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Analysis of vehicle specific power and road grade in a high-altitude city

Análisis de potencia-específica-vehicular y grado de la carretera en una ciudad a gran altitud

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ABSTRACT: Vehicles are a major source of atmospheric pollutants and greenhouse gases. Real Driving Emissions (RDE) testing is used to study the real-world effects of parameters that are not considered in laboratory testing but that can influence fuel consumption and vehicle emissions. This paper analyzes the vehicle specific power (VSP) and the effects of positive and negative road slopes on the fuel consumption of a sport utility vehicle (SUV). The vehicle was tested on a route at an altitude of 2750 meters in Riobamba, Ecuador. The circuit design included urban, rural, and highway driving that met the requirements of European Union (EU) Regulation 2018/1832. Low-cost devices were used to record data from the road tests to determine fuel consumption as a function of road slope. VSP+ analysis revealed that there is a good correlation with fuel consumption, with an R^2 of 0.86. For road slopes of -6% to +6%, the percentage variation in fuel consumption is linearly correlated $(R^2 = 0.85)$ with the slope variations.

RESUMEN: Los vehículos son una importante fuente de contaminantes atmosféricos y gases de efecto invernadero. Las pruebas de emisiones en carretera en conducción real (RDE) se utilizan para estudiar los efectos en el mundo real de parámetros que no se tienen en cuenta en las pruebas de laboratorio pero que pueden influir en el consumo de combustible y las emisiones contaminantes de los vehículos. En este trabajo se analiza la potencia específica del vehículo (VSP) y los efectos de la pendiente positivas y negativas de la carretera en el consumo de combustible de un vehículo deportivo utilitario (SUV). El vehículo fue probado en una ruta sobre los 2750 m de altitud en Riobamba, Ecuador. El diseño del circuito incluyó conducción urbana, rural y en autopista que ajusta a los requisitos del Reglamento 2018/1832 de la Unión Europea (UE). En el registro de datos de las pruebas en carretera se utilizaron dispositivos de bajo costo para determinar el consumo de combustible en función de la pendiente de la carretera. El análisis de la VSP+ reveló que, existe una buena correlación con el consumo de combustible, con un R^2 del 0,86. Para pendientes de carretera de -6% a +6%, la variación porcentual del consumo de combustible está correlacionada linealmente $(R^2 = 0,85)$ con las variaciones de la pendiente.

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1. Introduction

Road transport continues to significantly contribute to fossil fuel consumption and, therefore, to air pollution, especially in urban areas with heavy traffic [1]. According to the World Health Organization, air pollution caused 4.2 million deaths worldwide in 2019 [2]. To improve air quality, for example, European legislation has established stricter homologation limits and, as of September 2017, a new real driving emissions (RDE) test was introduced to measure the emissions of all new car models under real driving conditions [3]. In the last decade, many researchers worldwide have measured real driving emissions and fuel consumption. The results revealed that real emissions often differ significantly from emissions measured in the laboratory using standard procedures [4].

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Many parameters that are not considered in laboratory tests can affect fuel consumption and exhaust emissions in real-world driving conditions [5, 6]. Altitude and road grade are real-world driving parameters that have a significant impact on vehicle emissions [7–10]. Many studies have shown that road grade has a significant effect on vehicle exhaust emissions: a positive road grade during

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vehicle motion causes additional load, while a negative grade reduces load [11–13]. A study conducted in 2017 revealed that on-road tests with a 5% grade resulted in an increase in fuel consumption and nitrogen oxide emissions of 85% and 115%, respectively, compared to a flat route [14]. In contrast, an experimental study indicated that vehicle exhaust emissions are more affected by downhill grades than by uphill grades [15]. On the other hand, a study found that fuel consumption and exhaust emissions are underestimated by 16% to 22% if positive road grades are not considered, while fuel consumption and emissions are overestimated by 22% to 24% if negative road grades are not considered [16]. A more recent study showed that dynamometer measurements are lower than actual emission rates because the homologation driving cycle does not consider road grade [17].

Over the past few decades, the automotive industry has paid little attention to the additional power requirements imposed by road grade; nowadays, it is clear that elevation can drastically affect the fuel/energy consumption of vehicles powered by conventional, hybrid, or electric configuration, as it requires additional power during ascents and/or descents that could be recovered through regenerative braking systems to improve vehicle efficiency using current technologies [18]. Currently, vehicle owners around the world are very interested in new propulsion technologies that allow them to reduce fuel/energy consumption and, consequently, the impact on the environment [19]. Studies have shown that, if drivers do not take into account road grade, they may choose a route that increases the vehicle's fuel consumption [20]. On the other hand, with the increasing electrification of road transport, road grade data is important in the continued development of hybrid and electric vehicle technologies [21].

