Data and Metadata. 2025; 4:838
doi: 10.56294/dm2025838

ORIGINAL

Effects of altitude on On-Board Fuel Consumption and CO_2 Emissions of a Vehicle: An analysis based on experimental data

Efectos de la altitud en el consumo de combustible y las emisiones de CO_2 a bordo de un vehículo: Un análisis basado en datos experimentales

Fredy Rosero[1], Carlos Xavier Rosero[1], Fausto Tapia[1], Daniel Arias[1]

[1]Universidad Técnica del Norte, Faculty of Engineering in Applied Sciences. Ecuador, Ibarra 100102.

Cite as: Rosero F, Rosero CX, Tapia F, Arias D. Effects of altitude on On-Board Fuel Consumption and CO_2 Emissions of a Vehicle: An analysis based on experimental data. Data and Metadata. 2025; 4:838. https://doi.org/10.56294/dm2025838

Submitted: 14-07-2025 **Revised:** 11-09-2025 **Accepted:** 03-12-2025 **Published:** 04-12-2025

Editor: Dr. Adrián Alejandro Vitón Castillo

Corresponding Author: Fredy Rosero

ABSTRACT

Fuel efficiency and CO_2 emissions of vehicles are influenced by various factors, including altitude, whose effect is often ignored or underestimated. This study evaluates the effect of altitude on fuel consumption and CO_2 emissions in a light vehicle through an experimental campaign in four cities in Ecuador located between sea level and 3,000 meters above sea level. Fuel consumption and engine operation data were obtained through the OBD system. This information was used to generate engine maps and analyse vehicle performance at different altitude levels. The results showed that in cities at higher altitudes, the vehicle operated with engine loads above 70 % due to slopes greater than 7 %, while in coastal cities the loads were lower. Under similar engine load conditions, both fuel consumption and CO_2 rates were lower in high-altitude cities, showing a positive effect of altitude on combustion. However, energy-based emission factors were higher in high-altitude cities, probably due to lower air density. In terms of distance, fuel consumption and CO_2 emission factors were up to 7 % higher in high-altitude cities. Overall, this study proposes a low-cost methodology and shows the importance of considering the effect of altitude when designing sustainable transport strategies for Latin American cities.

Keywords: Fuel Consumption; CO2 Emissions; Altitude; OBD Data; Altitude; Vehicle Emissions.

RESUMEN

La eficiencia del combustible y las emisiones de CO_2 de un vehículo están influenciadas por diversos factores, entre ellos la altitud, cuyo efecto frecuentemente es ignorado o subestimado. El presente estudio estudio evalúa el efecto de la altitud sobre el consumo de combustible y las emisiones de CO_2 en un vehículo liviano, mediante una campaña experimental en cuatro ciudades del Ecuador ubicadas entre el nivel del mar y los 3000 m.s.n.m. Los datos de consumo y operación del motor se obtuvieron a través del sistema OBD. Esta información fue aplicada para generar mapas de motor y analizar el desempeño vehicular a diferentes niveles de altitud. Los resultados mostraron que en las ciudades con mayor altitud el vehículo operó con cargas de motor superiores al 70 %, debido a pendientes superiores al 7 %, mientras que en ciudades costeras las cargas fueron menores. Bajo condiciones similares de carga de motor, tanto el consumo como las tasas de CO_2 fueron menores en ciudades de altura, mostrando un efecto positivo de la altitud sobre la combustión. Sin embargo, los factores de emisión basados en energía resultaron más altos en ciudades de altura, probablemente por una menor densidad del aire. En términos de distancia, los factores de consumo y emisiones de $CO_{2,}$ fueron hasta un 7 % más altos en ciudades de altura. En general, este estudio propone una metodología de bajo costo y muestra la importancia de considera el efecto de la altitud para diseñar estrategias de transporte sostenible para ciudades de Latinoamericana.

Palabras clave: Consumo de Combustible; Emisiones de CO2; Altitud; Datos OBD; Altitud; Emisiones del Vehículo.

INTRODUCTION

Over the past decade, road transport has led to a rise in oil consumption by several million barrels per day, making up over 45 % of the increase in global oil demand.[1] Currently, the road transport sector consumes approximately 20 % of the world's energy and is one of the largest emitters of greenhouse gases (GHG) and accounts for about 25 % of global energy consumption.[2] In Latin America, fossil fuels make up about 65 % of the region's energy mix, and road transport is still the main source of GHG emissions. This sector uses almost 37 % of the total energy consumed in the region.[3] In Ecuador alone, the road transport sector is responsible for approximately 90 % of the gasoline demand, which represented about 1 048 016 kgal in 2023.[4] Therefore, this sector is one of the highest energy-consuming sectors in the country.

Fuel consumption and CO_2 emission factors of spark-ignition engine vehicles can significantly under real traffic conditions compared to values measured during type-approval process.[5] These differences are influenced by both internal factors (e.g. fuel type, engine condition, and powertrain configuration) and external factors(e.g. driver behaviour, road conditions, and altitude).[6] Among these, altitude is often underestimated, but plays a critical role.[7] As altitude increases, atmospheric pressure and air density decrease, resulting in changes in both fuel consumption and emissions in internal combustion engines.[8] This phenomenon is especially relevant in Latin America, where the Andean Mountain range extend across several countries, altitude can significantly affect vehicle performance. Cities in Andean countries such as Ecuador, Colombia, and Peru are commonly located at elevations above 2000 meters above sea level (masl). Consequently, the effect of altitude on vehicle performance, fuel consumption and CO2 emissions is a key factor that should not be overlooked.

