We then verify this final consumption volume and repeat the entire process in subsequent experiments to ensure the data's reliability and consistency under different temporary loads. Furthermore, Table 4 outlines the key properties of Extra and Ecopais fuels, which are prevalent in the region, their differing compositions—including octane ratings, densities, and additive formulations—markedly affect combustion efficiency and the composition of exhaust gases, influencing emission profiles under standardized transient conditions [30].

Table 4. Properties of fuels [12]

Parameters	Extra	Ecopais
Octane number (RON)	87	87
Sulfur content (%)	0.065	0.065
Gum content (mg/100 ml)	3	3
Aromatic content (% vol.)	30	30
Olefin content (% vol.)	18	18
Boiling point (°C)	220	220
Density (kg/m³)	723	749
LHV (kJ/kg)	45124	44739

2.4 Simplified Combustion Emission Factors Determination Model

The accurate assessment of how vehicles impact our atmosphere necessitates a multidimensional methodology that harmonizes chemical principles with rigorous experimental observation. By meticulously characterizing the primary products of air-fuel combustion—specifically CO, HC, CO2, H2O, C3H6, N2, and NO this approach pinpoint the exact chemical drivers of atmospheric degradation [31]. Central to this evaluative process is a simplified combustion model; this analytical tool leverages fundamental parameters, such as fuel density and carbon stoichiometry, to derive mass-based emission factors (g/km) through a comprehensive balance of C,H,O, and N atoms [32]. This stoichiometric foundation is based on the conservation of mass. It enables researchers to convert raw volumetric concentrations into reliable mass-based emission rates. When used with complex transient protocols like the IM240 dynamic cycle on a chassis dynamometer, this method gives an accurate view of a vehicle's environmental impact under simulated real-world conditions [27]. Moreover, by using CO2 emissions as a reliable indicator of fuel consumption, this framework separates the chemical effects of the fuel from the engine's mechanical response. This creates a strong diagnostic tool for optimizing the combined engine-fuel system. It ensures that improvements in fuel chemistry and engine calibration work together to meet modern environmental standards [33].

Key combustion products from the thermal process include CO, H_2O, CO_2, and C_3H_6. Moreover, N_2 and NO exert significant influence on atmospheric pollution. In mass balance calculations, any excess oxygen is omitted; thus, the combustion equation is formulated as Eq. (1):

$$CH_y + m(0.21\,O_2 + 0.79N_2) \rightarrow aCO + bH_2O + cC_3H_6 + dCO_2 + eN_2 + fNO \quad (1)$$

The atoms involved in combustion are neither created nor destroyed, but rather transformed. Hence, the following equations for the mass balance are derived, as Eq. (2)-(5):

Element	**Reactants**		**Products**	
Carbon	1	=	a + 3c + d	(2)
Hydrogen	y	=	2b + 6c	(3)
Oxygen	0.42m	=	a + b + 2d + f	(4)
Nitrogen	1.58 m	=	2e + f	(5)

Finally, to obtain the emission factors in grams of pollutant per kilometer, the fuel density and fuel consumption are accounted for [33]. This allows for comparison of the emission factors between ecopais and extra fuels based on the IM240 dynamic test. This methodology facilitates a direct quantitative assessment of how variations in fuel composition influence the generation of specific exhaust gas constituents under standardized driving conditions [32], as Eq. (6)-(8).

$$EF_{CO} = \frac{g_{CO}}{km} = \frac{28*\frac{\%\,CO}{\%\,CO_2}}{\frac{\%\,CO}{\%\,CO_2}+\left(3*\frac{\%\,HC}{\%\,CO_2}\right)+1} * \frac{\rho_{comb}*CC}{0.01425} \quad (6)$$

$$EF_{HC} = \frac{g_{NO}}{km} = \frac{42*\frac{\%\,HC}{\%\,CO_2}}{\frac{\%\,CO}{\%\,CO_2}+\left(3*\frac{\%\,HC}{\%\,CO_2}\right)+1} * \frac{\rho_{comb}*CC}{0.01425} \quad (7)$$

$$EF_{NO} = \frac{g_{NO}}{km} = \frac{30*\frac{\% NO}{\% CO_2}}{\frac{\% CO}{\% CO_2}+\left(3*\frac{\% HC}{\% CO_2}\right)+1} * \frac{\rho_{comb}*CC}{0.01425} \quad (8)$$

