Evaluation of the electric bicycle as an alternative mobility in the city of Cuenca, Ecuador

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Abstract

In recent years, cities have been designed for vehicles and large infrastructures have been constructed for their circulation. As a result, vehicular congestion has significantly increased air pollution. Consequently, intermediate cities are looking for more sustainable mobility options before they face road collapse. The objective of this study was to evaluate an electric bicycle as an alternative mobility option in the city of Cuenca, Ecuador. The analysis was done considering these four aspects: energy, environment, cost, and time. Previous work published by local city government was considered to determine the most representative routes taking into account how people moves in Cuenca. Data collection was carried out with GPS devices in order to propose a dynamic vehicle equation to determine energy consumption. The results were compared to light-duty vehicles operating on gasoline. Hence, it was concluded that the electric bicycle is a viable option since it consumes less energy than a vehicle, emits fewer emissions, and costs less to cover the same distance. In near future, this information could be useful for local government to encouraged new mobility politics.

Keywords
ebike, energy consumption, atmospheric emissions, sustainable urban mobility

1. Introduction

Since the 1950s, cities have been planned around vehicles with the construction of large highways, thus encouraging their usage in urban areas. In 2016, the United Nations held the "Habitat III" Conference on Housing and Sustainable Urban Development in the city of Quito, Ecuador, where the foundations were laid for more sustainable populations for the next 20 years. Complications will arise when the time comes to implement the different initiatives proposed by the participating countries. In the last two decades, cities have grown up to five times more than their inhabitants. This has created problems when providing services, since costs increase. Therefore, more compact cities, if well planned, require less displacement, which generates less pollution.

Cities occupy a mere 2% of the earth's surface but generate 70% of greenhouse gases. Therefore, it is necessary to have less polluted cities and one of the options is to promote the use of public transport with bicycles as a mobility alternative (Monzón, Rondinella, & Equipo Investigador PROBICI, 2010).

Environmental pollution in cities is a widespread problem worldwide. This is why researchers from different countries conduct studies and seek new technologies to mitigate the effects of less sustainable transport means. Therefore, the electric bicycle can be seen as an alternative transportation option due to the good results obtained by its use around

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the world, which include reductions in vehicular congestion and atmospheric emissions, as well as health improvements in its users (Asian Development Bank, 2009).

Focusing on intermediate cities might generate considerable sustainable development, since they are not defined only in terms of demographics and dimensions, but rather have a balanced government that allows greater citizen participation. Another aspect to consider is the social and cultural features that could provide a better quality of life. The population of this type of cities ranges from fifty thousand to one million inhabitants, which, in terms of administration and budgets, allow more controlled progress (Bellet & Llop Torné, 2002; United Cities and Local Governments UCLG, 2016).

In 2015, the city of Cuenca, Ecuador, received the designation as an "intermediate city" from the United Nations Organization (UN) through a contest involving dozens of cities around the world (Ochoa, 2015). Consequently, evaluating new mobility alternatives for citizens is paramount. The number of vehicles in the city of Cuenca, based on data from the Municipal Mobility, Transit and Transportation Company (EMOV), was estimated at 114408 registered vehicles in 2015 , representing an annual growth of 8000 units, approximately 7% annually (El Tiempo, 2015).

The electric bicycle (e-bike) is a light, two-wheeled vehicle powered by pedals with an electric motor that complements the energy exerted directly on the pedals by the cyclist (VAIC, 2016). For this reason, the electric bicycle overcomes some disadvantages of the conventional bicycle, especially when facing steep slopes on the road without exhaustion and sweat. This transport also has access to bike paths and it does not require a driver's license, nor does it require vehicle registration (Campbell, Cherry, Ryerson, & Yang, 2016). The demand for the electric bicycle has exceeded all expectations, presenting higher growth than any other means of transport. It is forecasted that by 2010, there will be around 466 million units worldwide (Du et al., 2013).

