# ANALYSIS OF THE ROLE OF ALTITUDE AND TEMPERATURE ON THE PERFORMANCE OF THE IGNITION INTERNAL COMBUSTION ENGINE USED FOR LIGHT VEHICLE PROPULSION

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**Summary**
The present paper presents the impact of altitude on the performance of a ignition combustion engine. In order to obtain the results, 10 different models of vehicles widely used in the Andean region of Latin America were analyzed, which during a period of three years were instrumented in such a way that they can be obtained at the rate of one reading per year. Second, data referring to the operation of the engine, the dynamics of the vehicle and the emissions generated to the environment, in a wide altimetric strip between 0 and 4500 meters above sea level. In addition, data on environmental conditions were collected in such a way that the analysis of the impact of altitude can also be extended to factors such as environmental temperature. Although there are developed operation simulators where pressure and temperature parameters are modified under international regulations, ISA, the results obtained are from real conditions of conduction which gives a significant advantage of reliability over the data obtained. Guidelines of the European Commission require an approval on emissions generated at different altitude conditions hence the importance of having a baseline regarding the real effect of altitude on performance and emissions. In particular, there is a clear increase in vehicle emission readings in altitude conditions above 2500 meters above sea level, which emphasizes the need for strategies dedicated to reducing emissions in altitude operations. There are few studies of the behavior of a light engine at higher altitude conditions and its behavior is not significantly documented since most engines were manufactured and applied to sea level.

**Abstract**

This paper presents the impact that altitude has on the performance of a spark ignition combustion engine. In order to obtain the results, ten different models of vehicles widely used in the Andean region of Latin America were analyzed, the same ones that, during three years, were instrumented in such a way that they can be obtained at the rate of one reading per second, data referring to the engine operation, vehicle dynamics and emissions generated into the environment, in a wide altimetric range between 0 and 4500
m.a.s.l. In addition, data on environmental conditions were collected in such a way that the analysis of the impact of altitude can also be extended to factors such as environmental temperature. Although operating simulators are developed where the pressure and temperature parameters are modified under international regulations, ISA, the results come from real driving conditions, which gives a significant reliability advantage over the data obtained. Furthermore, directives of the European Commission require approval of the emissions generated at different

altitude conditions, hence the importance of having a baseline regarding the real effect of altitude on performance and emissions. In particular, there is an apparent increase in vehicle emission readings in high-altitude conditions, which emphasizes the need for strategies to reduce emissions in high-altitude operations.

**Keywords:-** Internal combustion engine, standards, altitude, emissions, performance.

## INTRODUCTION

Regulations such as the Harmonized Light Vehicle Testing Regulations, WLTC, require the evaluation of vehicle performance at different altitude conditions for engine optimization and emission reduction, for this reason it is imperative to collect vehicle operation data at low pressure and low temperature conditions . 1] Latin America is a true laboratory for this type of conditions because it has cities above 4000 meters above sea level. And with temperatures close to 0°C.[2][3]

