UNIVERSIDAD POLITÉCNICA SALESIANA
SEDE CUENCA

CARRERA DE INGENIERÍA MECÁNICA AUTOMOTRIZ

Trabajo de titulación previo
a la obtención del título de
Ingeniero Mecánico Automotriz

ARTÍCULO ACADÉMICO:

"ANALYSIS OF ENERGY CONSUMPTION EFFICIENCY OF AN ELECTRIC VEHICLE IN A CITY WITH VARIABLE RELIEF"

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CUENCA - ECUADOR

2021

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AGRADECIMIENTO

Agradezco a Dios por ser guía y fortaleza para superarme a lo largo de mi vida, además a mis padres por ser un pilar fundamental para cumplir mis metas, con su apoyo, confianza y consejos son el impulso que me motiva y me ha ayudado a culminar con éxito mis estudios universitarios.

A todo el personal docente de esta prestigiosa institución como es la Universidad Politécnica Salesiana por la formación académica y moral que me han brindado a lo largo de la vida universitaria. De manera especial al Ingeniero Adrián Sigüenza, M, Sc. quien con su sabiduría y experiencia ha sido tutor y amigo para la culminación de este proyecto.

Bryam Orlando Cochancela Cambisaca

AGRADECIMIENTO

Quiero expresar mi gratitud a Dios por bendecirnos la vida, por guiarnos a lo largo de nuestra existencia, y ser la fortaleza en aquellos momentos de dificultad y de debilidad.

Gracias a mis padres y hermanos por ser los principales promotores de mis sueños, por confiar y creer en nuestras expectativas, por los consejos, valores y principios que me han inculcado.

Agradezco también a los docentes de la Universidad Politécnica Salesiana, por haber compartido sus conocimientos a lo largo de la preparación de mi profesión, de manera especial, al ingeniero Adrián Sigüenza tutor de nuestro proyecto de investigación quien ha guiado con su paciencia y rectitud para culminar de la mejor manera nuestro trabajo de investigación.

Marco Giovanny Rodríguez Calle

DEDICATORIA

Este proyecto va dedicado a Dios y a mi familia por siempre estar presentes en mi vida con su amor, confianza y apoyo incondicional, siendo el soporte ante cualquier tropiezo. Les dedico este triunfo como gratitud por siempre haber creído en mí, siendo este la motivación más importante para no rendirme y luchar por mis metas y sueños.

Bryam Orlando Cochancela Cambisaca

DEDICATORIA

Este trabajo va dedicado a mis padres Carlos y Mariana quienes con su amor, paciencia y esfuerzo me han permitido llegar a cumplir hoy un sueño más, gracias por inculcar en mí el ejemplo de esfuerzo y valentía, de no temer las adversidades porque Dios está conmigo siempre.

A mis hermanos y esposa por su apoyo incondicional, durante todo este proceso, por estar conmigo en todo momento. A toda mi familia porque con sus consejos y palabras de aliento hicieron de mí una mejor persona y de una u otra forma me acompañan en todos mis sueños y metas.

Marco Giovanny Rodríguez Calle

Scientific paper

ANALYSIS OF ENERGY CONSUMPTION EFFICIENCY OF AN ELECTRIC VEHICLE IN A CITY WITH VARIABLE RELIEF

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Abstract

Electric vehicles are slowly becoming a sustainable mobility alternative, since the deployment of this means of transportation in the world has allowed opening lines of research focused on energy efficiency and environmental pollution, encouraging the development of projects that were not previously considered for the consolidation of this means of transportation. This study aims to address the obstacles to the development and growth of the electric vehicle fleet. Additionally, it presents an analysis that defines the energy efficiency behavior of electric vehicles (EV) in real driving conditions in a Latin American city, where parameters as driving modes, road inclination, vehicle weights, and vehicle congestion are considered. Significant response variables such as battery state of charge, traveled and time are also obtained, which are achieved in field tests with a variation of working conditions that obey a design of experiments with response surface where the working parameters of the variables are controlled. The variables obtained are processed by Pearson correlation and classified by applying the KNN algorithm. Lastly, the results of the study are presented in contour lines, demonstrating the influence of each of the variables on the energy consumption efficiency of the EV, in order to establish strategies and/or methodologies to develop greater efficiency in the vehicle, which leads to better autonomy.