The effect of road grade depends on the vehicle's speed and acceleration, as both contribute (along with grade) to the overall power demand. VSP is a well-established way to consider the contribution of kinematics along with road grade [22, 23]. VSP is defined as the energy consumption of a vehicle to overcome rolling resistance and aerodynamic drag, expressed in W/kg; the main factors are speed, acceleration, and road grade [24, 25]. VSP is useful in mathematical models of vehicle air pollution emissions and for analyzing vehicle dynamics in road tests [26, 27]. As the calculation of VSP considers road grade, among other factors, it has become an interesting tool to add a better understanding of the dynamics of RDE tests [28–31]. The most widely used macroscopic models for light vehicles do not consider road grade among the parameters that influence vehicle emissions, and the resulting error is not negligible. More accurate microscopic models, such as the MOVES (MOtor Vehicle Emission Simulator) from the US Environmental Protection Agency, on the other hand, calculate on-road exhaust emissions considering road grade through VSP [32].

The objective of this paper is to analyze the VSP and the influence of road grade on the fuel consumption of a sport utility vehicle. Real driving cycles were performed in Riobamba, Ecuador; the selected routes were chosen in accordance with the new RDE procedure described in EU Regulation 2018/1832. The analysis focused on the VSP and the correlation between fuel consumption and road grade.

2. Methodology

2.1 Vehicle and measurement description

This study was conducted using a Ford Escape 3 L SUV. The main features of the engine and vehicle are summarized in Table 1.

Table 1 Vehicle characteristics

Items	Value
Number of cylinders	6
Engine configuration	V-engine
Displacement (cm^3)	2966
Maximum Power	176 kW/6500 rpm
Maximum Torque	223 Nm/4300 rpm
Gross Vehicle Weight Rating (kg)	1986
Transmission	Manual M5
Emission Standard	Euro 3

To carry out RDE tests, the vehicle was instrumented with an automotive diagnostic device (ELM 327) connected to the vehicle's OBD-II. The OBD-II uses Parameter Identifier codes (PIDs, which are used to measure parameters in real time) to request data from the Electronic Control Unit (ECU). The ELM327 is an OBD-II integrated interpreter chip that can interface with the necessary electronic circuits to establish communication with the vehicle's ECU through the OBD-II port. The protocols supported by this device are ISO 15765-4 (CAN), SAE J1939, and ISO 9141-2, among others [33], and it has a built-in Wi-Fi module that allows wireless connection to a mobile app (Torque Pro) for reading and recording vehicle data.

The parameters selected during the data collection campaign were vehicle speed, engine RPM, airflow, fuel flow, oxygen ratio in the exhaust gas, and engine coolant temperature. The mobile device's GPS (Global Positioning System) was also used to acquire the vehicle's latitude, longitude, altitude, and speed. All data were stored by the mobile application at a frequency of 1 Hz.

2.2 Test route

The RDE tests were carried out in the city of Riobamba, Ecuador (see Figure 1). The RDE route was determined in accordance with EU Regulation 2018/1832 and consists of three consecutive parts: urban, rural, and motorway. The urban route starts from the Escuela Superior Politécnica de Chimborazo (ESPOCH) and goes to Av. Bicentenario (beginning of the airport tunnel); the vehicle speed was less than or equal to 60 km/h. The rural route covered Av. Bicentenario de Riobamba in the north direction to the E35 South Highway (new access to the city of Riobamba); the vehicle speed ranged from 60 km/h to 90 km/h. The motorway route went from the intersection of the South Highway (E35) to the entrance to the Museo del Hielo of the South Highway (E35); the vehicle speed was greater than 90 km/h (greater than 100 km/h for at least 5 minutes, as required by EU legislation). The tests were conducted in the months of June and July, covering a temperature range of +8 °C to +17 °C and a relative humidity range of 45% to 78%, in three different time periods: morning from 07:00 to 10:00, noon from 11:00 to 14:00, and evening from 15:00 to 18:00.