2.5 Analysis of Variables

In the present study, Table 5 delineates the independent variables—vehicles (S-Cross designated as -1 or SC; BT-50 designated as 1 or BT) and fuels (Extra as 1 or EX; Ecopais as 2 or EC)—alongside the dependent variables, namely nitrogen oxides and hydrocarbons, obtained from replicated experiments (12 treatments across three blocks in the factorial design) using each fuel-vehicle combination during IM240 chassis dynamometer simulations of standardized transient driving cycles. This 2×2 factorial setup enables robust assessment of main effects and interactions on emissions, consistent with established dynamometer protocols [34]. Statistical analysis employed software, using one-way ANOVA to test for significant differences among the four treatment groups, followed by post-hoc LSD multiple comparison tests at a 95% confidence level (α=0.05) to pinpoint pairwise disparities and ensuring high statistical power for detecting fuel- and vehicle-specific impacts on pollutant profiles [35].

Table 5. Variables and designations

Factores	**Niveles**	**Designación 1**	**Designación 2**
Vehicles	S-Cross	-1	SC
	BT-50	1	BT
Fuels	Extra	1	EX
	Ecopais	2	EC

The nomenclature and designation of the levels of the study factors are presented in Table 6. The statistical design of the treatments is described in Table 7 and provides an adequate method for representing the study variables, as well as comparing and analyzing the results through the response surface.

Table 6. Statistical design of treatments

No.	**Block**	**Vehicles**	**Fuels**
1	1	-1	2
2	1	-1	1
3	1	1	1
4	1	1	2
5	2	1	1
6	2	1	2
7	2	-1	1
8	2	-1	2
9	3	-1	1
10	3	1	2
11	3	-1	2
12	3	1	1

Table 7. Treatment for the analysis of significant differences and comparison

No.	**Vehicles**	**Fuels**
1	SC	EX
2	SC	EC
3	BT	EX
4	BT	EC

3. Results

3.1 Fuel Consumption

Fuel consumption represents a fundamental parameter in the calculation of emission factors; therefore, its measurement was recorded in each test to optimize the precision of the estimates. Table 8 compiles the consumption values corresponding to each repetition of the tests conducted with both types of gasoline, enabling the identification of differences in performance expressed in kilometers per liter or gallons of fuel. The obtained averages demonstrate that Extra gasoline exhibits higher performance in both vehicles compared to Ecopais gasoline.

Figure 2 illustrate the multiple range test and the corresponding box-and-whisker plot for the dependent variable, applying Fisher's least significant difference procedure at a 95.0% confidence level. The results demonstrate significant differences between the vehicles, with the SC model exhibiting the best performance; additionally, both vehicles show a common trend toward improved maximum performance in km/L when using EX and EC gasolines, the latter containing 5% ethanol.

Table 8. Consumo de combustible de BT-50 y S-Cross.

Vehicles	**Unit**	**Extra**				**Ecopais**			
		Measurement 1	**Measurement 2**	**Measurement 3**	**Average**	**Measurement 1**	**Measurement 2**	**Measurement 3**	**Average**
BT	(km/L)	9.14	9.01	9.14	9.10	8.65	9.14	8.53	8.78
SC	(km/L)	17.78	17.78	16.84	17.47	16.41	16.84	17.30	16.85

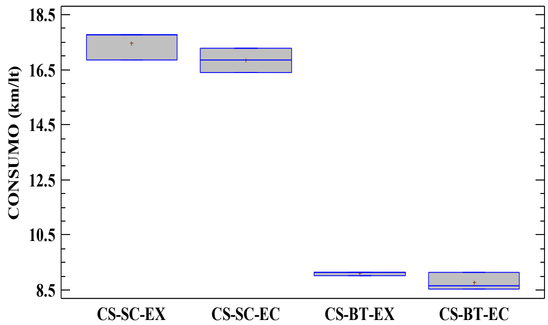


Figure 2. Comparación del consumo de combustible entre vehículos y gasolinas

3.2 Emission factors

Table 9 shows the average values of the three emission factors derived from the tests conducted with both fuels in each vehicle. In the BT vehicle, the combustion of Extra gasoline generated higher emissions of the three pollutants compared to Ecopais gasoline. Similarly, in the SC vehicle, Extra gasoline produced elevated levels of CO and HC, while Ecopais gasoline exhibited higher NOx emissions.

