Comparison of gasoline, hybrid and electric vehicles

Comparación de automóviles a gasolina, híbrido y eléctrico

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Abstract

It is well known that hybrid and electric cars have been proposed and considered as the available alternative to gasoline vehicle, to try and reduce the consumption of fossil fuels to meet global environmental objectives. Therefore, the average user should have an analytical comparison to determine if the available alternatives are useful to them and their particular situation. As such, this project aims to provide a purchasing recommendation to the average user based off their needs while highlighting the strengths and weaknesses of the three types of automobiles available: gasoline, hybrid and electric. To complete this comparison, the best-selling cars in Mexico of each available category, with similar measurements and passenger capacity, were selected. Subsequently, it was decided that a journey of over 1000 km across the country would be the best comparison, deciding on the travel route to start from Torreón, Coahuila to Puebla, Puebla. After calculating the total energy needed for each vehicle to complete the same route, the stops needed to recharge and complete the route, as well as the time needed, it was concluded that compared to the gasoline car, the hybrid is an option with similar performance on long trips, while the electric car is not recommended for long trips like the one analyzed in this report.

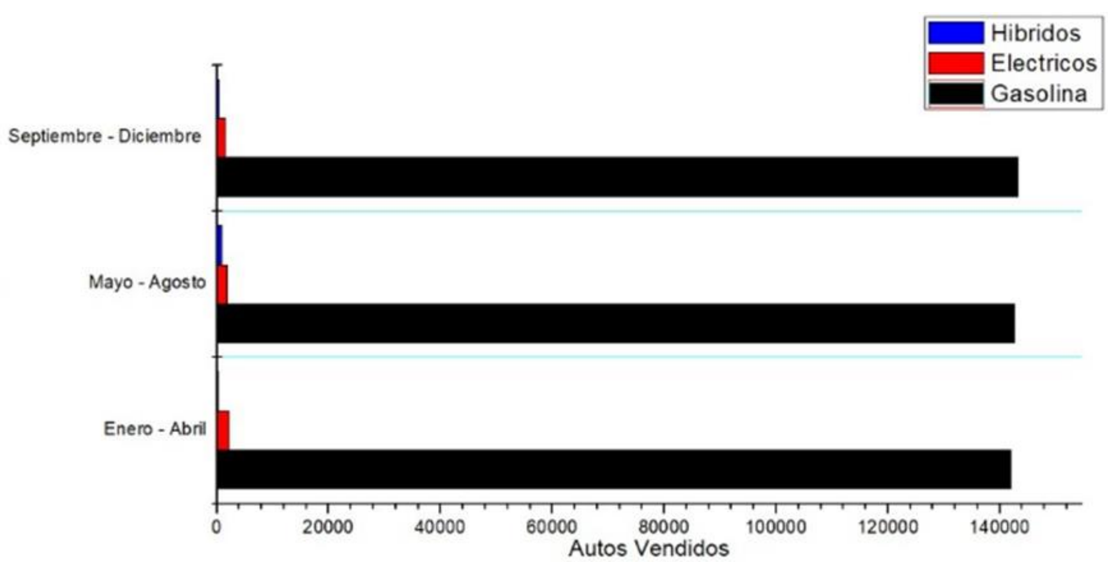
Car comparison, Comparative analysis, Mobility alternatives, Electric vehicles, Hybrid vehicles

9 Introduction

In the current context, the challenges that society faces with climate change and the need to reduce greenhouse gas emissions are of common interest. It is also well known that light-duty automobiles are one of the main environmental pollutants. In Mexico alone, private automobiles generate 18% of CO_2 emissions, the main gas that causes the greenhouse effect (IMCO, Instituto Mexicano para la Competitividad A.C., 2022). Due to this, more sustainable transportation alternatives have emerged in recent years, such as hybrid and electric vehicles, which seek to reduce gasoline consumption and promote the adoption of more environmentally friendly technologies. However, despite their availability in the market for years, in 2022, more than 1.1 million units of light vehicles were sold in Mexico, 98% of which were gasoline-powered, while only 1% were hybrid and 1% electric cars (Statista Research Department, 2023).

Figure 9.1 below shows a graph representing the number of cars sold in 2022. It should be noted that the number of electric and hybrid cars sold was minimal compared to gasoline cars.

Figure 9.1 Number of light-duty cars sold in Mexico, 2022



Source of Consultation: (Statista Research Department, 2023)

The automotive market in Mexico shows a dominant position of gasoline vehicles, due to their recognition and demand by consumers, as they adapt to diverse needs. However, the growing concern to reduce fossil fuel consumption has given rise to two new categories in the personal transportation market: electric and hybrid cars. These options provide an alternative to reduce dependence on fossil fuels, especially if the electric part comes from renewable energy sources.

Despite this, it is evident that most Mexicans are not sufficiently informed or interested in learning about the new technologies available in the automotive sector. However, Mexico has committed to reduce CO2 emissions, setting the goal of a 25% decrease by 2030, according to the General Law on Climate Change (Secretaría de Medio Ambiente y Recursos Naturales, 2015). To achieve these goals within the proposed timeframe, it will be necessary to change the purchasing trend over the next decade. This is difficult to achieve if average consumers lack interest and knowledge about the benefits and opportunities offered by new technologies compared to traditional vehicles.

This study explores and compares gasoline, electric and hybrid vehicle technologies in order to provide a comprehensive and objective assessment for consumers. The relevance of this topic lies in its ability to address current environmental and energy challenges in the transportation sector. The added value of this study lies in its comparative and comprehensive approach, providing a solid basis for informed decision making. Each type of vehicle has unique characteristics, from internal combustion engines in gasoline vehicles to electric systems in electric and hybrid vehicles. The problem it seeks to address is the lack of clear information for consumers when choosing between these technologies, with the central assumption that a detailed analysis will enable more conscious decisions and contribute to pollution reduction.

The chapter is structured to understand the mathematical calculations made to complete this study, presenting the equations used, with their components and meanings. The following parts of the chapter are to understand the performance of the different types of cars, in order to compare them.

9.1.1 Energy

Energy is the capacity of bodies to do work and produce changes in themselves or in other bodies (Secretaría de Energia de la República de Argentina, 2003). That is, the concept of energy is defined as the ability to make things work, having different ways to affect a body, we have different equations that help us to calculate certain parts that make up the total energy required to complete the desired work. As well as they are divided into different types of energy such as:

9.1.1.1 Kinetic energy

Kinetic energy is the energy associated with bodies in motion, depending on the mass and velocity of the body. The way to calculate it is presented in Equation 1.

$$E_K = \frac{1}{2} m V^2 \tag{1}$$

In this equation we have the following variables to consider:

- The mass of the car and passengers, measured in kilograms.
- The speed at which the car moves, measured in meters per second.