Keywords: Autonomy, efficiency, electric vehicle, energy consumption.

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1. Introduction

In Ecuador in 2016, about 99% of the energy consumed in transportation is covered by petroleum derivatives, which implies an extreme dependence on non-renewable energy sources and whose combustion is one of the main sources for the generation of greenhouse gases [1]. This has led to a considerable increase in air pollution in urban areas, where vehicular traffic is the main source of pollution. [2].

It is in this scenario where the electric vehicle assumes an important role by being able to contribute to a reduction in the growing need for petroleum products, allowing mobility that is environmentally and socially sustainable, in other words, to develop a transportation system that contributes to economic and social well-being without depleting natural resources, destroying the environment or harming human health. [3].

For this reason, the authors intend to make inroads with alternative technologies, such as electric vehicles, which are becoming a priority at a global level and point to significant commercial growth.

EV adaptation is different in each country, as EV use is affected by consumer demand, market prices, availability of charging infrastructure and government policies in each country, such as purchase incentives, emissions regulation and fuel economy standards.

Nonetheless, the demand for private electric vehicles worldwide has not been the most favorable, since of the 1 billion vehicles in circulation, only 5.1 million are electric vehicles [3], one of the causes being the low efficiency (Km/kWh) in EVs, which is related to a real autonomy lower than that proposed by the manufacturers.

This is why the importance of using tools and resources in the development of research and studies in the generation of strategies that focus on improving the efficiency of electric vehicles (EVs) is emphasized.

This is the case presented by the authors in reference [4], who studied the efficiency of electric vehicles in the city of Madrid-Spain, determining vehicle consumption factors on different routes (urban, interurban and highways) and thus defining the real efficiency of five types of vehicles that are marketed in the aforementioned country.

Other studies developed by Laitinen *et al.*[5] and Soltani-Sobh *et al.* [19] investigated the possibility of increasing electric vehicle energy efficiency in the United States. The tests were carried out in different driving cycles, determining consumption factors and optimum operating parameters, concluding that the improvement depends on the driving cycles and characteristics.

In the article [6] the authors analyze the power losses generated in electric vehicles, establishing the optimal operating point that allows obtaining the highest efficiency and autonomy of the EV.

The authors of the articles [7] and [8] consider parameters that influence the energy consumption of the electric vehicle, analyzing variables such as vehicle weight, battery specific energy, rolling and drag resistance, driver behavior, and gearbox ratio among other factors with the objective of providing an approach to improve the cost-benefit of electric vehicles in the future.

On the other hand, the studies presented in [9] and [10] analyze energy consumption with the aim of focusing on the optimization of EVs, through improvements not only in EV behavior, but also tools, processes and methodologies that contribute to the growth of this technology.

Additionally, studies as [11] and [12] were developed that analyze the energy efficiency of EVs considering factors such as road orography, traffic conditions, driving styles and ambient temperature including urban, mixed and high speed characteristics, based on real data and collected with different driving conditions.

Similarly, studies [13] and [14] analyze the influence of the driver on the energy consumption and power requirements of the EV, through tests on a dynamometric bench applying driving cycles allowing to quantify the results obtained in these tests.

This study analyzes the behavior of the EV in a Latin American city, determining the real efficiency of the vehicle and proposing conditions that allow the development of the best performance.

2. Materials and methods

2.1. Efficiency in electric vehicles

In order to define the efficiency of electric vehicles, the influence of certain factors that alter their behavior must be considered [17].