Table 9. Emission factors for the BT and SC vehicles

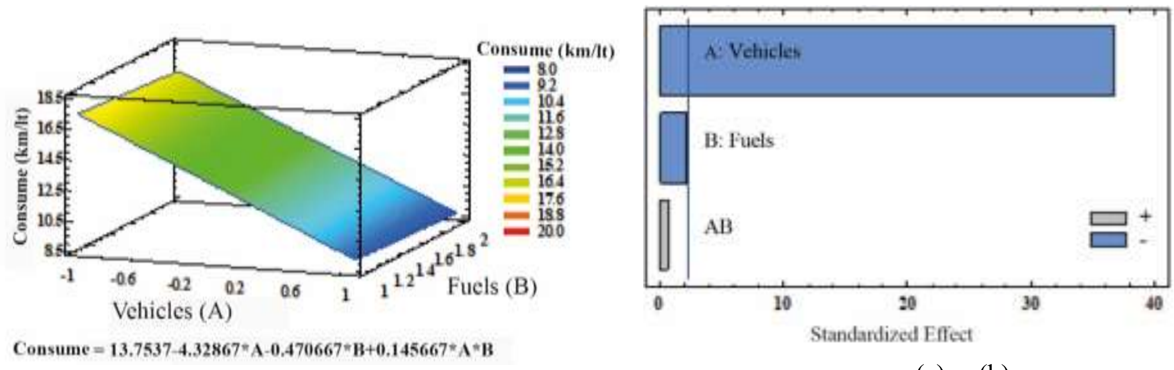
	Extra		**Ecopais**	
Parameters	**BT**	**SC**	**BT**	**SC**
FCO (g/km)	5.080	1.855	4.860	1.412
FHC (g/km)	0.064	0.015	0.050	0.008
FNOX (g/km)	0.539	0.046	0.440	0.071

Pollutant analysis showed that Ecopais gasoline acts as an effective thermochemical modulator. It significantly reduces incomplete combustion products. Factor CO: The SC vehicle had the lowest CO levels, reaching an optimal value of 1.412 g/km with EC gasoline. In the BT vehicle, EC gasoline lowered CO from 5.080 g/km to 4.860 g/km. These reductions, up to 60% under high-load conditions in dynamic tests, come from ethanol's natural oxygen content, which speeds up oxidation in the oxygen-poor environment of high altitudes. Factor HC: We observed statistically significant reductions with EC gasoline, resulting in decreases of 20% in the BT vehicle and 35% in the SC vehicle. The lowest HC factor was 0.008 g/km for the SC vehicle using EC gasoline. This trend confirms that the additional oxygen availability in biofuels promotes more complete combustion, counteracting the atmospheric limitations of low air density; Factor Nox: Unlike CO and HC, NOx emissions exhibited highly vehicle-dependent behavior. In the BT vehicle, the use of Ecopais gasoline led to a reduction in NOx (from 0.539 to 0.440 g/km). Conversely, the SC vehicle showed a 33.13% increase in NOx emissions with EC gasoline (rising from 0.046 to 0.071 g/km). This divergence is explained by the interplay between combustion chamber temperatures and the oxygen content of ethanol; while altitude generally limits thermal NOx by reducing peak temperatures, the oxygenated fuel can locally elevate temperatures, thereby fostering nitrogen oxide production in specific engine calibrations.

4. Discussion

4.1 Fuel Consumption of Vehicles

Figure 3, reveals notable disparities between the vehicles, with the SC model demonstrating superior fuel efficiency relative to the BT model. Furthermore, both vehicles displayed enhanced peak performance in terms of km/L when fueled with EX gasoline compared to EC gasoline, which incorporates 5% ethanol, primarily due to ethanol's lower volumetric energy density, which necessitates higher fuel volumes for equivalent energy delivery [36].