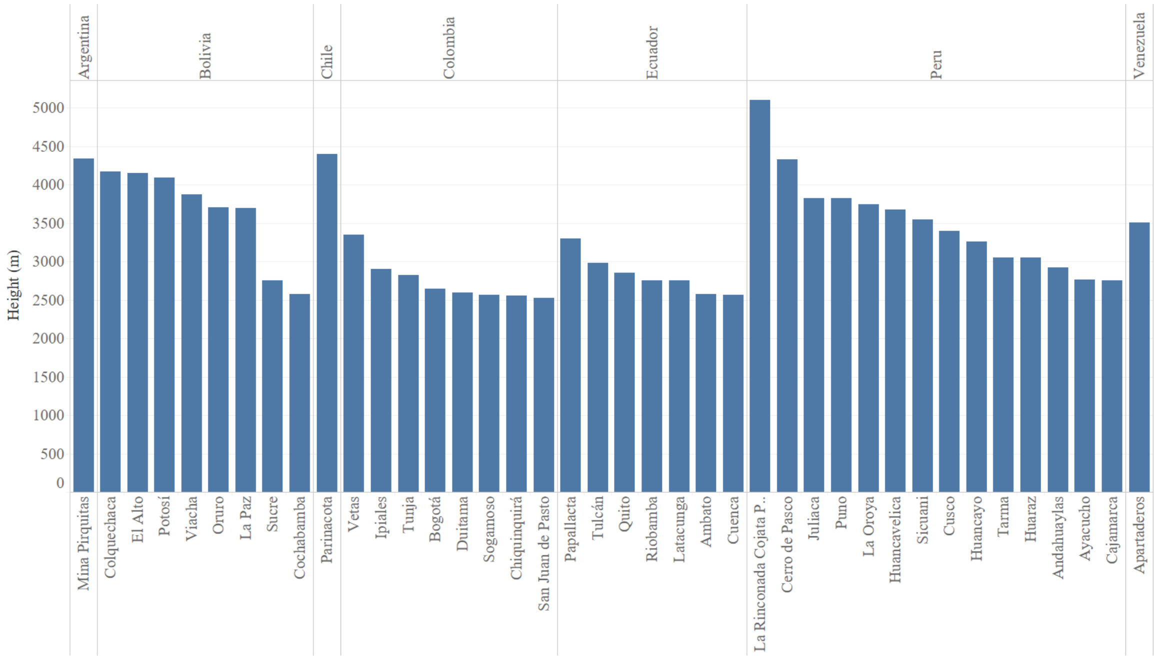


*Fig. 1. Altitudes above sea level of several cities in Latin America*

Due to the reduction of ambient pressure the density of the air is also affected and with it the behavior and response of the engine. Certain variables that are affected by air density such as: fuel droplet size, lower coalescence, spray angle , spray penetration, ignition advance, airflow entering the engine, mechanical load, gas purge and soot formation determine a variation in fuel consumption, Several of these methods have been previously studied under different methods: theoretical, practical and computational.[ 4]

Several studies have been conducted on compression ignition engines emphasizing the work on altitude while maintaining constant temperatures.

with measurements of CO, HC and NOx and particulate matter, where it has been verified that at a higher speed the generation of carbon monoxide and hydrocarbons decreases in contrast to NOX and PM which increase with speed. In the case of diesel engines, the generation of CO, HC and PM increased with increasing altitude while NOX increased between 1000 m and 2400 m to descend to 3200 m .[5]

In the present study, the amount of fuel required to generate a constant unit of relative power has been analyzed, product of the relationship between the power and the mass of the vehicle expressed in tons [Kw / Tn]. Laboratory studies use pressure simulators using turbochargers to modify the air intake pressure as a result of varying altitude at which the vehicle operates. 6]

The vehicles in their factory configuration, that is, in the mapping that internally carries the automotive computer, ECU, are designed in such a way that they operate in the best possible way in conditions of zero meters above sea level, however many of the cities in which they operate can easily exceed 4000 masl, as is the case of several of the cities in Latin America and clearly this difference in altitude and with it the density of the air will generate changes in the performance of the engine.[ 1]

When a gasoline engine operates, the sucked air is monitored by the engine's airflow sensors (MAF) or, failing that, by pressure (MAP) and temperature (IAT) sensors that based on the calculation approximation based on the ideal gas equation , **error! The source of the reference cannot be found**. , with motor speed (CKP) manage to determine the air intake of the engine expressed in grams per second.

$$P * V = m * R * T \quad \text{Ec. 1}$$

This value of air entered into the engine is read by the ECU, so that based on the use of a map, previously entered by the engineers who designed and tested the engine at low altitudes, the amount of fuel that must be determined be injected into the engine, regulated based on the pulse width at which the injector will be open. The amount of fuel entered should maintain a ratio close to 14.7 parts of air for each part of fuel (this by mass) so that you can comply with a stoichiometric ratio that chemically and theoretically ensures correct engine performance in terms of performance and low emissions.[ 7]

Under what has been said in the previous paragraph it is understood that theoretically a decrease in the density of the air will cause a lower entry of fuel, however it is necessary to carry out a broader analysis in view of the fact that a decrease in the work done by the engine in each lap will require a greater amount of accelerations unbalancing the balance again. of consumption.