Considering the previous, the city of Cuenca needs a study to evaluate the electric bicycle like an alternative to the mobility. Therefore, the objective of this research is to define analysis routes around the city and, based on the energy consumed in each of them, then estimate CO2 reductions. It also aims to determine the time and cost of using the electric bicycle as a mobility alternative around the city of Cuenca compared to a light duty vehicle.

2. Materials and Methods

2.1 Materials

2.1.1 Bicycle

The bicycle used in this study was a simple model of mountain bike equipped with an electric system of propulsion. Figure 1 shows the technical specifications of each installed component in the bicycle. The electric brushless and gearless motor is located in the rear wheel which is air ventilated. The Li-Ion battery box is mounted on the topside of the downtube that supplies the power to the motor. The activity could be monitored in the display located on the handlebar.

2.1.2 Global Positioning System (GPS)

A portable GPS receiver with the function of recording routes on an SD card is used. The mass of the device is 130 g. It has an internal battery that lasts 6 hours, a refresh rate of 20 Hz, a resolution of 0.01 km / h and a 0.1 km / h accuracy rate.

2.1.3 Energy analyzer

A device is used to determine the energy consumed when charging the battery of the electric bicycle, which operates at a voltage between 120 V, 60 Hz, with a maximum operating current of 15 A.

Figure 1. Electric bicycle used in the study around the city

2.1.4 Test Vehicles

Eleven light vehicles were used in the tests. They were equipped with spark ignition engines (MEP) of different makers and models including Hyundai: Accent (1), Sonata (1), Tucson (1), Chevrolet: Captiva (1), Gran Vitara (1), Aveo emotion (1), Active Aveo (1), Aveo family (1), Corsa Evolution (1) and Toyota: Yaris (2). The manufacturing year of the oldest vehicle was 2007 and the displacements of the engine ranged between 1 600 – 2 400 cm^3.

2.1.5 OBD Reader/Recorder

Device capable of acquiring and registering data of the CAN bus of the car under the protocols ISO 15765-4 (CAN, 11- / 29-bit, 250/500 kbps), SAE J1850 PWM & VPW, ISO 9141-2, ISO 14230-4 (KWP). The recorder was connected directly to the J1962 OBD connector. It had a generic OBD-II database that defined approximately 100 parameters according to the SAE J1979 standard and through software it was determined which parameters were available in the vehicle to create a unique database for each vehicle model. The user could select the parameters to be acquired (Twelve, Road, & Michigan, 2015).

2.2 Methods

2.2.1 Routes for analysis

To determine the routes for analysis several parameters and information were considered. First, the average distance traveled by citizens, then the Mobility Plan and Public Spaces of the city of Cuenca of 2015, and finally, information on the "4 Ríos" tramway project, which is in the construction stage.

Conventional bicycles could efficiently cover distances up to 7 km, or even up to 15 km with pedal assisted system (e-bike). Therefore, a common cyclist could cover an area of 150 km^2 around his residence. In general, half of urban car trips cover less than 5 km (Monzón et al., 2010).

The Mobility and Public Spaces Plan of the city of Cuenca was essential for the route design, since it provided data on vehicle composition, roadway capacity, degree of saturation, slopes, reason for travel, etc. The vehicle composition reflected that light automobiles are the main elements that circulate in the city, at 90,08%, buses represent 2,70%, cargo at 3,57%, motorcycles at 2,94% and bicycles only 0,71%. The capacity of the road and the degree of saturation warned that the historical center is collapsed; this allowed the planning of routes in highly congested areas to decrease the number of cars and make way for bicycles (Municipalidad de Cuenca, 2015).

The route of the 4 Ríos tramway project was also considered, since there will be the possibility of integrating mass transport with the use of the bicycle (El Comercio, 2014). Six routes of analysis were defined with the University of Azuay as a starting point (see Figure 2, green). In addition, the route of "4 Ríos" tramway is marked in red, where each of the studied trips crosses through different stations of this massive transport. On the other hand, it was observed that the city is within a radius circumference of 5 km (see Figure 2, white).