(a) (b)

Figure 3. A figure with two subgraphs: (a) Response surface for fuel consumption analysis; (b) Standardized Pareto chart for fuel consumption.

Conversely, the BT and SC vehicles exhibited a 3.7% increase in fuel consumption when using Ecopais gasoline relative to extra gasoline [9]. Ramadhas et al. corroborated these observations, reporting elevated fuel consumption for a gasoline-ethanol blend under 50% engine load and 4500 rpm conditions compared to neat gasoline [37]. Moreover, these findings align with investigations indicating that escalating ethanol proportions in blends linearly elevate specific fuel consumption, as brake specific fuel consumption rises with higher ethanol percentages owing to reduced energy content [36, 38]. Figure 3 illustrates the interplay among fuel consumption, fuel type, and vehicles and delineates the corresponding mathematical model.

The experimental results show an efficiency limit of 17.466 km/L. This peak performance comes from combining reduced ethanol levels and smaller engine sizes [38]. Figure 3(b) presents statistical evaluations. These evaluations, especially the standardized Pareto analysis, highlight the importance of the vehicle factor as the main influence on system response. Fuel composition also plays a significant role, although it is nearly significant.

These findings change how we think about fuel economy. They suggest we should not view it as a result of separate factors. Instead, we should consider the relationship between automotive design and fuel properties. This unified view offers a key approach to improving energy-efficient vehicle designs. It provides useful guidance for reducing fuel use during the demanding IM240 standardized cycle [25]. Importantly, the relationship between fuel composition and engine features, especially displacement, strongly affects fuel economy. Lower ethanol levels and smaller engine sizes lead to better efficiency. This is consistent with extant literature documenting elevated brake specific fuel consumption with increasing ethanol content in gasoline blends, ascribed to ethanol's inferior volumetric energy density vis-à-vis gasoline [36, 39, 40].

4.2 Emission factors

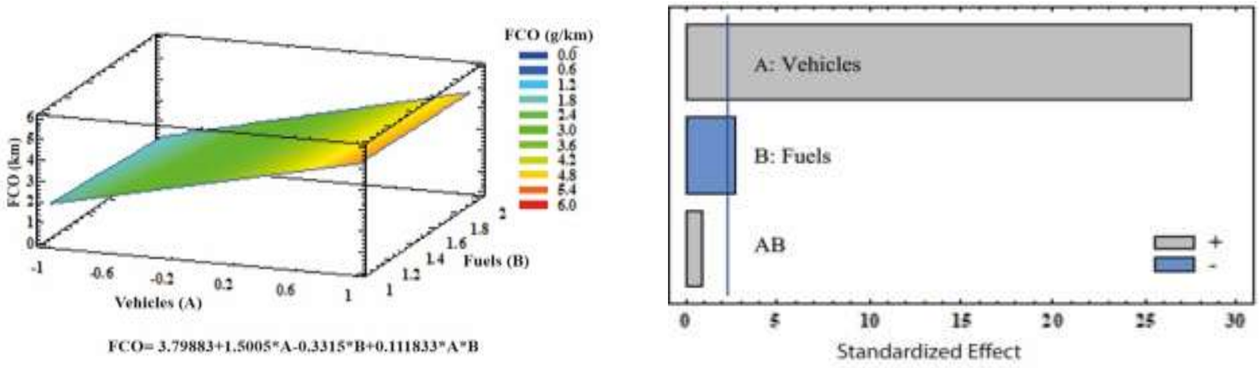
4.2.1 The CO Emission Factor

As illustrated in Figure 4, carbon monoxide emissions display substantial differences among the tested vehicles, with the SC model yielding superior outcomes relative to the BT model. A marked tendency toward higher CO levels emerged with EX gasoline compared to EC gasoline, an effect especially pronounced in the BT vehicle. These observations indicate that engines with larger displacements are more susceptible to incomplete combustion processes prevalent in high-altitude conditions. This elevation in CO emissions with neat gasoline aligns with prior studies reporting proportional rises in CO production upon shifting from biofuel blends to conventional gasolines [36].