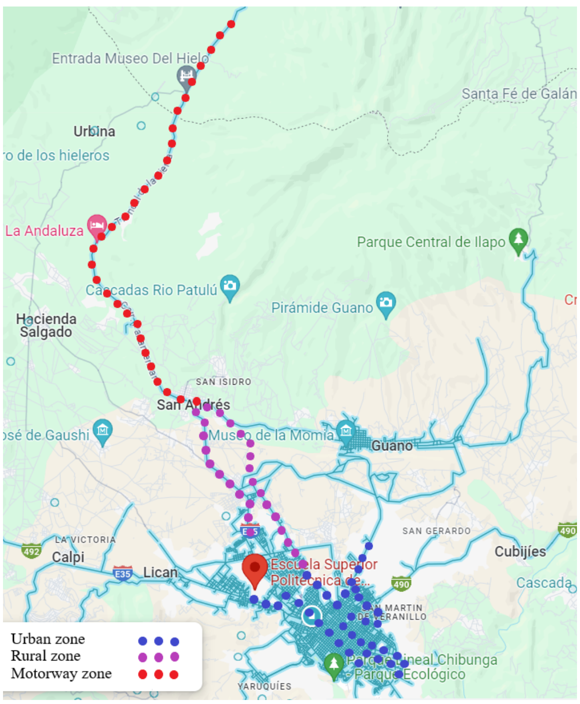

Figure 1 Route RDE in the Riobamba area

A total of 7 tests were conducted with the same driver and a passenger. The driver always followed the RDE circuit path, respecting the speed, distance, and time limits established for each zone (urban, rural, and motorway) under the described conditions to ensure that the results were sufficiently repeatable and to minimize disturbances in the analyzed variables.

2.3 Data processing

The OBD and ELM327 signals were aligned along a fixed time offset based on the comparison of the vehicle's speed. The altitude data coming from the mobile app's GPS, second by second, are corrected with information from the weather stations of the Ecuadorian National Institute of Meteorology and Hydrology. The GPS latitude and longitude coordinates are also processed on the website www.gpsvisualizer.com to obtain the altitude from digital elevation maps (GPSvisualizer, 2023).

In this work, fuel consumption was determined based on fuel flow (which is a measure of the liters of fuel burned by a vehicle measured in liters per hour) obtained through the OBD-II of the test vehicle, according to Equation 1:

$$FC = \frac{FF \cdot \rho}{3600} \tag{1}$$

where FC is the fuel consumption in g/s, FF is the fuel flow in L/h, ρ is the fuel density in g/L and 3600 is a conversion factor. An alternative method for calculating fuel consumption independent of fuel flow measurements from the OBD-II PIDs is presented in [34].

All data analysis and data quality assurance presented in this document follow the recommendations of the EU Regulation 2018/2819. The mean value corresponding to the seven tests performed and the confidence interval are represented, considering a confidence level of 95%. For all RDE tests, v*a_pos95, RPA, accumulated positive lift gain and other parameters were analyzed.

Second-by-second VSP+ is determined from speed and altitude data; according to the procedure described in Ref. [35], using Equation 2 proposed in Ref. [24]:

$$VSP = v \cdot (1.1 \cdot a + 9.81 \cdot \text{ grade } + 0.132) + 3.02^{-4} \cdot (v + v_w)^2 \tag{2}$$

where VSP is the vehicle specific power in W/kg; v is the instantaneous vehicle speed in m/s; a is the instantaneous vehicle acceleration in m/s^2; grade is the vertical lift to distance ratio in %; and v_w is the wind speed in m/s; the result.

The road grade is defined by Equation 3

$$\text{grade } = \frac{\text{saltitude}}{\Delta x} \tag{3}$$

where Δx is the horizontal projection of the RDE test trajectory.
The maximum and minimum VSP+ values derived from the Worldwide Harmonized Light Vehicles Test Cycle VSP+ points are determined using Equation 4 and Equation 5, respectively.

$$VSP + Max = -0.0019 \cdot X^2 + 0.472 \cdot X + 0.6 \tag{4}$$

$$VSP+\text{ Min } = 0.00128 \cdot X^2 + 0.0028 \cdot X + 0.57 \quad (5)$$

where X is the instantaneous velocity in km/h.