9.1.1.2 Potential Energy

Potential energy is the capacity of bodies to do work W, depending on their configuration in a system of bodies exerting forces on each other. It can be thought of as the energy stored in a system, or as a measure of the work that a system can deliver (W. Sears, W. Zemansky, & Young, 2009). The way to calculate it is presented in Equation 2:

$$E_U = mgh \tag{2}$$

In this equation we have the following variables to consider:

- The difference in altitudes between each state, divided into each segment of the path, measured in meters.

- The total mass of each vehicle and passengers, measured in kilograms.

- The gravity constant, measured in meters over second squared.

9.1.1.3 Drag energy

Drag energy comes from the multiplication of the friction force or frictional force (created by the resistance offered by a fluid when an object moves through it) and the distance traveled (Gencel, 2012). The way to calculate it is presented in Equation 3:

$$E_F = F \times d = \frac{1}{2} \times \sigma \times A \times v^2 \times \rho \times d \qquad (3)$$

In this equation we have the following variables to consider:

- The drag force considers:
  - The drag coefficient of the cars, taking an average 0.27 for the three vehicles.
  - The cross-sectional area of each car, measured in meters squared.
  - The velocity at which each vehicle is traveling, squared, resulting in m^2/s^2.
  - The density of the air, a constant of 1,225 kg/m3, since this is the medium in which the trip is made.
- The distance traveled, measured in meters.

9.1.1.4 Friction energy

Finally, the friction energy of the tires with the pavement was considered, which, like the drag energy, is obtained from the multiplication of a force (the friction force, created between two surfaces in contact, opposing sliding) and the distance traveled (W. Sears, W. Zemansky, & Young, 2009). The way to calculate it is presented in Equation 4.

$$E_F = F \times d = \mu \times N \times d = \mu \times mg \times d \qquad (4)$$

In this equation we have the following variables to consider:

- The frictional force is calculated from:
  - The coefficient of friction between the two surfaces to be considered. A coefficient of 0.12 is taken due to the composition of the tires and regular concrete (AVSLD International, 2013).
  - The normal force, being the force exerted by a surface when a body rests on it. In the case to be considered of a horizontal car, the normal is replaced by the weight of the car; that is, the mass (in kilograms) times the gravity (meters over second squared).
- Similar to the previous equation, the distance traveled, measured in meters.

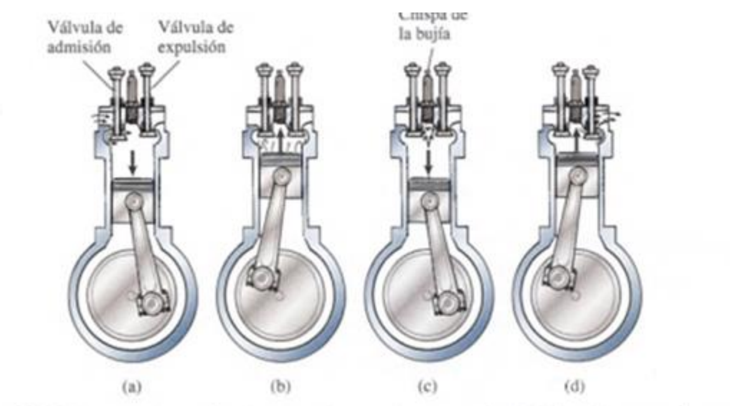
Finally, a single equation is observed as a summation of all the previous ones. The total energy of a body in motion is given in Equation 5:

$$E_T = E_K + E_U + E_R + E_F \qquad (5)$$

9.1.2 Gasoline car

The gasoline car, the most common model and known to the average user, runs on an engine that has gasoline as fuel and this goes through the Otto cycle. The gasoline engine is also known as a four-stroke engine, shown in Figure 9.2 (Tippens, 2001).

Figure 9.2 The four-stroke gasoline engine (a) Intake stroke (b) Compression stroke (c) Working stroke (d) Exhaust stroke



Source: (Tippens, 2001)

a. Intake stroke: where the engine's four-stroke process starts.

b. Compression stroke: the mixture enters through the intake valve, which closes during the compression stroke.

c. Working stroke: the piston moves up causing a pressure rise, before it reaches the top, the mixture ignites, which causes a change in temperature and pressure in the working stroke.

d. Ejection stroke: The products resulting from combustion are expelled from the engine and released into the environment. Among these products is, to a large extent, CO_2.

In summary, it can be said that the gasoline engine works from a spark that ignites the mixture of gasoline and air. This engine has an efficiency of 25%, compared to the diesel or gas oil engine which has an efficiency between 40% and 45%, due to the fact that the larger and more refined the engine, the better its performance (Tippens, 2001). Table 9.1 shows the comparison between the energy yield of a gasoline engine and a diesel engine.

Table 9.1 Comparison between gasoline and diesel

Fuel	Energy per liter	
Gasoline	32,18 MJ/l	8.94 kWh
Diesel	35,86 MJ/l	9.96 kWh

Source: (Tippens, 2001)

According to Pemex figures, between January and May 2022, an average of 1 million 19 thousand barrels of fuels were consumed daily, of which 81.95 are magna gasoline, while the other 18.1% is premium gasoline. It was also reported that during said year fuel sales grew 39.3% at annual rate in the month of June. (Usla, 2022) The increase in gasoline consumption has caused, as a direct consequence, the production of more greenhouse gases, especially in large cities with millions of cars in use per day. There have been initiatives to reduce this consumption and pollution, which in addition to affecting the atmosphere, can affect human health; a national example is the "Hoy no circula" program, applied in Mexico City (the 16 municipalities) and in 18 municipalities of the State of Mexico. Such program consists of restricting the use of polluting cars certain days of the week, having a penalty or fine in case of disregarding the program (Comisión Ambiental de la Megalópolis, 2018). However, these same measures have boosted the alternatives that car manufacturers have designed: electric and hybrid cars, which are exempt from the program and can circulate any day of the week without any penalty (Baysan Quality Blog, 2019).

9.1.3 Electric cars

Electric cars, as their name suggests, are vehicles that run on electric energy, propelled only by a lithium electric motor. This type of motor eliminates the need for a fossil fuel for its operation, since they are powered by the electric energy stored in the battery. These batteries can be made of different materials and with different capacities, but they are all recharged by plugging the vehicle into the mains with an estimated full charge time of 6 to 8 hours or quick charges of 15 to 42 minutes, depending on the model, or by taking advantage of the braking energy. The regenerative braking system allows them to harness energy causing more energy efficiency (Díez González, 2019). Figure 9.3 shows the electric motor and its components.

Figure 9.3 Components of an electric motor

Source: (Díez González, 2019)

The energy efficiency of this type of motors is almost 75% compared to 25% of the rest of traditional vehicles, due to a decrease in energy loss and use during braking, which contributes to greater savings, in addition to eliminating the emission of polluting gases (Díez González, 2019).

Electric vehicles commonly use permanent magnet synchronous motors, which allow them to achieve efficient mobility. These motors work by transforming electrical energy into mechanical energy through electromagnetic rotation. The field excitation in synchronous motors comes from a small generator or other DC source. In this type of motor, the interaction between two magnets, which attract or repel depending on the alignment of their poles, generates a forward or backward displacement. (Bonfiglioli Riduttr Industrial, 2019).