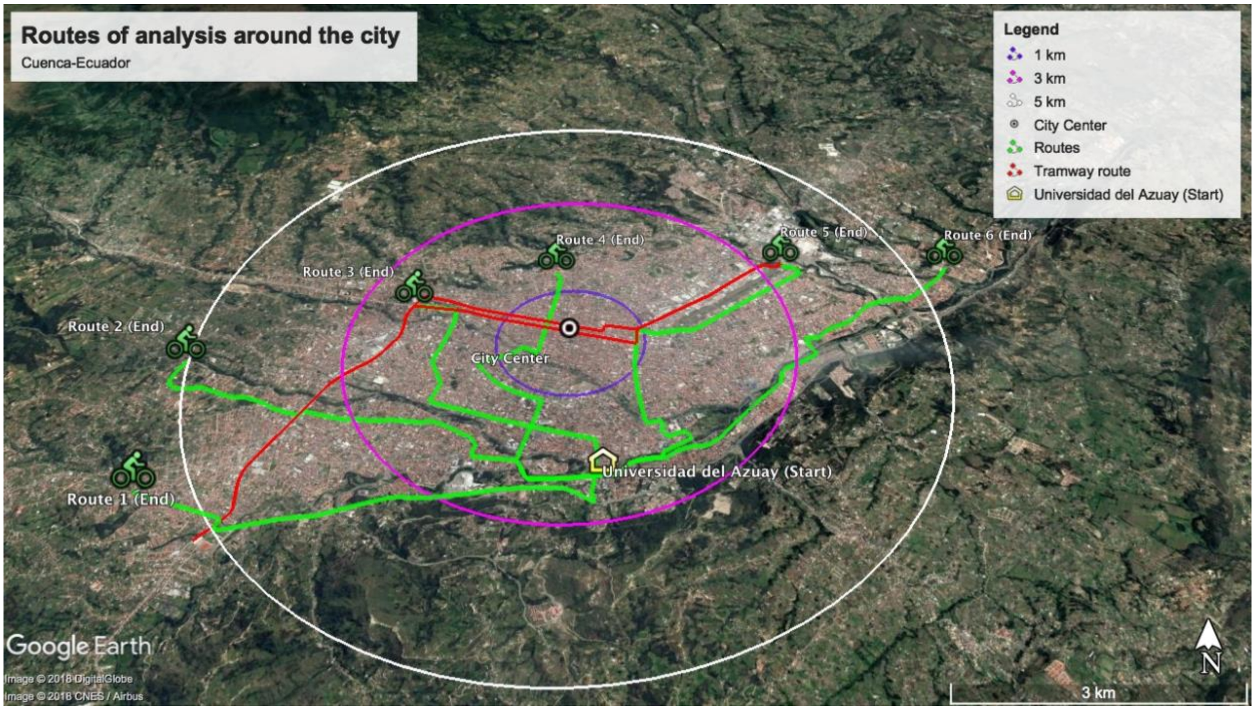

Figure 2. Routes of analysis around the city. Source: Google Earth / Imagery date: 07-19-2017

The six routes of analysis extend from the southwest to the northeast, each of them with an average distance of 6.5 km. The roads were combinations of asphalt and concrete with variable slopes and his details are shown in the Table 1.