3. Results and discussion

3.1 Analyzing RDE test

The complete route covered approximately 56 km and an altitude range of 2665 to 3540 m. The main route parameters for all RDE tests and the comparison with legislative requirements are summarized in Table 2. The established route complies with most of the requirements proposed by EU Regulation 2018/1832 [36], except for the altitude condition that exceeds 1300 m, established as an extended condition. Beyond compliance with the parameters/requirements of EU Regulation 2018/1832, the route developed in the city of Riobamba will allow future studies to be carried out to analyze the performance and emissions of vehicles in extreme conditions, i.e., in high-altitude conditions.

Figure 2 shows the altitude profile of the RDE tests as a function of distance traveled. The motorway section shows the steepest slope. The rural section has a moderate double slope. The urban section is characterized by a nearly flat profile. The result of the accumulated positive elevation changes of the RDE test, calculated by integrating all the positive elevation changes of the road, as required by EU Regulation 2018/1832, is 2131 m/100 km, which is higher than the maximum permitted value of 1200 m/100 km. In addition, the difference in altitude between the start and end of the RDE route is almost 725 m, which is also higher than the 100 m required by the RDE Regulation.

It is relevant to highlight that the differences found in the circuit design with respect to the RDE Regulation are due to the location of the study city (high mountain region in the Andes Mountains), a characteristic of most Latin American countries. These differences, in turn, amplify the importance of this research work, which provides new results for cities located at high altitudes.

3.2 Analysis of v*a_pos95 and RPA

To determine whether a journey is driven too aggressively or smoothly, EU legislation establishes some limiting dynamic conditions that must be verified in the urban, rural, and motorway legs of the RDE route, namely, a minimum limit for relative positive acceleration (RPA) and a maximum limit for the 95th percentile of speed and the product of positive acceleration (va_pos95) as a function of speed. Figures 3 and 4 show the RPA, va_pos95, and limit curves as a function of vehicle speed for the different RDE tests, respectively. When examining the RPA, it is

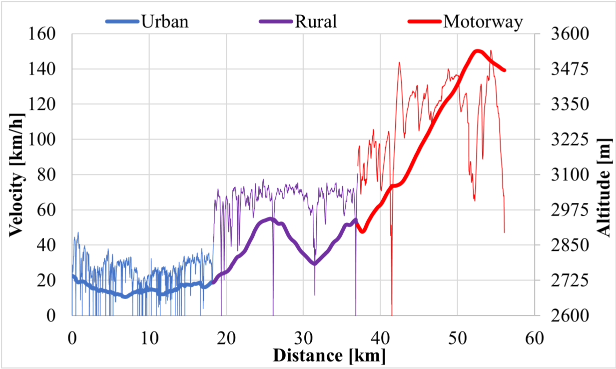

Figure 2 Velocity and altitude profiles on the RDE route

observed that the values are sometimes very close to the minimum limit, mainly in the urban and rural legs, and a few values below the minimum limit in the rural leg. The values of the motorway leg are above the limit, which defines the driving as sufficiently dynamic and, therefore, normal. The v*a_pos95 values, on the other hand, are below the prescribed maximum limit, for all values of the urban and rural legs. The values of the motorway leg are above or close to the prescribed maximum limit.