Previous research conducted around the world has extensively examined the influence of altitude on fuel consumption and emissions in internal combustion engines used in road transport. He et al.[9] conducted altitude simulation tests on a diesel engine and observed that, between 1000 and 2000 m, emissions of hydrocarbons (HC), carbon monoxide (CO), and smoke increased by 30 %, 35 %, and 34 %, respectively. Wang et al.[10] used a mobile test bench to evaluate heavy-duty diesel engines and reported significant reductions in thermal efficiency, particularly within the 1030–1600 rpm range at elevated altitudes. In Europe, Ramos et al.[8] investigated a light-duty vehicle's performance at altitudes ranging from 0 to 2300 m using both diesel and alternative fuels. Liu et al.[11] used Portable Emission Measurement Systems (PEMS) to study the particle number and size distribution of a diesel vehicle under different vehicle-specific power (VSP) conditions and altitudes. Kan et al.[12] explored the impact of altitude (0–4500 m) on combustion and ignition parameters in diesel engines during cold-start acceleration phases, identifying increased ignition delay and combustion inefficiency.

In Latin America, research has addressed real-world high-altitude effects in dense urban contexts. Giraldo[13] analysed the fuel consumption and pollutant emissions of diesel buses operating in Mexico City, located above 2200 masl. Their findings revealed that NOx emissions were three times higher than those of comparable buses operating at lower altitudes, and that both fuel consumption increased notably due to the combined effects of reduced oxygen availability. In addition, Gómez et al. developed a high-resolution spatiotemporal vehicle emission inventory for the medium-sized Andean city of Manizales, Colombia. Their study identified several urban emission hotspots and demonstrated that simplified top-down estimation methods tend to underestimate emissions in central urban areas with high traffic density. These findings highlight the critical need for refined emission inventories to improve air quality management and support atmospheric modelling efforts in mid-sized cities. In Ecuador, several studies have explored vehicle efficiency using different fuel types and real-world driving data from taxi fleets.[6,14] However, these studies were conducted in areas with relatively small altitude differences, limiting the relevance of their findings to cities located at significantly different elevations. Together, these results underscore the need to evaluate the effect of altitude on vehicles operating in mountainous regions of Latin America, where large populations rely on fossil fuel-powered vehicles.

Based on the literature review, several research gaps have been identified: (1) Most existing studies rely on controlled laboratory tests or simulation tools, which fail to fully capture real-world engine behaviour under actual driving conditions; (2) the engine mapping approach has not yet been applied to investigate the effects of altitude on vehicle engine performance and fuel consumption ; (3) In Latin America, where there are coastal cities at sea level and other Andean cities located above 2000 masl, there are no studies evaluating the same vehicle's performance across different altitudes.

To address these research gaps, this study proposed an original method based on the engine mapping approach to assess the effects of altitude on the fuel consumption and carbon dioxide (CO2) emissions of a vehicle engine. The proposed method was applied in a gasoline-powered vehicle operating under real-world traffic conditions in four cities in Ecuador, ranging from sea level to 3000 masl.

The key research questions addressed in this study are as follows:

- How do engine speed and load operating patterns vary for cities located at different altitudes?
- How does altitude affect average fuel consumption and CO_2 emission rates in different areas of the engine map?
- What is the variation of the fuel consumption and CO_2 emission factors in terms of distance of the vehicle operating at different altitudes?

METHOD

Test vehicle

The vehicle selected for this study was a compact sedan manufactured by Great Wall Motors, a Chinese automaker. It was equipped with a 1500 cm^3 gasoline engine with multi-point indirect injection, a five-speed manual transmission, front-wheel drive, and variable valve timing. This configuration complies with Ecuadorian homologation standards, which are equivalent to Euro 3 regulations. The main technical specifications of the vehicle are provided in table 1. The choice of vehicle was based on its alignment with the predominant characteristics of the Ecuadorian passenger car fleet. According to national statistics, over one-quarter of the country's registered vehicles are sedans, and the majority operate on low-octane gasoline.(15) In recent years, Chinese-manufactured vehicles have significantly increased their market share in Ecuador. These trends justified the selection of a gasoline-powered Chinese sedan with a 1500 cm^3 engine, which reflects the technical profile of a large segment of the local vehicle population. It is important to note that the vehicle underwent and successfully passed the mandatory Technical Vehicle Inspection shortly before the experimental campaign, ensuring it was in proper mechanical condition for reliable data collection.

Table 1. Technical specifications of the tested vehicle

Vehicle Parameter	Value
Fuel type	Gasoline
Model name	Great Wall C30 Comfort
Model year	2018
Gross vehicle weight (t)	1535
Weight (t)	1160
Length/Width/Height (m)	4,45/1,71/1,49
Max passengers	5
Axle configuration	4 × 2
Gearbox	Manual (5)
Number of engine cylinders	4 in-line
Engine total displacement (cm3)	1497
Engine maximum power (kW@rev/min)	78@6000
Engine peak torque (N.m@rev/min)	138@4000 – 5500
Fuel injection type	Indirect injection
Compression ratio	10.5:1

Instrumentation and Data Acquisition

To ensure accurate and comprehensive data collection, the instrumentation was selected to capture both vehicle kinematics and key engine operating parameters, along with a direct measurement of fuel consumption. This approach prevented reliance on estimated data and improved the reliability of subsequent analyses. The data acquisition system and sensors were required to meet several criteria: (i) a minimum sampling frequency of 1 Hz, (ii) straightforward configurability, (iii) power supply compatibility with 12 V systems or the vehicle's OBD-II port, (iv) synchronized operation for at least one hour, and (v) non-intrusive installation to preserve normal vehicle performance.

Based on these requirements, two data loggers and three sensors were used during both the preliminary tests and the main experimental campaign. The data loggers consisted of an ELM327 interface and a CANEdge2 module. The ELM327 was connected to the vehicle's electronic control unit (ECU) via the OBD-II port and enabled wireless access to real-time engine data using third-party applications. The CANEdge2 logger, connected through a CAN bus network, recorded high-resolution data from the installed sensors onto an external memory card. It featured a compact design, a 50 µs internal clock resolution, and was fully compatible with open-source software and decoding libraries.

