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From on-road trial evaluation of electric and conventional bicycles to comparison with other urban transport modes: Case study in the city of Lisbon, Portugal

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ABSTRACT

Increasing energy costs, energy consumption and emissions profiles prompted the promotion of different transportation alternatives. This research work addresses the comparison of trip dynamics, energy consumption, CO_2 and NO_x Well-to-Wheel impacts of 5 transportation alternatives (conventional and electric bicycles, conventional and electric vehicles and an urban bus) in Lisbon, Portugal. On-road monitoring of a specific route in Lisbon revealed that bikers using electric bicycles increased their average speed between 8% and 26% compared to their use of the conventional bicycle, especially in the route sections with positive slopes (up to 49% increases). Electric bicycles result in a Tank-to-Wheel energy consumption of 0.028 MJ/km, allowing an average autonomy of 46 km between recharging. When comparing the 5 transportation alternatives, the electric bicycles presented a higher travel time of 13.5%, 1.9% and 7.8% over the bus, low powered electric vehicle, and standard electric vehicle/conventional technologies, respectively. Regarding the Well-to-Wheel energy consumption analysis, the results indicated that, when compared to the other transportation solutions, the electric bicycle only uses 11%, 3%, 1%, 2% and 4% of the energy required when using the low powered electric vehicle, standard electric vehicle, conventional gasoline and diesel technologies and bus, respectively. Furthermore, the analysis of Well-to-Wheel emissions reveals that the electric bicycle has 13% and 4% lower CO_2 emissions and 12% and 4% lower NO_x emissions when compared to the low powered and standard electric vehicles, respectively. This research work allows sustaining that bicycles can be considered interesting solutions for urban trips, with comparable trip times to other transportation modes, as well as zero local emissions and reduced Well-to-Wheel pollutant impacts, contributing significantly for the improvement of the overall urban air quality.

1. Introduction

Over the last decades a growing concern with increasing energy consumption accountable to the transportation sector has been observed, leading to increasing challenges on how to decrease energy consumption as well as local and global emissions. In 2011, the road transportation sector was responsible for 33% of the European final energy consumption, with the road transportation sector accountable for 82% of that energy consumption [1].

Vehicle's efficiency improvement and promoting alternative vehicle technologies and energy sources have been the main focus of action to address this issue [2]. The use of alternative fuels such as hydrogen and electricity is regarded as a solution to significantly reduce the amount of CO_2 emitted by the transportation sector and increase renewable energy penetration [3–5]. Furthermore, the shift to hydrogen or electricity would bring a particularly beneficial impact for urban systems due to their zero local emissions. However, such technologies still face major downsides that prevent them from being true alternatives, mainly because they will only have a significant impact on a long-term scale due to the fleets low renovation rates [6]. Furthermore, this technology driven

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Abbreviations: B, biker; CB, conventional bicycle; CO_2, carbon dioxide; EB, electric bicycle; EV, electric vehicle; GPS, global positioning system; ICEV-CI, internal combustion engine compression ignition; ICEV-SI, internal combustion engine spark ignition; L-EV, low powered electric vehicle; NO_x, nitrogen oxides; OBD, on-board diagnostic port; TTW, Tank-to-Wheel; VSP, Vehicle Specific Power; WTT, Well-to-Tank; WTW, Well-to-Wheel.

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approach may not be completely successful unless a behavioral change happens enabling users to be more efficient when using the different transportation modes. Considering the transportation users choice and drivers behavior is, consequently, vital to the reduction of the transportation sector's environmental foot-print [7].

One alternative to mitigate the impacts of the transportation sector, particularly in urban environments, is to decrease the demand for energy intensive modes of transportation and to promote alternatives that provide a low-priced, less noisy and more sustainable alternative than a daily car commute. Generally, these alternatives are related with the use of more efficient vehicle technologies and with a shift to the public transportation system (bus, trains, subway systems and others), encouraging users to adopt vehicle sharing schemes (such as cars or bicycles), and alternative transportation modes such as walking, private bicycles or others [8]. The promotion of each of these pathways requires the development of diversified transportation policies, considering both their strengths and drawbacks, in order to encourage people to use them.