Table 1: Routes details

Route	Distance	Elevation Gain / Loss	Max slope	Avg slope
1	6.34 km	190.0 m, -101.0 m	14,0%, -16.6 %	4.4%, -4.5%
2	6.77 km	146.0 m, -48.5 m	11.2%, -10.1%	2.8%, -2.8%
3	5.28 km	84.5 m, -23.0 m	8.5%, -5.1%	2.2%, -1.5%
4	5.95 km	135.0 m, -38.6m	11.2%, -7.3%	3.1%, -2.1%
5	6.92 km	64.6 m, -85.3 m	0.0%, -12.1%	2.1%, -2.1%
6	6.71 km	52.0 m, -121.0 m	8.6%, -8.0%	2.3%, -2.5%

Once the routes were defined, each of the vehicles was equipped with a GPS. Data collection was done randomly, every day of the week including weekends and holidays at different times; that is, at peak and off-peak hours. The cyclists were of different ages, physical frame, and gender. The percentage of assistance when riding the electric bicycle was left to the cyclist's criteria depending on their need to progress without problems, and by the different slopes around the defined routes. With the help of 50 people pedaling approximately for 6 months, around 1500 km were covered with the electric bicycle in this study.

The experiment was made for the electric bicycle and the test vehicles covering each route 16 times, eight times in the forward direction and eight times in the return direction.

2.2.2 Vehicle Dynamics

The time and position data recorded every second by the GPS served as a starting point to calculate the following: distance traveled (m), speed (m/s), acceleration (m/s^2), and slope (rad). In order to determine the energy consumed in each trip, vehicular dynamics was used to find the resistances to movement as shown in Figure 3 and their equations are as follows (Sousa, Costa Branco, & Dente, 2007):

$$F_a = M.\mathbf{a} \quad (1)$$

$$F_g = M.g.\,sen\,\boldsymbol{\theta} \quad (2)$$

$$F_{air} = \frac{1}{2}.\rho.M.C_D.A_f.\mathbf{v}(\mathbf{t})^2 \quad (3)$$

$$F_r = M.g.C_R.\cos\boldsymbol{\theta} \quad (4)$$

where F_a is the inertial force; F_g is the gravitational force, F_{air} is the drag force and F_r is the Rolling resistance, M is the mass of the vehicle including the pilot; a is the instantaneous acceleration, g is the gravity (9,81 m/s^2), θ is the slope of the road, ρ is the air density (1.29 kg/m^3), C_D is the aerodynamic coefficient (1.15 for a bicycle (Gordon Wilson, 2004), 0.32 for a light vehicle (Guillespie, 1992), A_f is the front area of the vehicle (0.55 m^2 for an urban type bicycle with the cyclist in upright position (Gordon Wilson, 2004), 2m^2 for a light vehicle approximately (Wong, 2001), v is the instantaneous velocity, t is equal to time y C_R is the coefficient of rolling distance (usually between 0.003 – 0,0008 in bicycles that travel on asphalt and/or concrete; 0,013 for vehicles that circulate on asphalt and/or concrete (Bosch, 2005).

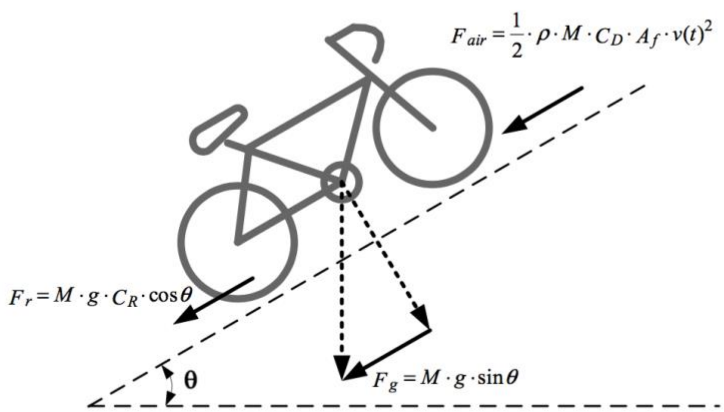

Figure 3: Applied force in a vehicle

The sum of all the forces opposed to the movement determine Fx, which represents the amount of force necessary to move at a specific time.

$$F_x = F_a + F_g + F_{air} + F_r \quad (5)$$

Therefore, with the necessary force in the wheel, the power of resistance to travel, P_w (Bosch, 2005) can be determined as shown in (6).

$$P_w = F_x.\mathbf{v} \quad (6)$$

where P_w is the power; F_x is the resistance to movement; and v is instantaneous speed.