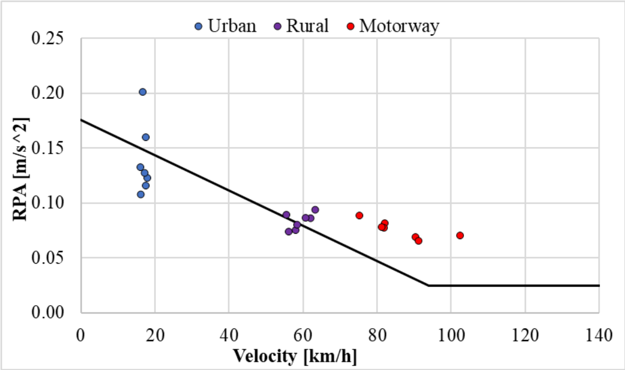

Figure 3 Distribution of the dynamic parameter RPA

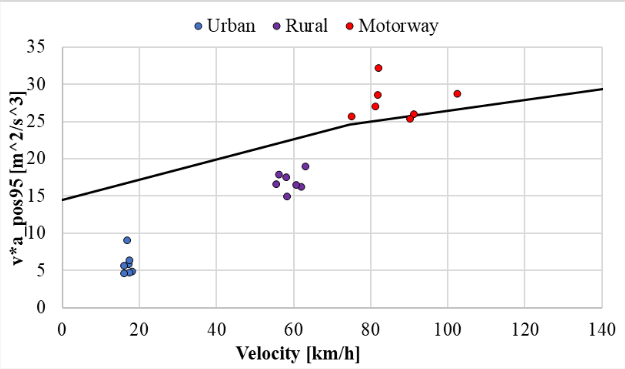

Figure 4 Distribution of the dynamic parameter v*a_pos95

Table 2 Vehicle characteristics

RDE characteristics	RDE test min	Max	Legislative requirements
Total duration(min)	91.9	101.5	90–120 min
Total distance (km)	56.1	56.5	>48 km
Urban distance, km (share,%)	18.1 (32.4)	18.4 (32.5)	>16 km (29–44%)
Rural distance, km (share,%)	18.7 (33.5)	18.9 (33.3)	>16 km (23–43%)
Motorway distance, km (share,%)	19.0 (34.1)	19.4 (34.2)	>16 km (23–43%)
Urban average speed (km/h)	16.1	18.1	15–40 km/h
Rural average speed (km/h)	60.9	62.9	60 km/h to 90 km/h
Motorway average speed (km/h)	90.4	102.4	>90 km/h
Altitude (m)	2665	3540	Moderate 0–700 m, Extended 700–1300 m
Cumulative altitude gain (urban), m/100 km	1126		1200 m/100 km
Ambient temperature (°C)	8 °C	17 °C	Moderate 0–30 °C, Extended -7–35 °C
Stop percentage	17.1	29.9	6–30% of urban time

3.3 Analysis of VSP+ from RDE test

Figure 5 shows the VSP+ of the RDE test. VSP+ tends to increase with high accumulated altitude gain, reflecting the driver's increased power requirement. When analyzing the VSP+ Max curve, around 18.6% of the VSP+ points are above the curve. The positive slope on the highway section contributes most to the higher VSP+ values. On the other hand, in the rural section, VSP+ points above the maximum were also produced even when driving on a negative road slope.

While analyzing the VSP+ Min curve, around 18.9% of the VSP+ points are below the curve. Therefore, the driver needs less power than in the laboratory test, due to lower accelerations. On average, 92.8% of the VSP+ points below the VSP+ Min curves occurred when driving on a negative road slope.

The concentration of VSP+ points in urban, rural, and highway journeys (higher or lower points) relative to VSP+ Max/Min indicates the need for more or less vehicle power, respectively. The dispersion of VSP+ points is higher for highway and rural journeys than for urban journeys. This higher dispersion is due to the elevated altitude gain and is related to the EU RDE Regulation requirement that the altitude difference between the start and end of the journey must be less than 100 m; for this reason, when the vehicle travels the rural journey, half of the journey is done on a steep positive slope of the road, but the other half of the journey is done on a steep negative slope of the road. While in the highway journey, most of it is done on a steep positive slope of the road. There is a higher demand for VSP+ above the maximum curve when driving uphill.

It is also observed in Figure 5, negative VSP+ points, which v*a_pos95 counts as valid. Around 4.9%, this means the vehicle is increasing speed while going downhill (see Figure 2) with low or zero fuel consumption.

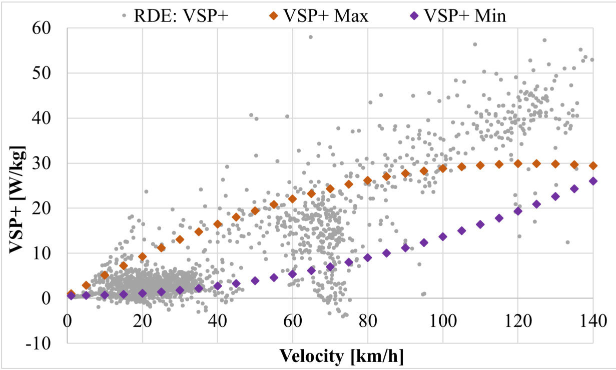

Figure 5 VSP+ for RDE test

3.4 Fuel consumption comparison between VSP+ and road grade

According to some authors, the driver's behavior at the wheel and the slope of the road has a significant influence on fuel consumption and, therefore, on CO_2 emissions [8, 35, 37]. Different fuel injection technologies can also produce diverse results. Figure 6 shows fuel consumption against RPA, va_pos95, and VSP+, respectively. VSP+ is more closely correlated with fuel consumption than RPA and va_pos95, as seen in Figure 6, with an R^2 coefficient of around 0.86. Meanwhile, the R^2 coefficients of RPA and v*a_pos95 are around 0.02 and 0.46, respectively. The higher power demand by the driver on rural and highway routes of the RDE test (see Figure 2) in conditions of high-altitude gain is reflected in the VSP+ point groups. On the other hand, VSP+ will be a good indicator when analyzing vehicle emissions under real driving conditions, mainly CO_2 emissions.