As for permanent magnet electric motors, they typically use ferrite magnets attached to the rotor, resulting in energy efficiency and power density approximately 25% higher than conventional induction motors. When high-capacity neodymium magnets are used, performance can be increased by 50% to 100% compared to induction motors.

Permanent magnet synchronous motors rotate in synchrony with the power frequency and can generate any torque up to the motor's maximum. These motors, being permanently excited, respond optimally to load variations. A synchronous motor consists of a stator, which is a hollow, fixed cylinder responsible for transmitting motion to the rotor by generating a rotating magnetic field. The stator acts as a magnet whose polarity constantly changes to allow displacement. The synchronous speed, which corresponds to the speed of the rotating magnetic field, is a fundamental factor in its operation. On the other hand, the rotor is a cylinder that rotates inside the stator and is connected to the gears that drive the vehicle. The alignment of the rotor and stator poles causes the motor to stop. To keep the rotor in the stator in motion, the polarity of the rotor magnets is reversed by means of coils connected to a rotating collector. This configuration ensures that the magnetisms between the stator and rotor never align, thus allowing the rotor to continue spinning (Bonfiglioli Riduttr Industrial, 2019).

Fast charging of electric car batteries has been a significant challenge compared to the time required to fill a tank of gasoline in an internal combustion vehicle. However, significant advances in charging technology and networks have been made to improve the speed of charging electric vehicles. Fast charging, which takes place at high-powered charging stations, can charge an electric vehicle in a much shorter time, typically 30 minutes to an hour. On the other hand, this process can increase the temperature of the battery due to the intense energy flow, which can have a negative impact on long-term durability and accelerate battery degradation.

To address these challenges, automakers and charging companies are implementing measures to regulate battery temperature during fast charging and optimize thermal management systems. More advanced battery technologies are also being developed that can better withstand fast charging without compromising performance and lifetime.

In summary, fast charging offers shorter charging times for electric vehicles, but can affect battery life due to temperature rise. Efforts are underway to mitigate these effects through temperature regulation and the development of more advanced battery technologies (Stone, 2021).

9.1.4 Hybrid automobile

A hybrid vehicle combines an internal combustion engine with one or more electric motors to generate the necessary energy to propel the vehicle. The operation of a hybrid vehicle is integrated with a system known as "start-stop", which is responsible for turning the internal combustion engine on and off as needed.

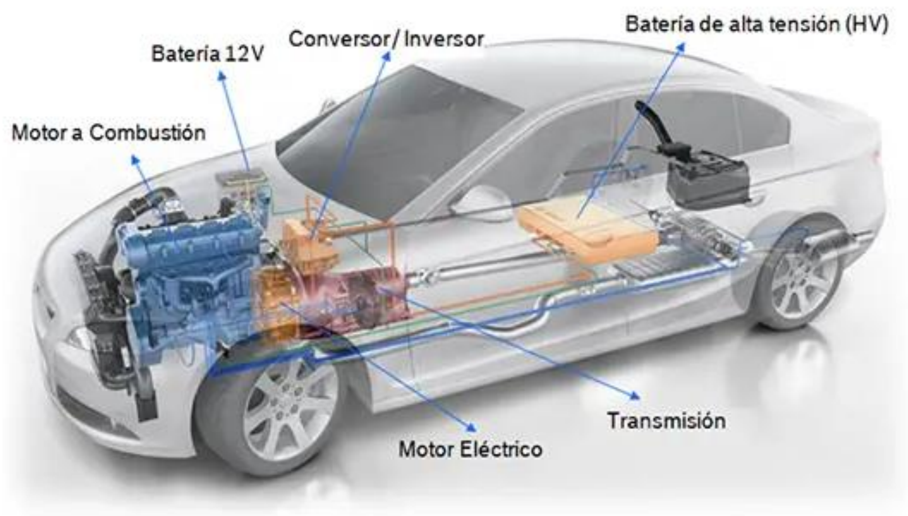
The hybrid vehicle operates in different speed ranges for both engines: on short trips and at low speeds, the electric motor is the only one in operation, while on long trips and at high speeds, both engines work together.

An outstanding feature of the hybrid vehicle is the regenerative braking, which allows the battery of the electric motor to be recharged each time the vehicle is braked. This results in fuel savings of approximately 50% compared to a vehicle equipped only with an internal combustion engine. Unlike electric vehicles, hybrids do not need to be plugged in, as the internal combustion engine and regenerative braking allow efficient performance of the electric motor, which helps to significantly reduce gasoline consumption in urban environments.

The savings in pollutant emissions can reach up to 80% (Alfaro, 2022). The efficiency of these cars is higher on short trips in the city, where only the electric motor is used, resulting in lower fuel consumption (Antonio, 2022).

The internal combustion engine (ICE) of a hybrid vehicle is similar to that found in conventional vehicles and can be gasoline or diesel. The ICM is primarily used to charge the vehicle's battery and provide additional power when needed. During operation, the ICM can directly drive the wheels or recharge the battery. On the other hand, the hybrid vehicle's electric motor is powered by electricity stored in a battery. This electric power drives the vehicle at low speeds or acts as a backup to the ICM in situations of high power demand. In addition, the electric motor also acts as a generator by converting the vehicle's kinetic energy into electricity during braking or deceleration, through a process known as regenerative braking. The main components of this motor are shown in Figure 9.4.

Figure 9.4 Components of a hybrid car



Source: (Rodriguez, 2023)

The hybrid car uses the electric motor up to 60 km/h, if more power is needed the system activates the combustion engine, which is more effective at higher speeds.

The system of these cars detects when it is necessary to use an engine. While the gasoline engine is being used and the car is braking, at the moment of braking some energy is recovered from the electric motor, making its autonomy effective. (Toyota, 2021).

In this work, a comprehensive comparison of the best-selling cars of the three types of automobiles: gasoline, hybrid and electric, is made in order to provide the average consumer with a purchase recommendation based on individual needs. Through a detailed analysis and calculation of costs and travel times, the strengths and weaknesses of each option will be highlighted, thus providing a clear and complete view of the alternatives available in today's market.

9.2 Methodology to be developed

In this study, public information on sales in Mexico was used to determine consumer preferences in the last year with respect to the three types of vehicles available in the market: gasoline, electric and hybrid.

A comparative table between the cars investigated is presented in Table 9.2 below, with the data provided through each car's manual.

Table 9.2 Comparative table of cars

	Electric JAC e10X	Hybrid Toyota Prius	Gasoline Nissan Versa
Performance.	Batteries and motor (electrical to mechanical power)	Electricity, fuel (electrical and chemical to mechanical energy)	Fuel, (chemical to mechanical energy)
Efficiency.	75%	11%	25%
Weight (kg).	1555	1380	1104
Frontal area (m^2).	2.49	2.5	2.55
Estimated life time.	180000 km.	200.000 km.	250.000 km.