Finally, the energy consumed in each route can be determined for each of the vehicles with equation (7).

$$E = P_w . \Delta t \qquad (7)$$

where E is the energy (kWh); Δt is the time interval (h).

To determine CO_2 emissions of each of the vehicles, the following equation is applied (8).

MEP: $$E_{CO_2} = FE_{CO_2} . d_r \qquad (8)$$
Thermoelectric: $$E_{CO_2} = FE_{CO_2} . E_r \qquad (9)$$

where E_{CO_2} is the carbon dioxide emission (g), FE represents the factor known as emission per kilometer travelled o kilowatt hour (MEP: 228,9 g/km (United States Environmental Protection Agency, 2008) or fuel oil thermoelectric: 273,6 g/kWh (MAGRAMA, 2012), d_r is the distance travelled (6,5 km/route, approximately), and E_r is the required energy per route.

To establish the cost of traveling a specific distance, it was important to know the rate of electric power for each kilowatt hour consumed (the average residential consumption in Ecuador is 198.7 kWh / month) (Baquero & Quesada, 2016), so the rate would be $0.097 USD / kWh) (ARCONEL, 2016). Also, it was necessary to know the retail price of gasoline (PVP, for its acronym in Spanish), which in the case of Ecuador is subsidized by the central government (Regular: $1.48 / gal, Premium: $2.32 / gal) (EP Petroecuador, 2016).

The equations used to calculate the costs in each case are shown in (10) and (11).

MEP: $$C = d_r . PVP_{gasoline} \qquad (10)$$
Thermoelectric: $$C = E_{ruta} . PVP_{electricy} \qquad (11)$$

2.2.3 Mechanical Efficiency

To conclude, the calculation of the energy consumed (7) to move the vehicle and electric bicycle respectively, is linked to two performance ranges: maximum and minimum. For the vehicle, the total performance range (engine, drive train and accessories) was between 23% - 29% (Calvo Martín, 1997; González Calleja, 2015). The electric bicycle had a total efficiency (electric kit, chain transmission) that ranged between 74% - 93% (Asian Development Bank, 2009; Lemire-Elmore, 2004; Pérez, Rodríguez, Sancho, & Sánchez, 2007).

3. Results

After collecting the data from each of the vehicles, the comparative results can be presented in four areas: energy, emissions, cost and time.

3.1 Energy

In terms of energy consumption, in the most efficient scenario, the light vehicle required approximately 40 times more energy than the electric bicycle to travel 6,5 km (see Table 2).

Table 2: Average energy consumption with the maximum and minimum performance

Vehicle [kWh/route]		Electric Bicycle [kWh/route]	
$\eta_{min} \approx 23\%$	$\eta_{max} \approx 29\%$	$\eta_{min} \approx 74\%$	$\eta_{max} \approx 93\%$
5,134±0,0294	3,950±0,227	0,126±0,005	0,099±0,004

The Figure 4 compares the energy consumed by each vehicle with its maximum and minimum performance. There is a clear difference between the energy demands of the vehicle versus the electric bicycle by approximately 97%.