The sensors integrated into the CAN network included two DFM ACAN 100 fuel flow meters—installed in both supply and return fuel lines—and a GNSS positioning system (CANMod.gps). The DFM meters allowed for direct fuel flow measurement across various fuel types, including those with kinematic viscosities between 1,5 and 6 mm^2/s. The CANMod.gps module incorporated a GNSS antenna and an inertial measurement unit (IMU), enabling precise geolocation, acceleration, and gyroscopic data acquisition. Communication between the sensors and the CANEdge2 required specific wires: a standard CAN cable for the fuel flow meters and an RS232 interface for fuel consumption data transmission. The final configuration of the instruments mounted on the vehicle for this study is shown in figure 1.

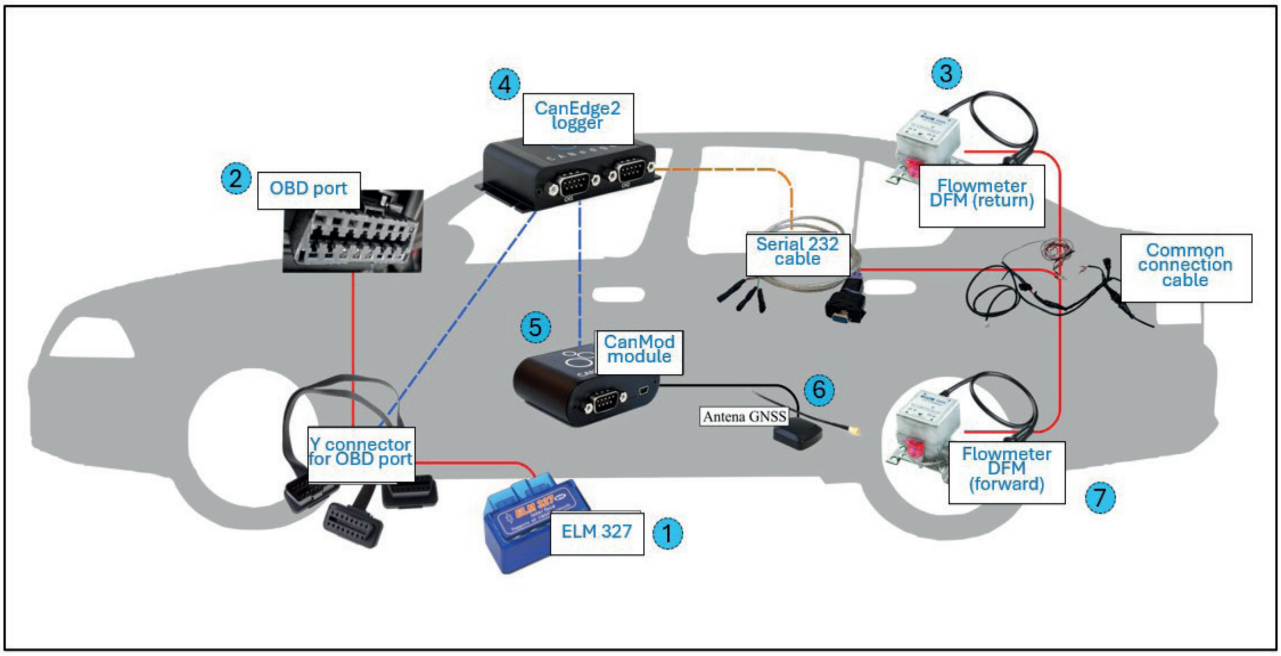

Figure 1. Configuration of selected instrumentation

Experimental Campaign

The experimental campaign was conducted in Ecuador across four cities with different altitudes: Manta, Santo Domingo, Ibarra, and Tulcán. In each city, two test routes were performed, each lasting approximately 50 minutes. Each route consisted of three distinct segments: urban, suburban, and highway. The tests were carried out during peak traffic hours, with the same driver operating the vehicle throughout the study. The air conditioning system remained off to avoid influencing fuel consumption. These conditions allowed the vehicle's real-world operation to be characterized, capturing the most representative engine operating conditions. The final equipment configuration for the experimental campaign is illustrated in Figure 1. This was successfully established after several pilot tests of communication between the different devices were carried out.

Although the objective was to characterize the vehicle's engine operation under real traffic conditions, the test routes were not fully standardized. No prior kinematic study was conducted to establish a standardized RDE (Real Driving Emissions) route for each city, as this was beyond the scope of the study. However, efforts were made to ensure that vehicle operation and driving conditions reflect typical usage patterns. This was achieved by incorporating roads with heavy traffic in city centers, suburban roads with average speeds below 90 km/h, and highway segments with minimal traffic and cruising operation. The urban segment was the longest in duration.

Tulcán was the highest-altitude city selected, located in Carchi province at an average altitude of 2980 meters above sea level (masl), with an average temperature of 13,5°C and an atmospheric pressure of 71,85 kPa. Ibarra, situated in the Ecuadorian highlands within Imbabura province, was the second-highest city at 2,225 masl, with an average temperature of 16,9°C and an atmospheric pressure of 77,23 kPa. In contrast, Santo Domingo, in Santo Domingo de los Tsáchilas province, was at an intermediate altitude of 550 masl, with an atmospheric pressure of 94,89 kPa and an average temperature of 22,1°C. Finally, Manta, a coastal city in Manabí province, was selected to compare engine operation at higher atmospheric pressures, with an altitude of 6 masl, an atmospheric pressure of 101,25 kPa, and an average temperature of 25,5°C. The details of each city's characteristics are presented in table 2.