Based on the GPS data acquired during the RDE test, the road grade was estimated for the rural and highway routes, which are characterized by large changes in grade. The GPS altitude data were validated and corrected using the elevation data from topographic maps. Figure 7 shows

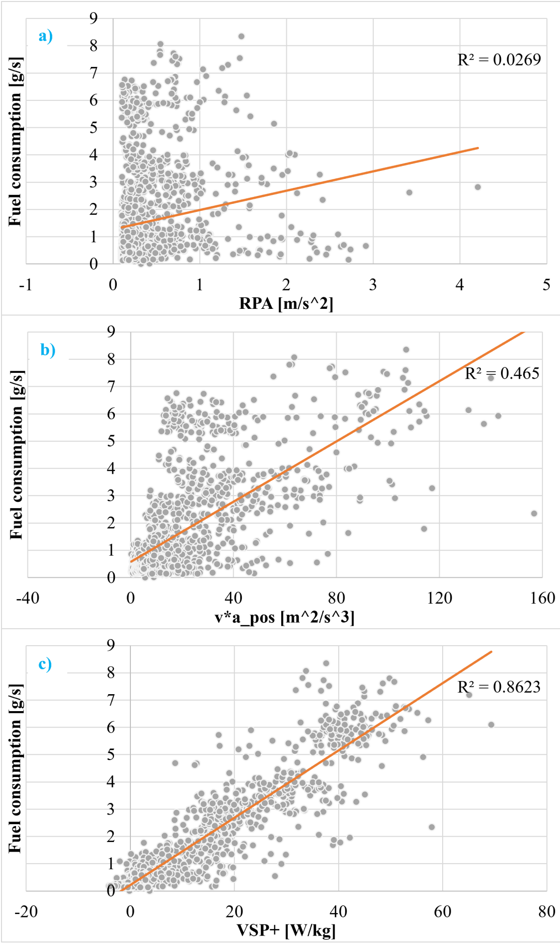

Figure 6 VSP+ for RDE testFuel consumption vs. a) RPA, b) v*a_pos95, and c) VSP+g6

the fuel consumption and load grade plots for the rural and highway routes, and a section of the rural route that comprises kilometers 21-31, which has a similar positive and negative road grade. In the rural route, the scatter of the points shows a considerable correlation between fuel consumption and road grade, with an R_2 of around 0.31. On the other hand, the highway route shows a very low correlation. This is due to the fact that a large group of points are at a load grade between 5 and 6% with high fuel consumption.

The set of points analyzed for the section from Km 21 to 31 of the rural route shows a higher correlation between fuel consumption and road load with an R_2 of around 0.43. At higher altitudes, vehicle fuel consumption increases. However, it is important to note that something beyond altitude gain also influences fuel consumption, such as ECU strategy, catalyst design, or less aggressive driving behavior. On the other hand, it is important to remember that, during descent, the car's throttle is closed and, due to this, at high altitude gain, final fuel consumption may be lower than at low or medium altitude gain.