- Vehicle weight
- Travel distance
- Percentage of inclination
- Ambient temperature
- Maximum speed

2.2. Characterization of factors considered in the study

2.2.1. Vehicle weight (kg): Three preset weight measurements described in Table 1 are used as reference.

Table 1. EV weights

WEIGHGT	QUANTITY (Kg)	CONDITION
Minimum	1642	-Vehicle weight - Driver -1 companion
Medium	1792	- Vehicle weight -Driver -3 companions
Maximum	1942	-Vehicle weight -Driver -4 companions -Additional weight

2.2.2. Travel distance (km): The travel values are determined through the use of a mobile app (Moovit) that allows establishing the distances traveled on each of the routes, with minimum distances of 13.3 km and maximum distances of 24.5 km between the preset routes.

2.2.3. Degree of inclination (slope): This factor was determined by using the *open route service* web page, which establishes minimum and maximum slope values for each of the routes. The same that present stretches with varied inclination ranges in which values between 0º and 9.09º are found.

Additionally, external noise factors can be established, such as:

2.2.4. Ambient temperature: This is one of the factors that affect the process of chemical reactions that occur in the electric vehicle battery. The optimum operating temperature for the EV is estimated to range from 15ºC to 25ºC as shown in Figure 1 [22].

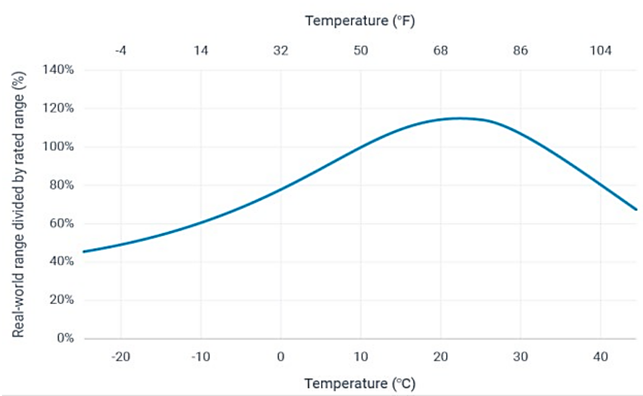

Figure 1. EV autonomy curve in function of temperature.

2.2.5. Maximum speed: is an external factor that must be taken into account since roads have a speed limit established for each of them and can be of different types: urban (30 km/h), interurban (65 km/h) and highway (90 km/h).

2.3. Routes for data acquisition

In order to perform the data acquisition, routes are defined in which all the study factors can be involved and variations in them can be obtained, which is why the routes of fifteen of the main bus lines that run throughout the city of Cuenca in Ecuador are used as a reference.

The selected routes cover urban, interurban and rural areas in order to subject the vehicle to different real driving conditions encountered on a daily basis.

The mobile app (Moovit), which is a public transportation application and mapping service developed by the software company *"Israel Moovit. Inc."*, applied in the city of Cuenca, as shown in Figure 2.