Variable	City A (3000 masl)	City B (2300 masl)	City C (650 masl)	City D (0 masl)
City name	Tulcán	Ibarra	Sto. Domingo	Manta
Average altitude (masl)	2980	2225	550	6
Average atmospheric pressure (kPa)	71,85	77,23	94,89	101,25
Average maximum temperature(°C)	18,3	22,5	25,	29,7
Average temperature (°C)	13,5	16,9	22,1	25,5
Average minimum temperature (°C)	6,5	6,7	20	21,2
Relative humidity (%)	77,7	78,25	87,3	79,8

Table 2. Detailed Climatic and Geographic characteristics for selected cities

Method for developing engine maps

To analyse the effects of altitude on engine behaviour, engine maps were constructed for a gasoline vehicle operating under real-world conditions in multiple Ecuadorian cities, ranging from sea level to 3000 masl. The engine maps were generated using a data-driven approach focussed on three key variables: engine speed, engine load, and a third parameter of interest (e.g., fuel consumption or CO_2 emission rate). The development process comprised two stages. First, raw experimental data were segmented into engine speed-load bins, following the grid-based methodology proposed in previous studies.[16] Within each grid cell, the third variable was aggregated by computing the mean, after detecting and filtering outliers through statistical dispersion (standard deviation) and frequency analysis. This step ensured robust representation of operating points.

In the second stage, the processed grid data were used to create two-dimensional contour maps using the ggplot2 package in R Studio.[17] Colour scales were applied to discretize and visualize the third variable across the engine operating range, using predefined intervals and a divergent palette to enhance interpretability. By applying this method to datasets collected from cities at different altitudes, the resulting maps enabled comparative analysis of how elevation influences fuel consumption and emission patterns across real-world driving conditions.

Calculation of emission rates and distance-specific emission factors

To quantify fuel consumption and CO_2 emissions across varying altitudes, a data-driven framework was implemented using instantaneous measurements collected via OBD-II from a single vehicle operating for four Ecuadorian cities. The CO_2 emission rate at each timestamp was estimated based on stoichiometric combustion principles of gasoline ($C_8 H_{18}$), assuming a hydrogen-to-carbon atomic ratio (H/C) of 2,25. The instantaneous CO_2 emission rate (ER_{CO2}) in grams per second (g/s) was calculated using the following expression:

$$ER_{CO_{2}i} = FC_{i,t} \cdot \frac{44}{12+\left(\frac{H}{C}\right)} \quad (1)$$

Where rate ($FC_{i,t}$) is the instantaneous fuel consumption in g/s, and the constant 44 corresponds to the molar mass of CO_2. Subsequently, distance-specific fuel consumption $(\overline{FC})_i^d$ and CO_2 emission factors $(\overline{EF})_{CO2i}^d$ were computed by aggregating instantaneous data over the full driving cycle in each city (i). These indicators were derived using the following equations:

$$\overline{\mathrm{FC}}_i^d = \frac{\sum_{t=1}^{T_i}(FC_{i,t})}{\sum_{t=1}^{T_i}(d_t)} \quad (2)$$

$$\overline{\mathrm{EF}}_{CO_{2}i}^d = \frac{\sum_{t=1}^{T_i}\left(ER_{CO_{2}i,t}\right)}{\sum_{t=1}^{T_i}(d_t)} \quad (3)$$

Where $((\overline{FC})_i^d)$ is the distance travelled at time t, and T_i is denotes the total number of time steps for trip developed by city. This methodology enabled altitude-specific comparisons of vehicle efficiency and emissions, supporting the analysis with fine-grained temporal and spatial resolution derived from real-world driving data.

RESULTS AND DISCUSSION

The results presented in this section address the research objectives and are structured into four main subsections: (a) engine operation patterns are analysed under different altitude conditions, (b) fuel consumption engine maps are presented to visualize how fuel demand varies across the engine's operating range in each city, (c) CO_2 emission engine maps, and (d) effect of altitude on fuel consumption and emission factors at the trip level.

Engine Operation Patterns

Figure 2 illustrates the engine operating patterns expressed as engine load versus engine speed, for tested vehicles in four cities located at different altitudes: City A (3000 masl), City B (2300 masl.), City C (650 masl.), and City D (0 masl). Each point corresponds a one-second engine operation record. In general, two distinct patterns emerge: one corresponding to the high-altitude Andean cities (Cities A: Tulcán and B: Ibarra), and another associated with the low-altitude coastal cities (Cities C and D). In the Andean cities, vehicles predominantly operate at high engine loads (>70 %) across a wide range of engine speeds. This behaviour is likely driven by the challenging topography, where frequent uphill and downhill segments increase engine demand. Conversely, in the coastal cities, engine load values are more broadly distributed and tend to concentrate below 50 %, particularly at lower engine speeds. This can be attributed to the predominantly flat terrain and short elevation changes characteristic of these regions.