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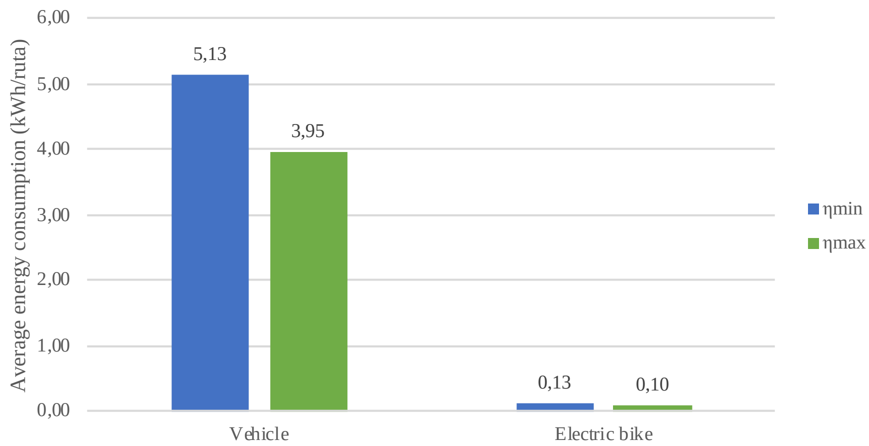

Figure 4. Energy comparison between the electric bicycle and a light duty vehicle

With the energy analyzer it was determined that the full charge of the bicycle battery was made with 471 W. Relating this power with the energy consumed in route, it was possible to determine a range of circulation between 24.44 and 31.11 kilometers, depending on the assistance selected and above all, the topology of the road.

3.2 Emissions

The estimation of carbon dioxide emissions was made using light vehicle emission factors from the United States Environmental Protection Agency (USEPA) (United States Environmental Protection Agency, 2008) and assuming that electricity production came from a thermoelectric plant (MAGRAMA, 2012). It should be noted that, if electricity came from a renewable source such as hydroelectric plants, emissions were considered void (Pew Research Center, 2009). Thus, Table 2 estimates the CO_2 emissions for each of the vehicles.

Table 1: Carbon dioxide emissions per route

Vehicle [g/route]	Electric Bicycle [g/route]	
$\eta \approx 26\%$ 1 502.92±26,85	$\eta_{mín} \approx 74\%$ 34,47±1,396	$\eta_{máx} \approx 93\%$ 27,21±1,102

The light vehicle emitted 55 times more CO_2 than the electric bicycle per route traveled; this equated to a difference of approximately 98% (see Figure 5).

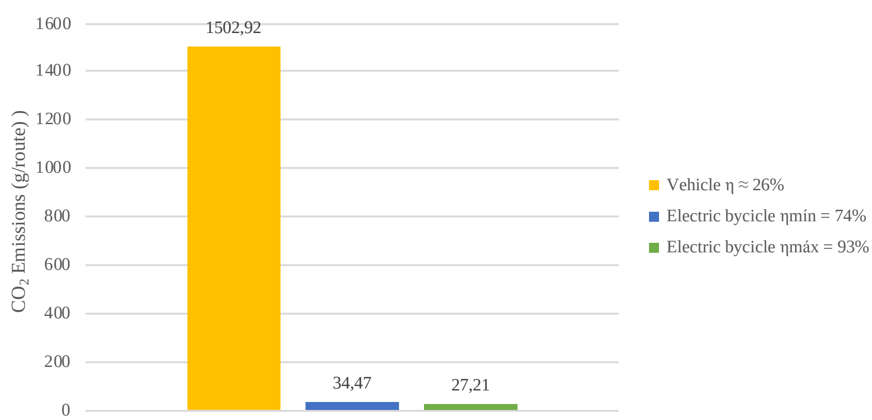

Figure 5. Carbon dioxide emissions

3.3 Cost

The costs of using each of the means of transport was linked to the retail price of gasoline and the kilowatt hour of electric power (see Table 2).

Table 2: Cost of electricity and gasoline in Ecuador

Electricity	Gasoline	
	Regular	Premium
USD/kWh)	USD/gal	USD/gal
\$0,10	\$1,48	\$2,32

With the OBD reader / recorder connected to the light test vehicles, the average consumption of 9,54 ± 1,028 liters / 100 km was determined. Thus, covering the average route of 6.5 km cost \$0,24 with regular gasoline and \$0,38 with premium gasoline. That is, the kilometer traveled would have cost \$0,04 and \$0,06 with regular and premium, respectively. These costs did not include vehicle maintenance.