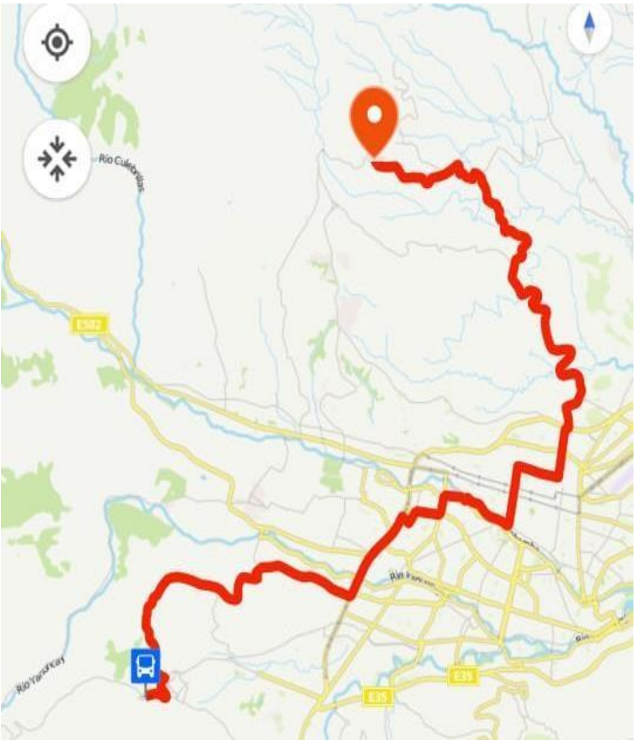

Figure 2. Mapping a *MOOVIT* Test Route

Besides, Figure 3 shows a schematic extracted from the *"open route service"* web page, which provides information on the degrees of inclination in each of the established routes.

Figure 3. Profile of slopes on an Open Route Service test

Each selected test route has its own characteristics such as type of roadway, traffic conditions, speed limits and weather conditions that influence real driving tests.

The selected routes are specified in Table 2.

Table 2. Route characteristics

Nº of Route	Distance Km	Speed Average Km/h	Degree of inclination minimum/maximum
Route 1	18,1	34.27	0º / 8,53º
Route 2	15,7	32,14	0º / 8,53º
Route 3	17,8	35,59	0º / 8,53º
Route 4	19,4	33,03	0º / 5,14º
Route 5	24.5	32.56	0,57º / 8,53º
Route 6	17	33,33	0º / 8,53º
Route 7	13,5	32,4	0º / 8,53º
Route 8	16,6	36,81	0º / 9,09º
Route 9	21,9	34,29	0º / 8,53º
Route 10	13.3	32,09	0º / 1,71º
Route 11	15.4	33,85	0º / 8,53º
Route 12	16,3	30,61	0º / 5,14º
Route 13	22,4	32,26	0º / 9,09º
Route 14	18,7	35,84	0º / 8,53º
Route 15	14.7	32.54	0º / 8,53º

The variety of routes as well as the difference between the routes provide data with which to study the behavior of the vehicle under different driving conditions.

2.4. Vehicle characteristics

The vehicle used for the above mentioned field tests is the "KIA SOUL" EV.

Figure 4. "KIA SOUL" EV

The technical specifications of the vehicle are detailed in Table 3.

Tabl3 3. Vehicle Characteristics

Parameter	Value
Maximum power (CV)	109
Maximum power (Kw/rpm)	81,4
Maximum torque (Nm/rpm)	285 / 0-2.780
Battery capacity (Ah)	75
Battery voltage (Volts)	370
Maximum speed (Km/h)	145
NEDC autonomy (Km)	202

2.5. Characteristics of the city

The city of Cuenca is characterized by its irregular geographical conditions, which intervene in each of the tests, influencing the efficiency of the EV.

Table 4. Characteristics of the city of Cuenca

Parameter	Value
Average temperature (ºC)	14 - 18
Humidity (%)	60
Surface (Km^2)	124
Latitude	2º53'57''
Altitude (m.a.s.l.)	2550

2.6. Definition of efficiency

In order to determine the energy efficiency of the different vehicle alternatives on the market, the starting point for comparison must be the same. In studies [4] and [14], fuel consumption is given in miles per gallon (mpg) or liters per 100 km traveled.

To establish a comparison between combustion vehicles and EVs, the energy used by the former is determined by the calorific value of the fuel, while consumption in EVs can be expressed in (kWh/100 km) [20].

Therefore the efficiency of a combustion vehicle is stated in the following equations [21]:

2.6.1. Mechanical efficiency (ηm): refers to the indicated power of the mechanical losses and is calculated:

$$\eta m = \frac{Ne}{Ni} \quad (1)$$

Where *Ni* is the indicated power of a motor and *Ne* is the effective power.

2.6.2 Indicated efficiency (*ηi*): This is lower than the thermal efficiency, because of additional losses due to the imperfection of the cycle.

$$\eta i = \frac{3600}{gi * Hu} \quad (2)$$

Where *gi* is the indicated specific fuel expense and *Hu* is a calorific value constant equal to 44.