The use of more efficient vehicles or technologies is usually associated with higher purchase costs [9]. Electric vehicles present significant benefits in the Tank-to-Wheel stage (which corresponds to its usage stage) with lower energy consumption impacts and zero local pollutants emissions [6,10,11]. Moreover, the acceptance and adaptation to electric vehicles has been positive, but some issues related to charging routines and range anxiety still persist [12].

Additionally, while most cities offer some sort of public transportation system, the promotion of vehicle sharing schemes and alternative transportation modes has risen only recently [13,14]. More than 400 cities in the world have car-sharing systems, mostly located in Europe (≈80%), followed by North America (≈18%) and by Oceania (≈2%) [15]. The most widely known operators reveal a growing tendency. In Paris, the main operator has 1750 electric vehicles, offers 4000 charging points and has more than 65,000 registered subscribers. A US based system has been expanding worldwide, reaching 777,000 members and offering nearly 10,000 vehicles, while a Germany based system that started in 2008 has already expanded to 18 cities worldwide with over 350,000 customers and offering 6000 conventional and alternative vehicles. Another system deployed with a vast distribution in US, Europe and Australia since 2008 has reached 150,000 users. These 4 operators are the biggest systems with more than 100 vehicles per city, representing 47% of the total systems and have been promoting the use of alternative vehicles in their fleets [15].

Considering the alternatives presented earlier, the use of bicycles can be one of the most advantageous since it allows users to move at significant speeds for short distances (typical in urban environments), resulting in health benefits and zero emissions [16]. Using bicycles enables people to travel longer, faster and with less effort than walking, while having a low impact on the environment, thus making it an efficient transportation mode for urban mobility. As a result, there has been a growing awareness on the importance of cycling worldwide [17]. In many developing countries, namely in Asia, two-wheelers are a first inexpensive step towards individual mobility. A growing number of cities have been trying to integrate them in the daily mobility of their citizens, which for some countries has resulted in a significant share of trips being done with bicycles, such as the Netherlands (26%), Denmark (18%) and Germany (10%) [18]. In 2008 in the city of Amsterdam, 38% of all trips were performed by bicycles, with 50% of Amsterdam's residents riding a bike on a daily basis and 85% riding one at least once a week [19]. The promotion of bicycles in urban mobility requires the development of specific policies that impact the trip at all levels, whether when riding (through traffic calming and safe bikeways), parking (by offering secure locations) or moving it around the city (through the integration of bicycles with public transportation systems). Safety is one of the most relevant issues to consider when promoting bicycles. Due to being physically unprotected, bikers are more vulnerable to accidents than vehicle drivers and riders of public buses [20]. The safety concerns can be aggravated in the case of electric bicycles due to their ability for higher speeds, which can impact maneuverability and visibility [21].

Over 300 bike sharing systems have been deployed around the world, with a higher concentration in Europe (≈78% of the systems) and mainly owned by municipalities (≈72%) [22]. While the use of conventional bicycles in an urban context has been promoted with significant success in several cities, namely Paris and London with 25,000 and 8000 deployed bicycles respectively [23–25], they still have several problems that make their widespread use difficult. Some of the drawbacks associated with conventional bicycles include the difficulty to travel for long distances and in hilly conditions, the possibility of arriving sweaty or fatigued to the final destination, such as the work place [26], and being exposed to extreme cold or hot climates, among others. Several of these problems can be solved through the use of electric bicycles [26]. Electric bicycles can help reduce the trip effort required as well as travel time [27], though at a higher cost due to the additional requirement of electricity.