Therefore, traveling 6,5 km by electric bicycle cost \$0.01 (not including maintenance costs). With respect to the expenses, it was determined that maintaining a bicycle was much cheaper than a vehicle.

3.4 Time

Transfer time was a decisive factor when moving from one point to another. In the analysis routes with an average of 6.5 km, the duration of the trip was 36,81 minutes on a conventional bicycle (without assistance), 18,75 minutes on an electric bicycle, and 15,18 minutes on a light vehicle (see Figure 6).

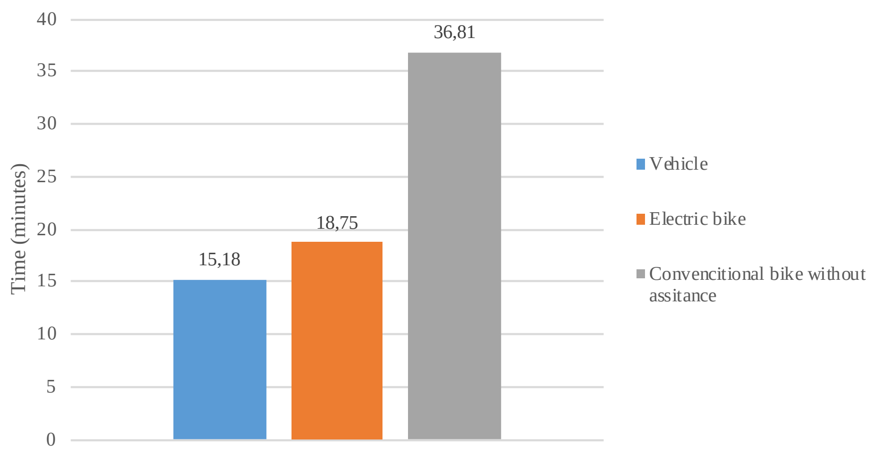

Figure 6. Average travel time on a 6,5 km route

4. Conclusions and Recommendations

After conducting tests with an average route of approximately 6.5 km, it can be concluded that the bicycle is a feasible alternative for mobility in the city of Cuenca, Ecuador. In energy terms, it consumes 40 times less energy than the light vehicle, which in most cases is underutilized. Moreover, the electric bicycle uses 0.99 ± 0.004, while a vehicle equipped with an ignition combustion engine consumes 3.950 ± 0.227 kWh / route. This represents a 97% difference. Therefore, in this aspect, the use of the electric bicycle is certainly viable.

In terms of carbon dioxide emissions, there was a significant difference between the two means of transport, even though an electric bicycle that charges its batteries from a thermoelectric plant emits 55 times less than a vehicle. Were the load to be made from a renewable source such as hydroelectric, as is the case in our country, the difference would be much wider. A vehicle emits 1502.92 ± 26.85 g_{CO2} / route and an electric bicycle 27.21 ± 1102 g_{CO2} / route.

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Another important factor to consider is the cost of using each type of transport. The route by vehicle costs $ 0.24 USD/route with regular gasoline and $ 0.38 USD/route with premium gasoline. Therefore, the kilometer traveled would cost $ 0.04 USD / km and $0.06 USD / km with regular and premium, respectively. On the other hand, traveling by electric bicycle costs $0.01 USD / route and 0.0015 USD / km. It should be noted that maintenance was not considered in either case. The difference in cost is 95%, which favors the bicycle.

In contrast, in the case of travel time, vehicles have a slight advantage. The duration of the trip in a vehicle was 15.18 minutes, while cycling was 18.75 minutes; this represents a difference of 19%, which equates to 4 minutes approximately. In sum, the results obtained show a high possibility that the vehicle can be replaced by the electric bicycle to circulate around the city.

It is recommended that research projects such as these be shared with authorities dedicated to the planning and development of intermediate cities, with the aim of building more sustainable cities.

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