2.6.3. Effective efficiency (ηe): is the part of the heat that is transformed into effective work.

$$\eta e = \eta i * \eta m \quad (3)$$

In the same way as a combustion vehicle, the EV also presents a characteristic equation that allows to determine its efficiency, applying the following equation:

$$\eta = \frac{d}{(0.27 * (SOC))} \quad (4)$$

Where η is the vehicle efficiency, d is the distance traveled and SOC is the EV battery state of charge [4].

2.7. Data acquisition

Data acquisition is performed using EmoLab 2.0 software, which provides instant information on vehicle behavior based on the study factors, through the OBD II port.

All the races are held at the same time, from 9:00 am to 1:00 pm, in a city that stands out for its variations in relief and its location at 2550 meters above sea level.

2.7.1. Sampling protocol

This process must take into account the variables that directly or indirectly influence the data collection process, the same variables that affect the response variables. By taking a range of values as a reference and thus ensuring that the results are similar and have no significant changes.

Thus, Figure 5 describes the data acquisition protocol, in which each block is constituted as shown below:

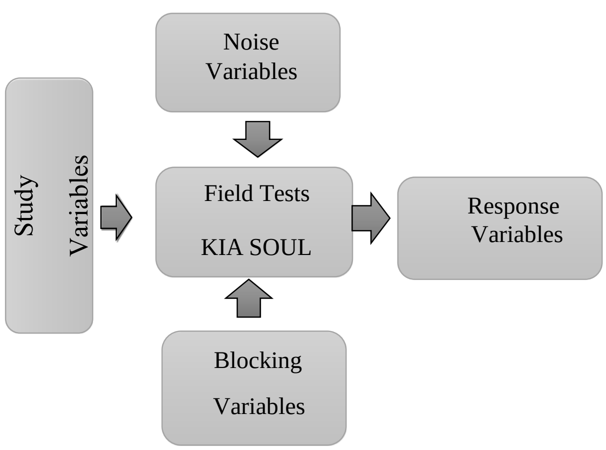

Figure 5. Block diagram for data acquisition

- **Study variables:** This section considers the total weight of the vehicle, which ranges from 1642 kg to 1942 kg. Another influential factor is the distance traveled on each test route, which ranges from 13.5 km to 24, 5 km. Finally, the degree of inclination of the roadway ranges from 0º to 9.09º and is a relevant variable for the vehicle to be more or less efficient.
- **Noise variables:** are not controllable and have an influence on the acquired data, generating sporadic additional energy consumption, such as vehicular congestion and traffic lights that cause constant starts and stops.
- **Blocking variables:** are present in each of the tests performed, establishing certain conditions:
  - Participation of the same driver, maintaining similar driving patterns.
  - Pre-established routes.
  - Permitted speed limits.
  - Conditioning of peripherals, including the same position of the windows, air conditioning, lights, pens and radio turned off.
- **Field Tests:** The data are compiled with the variables described above using the "KIA SOUL EV" vehicle, in order to generate data that provide information on the behavior of the vehicle when all of the variables mentioned above are involved.
- **Response Variables:** are those that result in the state of charge of the battery, against which a definition of efficiency can be made on the basis of consumption by applying the formula described later (6). These variables allow us to observe the real behavior of the vehicle as a function of state-of-charge consumption [16] and [18], using EmoLab 2.0 software with a sampling rate of one data per second.

3. Results and discussion

The tests are performed with three different weight conditions (minimum, average and maximum) demonstrating that EV battery consumption is directly proportional to weight (kg).

Figure 4 shows the actual behavior of the vehicle and the influence on consumption when having more or less weight, the blue curve represents a trip with minimum load, the orange color shows the trip with medium load, and finally, the gray color represents the travel with maximum load.