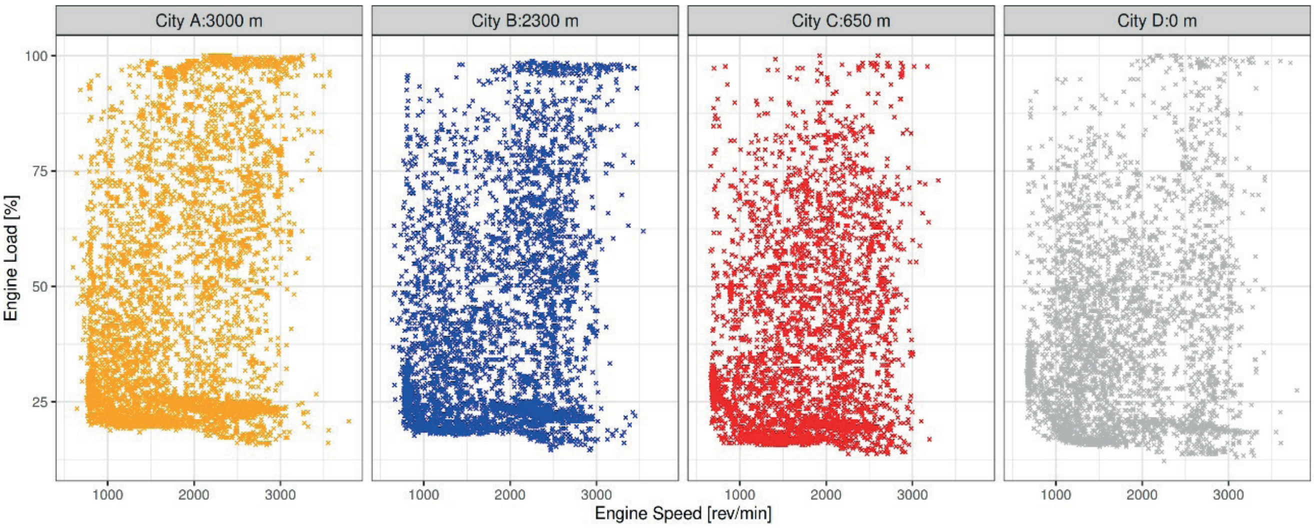

Figure 2. Typical engine operation patterns for cities at different altitudes

Engine maps of fuel consumption

Figure 3. presents engine fuel rate maps for vehicles tested in four cities located at different altitudes. The colour gradient indicates average fuel consumption rates (in g/s) across zones defined by engine speed and load. In all four cases, fuel consumption increases with both engine speed and load, with the highest rates occurring in zones combining high load and high revolutions per minute. This result is in line with what is expected from the thermodynamic behaviour of Otto cycle engines.

However, the maps also reveal that, for similar engine operating conditions, vehicles tested in high-altitude Andean cities (City A: 3000 masl and City B: 2300 masl) exhibit lower average fuel consumption rates compared to those tested in coastal cities (City C: 650 masl and City D: 0 masl). This trend is particularly evident in regions characterized by medium-to-high engine loads (50–100 %) and speeds between 1500 and 3000 rev/min. In these zones, the fuel maps for the Andean cities predominantly feature values in the 0,4–1,2 g/s range (green to blue), whereas the coastal cities display extended areas within the 1,2–2,0 g/s range (dark blue to purple).

The lower fuel consumption rates observed in high-altitude cities can be attributed to reduced atmospheric pressure, which leads to lower intake manifold pressure and reduced air volume entering the engine.[18] Studies have indicated that in high-altitude environments, the reduction in atmospheric pressure induces naturally aspirated gasoline engines to operate with increased valve lift, which mitigates intake manifold losses, enhances volumetric and thermal efficiency, and consequently results in lower fuel consumption.[19] These findings of the present study are consistent with those reported by Jiang et al., who also observed reduced fuel consumption in a vehicle tested at 3000 masl compared to tests conducted at sea level.[20]

It is important to clarify that these maps represent the average fuel consumption per operational bin, rather than the frequency of engine operation within those zones. The latter depends on the distribution of speed and load combinations observed during real-world driving. Recognizing this distinction is essential for accurately interpreting the maps in the broader context of fuel efficiency and vehicle performance across varying altitudes.