This significant mitigation of pollutants is primarily driven by the "oxygenating effect" inherent to ethanol-gasoline blends. In high-altitude urban centers such as Quito, where barometric pressure drops to approximately 732 hPa, the available partial pressure of oxygen per combustion cycle is severely diminished. This atmospheric constraint typically impairs complete carbon oxidation, inherently fostering the generation of carbon monoxide (CO). However, the oxygen content integrated into Ecopais (EC) gasoline functions as a vital thermochemical enhancer; it optimizes both combustion efficiency and air-fuel mixture preparation even within these oxygen-deprived environments. These findings are corroborated by chassis dynamometer assessments, which indicate that ethanol-gasoline matrices can sustain stable power delivery while effectively curtailing the byproducts of incomplete combustion [24].

The Response Surface Methodology (RSM) employed in this study demonstrated exceptional predictive robustness, yielding coefficients of determination (R^2) exceeding 0.90 [19]. This modeling illuminates a profound dependency of CO emissions on the non-linear synergy between specific vehicle architectures and chemical fuel formulations. Through the strategic utilization of biofuels, an optimal emission floor of 1.41 g/km was identified. Furthermore, the Pareto analysis underscores that CO levels are not merely the product of isolated variables but emerge from interconnected energetic dynamics. These insights validate the core hypothesis: the simultaneous optimization of engine configuration and fuel properties is indispensable for meeting environmental mandates without jeopardizing the system's overall energetic efficiency.

From a broader developmental perspective, these outcomes advocate for holistic automotive engineering paradigms to mitigate the ecological footprint of escalating global transportation demands. The identified non-linear interdependencies highlight a critical technical requirement: electronic control unit (ECU) recalibrations must be attuned to real-world atmospheric physics to ensure rigorous high-altitude compliance. Ultimately, the deliberate integration of bio-derived fuels—specifically the 5% ethanol Ecopais blend—stands as a cornerstone strategy for achieving greenhouse gas mitigation targets and preserving air quality within high-altitude metropolitan ecosystems.



(a) (b)

Figure 4. A figure with two subgraphs: (a) Response surface for FCO analysis; (b) Standardized Pareto chart for FCO

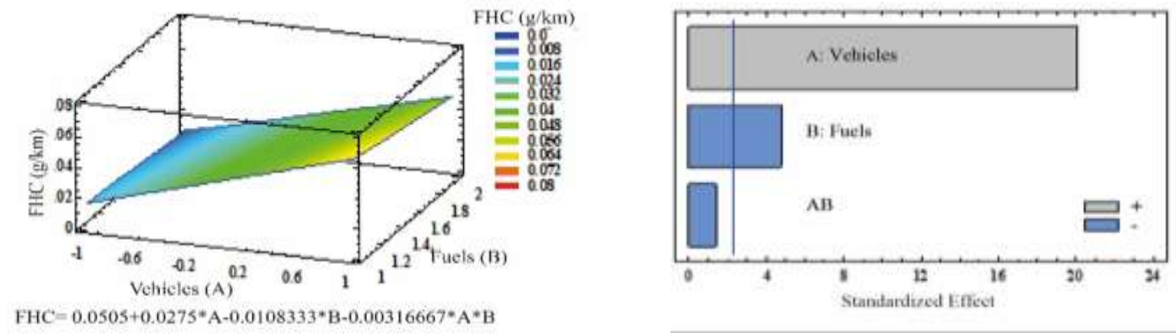
4.2.2 The HC Emission Factor

The experimental results presented in Figure 5 reveal statistically significant disparities in hydrocarbon (HC) emissions between the evaluated vehicles and fuel types, with the SC vehicle consistently achieving the lowest levels of unburned constituents. A pronounced and systematic trend toward elevated HC emissions was observed when operating with EX (Extra) gasoline compared to the EC (Ecopais) biofuel blend, an effect that was particularly exacerbated in the BT vehicle architecture. These findings align with the core hypothesis that at 2500 m s.n.m., where barometric pressure drops to 732 hPa, the resulting decrease in the partial pressure of oxygen compromises oxidation kinetics, thereby favoring incomplete combustion mechanisms.