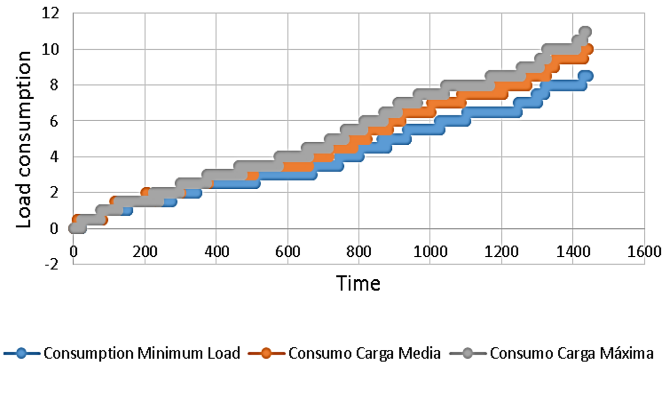

Figure 6. Comparative graph of consumption in different weight conditions.

The results of the aforementioned tests are shown in Table 5, demonstrating as a result the decrease in efficiency in the same distance traveled by having greater weight.

Table 5. Consumption results with increasing weight in the VE

WEIGHT	Quantity (Kg)	SOC consumption
Minimum	1642	8,5
Medium	1792	10
Maximum	1942	11

3.1. Data Classification

The data collected in each of the routes are analyzed and classified by applying the KNN (K-Nearest Neighbors) algorithm, which is used for pattern recognition, data extraction and outlier detection.

In order to have high precision in the results with the application of the KNN algorithm, 398 valid data were filtered to obtain characteristic graphs and the theoretical energy consumption efficiency equation.

In addition, Figure 7 shows the application of the "*Gaussian Bell*" method to analyze the normal behavior in the agglomeration of data and to observe in a general way the distribution of the sample and its frequency.

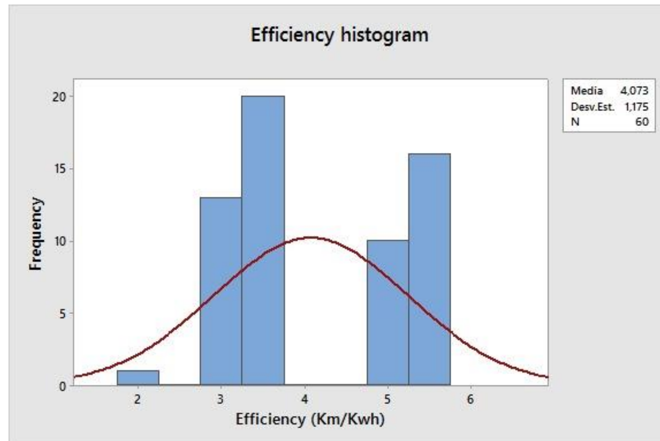

Figure 7. Application of the Gaussian Bell

3.2. Analysis of main effects

The influence of the study variables on vehicle efficiency is determined.

Figure 8 shows the study variable that provides the most information to the energy consumption efficiency model and determines the percentage of influence that each one has on the equation: weight 38%, slope 30% and travel 8%.

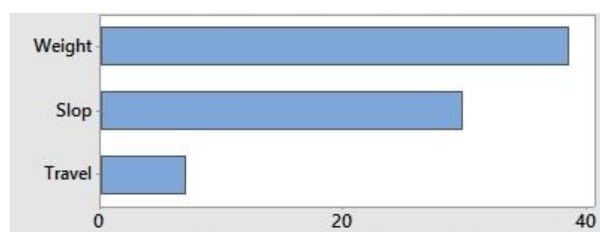

Figure 8. Multiple regression of efficiency

Figure 9 presents three sections of curves showing how efficiency varies if the configuration of one of the variables is changed.

The left section shows the weight curve with a behavior inversely proportional to efficiency, since the vehicle will need more energy to move as it increases.