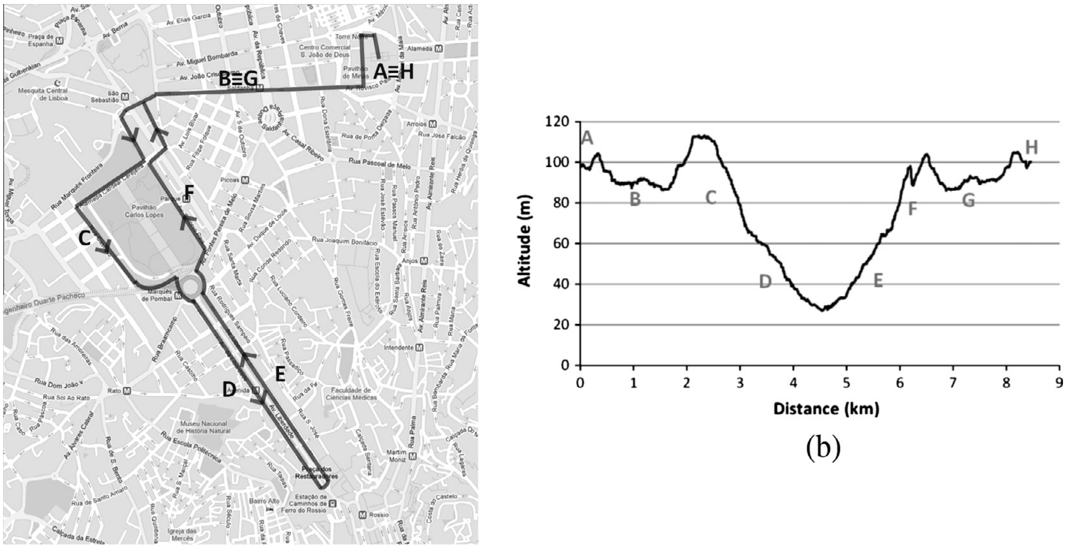
Despite the high expectations for electric bicycles, few studies have tried to understand the real world benefits that they convey in an urban environment. Furthermore, while previous studies addressed the estimated environmental impacts of electric bicycles compared to other transportation modes in China [28] and the users characterization and acceptance of this alternative technology in China [29] and in the United States [26], the experimental monitoring of bicycles has focused mostly on conventional bicycles [30,31].

In this sense, this research work addresses the impacts comparison of 5 transportation solutions focusing on a typical hilly route in Lisbon, Portugal. Taking advantage of on-road monitoring of a specific route in Lisbon, the trip time, distance and WTW energy consumption and emissions impacts were quantified for a conventional and electric bicycle, 2 conventional vehicle technologies, 2 electric vehicle solutions and an urban bus.

2. Methodology

2.1. Monitored route and transportation modes

In order to perform a transportation mode comparison of trip dynamics and energy impacts, a round-trip tour of approximately 8.5 km in Lisbon was chosen based on its diverse characteristics. The tour consisted on a round trip with departure from Instituto Superior Técnico (IST) main campus (point A and H of Fig. 1a) to downtown Lisbon, passing through the top of Parque Eduardo VII (sections C and F) and Avenida da Liberdade (sections D and E). Different parts of the city of Lisbon are covered in this route, including traffic intensive avenues, side roads with very little traffic and a street with a bike lane. This route corresponds to typical destinations and driving contexts in the city of Lisbon, close to possible locations of future bike-sharing stations. This tour has significant slopes, as shown in Fig. 1b, which presents the altitude profile of the tour.



(a)

(b)

Fig. 1. Route map (a) (source: Google Maps) and typical topography profile of the tour performed by the bikers (b). Sections of tour: A and H – IST main campus; B and G – Plain avenue with bike lane; C – Park (descendant); D – Av. Liberdade (descendant); E – Av. Liberdade (ascendant); and F – Park (ascendant).

As for the 5 transportation alternatives considered in the route described, their detailed characteristics are as follows:

- Conventional bicycle (CB) (Orbita Aluminio): with 21 gears and 15 kg of weight.
- Electric bicycle (EB) (QWIC Trend[2]): power-on-demand electric bicycle[1] with 25.7 kg, 6 electric gears, 7 mechanical gears and a detachable Li-ion battery with a 360 Wh capacity, provided by Prio Energy [32].
- Low-power electric vehicle (L-EV) with 4.8 kW of maximum power, 2.4 kW h lead-acid batteries and 300 kg of weight.
- Standard electric vehicle (EV) with 20 kW (boost of 30 kW) of maximum power, 16.5 kW h lithium-ion batteries and 975 kg of weight.
- Conventional spark-ignition vehicle (ICEV-SI) with 51 kW of maximum power, 998 cm^3 of displacement and 950 kg of weight, following EURO 5 standards.
- Conventional compression-ignition vehicle (ICEV-CI) with 55 kW of maximum power, 1242 cm^3 of displacement and 1140 kg of weight, following EURO 5 standards.
- Bus, with a typical length of 12 m, following EURO 3 standards, circa 200 kW of maximum power and weighting around 12,000 kg [33].