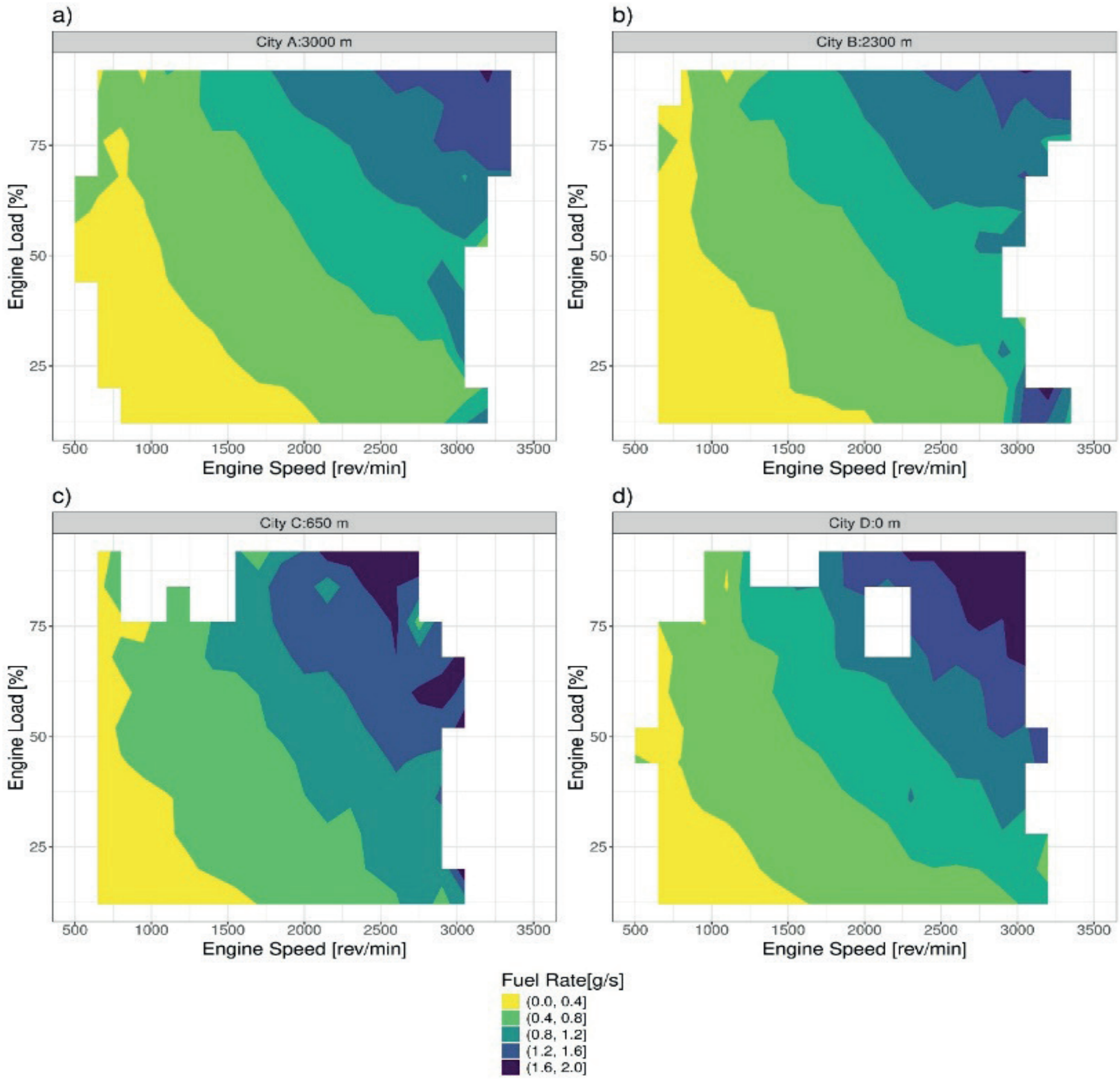

Figure 3. Engine maps for fuel consumption for cities at different altitudes

Engine maps of CO_2 emissions

Figure 4. presents engine maps showing CO_2 emission rates (in g/s) for vehicles tested in four cities located at different altitudes. As the tested vehicle was equipped with a spark-ignition engine operating under stoichiometric conditions, CO_2 emissions are directly proportional to the amount of fuel injected into the engine, as described in the Methods section. Consequently, the spatial distribution of CO_2 emissions closely mirrors the patterns observed in the previously analysed fuel rate maps. In all four cases, CO_2 emission rates increase with higher engine speeds and loads, as expected for Otto cycle engines.

When comparing the effect of altitude, low-load and low-speed regions show similar CO_2 emission rates across all cities, typically within the 0,0–3,0 g/s range (yellow to green). However, under medium-to-high load conditions (50–100 %) and engine speeds between 1500 and 3000 rev/min, the coastal cities—City C (650 masl) and City D (sea level)—exhibit broader regions with CO_2 rates exceeding 4,5 g/s (dark blue to purple), reaching values close to 10 g/s in some operating bins.

In contrast, vehicles tested in the high-altitude Andean cities—City A (3000 masl) and City B (2300 masl)—present fewer high-emission zones. Most of their operational regions fall within the 1,5–4,5 g/s range, and even under full-load conditions, very few zones exceed 6 g/s, unlike what is observed in coastal cities. This pattern reinforces the observation that, under comparable engine operating conditions (defined by speed and load), both fuel consumption and CO_2 emissions tend to increase as altitude decreases.

These findings are consistent with previous studies on light-duty vehicles, which have reported lower CO_2 emission rates at higher altitudes.[19] For instance, Zervas et al. observed that the CO_2 emissions of a gasoline-powered vehicle tested under two standardized driving cycles(e.g., NEDC, FTP) were significantly reduced at an altitude of 2200 masl compared to those measured at sea level.[21]