The central section represents the slope curve showing that when the vehicle is working at low slopes its efficiency will be the maximum, however, when increasing the degrees of inclination it will progressively decrease.

The right section shows the distance curve and reflects the same behavior as the previous ones; however, it generates a minimal decrease in efficiency, being the variable that least influences the reduction of efficiency.

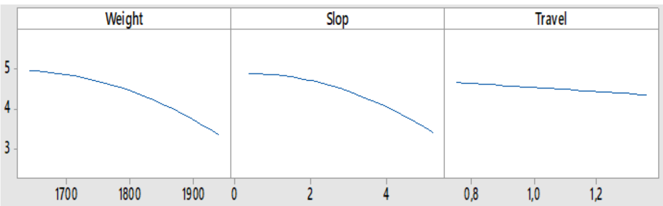

Figure 9. Main effects plot for efficiency.

3.3. Efficiency level curves

Figure 10 details how vehicle energy efficiency is affected by factors such as weight and slope. It is remarkable that while working with minimum values of these factors (weight up to 1800Kg and slope up to 3º) the efficiency will be higher, since the vehicle needs less energy to overcome the slope. On the contrary, the greater the weight (1942 kg) and the greater the degree of inclination (5, 14º), the more energy the vehicle requires to move, causing a progressive reduction in efficiency.

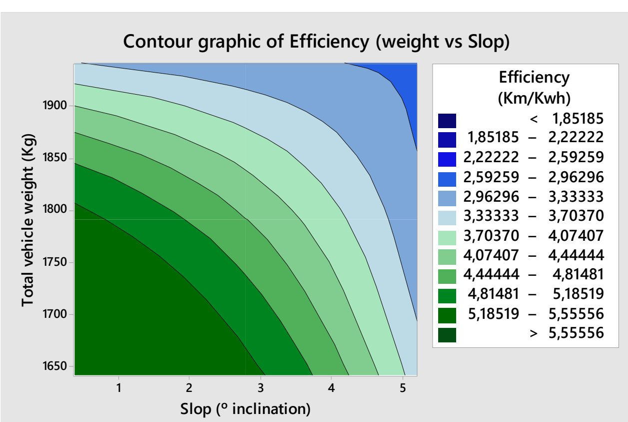

Figure 10. Efficiency level curve (weight vs. slope)

When relating factors such as travel distance and slope, energy consumption behaves as shown in Figure 11, in low slopes (up to 3º) and minimum travel distances (up to 0.9 km), greater efficiency is generated because the vehicle requires less effort to start its journey, while in steep slopes (5.14º) and long travel distances (1.3 km) the vehicle's efficiency is affected due to the high demands to maintain optimal operation.

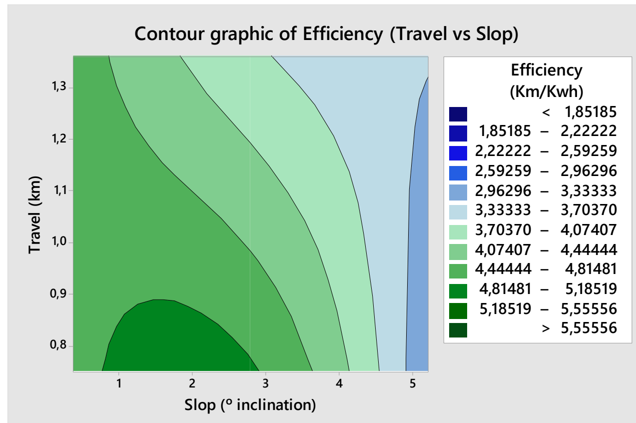

Figure 11. Efficiency level curve (travel vs. slope)

Figure 12 shows the behavior of efficiency in relation to weight and distance traveled. The optimum efficiency value is presented when the vehicle works with minimum weights (1800 Kg) and short distances (0.9 Km). However, efficiency is completely affected when its weight is increased to the maximum (1942 kg) because the vehicle requires more effort to move in constant starts.