Another criterion to consider is the aerodynamic force that acts on the vehicle, it is considered that any body that tries to overcome a gaseous fluid must overcome the resistance exerted by it , which depends mainly on: the density of the fluid, the shape of the body, the area of impact and especially the speed at which the The body moves in the fluid. The equation that rules the above is the **Error! The source of the reference is not found**. . [8]

$$F_{aerd} = 0.5 * \rho * A * Cd * V^2 \quad \text{Ec. 2}$$

The density of the air will have a decreasing effect on the drag force generated by the air in such a way that the increase in altitude "should" also decrease consumption. of fuel in view of the fact that traversing a less dense fluid clearly requires less effort. However, all of the variables discussed above must be analyzed together to determine the overall effect of altitude on consumption and emissions.[ 9]

Re-ignition at altitude is an increasingly important issue limiting the development of low-emission combustion chambers due to the current trend towards lean combustion. The variation of ignition limits quantitatively characterizes the degree of ignition deterioration under subatmospheric pressures (10 ~ 70 kPa) and low temperatures (253 ~ 301 K). From the analysis of the relationship air/liquid and Weber number, it has been shown that the increase in droplet size and reduced spray cone under altitude conditions are induced by three aspects, including insufficient downforce , increased viscosity strength of the liquid and increased surface tension. Poor atomization quality is detrimental to grain generation and flame propagation and eventually leads to deterioration of ignition yields.

The engines, being designed and manufactured for altitudes significantly lower than those that can be found in several of the cities of Latin America, present unusual behaviors to which the designers and builders had been accustomed and this causes that the cases of the operation at higher altitudes are not sufficiently documented. 1] [10]

## METHODOLOGY

The information was collected from several light vehicles powered by gasoline engines, operating under the otto ignition cycle caused by spark, the selection was made based on the vehicles with the highest running in the Ecuadorian national territory. The characteristics of the selected vehicles are shown in Table 1.

*Table 1. Characteristics of the selected vehicles*

| Vehicle | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Guy | Van ta | This n | Hatc hbac k | This n | This n | This n | This n | This n | Suv | Truck |
| Emissions standard | EURO III | EUR O IV | EUR o V | EUR o V | EUR O IV | EUR O IV | EUR O IV | EUR O IV | EURO V | EUR O IV |
| Displacement CC. | 1173 | 1399 | 1397 | 1397 | 1498 | 1498 | 1598 | 1799 | 1984 | 2237 |
| Compression ratio | 10:1 | 10:1 | 10.5: 1 | 10.5: 1 | 9.5:1 | 9.5:1 | 10.5: 1 | 9.8:1 | 9.6:1 | 10:1 |
| Type of admission | ON | ON | ON | ON | ON | ON | ON | ON | Turbocharge d | ON |
| Type of injection | MPFI | MPI CVV T | MPI CVV T | MPI CVV T | MPFI | MPFI | MPI | MPI | TFSI | MPFI |
| Maximum torque Nm-RPM | 106 @ 3500 - 4500 | 136 @ 5000 | 137 @ 5000 | 138 @ 5000 | 128 @ 3000 | 128 @ 3000 | 153 @ 3800 | 165 @ 4000 | 350 @ 1500 - 4500 | 190 @ 2.800 |
| Maximum power KW-PRM | 59 @ 6000 | 79 @ 6300 | 67 @ 6200 | 68 @ 6200 | 62 @ 5600 | 62 @ 5600 | 77 @ 5600 | 89,55 @ 5800 | 171.5 @ 4700 - 6200 | 79 @ 4600 |
| Empty weight Kg. | 1230 | 1133 | 1263 | 1074 | 1040 | 1040 | 5 | 1211 | 1830 | 1740 |

In order to evaluate the effect of external variables such as altitude and ambient temperature, it is necessary to previously instrument the vehicles on which the performance and emissions tests will be carried out with devices that allow the data shown in Table 2 to be collected.[ 11]