Source: (JAC, 2022), (Toyota, 2022), (Nissan, 2023)

Subsequently, a route of between 700 to 1500 km was selected, with an average duration of less than 24 hours, which stays within Mexico and presents different topographic conditions, such as ascents and descents. The route starts in Torreón, Coahuila, and with the help of the Google Maps tool (Google Maps, 2023) the best route for this trip was defined, as well as the sections to be analyzed and the average time of these sections for analysis. Data was collected on the differences in altitude on each section, as well as the average time and speed of travelers on each section, presented in Table 9.3.

Table 9.3 Path divided by the different altitudes, distance, time and average speed from each state to another

Section	Altitude difference (m)	Kilometers (km)	Total, Kilometers (km)	Hours	Speed (km/h)*	Speed (m/s)*
Coahuila to Durango	771	8	8	0.18	45	12.50
Durango to Zacatecas	545	174	182	1.82	95.4	26.50
Zacatecas to Aguascalientes	-555	268	450	2.96	90.4	25.11
Aguascalientes to Jalisco	530	101	551	1.12	90.4	25.11
Jalisco to Guanajuato	-690	80	631	0.88	90.4	25.11
Guanajuato to Querétaro	225	172	803	1.74	98.94	27.48
Querétaro to Tlaxcala	419	229	1032	2.31	98.94	27.48
Tlaxcala to Puebla	-104	84	1116	1.44	58.14	16.15
*With the approximate time to travel the distance given by Google Maps (Google Maps, 2023) and the measurement of this distance, the average speed of each journey could be calculated. Then a simple conversion from km/h to m/s was made.						

Source: (Wikipedia, n.d.)

As a next step, it will be calculated how many stops will be made for gasoline and/or electric charging, using the performance information that the manufacturers of each vehicle have publicly available. To do this, first calculate the energy required for each car in each already defined trip; this with the help of Equation 5, of the total energy of a moving vehicle. It is important to keep the units homogeneous in order to obtain correct results. Equation 6 shows the units required to solve Equation 5.

$$E_T = \frac{kg*(m/s)^2}{2} + (kg * [m/s^2] * m) + \frac{m^2*(m/s)^2*(kg/m^3)*m}{2} + (kg * [m/s^2] * m) \qquad (6)$$

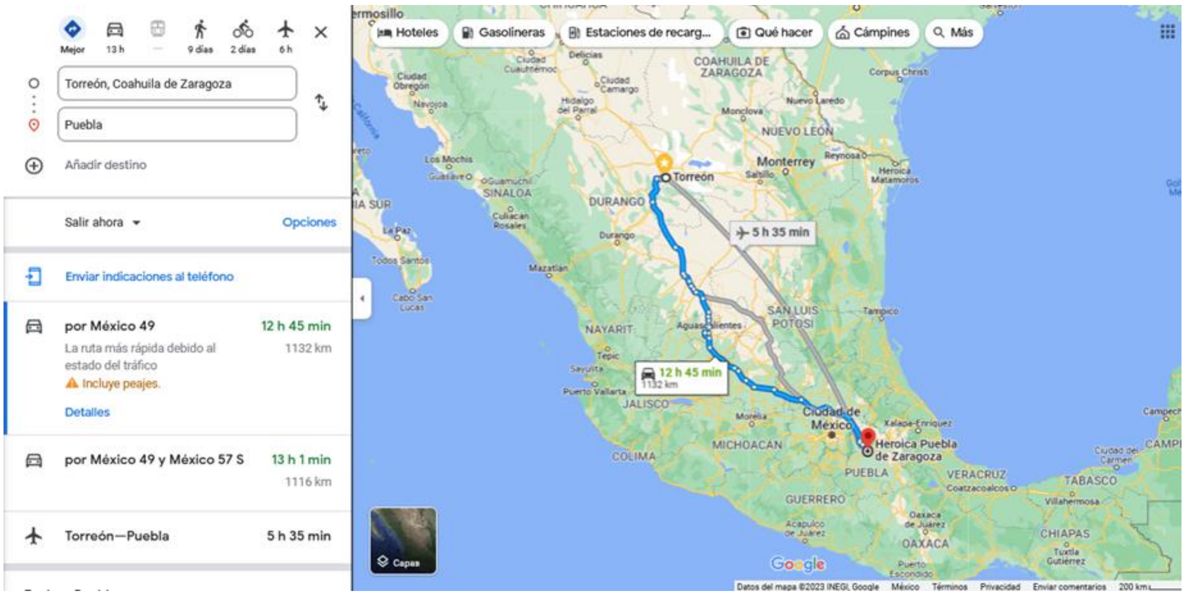
Once the amount of energy required for each section was obtained, it was evaluated whether each car was able to cover that energy with its performance and the energy available at the beginning of the section. In case a car was not able to cover the whole stretch, a stop was considered before reaching the minimum load level established. On the other hand, if the car was able to cover the required energy with the energy available at the beginning of the stretch, the amount of energy remaining in the car after the run was calculated, discounting the liters of gasoline or the percentage of battery used. In addition, the time required for each section and stop was estimated and added to the departure time of the three cars. However, in the event that the stops accumulated to a travel time of more than 20 hours at a time, a second calculation was considered, taking into account stops to sleep in a hotel, with average lodging costs at the point where the stop was made.

Finally, with the total number of stops necessary for the three cars to complete the same trip and the estimated time of arrival of each one, the costs associated with each car to complete the trip were calculated.

9.3 Results

This study compares the Nissan Versa (gasoline model), Toyota Prius (hybrid model) and JAC E10X (electric model) for the same route starting from Torreón, Coahuila to Puebla, Puebla. The approximate time taken by the Google Maps tool for this route is 12 hours and 45 minutes, for a total of 1116 km. Figure 9.5 shows a screenshot to demonstrate what the Google Maps tool shows when requesting a route from Torreón, Coahuila to Puebla, Puebla.

Figure 9.5 Screenshot, Torreon to Puebla Route



Source: (Google Maps, 2023)

To calculate the energy required of each car in each section of the route, in equations 1, 2 and 4 the mass of the vehicle along with the passengers must be taken into account. Noting that the capacity of the cars is 5 persons, a family of 5 persons was considered as the passengers for this trip. The average weights of a common family in Mexico (IMCO, Mexican Institute for Competitiveness, 2016) are presented in Table 9.4.

Table 9.4 Average passenger information

Passengers	Age	Average weight.
Child	2 years old	12 kg
Child	12 years old	41.5 kg
Youth	16 years old	58 kg
Adult	45 years old	71 kg
		Total: 253.5kg

Source: (IMCO, Mexican Institute for Competitiveness, 2016)

While Table 9.5 shows the additional data, necessary for the energy calculations presented in Equations 1, 2, 3 and 4.