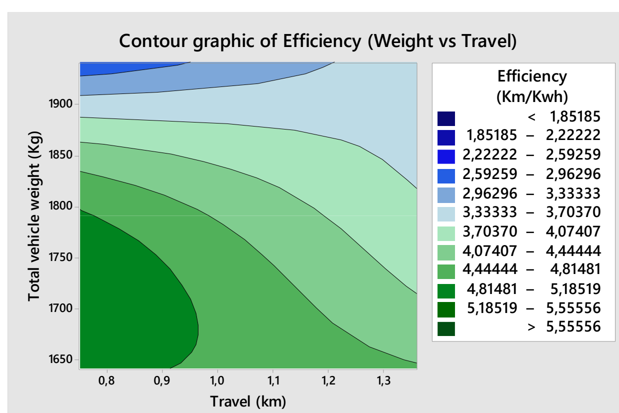

Figure 12. Efficiency level curve (weight vs. travel)

3.4. Final equation of the efficiency model.

Based on the data obtained in the tests, multiple regression is applied to develop the theoretical efficiency model, with which it is intended to predict the behavior of the same in the face of changes in the variables under study.

$$\eta = -16{,}9 + 0{,}0405W - 1{,}612\tan(\alpha) - 13{,}53d - 0{,}000016W^2 - 0{,}0601\tan^2(\alpha) + 0{,}000917W tan(\alpha) + 0{,}00727dW \quad (6)$$

Where:

- *w*= Loaded vehicle weight (kg)
- *d*= distance traveled (km)
- *tan* (α)= slope in ° of inclination

This model involves weight, travel distance and slope as the main variables of the equation, in order to adapt and adjust the theoretical efficiency model to the real model and thus be able to predict the EV efficiency when varying any of the factors.

3.5. Error

Once the theoretical efficiency model is obtained, it is verified how close it is to the real model by determining the error, and based on this result, the model can be validated for its application.

When determining a theoretical efficiency equation and comparing it with the real results, the degree of error is 1.1% as shown in Figure 13, which indicates that the theoretical results are very close to the real results. However, to obtain a lower percentage of error it is advisable to work with a larger database.

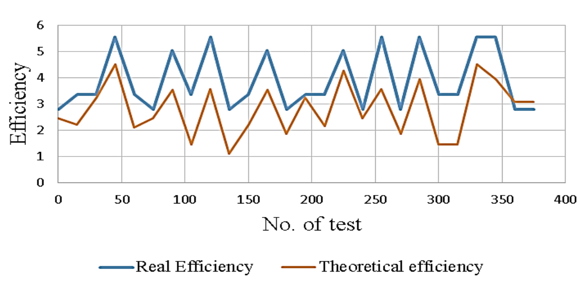

Figure 13. Comparative graph, actual efficiency vs. theoretical efficiency

4. Conclusions and recommendations

To acquire EV energy efficiency data, a test protocol is used, establishing meaningful routes that subject the vehicle to different driving conditions involving the study, noise and blocking variables.

Level curves are used to determine the variation in EV efficiency when presenting different behaviors of the study variables, defining that the conditions for optimum efficiency are to work with a maximum vehicle weight of 1800 kg, slopes of up to 3º and short distances.

Based on the main effects analysis, it is shown that weight and slope are the variables that have the greatest influence on EV efficiency, while the route has a lesser effect. These are the variables to be taken into account when defining routes that do not generate significant consumption in EV efficiency.

Through the study variables, an efficiency model is established based on real driving conditions in a city with variable relief characteristics. This model has an error of 1.1% with respect to the real model, which allows a quick calculation of efficiency in cities with these characteristics.

This study shows that the KIA SOUL EV vehicle in the tests performed shows maximum efficiency values of 5.56Km/Kwh, minimum of 1.85Km/Kwh and an average efficiency of 4.07Km/Kwh. Based on these results, new methodologies can be developed to meet society's expectations regarding EV.

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