*Table 2. Parameters monitored in vehicles*

| Emissions Analyzer Readings | Chemical formula | Reading of car sensors by OBD II | Reference PID (hex) |
|---|---|---|---|
| Carbon dioxide | $CO_2$ | Short- and long-term fuel | 06 / 07 / 08 / 09 |

| | | | |
|---|---|---|---|
| | | adjustment | |
| Carbon monoxide | CO | Car speed | 0D |
| Total, of hydrocarbons | THC | Engine load | 04 |
| Nitrogen dioxide | NO2 | Instant fuel consumption | 5E |
| Hydrogen monoxide | NO | Throttle position | 11 |
| Oxygen | The$_2$ | Motor speed | 0C |
| | | Coolant temperature | 05 |

To obtain the engine operation data, an OBDII device was used, with which the CAN BUS information frame was accessed, which was decoded, under the scheme shown in Fig. 1.

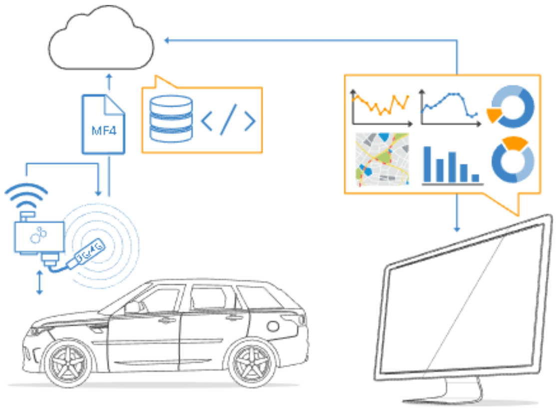


*Fig. 2. Diagram* of *connection and instrumentation of automobiles*

Once the information of the CAN BUS data frame has been obtained and decoded, it is possible to have a general visualization of the operating criteria second by second as shown in Fig. 3, in such a way that it becomes usable information for the next data analysis .


*Fig. 3. Data visualization*

The emission analyzer used was the Maha MET 3.1 the same that thanks to its data acquisition software recorded second by second the information displayed in the

| Gas | Symbol | Range | Units | Precision | Measuring method |
|---|---|---|---|---|---|
| Carbon dioxide | CO2 | 0 - 20 | % | 0.01 | Infrared Spectrometry |
| Carbon monoxide | CO | 0 - 15 | % | 0.01 | Infrared Spectrometry |
| Total Hydrocarbons | THC | 0 - 10K | ppm | 0.01 | Infrared Spectrometry |
| Nitrogen oxide | NOx | 0 - 5K | ppm | 20 | Electrochemical detection |
| Oxygen | O2 | 0 - 25 | % | 0.01 | Electrochemical detection |
| Lambda | $\lambda$ | 0.5 - 10 | - | 0.01 | Calculated |

*Table 3. Emissions monitored by the Met 6.3 Analyzer and* measurement *methods.*

Using the data obtained from emissions, they are converted into emission factors using the carbon balance and concentration readings in Table 3,

so that the units are $\frac{grams}{}$, according to Eq. 3.

It is also necessary to consider that the emissions database and the dynamic operating parameters of the car have a different measurement process and reading time . The data acquired with the OBD2 device has an immediate response while the emission readings require a longer time because the gases they must be generated, absorbed by the vacuum pump of the analyzer and finally recorded by the Maha Emission Viewer program, in such a way that a synchronization process is required between the readings based on statistical criteria such as Pearson correlation.

In Table 4, it is possible to visualize an approximation regarding the recording times of the two equipment, which is why the pairing of the data is justified in order to perform a subsequent data analysis.