Table 9.4 Required data

	Name	Dates
General	Gravity (m/s^2)	9.81
	Air density (kg/m^3)	1.225
	Drag coefficient (cars)	0.27
	Coefficient of friction (cars)	0.12
	Gasoline Efficiency (kWh/liter)	9
Total Yield (kWh)	Electric	31.4
	Hybrid	387
	Gasoline*	369
Weight (kg)	Passenger	253.5
	Electric	1555
	Hybrid	1380
	Gasoline	1104
*The kWh performance of the hybrid and gasoline model cars was obtained from the gasoline tanks that the manufacturer specifies for each car, multiplied by the energy yield per liter of gasoline (Table 1.2.2).		

Source: (W. Sears, W. Zemansky, & Young, University Physics, Vol. 1., 2001), (Gencel, On "friction" in moving fluids and their solid boundary and on "lost" energy, 2012), (AVSLD International, 2013), (JAC, 2022), (Nissan, 2023), (Toyota, 2022)

The energy required for each trip was originally calculated in Joules. However, for the use of future calculations, the units of Joules were converted to kWh, taking into account the conversion of 1 Joule= 3600000 kWh. The result of this calculation for the three cars is shown in Table 9.5 The complete results (with Joules and km/kWh) can be found in Annex I).

Table 9.5 Energy required by the cars to be analyzed, according to the distance to be traveled

Energy required (in kWh)			
Section	**Gasoline**	**Electric**	**Hybrid**
Coahuila to Durango	6.58	8.713	7.88
Durango to Zacatecas	93.70	119.739	109.56
Zacatecas to Aguascalientes	136.83	175.243	160.23
Aguascalientes to Jalisco	54.37	69.784	63.77
Jalisco to Guanajuato	38.99	49.838	45.60
Guanajuato to Querétaro	92.54	117.876	107.97
Querétaro to Tlaxcala	123.61	157.466	144.22
Tlaxcala to Puebla	39.52	51.735	46.98
Totals	586.14	750.39	686.2

Source: Own elaboration

Subsequently, the stops of each car along this route must be calculated. For this, two possible cases are considered:

- Case 1: The possible performance of the vehicle exceeds the energy demanded by the route, without exceeding a minimum limit of fuel/battery available. The minimums are: 10 liters of gasoline (for the internal combustion car and the hybrid) and 10% of battery (for the electric car).

- Case 2: The available energy of the vehicle is not enough to cover the energy cost of the trip. Then one or more stops must be considered to recharge the fuel or battery; as many stops as necessary to complete the stretch considered must be considered.

Based on these two cases, the initial and final liters/battery and their consumption in each section were calculated, in addition to the initial, final and consumed energy; as well as the time of the trip, considering an average time of 20 minutes for the gasoline refueling stops and approximately 42 minutes for the fast charging of the electric car. In addition, the Excel sheet divides the sub-sections of stops with initial kilometer and final kilometer, in order to know in which kilometer a charge should be made in each particular case. The complete tables, produced in Excel, will be available for review in Annex II.

Once the stops have been calculated, the geographical location of the stop made is obtained and the corresponding prices for the region are consulted to be taken into account in the cost calculation. In the case of the hybrid and internal combustion, the average price of gasoline in the different states where a stop was made was consulted. This price was then multiplied by the difference of the total tank capacity minus what was left in the tank at that stop, in order to obtain a car as full as possible for the next stop. Tables 9.6 and 9,7 below show the stops for the gasoline and hybrid car, along with a summary of the calculations made.

Table 9.6 Gasoline car analysis

Gas				
Kilometer	**Stop**	**Location**	**Gasoline price***	**Expense**
0	0	Torreón, Coahuila	$ 21.25	$ 871.25
450	1	Lagos de Moreno, Jalisco	$ 21.87	$ 677.97
1049	2	Villa Tezontepec, Hidalgo	$ 21.26	$ 670.27
Total, of Stops	2		**Total**	$ 1348.24
Total hours			12.63	**Days on the road**
Departure Time	06:00:00 a. m.	**Arrival time**	06:37:38 p. m.	0.53
*Gasoline prices may vary from day to day, however, for these calculations, the prices in the localities corresponding to May 15, 2023 are taken into account.				

Source: (Gasolina MX, 2023)

Note that a "zero" load is taken into account for the final price, which is the initial load, made before starting the trip. This load is a full tank load (equivalent to 41 liters), in order to obtain full capacity at the beginning of the trip. It was observed that, starting with a full tank, the first load should be made at kilometer 450, which is in Lagos de Moreno Jalisco; where 31 liters of gasoline should be loaded. The second stop is at kilometer 1049, in Villa Tezontepec, Hidalgo, where a refueling of 32 liters of gasoline is done.

Additionally, it is noted that, despite having two stops, the calculated time to complete this trip is around the 12 hours and 45 minutes that the Google Maps tool predicted for this trip (Google Maps, 2023).

Table 9.7 Hybrid car analysis

Hybrid				
Kilometer	**Stop**	**Location**	**Gasoline price**	**Expense**
0	0	Torreón, Coahuila	$ 21.25	$ 913.75
551	1	Encarnación de Díaz, Jalisco	$ 22.55	$ 855.51
803	2	Apan, Hidalgo	$ 21.26	$ 701.58
Total, Stops	2		**Total**	$ 1557.09
Total Hours			13.13	**Days on the road**
Departure Time	06:00:00 a. m.	**Arrival time**	07:07:58 p. m.	0.55
*Gasoline prices may vary from day to day, however, for these calculations, the prices in the locations corresponding to May 15, 2023, are taken.				

Source: (Gasolina MX, 2023)

For the analysis of the hybrid car, there is a great similarity with the analysis of the gasoline car, having a total of only two stops in the whole trip. In addition, a "zero" charge is also considered in which the 43-liter tank is filled before starting the trip. At the first stop there is a refueling of 38 liters of gasoline in Encarnación de Díaz, Jalisco. At the second stop, 33 liters of gasoline are refilled in Apan, Hidalgo. Note that, from the calculation of the energy required, the hybrid vehicle needs more energy than the gasoline model. This may be due to the weight of the car, thus affecting the amount of energy required to move the car over the same distance. However, this extra effort may also be reflected in the difference in the final costs of the analysis of the gasoline car and the hybrid.

On the other hand, it was noted that the calculation for the electric car was more extensive than the previous two, resulting in a travel time much longer than a day's travel or 20 hours of driving. The trip, considering only fast charges and assuming a continuous change of driver, takes 2 nights and 3 days of travel. For this reason, it was decided to do two analyses for the electric car: 1) Electric car analysis, considering only stops for fast charging. 2) Electric car analysis, considering slow and fast charging stops.

Assuming that there is indeed a family making this trip, it is most likely that the adults will opt to stay in a hotel along the way when it gets very late (around 10 pm). In this second analysis, it was considered that at the hotel they stay overnight there are slow charging stations to charge the car to 100% overnight. However, instead of considering only the 6 hours of charging needed for the vehicle, 8 hours of sleep were considered, taking into account that the family is mostly composed of minors.