The significant HC reductions achieved with EC gasoline—reaching 20% and 35% for the studied vehicles—concur with previous dynamometer evaluations, who documented a 57.68% decrease when transitioning to ethanol-blended formulations [4, 39]. This mitigation is primarily attributed to the "oxygenate effect" of ethanol; the fuel's intrinsic oxygen content serves as a thermochemical modulator that enhances mixture preparation and oxidation speed, partially counteracting the air-density-induced oxygen deficiency inherent to high-altitude environments. Such results provide robust empirical support for the integration of bio-based fuel alternatives as a strategic tool for environmental compliance in mountainous urban centers [14, 41].

The relationship between fuel composition and emissions is complex. Response Surface Methodology (RSM) has found an optimal hydrocarbon (HC) reduction level of 0.007 g/km by using biofuels like Ecopais. However, this reduction does not happen consistently across all driving conditions. Studies show that high levels of heavy hydrocarbons in certain biogasoline mixes can unexpectedly increase HC emissions, which complicates the anticipated environmental benefits. Additionally, the analysis needs to consider temporary driving conditions, such as cold starts or quick accelerations. These situations can temporarily lower catalytic converter efficiency and cause sharp increases in HC emissions, even with optimized fuel formulations [16].

Data from the Pareto analysis in Figure 5(b) shows that effective HC control depends on a nonlinear interaction between the vehicle's engine size and the fuel's chemical properties. This interaction highlights that focusing on single factors isn't enough; a broad approach is necessary to see significant reductions. Such a strategy should combine improvements in vehicle technology, like updated electronic control units (ECU), with fuel formulations designed for the specific thermodynamics of high-altitude areas. At about 2500 m above sea level, where barometric pressure drops to 732 hPa, the fuel becomes an important thermochemical regulator. Its volatility and oxygen content impact the system's ability to maintain stable combustion and meet strict environmental standards [42-43].



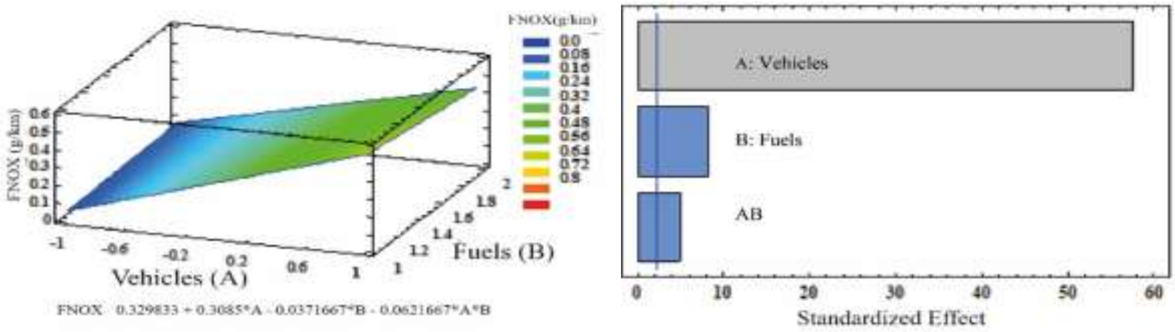
(a) (b)

Figure 5. A figure with two subgraphs: (a) Response surface for FHC analysis; (b) Standardized Pareto chart for FHC

4.2.3 The NOx Emission Factor

As illustrated in Figure 6, substantial inter-vehicle and inter-fuel variations in NOx emissions were observed, with the SC vehicle attaining the lowest NOx concentrations, consistent with pronounced vehicle-dependent effects documented in the contemporary literature. \