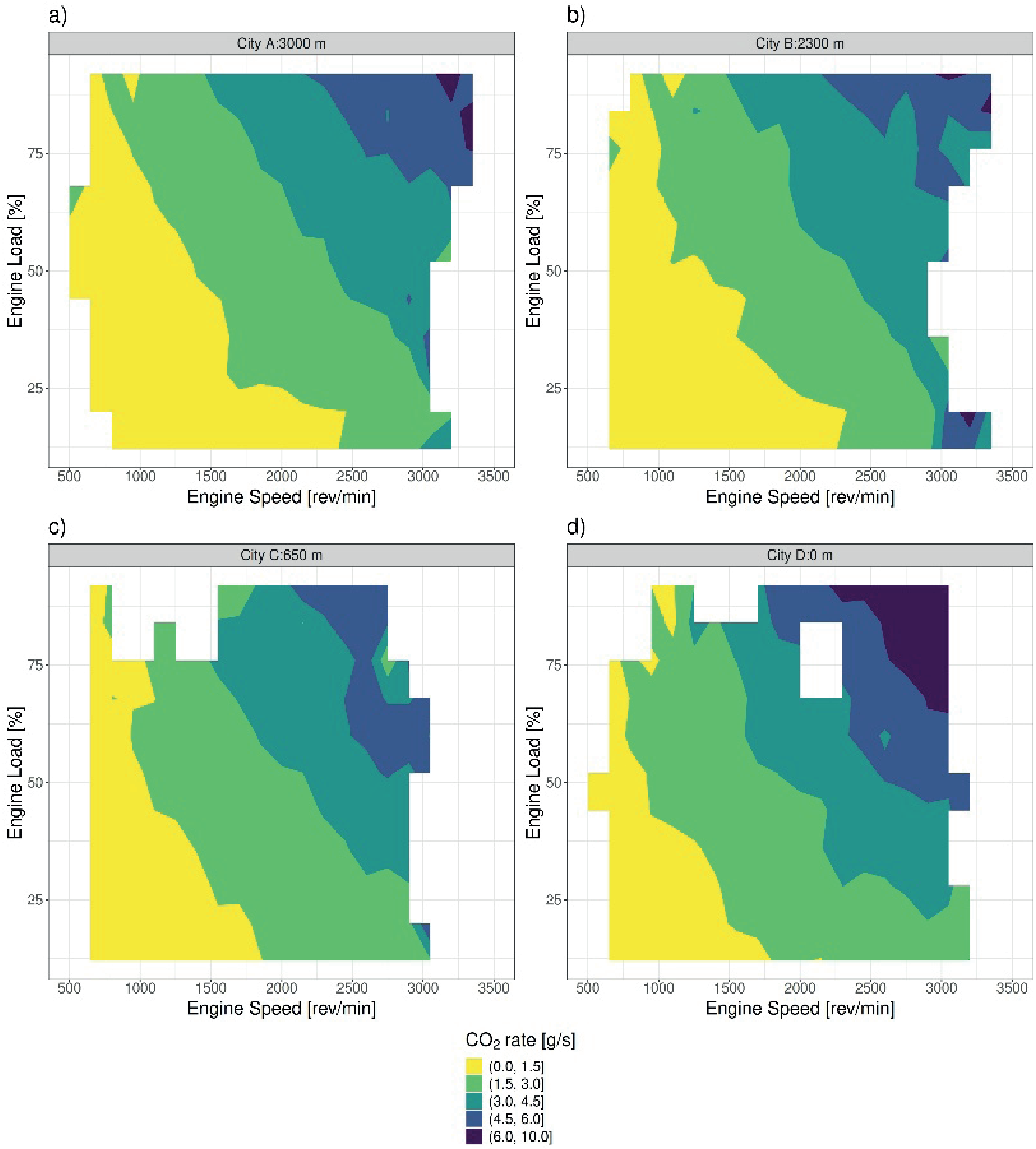

Figure 4. Engine maps for CO_2 rates at different altitudes

Effect of altitude on vehicle performance

Table 3 presents fuel consumption and CO_2 emission results for the tested vehicle in four cities located at different altitudes. The table includes cumulative positive traction energy and energy-based (g/kWh), as well as and distance-based (g/km) emission factors for both fuel consumption and CO2.Overall, the cumulative positive traction energy decreases by approximately 20 % as altitude decrease. The two high-altitude Andean cities, City A (Tulcán) and City B (Ibarra), exhibit higher energy demands than the lower-altitude cities, City C (Sto. Domingo, 650 masl) and City D (Manta, sea level). This trend reflects increased energy requirements likely associated with elevation-related factors such as road gradients.

Regarding energy-based emission factors, both fuel consumption and CO2 values shows a declining trend with decreasing altitude. For example, City A records the highest CO_2 emission factor at 1866,18 g/kWh, while City D shows the lowest at 1672,43 g/kWh, representing a reduction of approximately 10 %. These results suggest that although total energy demand decreases at lower elevations, variations in combustion efficiency and engine response to atmospheric conditions (e.g., air density) can significantly influence emission intensity.

Distance-based emission factors show relatively consistent fuel consumption values across all cities, ranging from 60,73 to 64,54 g/km. However, altitude-related differences are more pronounced in CO_2 emissions per kilometre. High-altitude cities such as City A exhibit higher values (199,28 g/km), whereas coastal City D reports lower emissions (187,52 g/km), indicating a reduction of about 6 %.

Interestingly, the higher distance-based CO_2 emission factors observed in high-altitude cities contrast with the results obtained from the engine map analysis in this same study, as well as with findings from previous studies.[20,21] This discrepancy could be attributed to other influencing factors, such as road gradient and vehicle acceleration, which may have predominated in the high-altitude test environments, thereby increasing fuel consumption.

Therefore, the lower distance-based emission factors recorded in coastal cities should be interpreted with caution. It is important to note that the driving routes selected in this study were not standardized and did not comply with Real Driving Emissions (RDE) protocols.[22] Consequently, each city involved a different driving cycle in terms of speed profile, terrain, and driving behaviour. For future studies, it is recommended to establish a test route with standardized characteristics in terms of duration, distance, and elevation gain. Overall, these findings underscore the complex relationship between altitude, vehicle energy demand, and emissions under real-world driving conditions.

Table 3. Overall vehicle performance of fuel efficiency, energy emissions, emission rates, and distance emissions for cities at different altitudes

City Ref	City name	Cumulative Positive Traction Energy (kWh)	Energy-Emission Factors (g/kWh) *		Distance-Emission Factors (g/km)	
			FC	CO_2	FC	CO_2
City A (3000 masl)	Tulcán	6,82	633,04	1866,18	64,54	199,28
City B (2600 masl)	Ibarra	6,70	558,54	1773,11	62,59	193,26
City C (650 masl)	Sto Domingo	6,26	545,39	1634,14	64,46	199,04
City D (0 masl)	Manta	5,47	611,41	1672,43	60,73	187,52

Note: * is relative to traction energy

CONCLUSIONS

The present study aimed to evaluate the effect of altitude on the fuel consumption and CO_2 emissions of a gasoline-powered vehicle under real-world driving conditions. To this end, an original method based on the engine mapping approach was applied using real-time data collected via the On-Board Diagnostics (OBD) system during an experimental campaign conducted in four Ecuadorian cities located at different altitudes, ranging from sea level to 3000 masl. The main findings are summarized as follows:

1. Engine mapping revealed that in high-altitude cities, vehicles operate above 70 % engine load due to topographic gradients, whereas coastal cities show lower loads, indicating reduced energy demand and different emission profiles.
2. When comparing similar engine operating zones, fuel consumption and CO_2 rates (g/s) were lower in high-altitude cities (Tulcán and Ibarra), suggesting altitude influences combustion behaviour under equivalent operational conditions.
3. Cumulative positive traction energy decreased by about 20 % from highland to coastal cities. However, energy-based CO_2 emission factors were higher at altitude, likely due to reduced combustion efficiency from lower air density.
4. Distance-based fuel consumption was similar across cities (60,73–64,54 g/km), but CO_2 emissions per kilometre were up to 7 % higher in high-altitude cities. This trend may reflect operational differences due to non-standardized driving cycles.

Overall, this research introduces a replicable methodology and provides relevant empirical data to support evidence-based environmental policy making. The results emphasize the importance of considering geographic and operational variability, such as altitude, when designing strategies to improve the environmental performance of urban transport in Latin American cities.