Once the synchrony between the two databases is achieved, it is possible to study the effect of altitude and temperature on fuel consumption with the certainty that the reaction in the performance and operation of the car corresponds to the moment in which this occurred, due to the Lag that is normally located in the range of±10 $segundos$. [12]

*Table 4. Estimation of recording times for* the *OBD2 device and the emission analyzer*

| OBDII | | WITH 6.3 | |
|---|---|---|---|
| Event | Time [s] | Event | Time [s] |
| Action of pressing the pedal | 1,5000 | Action of pressing the pedal | 1,5000 |
| OBD data logging | 0,0020 | Action of the electronic butterfly | 0,0010 |
| Data Capture App Torque | 1,0000 | Injection time | 0,0025 |
| Log on file | 0,5000 | Burning time | 0,0014 |
| | | Gas escape time | 0,0005 |
| | | Measurement time | 2,0000 |
| | | Log on file | 2,3000 |
| Total | 3,0020 | Total | 5,8054 |

## RESULTS

Using the results obtained, an analysis of the amount of fuel used to obtain a specific amount of power is performed. In Fig. 4, the consumption is analyzed to obtain negative powers, that is, moments in which the conditions of acceleration and slopes work in favor of the movement. It can be seen that between 0 and 1000 meters above sea level there is an increase in fuel consumption from 4.7 l / 100km to 5.7 l / 100km, while at 1500 meters above sea level consumption decreases to 3.7 l / 100km having a gradual increase until reaching 5.3 l / 100 km to 3500 meters above sea level.

A consumption analysis was also carried out when the power obtained was from 0 to 400 kw to the wheels, the operating parameters regarding consumption are shown in Fig. 5 the summarized data regarding consumption, at 0 meters above sea level fuel consumption is 4.7 liters per 100 km and increases Gradually as the altitude increases until it reaches 5.5 l/100 km at 1500 meters above sea level. Between 2000 and 3000 meters above sea level fuel consumption remains with values close to 4.2 l / 100 km and finally there is a considerable increase when at altitudes above 3500 meters above sea level reaching a consumption of 6 l / 100 km.