This diverse sample of vehicles was chosen to cover a wide variety of mobility solutions, both conventional technologies (CB, ICEV-SI, ICEV-CI, Bus) and alternative vehicle technologies (EB, EV, L-EV). Due to the EV high purchase cost, the L-EV was included as a midway between the EV and EB, as it has a significantly lower purchase cost when compared to EVs [34].

The bicycles and vehicle monitoring was performed during weekdays in the same time period from 10 a.m. to noon. Occupancy rates of 1 person for bicycles and vehicles and of 19% for the bus were assumed [33].

The CB and EB were monitored in the selected route with a portable laboratory [27] to simultaneously collect information on trip dynamics and corresponding energy requirements, which were effectively measured on the battery, in a second-by-second basis. The evaluation of the CB and EB was achieved through the monitoring of trips performed by 5 different bikers (B1 to B5), all male bikers in their twenties (average age of 28 years old) with an average weight of 70 kg. Each biker performed the same urban tour with both bicycles, which allowed obtaining an average CB and EB usage profiles. The bikers used the electric bicycle first and the conventional bicycle after, with a minimum resting period of 1 hour in-between, without any specific instructions on how to use both bicycles to guarantee their typical usage pattern.

For the vehicles' analysis, the real world second-by-second trip dynamics were collected with one common spark-ignition vehicle (ICEV-SI), while the results for the ICEV-CI and the standard EV were estimated with the Vehicle Specific Power (VSP) methodology [35]. This methodology allows comparing different technologies under similar power requirements in the same utilization conditions and is widely used for this purpose [35,36]. As a result, the energy estimates depend only on the vehicle, eliminating the effect of different trip characteristics (such as speed and acceleration). VSP combines speed, acceleration and road grade to estimate the power demand by vehicles under on-road conditions and is traditionally used on light-duty vehicles [37]. Its generic definition is presented in Eq. (1).

$$\begin{aligned} \mathrm{VSP} &= \frac{\frac{d}{dt}(E_{\mathrm{Kinetic}} + E_{\mathrm{Potential}}) + F_{\mathrm{Rolling}} \cdot v + F_{\mathrm{Aerodynamic}} \cdot v}{m} \leftrightarrow \mathrm{VSP} \\ &= v \cdot [a \cdot (1 + \varepsilon_i) + g \cdot sen(\theta) + C_{\mathrm{Roll}}] + C_{\mathrm{Aero}} \cdot v^3 \qquad (1) \end{aligned}$$

where E_{Kinetic} is kinetic energy, $E_{\mathrm{Potential}}$ is potential energy, F_{Rolling} is rolling resistance force, $F_{\mathrm{Aerodynamic}}$ is aerodynamic resistance force, v is speed, m is mass, a is acceleration, θ is road grade, ε_i is the effect of translational mass of powertrain rotating components (0.1), g is the gravitational constant (9.81 m/s^2), C_{Roll} is the rolling coefficient (0.132) and C_{Aero} is the aerodynamic coefficient (0.000302).

For the low power vehicle (L-EV), the real world trip dynamics and energy requirements were measured in a 1 Hz basis, similarly to what was done for the bicycles, since their power restrictions impose severe dynamic limitations, such as limited power and maximum speed [34].

For the bus evaluation, the average energy consumption and pollutants emission factors were estimated from Copert 4 [38,39] according to the Lisbon's bus operator (Carris) fleet characterization and driving context [33].

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[1] Power on demand electric bicycles provide the user with the choice of different levels of electric assistance.

Table 1
Summary of experimental design and methodologies used.