BIBLIOGRAPHIC REFERENCES

1. IEA. World Energy Outlook 2022. 2024. https://iea.blob.core.windows.net/assets/140a0470-5b90-4922-a0e9-838b3ac6918c/WorldEnergyOutlook2024.pdf

2. Review BS. BP Energy Outlook 2024 edition. Lo: 2024. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2024.pdf

3. Blanco Bonilla A, Ejecutivo S, Castillo T, García F, Mosquera L, Rivadeneira T, et al. Panorama Energético

de Amaérica Latina el el Caribe 2022. Quito, Ecuador: 2022. https://www.olade.org/publicaciones/panorama-energetico-de-america-latina-y-el-caribe-2021-2/

4. IIGE. Balance Energético Nacional 2023 . Ministerio de Energías y Minas.. Quito, Ecuador: 2024. https://www.recursosyenergia.gob.ec/wp-content/uploads/2022/08/Balance_Energético_Nacional_2021-VF_opt.pdf

5. Ntziachristos L, Mellios G, Tsokolis D, Keller M, Hausberger S, Ligterink NE, et al. In-use vs. type-approval fuel consumption of current passenger cars in Europe. Energy Policy 2014;67(2014):403–11. http://dx.doi.org/10.1016/j.enpol.2013.12.013

6. Rosero F, Rosero CX, Segovia C. Towards Simpler Approaches for Assessing Fuel Efficiency and CO2 Emissions of Vehicle Engines in Real Traffic Conditions Using On-Board Diagnostic Data. Energies 2024;17(19):4814. https://www.mdpi.com/1996-1073/17/19/4814

7. Jiang Z, Wu L, Niu H, Jia Z, Qi Z, Liu Y, et al. Investigating the impact of high-altitude on vehicle carbon emissions: A comprehensive on-road driving study. Sci Total Environ 2024;918(January):170671. https://doi.org/10.1016/j.scitotenv.2024.170671

8. Ramos Á, García-Contreras R, Armas O. Performance, combustion timing and emissions from a light duty vehicle at different altitudes fueled with animal fat biodiesel, GTL and diesel fuels. Appl Energy 2016;182:507–17.

9. He C, Ge Y, Ma C, Tan J, Liu Z, Wang C, et al. Emission characteristics of a heavy-duty diesel engine at simulated high altitudes. Sci Total Environ 2011;409(17):3138–43. http://dx.doi.org/10.1016/j.scitotenv.2011.01.029

10. Wang X, Ge Y, Yu L, Feng X. Effects of altitude on the thermal efficiency of a heavy-duty diesel engine. Energy 2013;59:543–8. http://dx.doi.org/10.1016/j.energy.2013.06.050

11. Liu J, Ge Y, Wang X, Hao L, Tan J, Peng Z, et al. On-board measurement of particle numbers and their size distribution from a light-duty diesel vehicle: Influences of VSP and altitude. J Environ Sci (China) 2017;57:238–48. http://dx.doi.org/10.1016/j.jes.2016.11.023

12. Kan Z, Hu Z, Lou D, Tan P, Cao Z, Yang Z. Effects of altitude on combustion and ignition characteristics of speed-up period during cold start in a diesel engine. Energy 2018;150:164–75. https://doi.org/10.1016/j.energy.2017.12.103

13. Gómez CD, González CM, Osses M, Aristizábal BH. Spatial and temporal disaggregation of the on-road vehicle emission inventory in a medium-sized Andean city. Comparison of GIS-based top-down methodologies. Atmos Environ 2018;179(June 2017):142–55. https://doi.org/10.1016/j.atmosenv.2018.01.049

14. Yupanqui DE. Determinación del rendimiento de combustible de una flota de taxis de 1400 centímetros cúbicos en la ciudad de Cuenca mediante parámetros de conducción normal. Univ del Azuay 2020;175. http://dspace.uazuay.edu.ec/bitstream/datos/7226/1/13172.pdf

15. AEADE. Anuario 2020 AEADE. Quito: 2020. https://abimapi.com.br/anuario/pdf/anuario_2020-3.pdf

16. Rosero F, Fonseca N, López JMJM, Casanova J. Real-world fuel efficiency and emissions from an urban diesel bus engine under transient operating conditions. Appl Energy 2020;261(December 2019):114442. https://doi.org/10.1016/j.apenergy.2019.114442

17. RStudio. RStudio: Integrated development environment for R. 2018;https://posit.co/download/rstudio-desktop/

18. Gao H, Wang R, Wen Z, Xiong X, Zheng Z, Lin S, et al. The real driving emissions characteristics of light-duty diesel vehicle in four typical cities with varying altitudes in China. Case Stud Therm Eng 2025;67(July 2024):105831. https://doi.org/10.1016/j.csite.2025.105831

19. Wang Y, Feng X, Zhao H, Hao C, Hao L, Tan J, et al. Experimental study of CO2 and pollutant emission at various altitudes: Inconsistent results and reason analysis. Fuel 2022;307(January 2021):121801. https://doi.org/10.1016/j.fuel.2021.121801

20. Jiang Z, Niu H, Jia Z, Wu L, Zhang Q, Zhang Y, et al. Comparison of vehicular emissions at different altitudes: Characteristics and policy implications. Environ Pollut 2025;367(January):125679. https://doi.org/10.1016/j.envpol.2025.125679

21. Zervas E. Impact of altitude on fuel consumption of a gasoline passenger car. Fuel 2011;90(6):2340–2. http://dx.doi.org/10.1016/j.fuel.2011.02.004

22. Triantafyllopoulos G, Dimaratos A, Ntziachristos L, Bernard Y, Dornoff J, Samaras Z. A study on the CO 2 and NO x emissions performance of Euro 6 diesel vehicles under various chassis dynamometer and on-road conditions including latest regulatory provisions. Sci Total Environ 2019;666(x):337–46. https://doi.org/10.1016/j.scitotenv.2019.02.144

FINANCING

This research was funded by the Universidad Técnica del Norte, within the research project 0000001349.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORSHIP CONTRIBUTION

Conceptualization: Fredy Rosero, Daniel Arias.
Data curation: Fredy Rosero, Daniel Arias.
Formal analysis: Fredy Rosero.
Research: Carlos Xavier Rosero, Fausto Tapia.
Methodology: Fredy Rosero, Daniel Arias.
Project management: Fredy Rosero.
Resources: Carlos Xavier Rosero, Fausto Tapia.
Software: Fredy Rosero, Daniel Arias.
Supervision: Fredy Rosero, Carlos Xavier Rosero.
Validation: Fredy Rosero.
Display: Fausto Tapia.
Drafting - original draft: Fredy Rosero, Carlos Xavier Rosero, Fausto Tapia, Daniel Arias.
Writing - proofreading and editing: Fredy Rosero, Carlos Xavier Rosero.