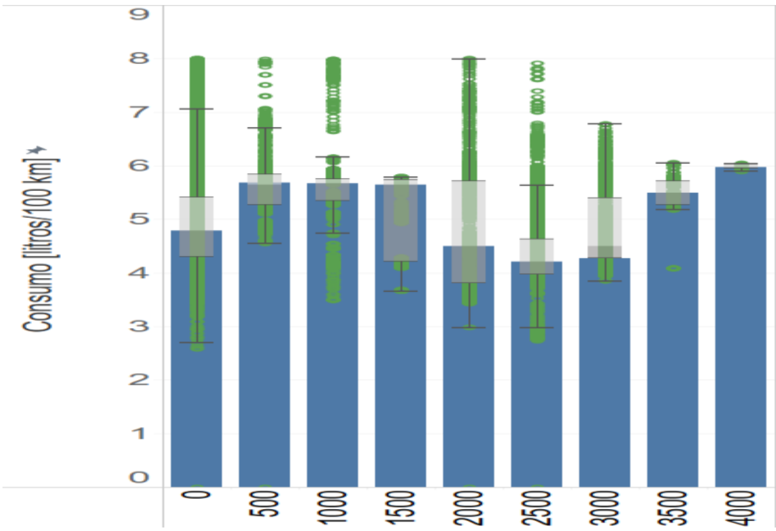


*Fig. 4. Fuel consumption as a function of altitude, for negative powers*

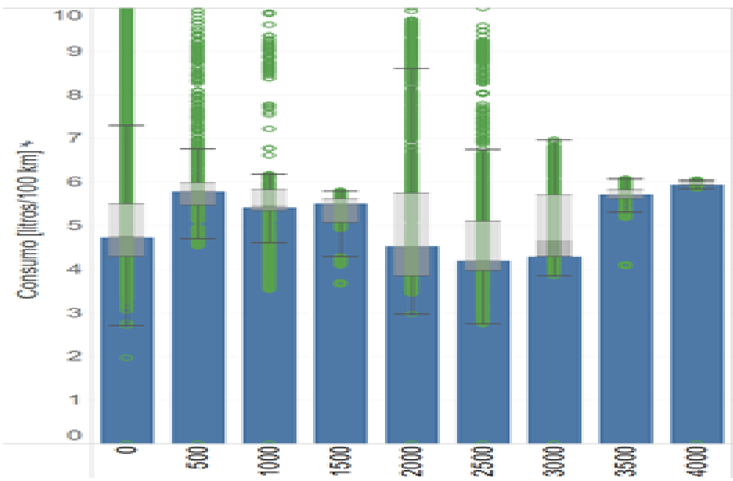


*Fig. 5. Fuel consumption when the powers obtained are between 0 and 400 Kw*

Using the global volume of data, the Tukey test is performed to verify if there is a statistically significant difference between fuel consumption at different altitudes, assuming as a null hypothesis the similarity between all the means of the data and the alternative hypothesis that the means are different.

The P value for this analysis of variance is less than 0.05, so the null hypothesis is rejected and the alternative hypothesis is accepted, Table 5. It is also possible to visualize in Fig. 7 the trend regarding consumption at different altitudes.

*Table 5. Analysis of variance for consumption values at different altitudes between 0 and 4000 meters above sea level*

| | GL | SC Tight | MC Tight. | F-value | P value |
|---|---|---|---|---|---|
| Altitude (m) (grouping) | 8 | 13772 | 1721.48 | 394.76 | 0.000 |
| Error | 132701 | 578681 | 4.36 | | |
| Total | 132709 | 592453 | | | |

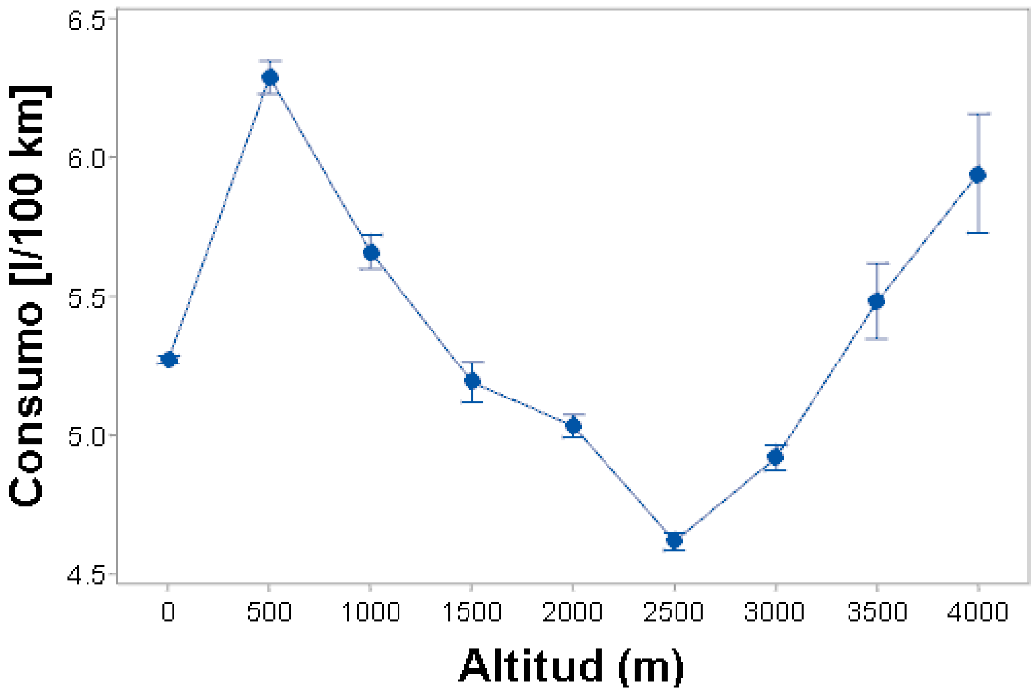


*Fig. 6. Tukey test* with *95% confidence for altitude consumption values*

The effect of temperature on fuel consumption was also analyzed and it was shown that in cold circulation spaces consumption is lower with values close to 3.7 l / 100 km, as the environment increases in temperature there is also an increase in fuel consumption. At 10°C the average consumption is 4.7 l/100 km, at 20°C the consumption is 4.9 l/100km, at 30°C the consumption is
5.3 l/100km and for higher temperatures the average fuel consumption increases to 6.4 l/100km.