The documented NOx emission factors in this investigation concur with observations regarding a reduction in the emission factor when employing ethanol-blended fuel in the BT vehicle. In contrast, the SC vehicle registered a 33.13% increase in NOx emissions with EC (Ecopais) gasoline relative to EX (Extra) gasoline, a result consistent with previous evaluations of analogous vehicles [43]. These vehicle-specific discrepancies are substantiated by studies documenting varied responses, such as a 1% NOx increment with E5 blends or lower NOx levels with pure gasoline depending on the testing conditions [42, 44]. NOx formation is profoundly influenced by the air-fuel ratio and combustion chamber temperatures; notably, while ethanol's oxygen content helps reduce CO and HC, it can elevate combustion temperatures and foster higher NOx production [45]. Such outcomes emphasize the paramount importance of engine architecture and calibration under high-altitude regimes [43]. Ultimately, the Pareto diagram in Figure 6(b) confirms that NOx abatement depends on the thermodynamic and chemical interplay between vehicles and fuels, with a minimum value of 0.046 g/km achieved in this study [46].



(a) **(b)**

Figure 6. A figure with two subgraphs: (a) Response surface for NOx analysis; (b) Standardized Pareto chart for NOx

5. Conclusions

The pursuit of energy efficiency and the mitigation of regulated emissions in spark-ignition engines are not governed by isolated variables, but rather by a complex nonlinear thermo-chemical coupling between engine architecture and fuel characteristics. Utilizing Response Surface Methodology (RSM), this research developed robust predictive models with coefficients of determination exceeding R2>0.90, demonstrating that while vehicle-specific factors—such as displacement and compression ratio—remain the primary drivers of fuel consumption gradients, their operational effectiveness is strictly contingent upon the fuel's chemical matrix. Consequently, achieving a true performance peak requires a systemic co-optimization strategy rather than attempting independent adjustments to mechanical or chemical components.

The introduction of Ecopais (5% ethanol) acts as a vital environmental modulator, serving as an oxygenating agent that restores oxidation kinetics in the oxygen-deprived atmosphere of high-altitude regions. Experimental data reveal a significant synergistic effect, where CO and HC emissions were curtailed by up to 60% under high-load conditions compared to traditional "Extra" gasoline. However, this environmental gain is inextricably linked to a 3.7% increase in fuel consumption, a performance penalty directly attributable to ethanol's lower volumetric energy density. This energy-environment trade-off underscores the necessity of managing engine-fuel interactions as a unified system to prevent viewing fuel chemistry in a vacuum.

Furthermore, nitrogen oxide behavior at a geopotential altitude of 2500 m above sea level exhibits pronounced sensitivity to the nonlinear interaction between electronic control unit calibration and fuel thermochemical properties. At a barometric pressure of approximately 732 hPa, reduced atmospheric density generally curbs thermal NOx formation through diminished peak combustion temperatures. Nonetheless, the oxygenated composition of ethanol-gasoline blends generates a thermodynamic contradiction: the inherent oxygen in the biofuel can provoke localized temperature spikes in the combustion chamber, thereby offsetting the altitude-related cooling. This effect was particularly pronounced in the SC vehicle configuration, which registered a 33.13% escalation in NOx emissions with Ecopais fuel. This substantial variability affirms that NOx reduction is neither an intrinsic nor universal benefit of biofuel use, but rather emerges from thermodynamic interactions peculiar to high-altitude conditions.

In essence, the overall performance of the engine-fuel system, measured by fuel efficiency and emissions, is determined by its unified adaptability to reduced oxygen partial pressures. These results highlight a crucial deficiency in conventional engine calibration protocols and underscore the urgent need for co-optimization frameworks tailored to high-altitude scenarios. Therefore, meeting stringent emissions regulations without compromising energy conversion efficiency requires a paradigm shift toward sophisticated control methodologies. Fundamentally, this entails the precise recalibration of the ECU's ignition and injection maps, adapted to the atmospheric conditions of high-altitude urban environments, to ensure combustion stability and urban air quality.

Author Contributions

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

CO	carbon monoxide
HC	Hydrocarbons
CO2 *H2O*	carbon dioxide water
C3H6	Propene
N2	nitrogen gas
CC	Consume fuel
FCO	carbon monoxide factor
FHC	Hydrocarbons factor
FNOx	nitrogen oxides factor
Greek symbols	
ρcomb	fuel density, kg/L
Subscripts	
gco	Grams carbon monoxide, gr
gNO	Grams nitrogen oxides,gr
gHC	Grams hydrocarbons, gr