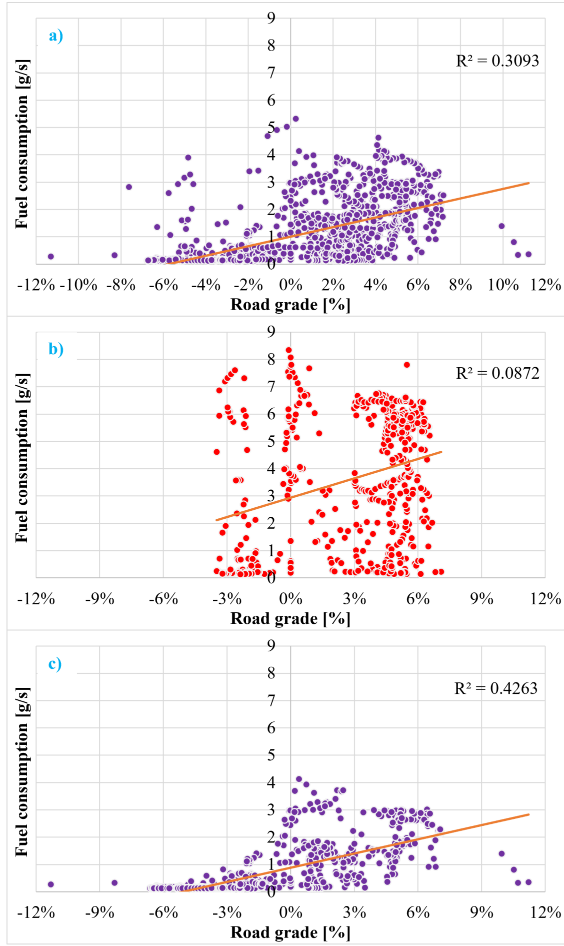

Figure 7 Fuel consumption and road grade a) rural route, b) motorway route, and c) km 21-31 rural route

Figure 8 shows the effect of road slope on fuel consumption in the rural route. The rural route was divided into consecutive road slope sections, which were evaluated by integrating the measured instantaneous values. The variations in fuel consumption due to road inclination were estimated by the relationship between fuel consumption for each road inclination interval. The analysis shows a significant correlation with an R_2 of around 0.85.

The proportions of fuel consumption are linearly correlated with the road slope, as can be seen in Figure 8. A route with a road slope of 6% resulted in a nearly 80% increase in fuel consumption compared to a route with a 0% slope. A negative road slope of 6% implied a decrease of almost 80% in fuel consumption compared to a route with a 0% slope. Note that the increases and decreases in fuel consumption associated with positive and negative road slopes are quite similar when the same slope value is considered. Similar observations and results have been reported by different authors [8, 13, 38].

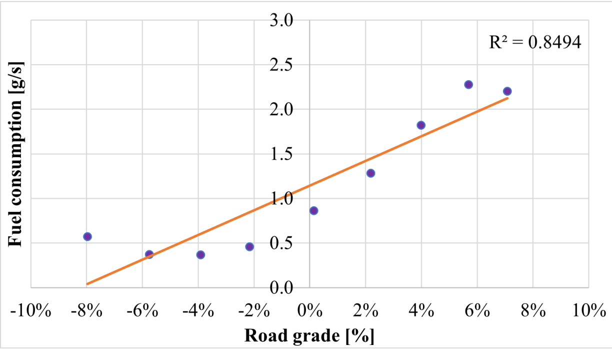

Figure 8 Effect of road grade on fuel consumption over the rural route

4. Conclusions

The RDE test dynamics in Riobamba, Ecuador, were analyzed. The results showed that VSP+ is a good indicator of fuel consumption, especially on hilly roads. VSP+ shows a good correlation with fuel consumption, allowing a better understanding of the dynamics of RDE tests. This is because VSP+ considers the road slope, unlike the dynamic parameters RPA and v*a_pos95. VSP+ is useful for evaluating the power requirement of the highest accelerations and altitude gain. The influence of the road slope was evident, with a direct correlation between the slope and fuel consumption in the rural section of the RDE test. The increases and decreases in fuel consumption associated with positive and negative road slopes were similar, and with the same slope value of 6% + and/or - it meant an increase/decrease of around 80% of the fuel consumption compared to a flat section.

At higher altitudes, vehicle fuel consumption increases. However, it is important to note that something beyond altitude gain also influences fuel consumption, such as ECU strategy, catalyst design, or less aggressive driving behavior.

The test analyzed here only covers a limited number of scenarios. Further research is needed to expand this analysis to more extensive conditions, such as different altitude gains, different driver behaviors, power-to-weight ratio, etc., to define the limits of VSP + more clearly as an RDE test indicator and its potential use to predict fuel consumption and develop fuel saving strategies in high altitude cities.

Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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Author contributions

L. Tipanluisa: Conceived and designed the analysis and wrote the paper. A. M. Melo-Arteaga and N. P. Barros-Merchán: Collected the data and contributed data analysis.

Data availability statement

The data was collected through monitoring tests on an RDE circuit using a sports utility vehicle in the summer season (ambient temperature between +9 °C and +18 °C, and altitude between 2660 and 3540 m), in the city of Riobamba and its surroundings; through the OBD-II module and the mobile application.

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