Vehicle	Trip properties	Quantification method for Tank-to-Wheel energy use and emissions	Typical error
EB	On-road measurements	On-road measurements	Average error <2% [41]
CB	On-road measurements	Not considered	Not applicable
L-EV	On-road measurements	On-road measurements	Average error <2% [42]
EV	Based on ICEV-SI	VSP methodology	Average error of 6.3% [42]
ICEV-SI	On-road measurements	VSP methodology	Data quality assured following procedures in literature [43]. Fuel consumption error below 0.2% [44]
ICEV-CI	Based on ICEV-SI	VSP methodology	Energy – average deviation of 2.2% and absolute deviation below 10%, from VSP application. NO_x – Average deviation of −6.2%from VSP application [45]
Bus	Based on operator data	Copert 4, based on fleet characteristics and activity	Below 10% [39]

The VSP methodology was also used to estimate the NO_x pollutant emissions (only for ICEV-SI and ICEV-CI), based on previous studies [40].

The trip characterization in terms of time, distance and WTW energy consumption and emissions was assessed, considering the route selected. Table 1 summarizes the experimental design and methodologies used as well as their typical errors.

2.2. On road monitoring laboratory

The on-road measurements were performed using a monitoring laboratory designed to assess energy and environmental impacts associated with motorized and non-motorized modes. This methodology was developed in previous works [34,36,46].

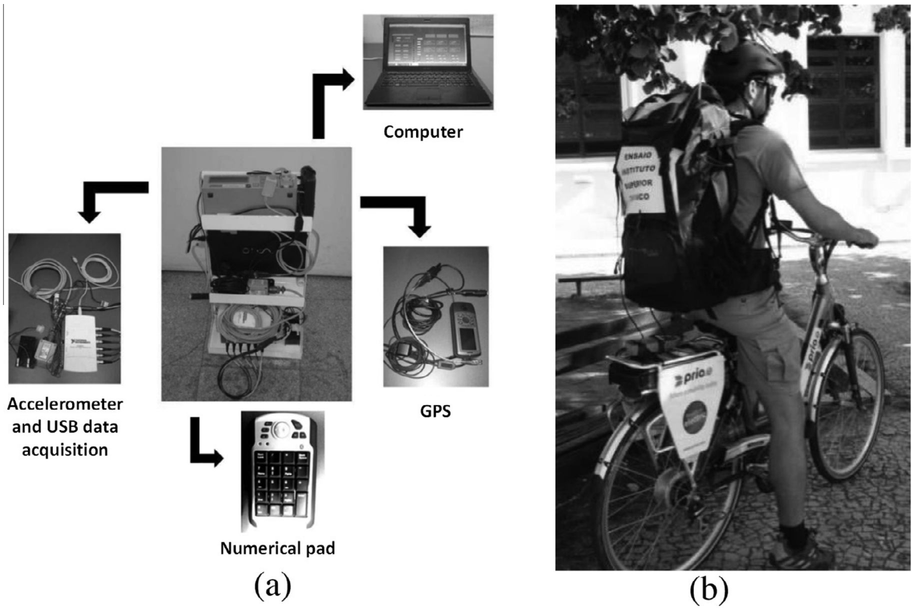
For non-motorized modes, the laboratory is composed by a GPS to record the dynamic profile of the trip (including location, altitude and speed), and voltage and current probes to assess the levels of electric assistance. This equipment is carried by the biker in a backpack weighting ≈8 kg, as shown in Fig. 2. When asked to carry the backpack, the bikers showed no resistance or inconvenience since in their daily routines they already carry backpacks weighting between 5 and 8 kg. In direct inquiries to the bikers they reported that they were not affected by the backpack weight.

The portable laboratory for motorized modes is equipped with a GPS to record the dynamic profile of the trip (including location, altitude and speed), an on-board diagnostic port reader and tailpipe gas analyzer for conventional technologies and voltage and current probes to measure electricity consumption [36]. All the components are connected to a laptop to record the data throughout the trips at 1 Hz. The vehicle data collected (in this case, from the ICEV-SI) includes information from vehicle OBD, namely vehicle speed and engine data.

Regarding non-motorized and motorized cases, all the equipment is connected to a laptop to record the data throughout the trip. The technical description of the equipment used is presented in Table 2. Since the equipment used has a different temporal resolution, the data was processed in a second by second time basis. The equipment described in Table 2 are commonly used by other authors for on-road monitoring applications namely the GPS [47], which provides speed with an accuracy of 0.05 m/s steady-state and altitude with an accuracy of 3 m, and a resolution of 0.3 m.