Table 9.7 shows the summary of the calculations for the electric car analysis, considering only fast charging through the project.

Table 9.7 Electric car analysis, fast charging stops

	Electric (fast charging stops)			
State	**# Quick stops**	**Parking price**	**Parking Expense**	**Total hours**
Coahuila	0	$ 22.5	0	56.00
Durango	6	$ 15	$ 90	**Days on the road**
Zacatecas	8	$ 20	$ 160	2.33
Aguascalientes	3	$ 48	$ 144	**Departure time (1st day)**
Guanajuato	2	$ 42	$ 84	06:00:00 a. m.
Querétaro	11	$ 30	$ 330	**Arrival Time (3rd day)**
Tlaxcala	1	$ 30	$ 30	10:36:40 a. m.
Total, Stops	**31**	**Total, Parking**	$ 838	
Price Home Load (0%-100%)	$89.77	**Total, Expenses**	$ 927.77	

Source: (Federal Electricity Commission, 2023)

It is noted that the electric car requires up to 32 stops for a trip of 1116 km. Average parking costs in each state were considered, assuming that a parking lot with fast charging available existed at each point that a stop was to be made. In addition, a "zero" charge was also considered for the electric car. However, to make this calculation, the highest cost per kilowatt-hour was obtained from CFE, being $ 2.859 Mexican pesos in DAC tariff for 2023 (Comisión Federal de Electricidad, 2023). Multiplying this price by 100% of the battery, we have a price of $ 89.77 Mexican pesos. At the end, this is added to the total cost of expenses and results in a cost of $927.77 Mexican pesos.

Similarly, Table 9.8 shows the summary of the calculations considering that, at 10:00 pm (except for the last day), the family would look for (and find) a hotel with car charging service. The price of the hotel was added to the cost to be considered.

Table 9.8 Electric car analysis, considering only slow and fast charging stops

		Electric (slow and fast charging stops)		
State	**# Quick Stops**	**Parking Price**	**Parking Expense**	**Total hours**
Coahuila	1	$ 20.00	$ 20.00	68.43
Durango	8	$ 25.00	$ 200.00	**Days on the road**
Zacatecas	4	$22.00	$ 88.00	2.85
Aguascalientes	3	$ 21.00	$ 63.00	**Price Freight at Home (0%-100%)**
Guanajuato	3	$ 20.00	$ 60.00	89.77
Querétaro	11	$ 50.00	$ 550.00	**Departure time (1st day)**
Tlaxcala	2	$ 30.00	$ 60.00	06:00:00 a. m.
Total, Stops	32	**Total, Parking**	$ 1,041.00	**Arrival Time (3rd day)**
Slow load stops				10:51:23 p. m.
Kilometer	**Location**	**Hotel price**	**Nights in hotel**	
335	Fresnillo, Zacatecas	$1,200.00	1	**Total expense**
709	San Luis de la Paz, Guanajuato	$940.00	1	$ 3,181.00

Source: Own elaboration

From Table 9.8 it is noted that there are a large number of total stops, so listing them is meaningless. However, Table 9.8 shows the most important stops in this second analysis: the slow-load stops, or sleep stops. These stops are important, as they comprise a large part of the expenditure considered for this analysis, as it considers the rental of two rooms in hotels in the given locations for the family of 5 (considered in this trip) to sleep.

Finally, a detailed comparison is made between the 4 analyses performed. This comparison is shown in Table 9.9.

Table 9.9 Final comparison of car analysis

Car Analysis	Gasoline	Hybrid	Electric (fast-charging stops)	Electric (slow and fast charging stops)
Full load performance (kWh)	369.00	387.00		31.40
Total energy required (kWh)	586.14	686.21		750.39
Travel hours	12.63	13.13	56.00	68.43
Charging time per stop (min)		20.0	1.0	360.0
Days on the road	0.5	0.5	2.3	2.9
Number of stops	2.0	2.0	31.0	31 (fast) 2 (slow)
Charge at the end (liters, % battery)	26.3	11.0	38%	44%
Total cost	$ 1,348.24	$ 1,557.09	$ 838	$ 3,181.00
Sales value	$ 326,900.00	$ 448,100.00		$ 439,000.00

Source: (JAC, 2022), (Toyota, 2022), (Nissan, 2023).

From this last comparison we noticed that the full-load performance of the gasoline and hybrid cars are more than ten times higher than the full battery charge of the considered electric car. However, the car that requires more energy to complete the stretch is just the electric car, due to its weight. Additionally, I noted that the cheapest car (sales value) and the one that takes the least time to complete the trip is the gasoline car. While the hybrid vehicle can compete with the time it takes to complete this trip, the retail value and total expense is much higher than the gasoline car. On the other hand, the electric car, despite being the slowest to complete the proposed route, when only fast charges are considered, is the car with the least mobility expenses on the trip.

Thanks to Table 9.9, the weaknesses and strengths of each car can be clearly seen. The gasoline car and the hybrid car are almost the same, as both use fossil fuel to meet their energy demands. This results in very similar times and consumption, with travel times and costs varying only slightly. On the other hand, the electric and its two analyses stand out from the same table as being so different. It is clear from the first data to compare that the electric is at a disadvantage, because while the other two vehicles have a performance capacity of more than 300 kWh, the battery of the electric only has 31.4 kWh of energy available. Based on this, the cost and time comparison, it can be stated that:

- The electric car is not recommended for long journeys, with prominent height differences and at high speeds. However, if a car is required to complete journeys at moderate speeds, within a city where there are no height differences or considerable reliefs, the electric car would be ideal. Considering that its full charge can be completed overnight, the additional cost on the electric bill for each 0-100% charge is $89.77; a much lower cost than filling the tank of a hybrid or gasoline car.

- While the electric car analysis full of fast charges is the lowest cost, the batteries are not designed to withstand fast charges as often. It is likely that before completing the run, the battery will reach its limit and stop working.

- The hybrid car is as recommendable as the internal combustion car for long trips. The purchase decision between a hybrid and a gasoline car depends purely on the customer's preference and budget, because although the hybrid car integrates more technologies and has a greater performance capacity than the gasoline car, it is also more than $100,000 Mexican pesos more expensive than the gasoline model.

9.4 Annexes

Annex I

Table 9.10 Calculation of energy required by vehicles in each stretch.