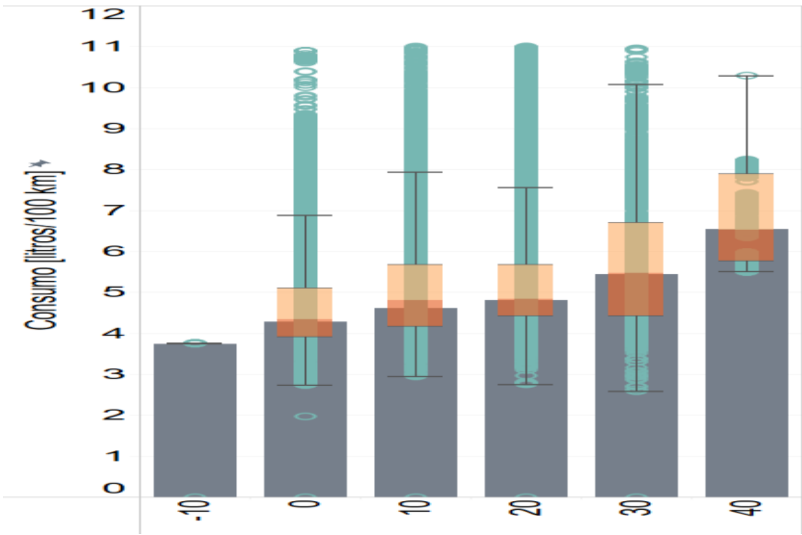


*Fig. 7. Effect of ambient temperature on fuel consumption*

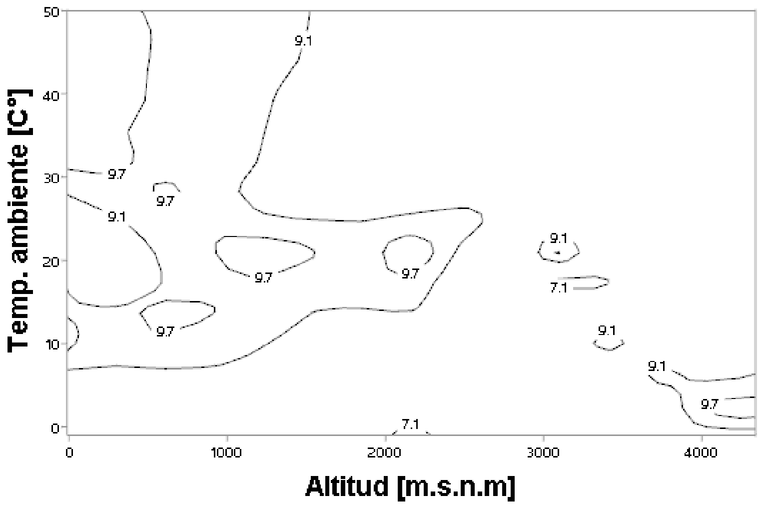


*Fig. 8. Contour diagram (temperature, altitude and consumption)*

**CONCLUSIONS**

Fuel consumption varies strongly depending on the altitude at which the vehicle powered by a gasoline internal combustion engine works, this range is close to 2 liters / 100 km.

The lowest consumption is obtained at 2500 meters above sea level while as it moves away from this measure (in values of higher and lower altitude) the consumption tends to rise to 6.2 l / 100 km.

Statistical tests such as analysis of variance and Tukey's similarity test certify the impact of altitude on fuel consumption.

Another factor that has an impact on fuel consumption is the ambient temperature, low temperatures maintain consumption at values of 4 liters / 100 km, while when the temperature increases (under similar delivered power conditions) consumption also increases to values of 6.5 liters/100 km.

The effect of temperature on air density has a negative effect on fuel consumption since a decrease in the mass of air entering the engine forces an increase in the rate of acceleration and with it fuel consumption.

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