2.3. Data collection and processing

Regarding bicycles, the GPS allows collecting speed, location and altitude information via an integrated barometric altimeter. The altimeter was adequately set up inside the backpack or in the vehicles, preventing the readings to be affected by pressure fluctuations due to movement. GPS signal losses were avoided with an external antenna. GPS readings of bicycle speed were subsequently processed to obtain distance travelled, acceleration and road grade. For the ICEV-SI, the speed profile was acquired from OBD data. Voltage probes were installed directly in the bicycle



(a) (b)

Fig. 2. Apparatus used for the real time monitoring (a) and experimental set-up on one of the bikers in an electric bicycle (b).

Table 2
Technical description of the equipment used.

Monitoring equipment	Data acquired	Temporal resolution of data	Used on	Accuracy	
GPS (Garmin GPS map 76CSx) [48]	Speed (km/h), altitude (m), location	1 s	EB, CB, L-EV, ICEV-SI	Speed Altitude	0.05 m/s steady-state 3 m
Voltage and current probes (Fluke i1010) [49]	Voltage, current	0.5 s	EB, L-EV	Current Voltage	2% + 0.5A Negligible, directly connected to NI DAQ board
OBD port reader	Vehicle speed, engine parameters	1 s	ICEV-SI	Depends on vehicle manufacturer	

and L-EV battery terminals, while current measurements were done on the circuit that connects the battery to the electric motor. The signals provided by the probes were collected by a National Instruments DAQ board. For battery voltage signal, a voltage divider circuit was placed before the DAQ board to account for the 0–10 V limit of the data collection device. Both GPS and battery data were collected in a solid-state disk PC using a program developed in LabView by the authors to integrate the different communication protocols (serial port and NMEA protocol for GPS and analog data via USB port for the voltage and current collected in the DAQ board) that allows synchronizing the data, capturing all the equipment readings in a 1 Hz basis.

The battery data was used to determine, at each point of the trip, the power provided to the electric motor according to the vehicle demands. This data was integrated along the trip to find the cumulative energy spent on the selected tour.

The Tank-to-Wheel (TTW) stage accounts for the emissions and fuel consumption that result from moving the vehicle through its drive cycle and was quantified using the methodology presented in Table 1. An additional life-cycle assessment layer was also considered, with particular interest when dealing with electric mobility. The layer considered was the Well-to-Tank (WTT), and its impacts result from the expended energy and emissions from bringing an energy vector from its source until its utilization stages. For WTT energy consumption and emissions of CO_2 and NO_x, reference factors were used for each of the different energy pathways considered (in this case, gasoline and diesel production and electricity production in the Portuguese electricity mix) [6,10]. The combination of the TTW and the WTT stages accounts for the Well-to-Wheel (WTW).

With the data collected, it was possible to understand and quantify how bikers adapted their usage profile (in terms of speed and acceleration) when making the transition from CB to EB, as well as the WTW energy consumption and environmental impacts of using other transportation modes in the same route.

3. Results

This section firstly analyses the comparison between conventional and electric bicycles regarding the trip dynamics and energy impacts. Secondly, a comparison between 5 transportation modes in the monitored route is performed, assessing the trip characteristics and energy and pollutant outcomes.

3.1. Conventional and electric bicycle trip results

Using the data collected by the GPS system and the electric energy usage profiles (obtained from the voltage and current probes), the trips performed by each biker with the CB and EB were compared, with over 8 hours of data globally collected.

While the trip performed by the biker was pre-defined, they were allowed to adapt their route based on obstacles, traffic and crossing roads positioning, which led to slightly different distances travelled. The total amount of time required by each biker in CB and EB to perform the desired route, the total distance traveled and the average speed can be seen in Table 3.

The changes in the route made by the bikers resulted in a deviation of distance travelled between 0.8 km and −0.7 km in comparison with the 8.5 km reference value of the trip. These changes represent approximately a 10% change in total distance travelled. Nonetheless, based on the analysis of the GPS, the overall directions of the route were maintained by all bikers.

The route average speed varied between 7.7 km/h and 16.6 km/h when using the EB and 7.1 km/h and 14.5 km/h when using the CB. For all the bikers, the use of the EB resulted in an increase of average speed during the trip when compared to the CB results. This increase ranged from 8%, corresponding to a 0.6 km/h higher average speed, to 26%, corresponding to a 2.1 km/h higher average speed.