	Energy required								
		Gasoline			Electric			Hybrid	
Section	Joules	kWh	km/kWh	Joules	kWh	km/kWh	Joules	kWh	km/kWh
Coahuila to Durango	2.37E+07	6.58	1.22	3.14E+07	8.713	0.92	2.84E+07	7.88	1.01
Durango to Zacatecas	3.37E+08	93.70	1.86	4.31E+08	119.739	1.45	3.94E+08	109.56	1.59
Zacatecas to Aguascalientes	4.93E+08	136.83	1.96	6.31E+08	175.243	1.53	5.77E+08	160.23	1.67
Aguascalientes to Jalisco	1.96E+08	54.37	1.86	2.51E+08	69.784	1.45	2.30E+08	63.77	1.58
Jalisco to Guanajuato	1.40E+08	38.99	2.05	1.79E+08	49.838	1.61	1.64E+08	45.60	1.75
Guanajuato to Querétaro	3.33E+08	92.54	1.86	4.24E+08	117.876	1.46	3.89E+08	107.97	1.59
Querétaro to Tlaxcala	4.45E+08	123.61	1.85	5.67E+08	157.466	1.45	5.19E+08	144.22	1.59
Tlaxcala to Puebla	1.42E+08	39.52	2.13	1.86E+08	51.735	1.62	1.69E+08	46.98	1.79
Totals		586.14	1.85		750.39	1.44		686.2	1.57

Source: Own elaboration

Annex II

Table 9.11 Gasoline vehicle route.

						Gasoline						
Section	Km Initial	Final Km	Initial Liters	Gasoline Consumption	Final Liters	Initial Energy (kWh)	Consumption (kWh)	Final Energy (kWh)	No. of Stops	Time (hours)	Start Time	End Time
Coahuila to Durango	0	8	41.00	0.7	40.3	369.00	6.58	362.4	0	0.2	06:00:00 a. m.	06:10:40 a. m.
Durango to Zacatecas	8	182	40.27	0.7	39.5	362.42	93.70	268.7	0	1.8	06:10:40 a. m.	08:00:06 a. m.
Zacatecas to Aguascalientes	182.00	450	39.54	29.5	10.0	355.84	136.83	219.0	1	3.0	08:00:06 a. m.	10:57:59 a. m.
Aguascalientes to Jalisco	450.00	557	41.00	15.2	25.8	369.00	54.37	314.6	0	1.2	10:57:59 a. m.	12:08:40 p. m.
Jalisco to Guanajuato	556.50	629	25.80	6.0	19.8	232.17	38.99	193.2	0	0.8	12:08:40 p. m.	12:56:44 p. m.
Guanajuato to Querétaro	628.92	819	19.76	10.3	9.5	177.80	92.54	85.3	1	2.1	12:56:44 p. m.	03:02:46 p. m.
Querétaro to Tlaxcala	818.81	1049	41.00	10.3	30.7	369.00	123.61	245.4	0	2.3	03:02:46 p. m.	05:22:05 p. m.
Tlaxcala to Puebla	1048.55	1122	30.72	4.4	26.3	276.46	39.52	236.9	0	1.3	05:22:05 p. m.	06:37:38 p. m.
Section						**Totales**	586.14	**Totales**	2	12.6		

Source: Own elaboration

Table 9.12 Hybrid vehicle route

						Gasoline						
Section	Initial Km	Final Km	Initial Liters	Gasoline Consumption	Final Liters	Initial energy (kWh)	Consumption (kWh)	Final Energy (kWh)	No. de Paradas	Time (hours)	Start time	End time
Coahuila to Durango	0	8	41.00	0.7	40.3	369.00	6.58	362.4	0	0.2	06:00:00 a. m.	06:10:40 a. m.
Durango to Zacatecas	8	182	40.27	0.7	39.5	362.42	93.70	268.7	0	1.8	06:10:40 a. m.	08:00:06 a. m.
Zacatecas to Aguascalientes	182.00	450	39.54	29.5	10.0	355.84	136.83	219.0	1	3.0	08:00:06 a. m.	10:57:59 a. m.
Aguascalientes to Jalisco	450.00	557	41.00	15.2	25.8	369.00	54.37	314.6	0	1.2	10:57:59 a. m.	12:08:40 p. m.
Jalisco to Guanajuato	556.50	629	25.80	6.0	19.8	232.17	38.99	193.2	0	0.8	12:08:40 p. m.	12:56:44 p. m.
Guanajuato to Querétaro	628.92	819	19.76	10.3	9.5	177.80	92.54	85.3	1	2.1	12:56:44 p. m.	03:02:46 p. m.
Querétaro to Tlaxcala	818.81	1049	41.00	10.3	30.7	369.00	123.61	245.4	0	2.3	03:02:46 p. m.	05:22:05 p. m.
Tlaxcala to Puebla	1048.55	1122	30.72	4.4	26.3	276.46	39.52	236.9	0	1.3	05:22:05 p. m.	06:37:38 p. m.
						Totales	586.14	**Totales**	2	12.6		

Source: Own elaboration

Table 9.13 Electric vehicle route, fast charges

Hybrid												
Section	Initial Kilometer	Final Kilometer	Initial Liters	Gasoline consumption	Final Liters	Initial Energy (kWh))	Consumption (kWh)	Final Energy (kWh)	No. of stops	Time (hours)	Start time	End Time
Coahuila to Durango	0	8	43	0.9	42.1	387.00	7.88	379.1	0	0.2	06:00:00 a. m.	06:10:40 a. m.
Durango to Zacatecas	8	182	42.1	12.2	30.0	379.12	109.56	269.6	0	1.8	06:10:40 a. m.	08:00:06 a. m.
Zacatecas to Aguascalientes	182	450	30.0	17.8	12.1	269.55	160.23	109.3	0	3.0	08:00:06 a. m.	10:57:59 a. m.
Aguascalientes to Jalisco	450	551	12.1	7.1	5.1	109.32	63.77	45.6	1	1.5	10:57:59 a. m.	12:25:01 p. m.
Jalisco to Guanajuato	551	631	43.0	5.1	37.9	387.00	45.60	341.4	0	0.9	12:25:01 p. m.	01:18:07 p. m.
Guanajuato to Querétaro	631	803	37.9	27.9	10.0	341.40	107.97	233.4	1	2.1	01:18:07 p. m.	03:22:25 p. m.
Querétaro to Tlaxcala	803	1032	43.0	16.0	27.0	387.00	144.22	242.8	0	2.3	03:22:25 p. m.	05:41:17 p. m.
Tlaxcala to Puebla	1032	1116	27.0	16.0	11.0	242.78	46.98	195.8	0	1.4	05:41:17 p. m.	07:07:58 p. m.
						Totales	686.21	**Totales**	2	13.1		

Source: Own elaboration

Table 9.14 Electric vehicle path, slow and fast loads

Electric (Fast charge)												
Section	Initial Kilometer	Final Kilometer	Carga Inicial	Battery Consumption	Final Charge	Initial Energy (kWh)	Consumption (kWh)	Final energy (kWh)	No. of stops	Time (hours)	Start time	End time
Coahuila to Durango	0	8	100%	28%	72%	31.40	8.71	22.69	0	0.18	06:00:00 a. m.	06:10:40 a. m.
Durango to Zacatecas	8	13	72%	62%	10%	22.69	19.55	3.14	1	0.98	06:10:40 a. m.	07:09:10 a. m.
	13	45	80%	70%	10%	25.12	21.98	3.14	1	1.69	07:09:10 a. m.	08:50:34 a. m.
	45	77	80%	70%	10%	25.12	21.98	3.14	1	1.69	08:50:34 a. m.	10:31:57 a. m.
	77	108	80%	70%	10%	25.12	21.98	3.14	1	1.69	10:31:57 a. m.	12:13:20 p. m.
	108	140	80%	70%	10%	25.12	21.98	3.14	1	1.69	12:13:20 p. m.	01:54:43 p. m.
	140	172	80%	70%	10%	25.12	21.98	3.14	1	1.69	01:54:43 p. m.	03:36:07 p. m.
	172	182	80%	21%	59%	25.12	6.59	18.53	0	0.21	03:36:07 p. m.	03:48:53 p. m.
Zacatecas to Aguascalientes	182	205	59%	49%	10%	18.53	15.39	3.14	1	1.21	03:48:53 p. m.	05:01:25 p. m.
	205	239	80%	70%	10%	25.12	21.98	3.14	1	1.73	05:01:25 p. m.	06:45:02 p. m.
	239	273	80%	70%	10%	25.12	21.98	3.14	1	1.73	06:45:02 p. m.	08:28:39 p. m.
	273	306	80%	70%	10%	25.12	21.98	3.14	1	1.73	08:28:39 p. m.	10:12:17 p. m.
	306	340	80%	70%	10%	25.12	21.98	3.14	1	1.73	10:12:17 p. m.	11:55:54 p. m.
	340	374	80%	70%	10%	25.12	21.98	3.14	1	1.73	11:55:54 p. m.	01:39:31 a. m.
	374	407	80%	70%	10%	25.12	21.98	3.14	1	1.73	01:39:31 a. m.	03:23:08 a. m.
	407	441	80%	70%	10%	25.12	21.98	3.14	1	1.73	03:23:08 a. m.	05:06:45 a. m.
	441	450	80%	19%	61%	25.12	6.00	19.12	0	0.21	05:06:45 a. m.	05:19:03 a. m.
Aguascalientes to Jalisco	450	473	61%	51%	10%	19.12	15.98	3.14	1	1.23	05:19:03 a. m.	06:32:39 a. m.
	473	505	80%	70%	10%	25.12	21.98	3.14	1	1.69	06:32:39 a. m.	08:13:52 a. m.
	505	537	80%	70%	10%	25.12	21.98	3.14	1	1.69	08:13:52 a. m.	09:55:05 a. m.
	537	551	80%	31%	49%	25.12	9.84	15.28	0	0.32	09:55:05 a. m.	10:14:05 a. m.
Jalisco to Guanajuato	551	570	49%	39%	10%	15.28	12.14	3.14	1	0.97	10:14:05 a. m.	11:12:32 a. m.
	570	606	80%	70%	10%	25.12	21.98	3.14	1	1.76	11:12:32 a. m.	12:58:22 p. m.
	606	631	80%	50%	30%	25.12	15.72	9.40	0	0.56	12:58:22 p. m.	01:32:01 p. m.
Guanajuato to Querétaro	631	640	30%	20%	10%	9.40	6.26	3.14	1	0.48	01:32:01 p. m.	02:00:56 p. m.
	640	672	80%	70%	10%	25.12	21.98	3.14	1	1.69	02:00:56 p. m.	03:42:30 p. m.
	672	704	80%	70%	10%	25.12	21.98	3.14	1	1.69	03:42:30 p. m.	05:24:04 p. m.
	704	736	80%	70%	10%	25.12	21.98	3.14	1	1.69	05:24:04 p. m.	07:05:38 p. m.
	736	768	80%	70%	10%	25.12	21.98	3.14	1	1.69	07:05:38 p. m.	08:47:12 p. m.
	768	800	80%	70%	10%	25.12	21.98	3.14	1	1.69	08:47:12 p. m.	10:28:45 p. m.
	800	803	80%	5%	75%	25.12	1.72	23.40	0	0.06	10:28:45 p. m.	10:32:06 p. m.
Querétaro to Tlaxcala	803	833	75%	65%	10%	23.40	20.26	3.14	1	1.56	10:32:06 p. m.	12:05:44 a. m.
	833	865	80%	70%	10%	25.12	21.98	3.14	1	1.69	12:05:44 a. m.	01:47:17 a. m.
	865	897	80%	70%	10%	25.12	21.98	3.14	1	1.69	01:47:17 a. m.	03:28:51 a. m.
	897	929	80%	70%	10%	25.12	21.98	3.14	1	1.69	03:28:51 a. m.	05:10:25 a. m.
	929	961	80%	70%	10%	25.12	21.98	3.14	1	1.69	05:10:25 a. m.	06:51:59 a. m.
	961	993	80%	70%	10%	25.12	21.98	3.14	1	1.69	06:51:59 a. m.	08:33:32 a. m.
	993	1025	80%	70%	10%	25.12	21.98	3.14	1	1.69	08:33:32 a. m.	10:15:06 a. m.
	1025	1032	80%	17%	63%	25.12	5.32	19.80	0	0.16	06:51:59 a. m.	07:01:19 a. m.
Tlaxcala to Puebla	1032	1056	63%	53%	10%	19.80	16.66	3.14	1	1.28	07:01:19 a. m.	08:18:17 a. m.
	1056	1088	80%	70%	10%	25.12	21.98	3.14	1	1.69	08:18:17 a. m.	09:59:51 a. m.
	1088	1116	80%	42%	38%	25.12	13.10	12.02	0	0.61	09:59:51 a. m.	10:36:40 a. m.
						Total Consumption	766.70	**Total, fast loads**	34	56.00		

Source: Own elaboration

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9.7 Conclusions

In this work, a comparative analysis of three types of automobiles: gasoline, hybrid and electric, was carried out with the objective of providing the average consumer with a purchase recommendation based on their individual needs. The study focused on highlighting the strengths and weaknesses of each option, considering both long-distance performance and environmental impact.

By selecting the best-selling cars of each type in Mexico, a detailed analysis of their characteristics was carried out and compared in terms of efficiency, autonomy and associated costs. In addition, a route of more than 1000 km was selected, from Torreón, Coahuila, to Puebla, Puebla, to evaluate the performance of the vehicles in real conditions.

The results obtained revealed that, compared to gasoline-powered cars, hybrid vehicles are an option with similar performance on long trips. On the other hand, electric cars were not recommended for this type of trips due to their limitations in terms of autonomy and the availability of charging points along the route.

In conclusion, this study provides consumers with a solid and objective comparison of the different types of cars available in the market, allowing them to make informed decisions based on their mobility needs and environmental considerations. However, it is important to keep in mind that electric vehicle technology is constantly evolving, and it is possible that some of the limitations identified in this study will be overcome in the future.

As future lines of research, it is suggested to extend the comparative analysis to other car models and explore the long-term economic and environmental impact of each option. In addition, it would be relevant to investigate the development of charging infrastructures for electric vehicles and their influence on the viability of these cars on long trips.

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