Additionally, using the GPS data collected, the average speed in each bicycle was calculated for different road slope values, as shown in Fig. 3. The analysis shows that the use of the EB leads to an increase on the average speed particularly in the sections of the tour with positive grades. While the average speed tended to decrease with the increase of the grade when using the CB, the bikers were able to stabilize or even increase their average speed on increasing positive grades when using the EB. On the other hand, for negative or zero grades, the differences between the average speeds obtained by the bikers with the two types of bicycles were minor.

The average speed obtained by each biker in negative, neutral and positive slopes is summarized in Table 4. The portions of the route with grades between −0.03 rad and 0.03 rad were considered

Table 3
Time, distance and mean speed by biker and bicycle technology.

Parameters	B1		B2		B3		B4		B5		Average		Standard deviation	
	EB	CB	EB	CB	EB	CB	EB	CB	EB	CB	EB	CB	EB	CB
Time (min)	39	45	69	66	54	59	43	44	31	35	47	50	15	12
Distance (km)	9.3	9.2	8.8	7.8	9.1	7.8	8.8	8.0	8.4	8.5	8.9	8.3	0.3	0.6
Average speed (km/h)	14.2	12.2	7.7	7.1	10.0	7.9	12.3	10.8	16.6	14.5	11.3	10.0	3.5	3.1

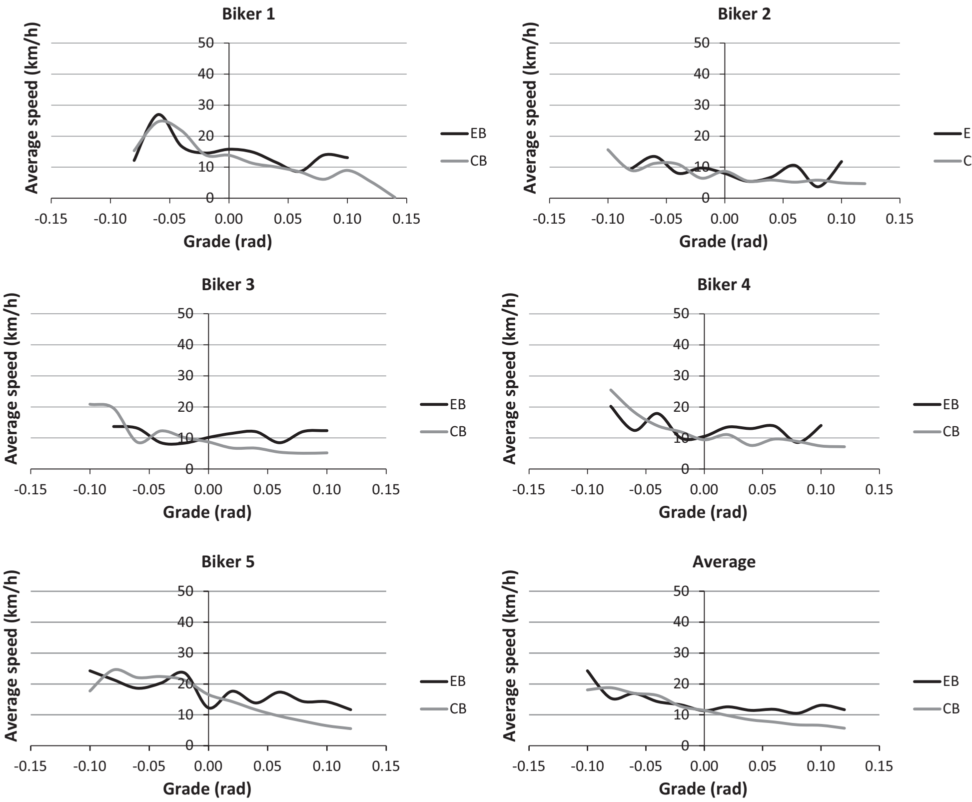


Fig. 3. Average speed as function of road grade for bikers 1–5 and for the average of bikers.

Table 4
Average speed increase by each biker in different slopes, when comparing the EB with the CB.

	Negative slope (%)	Neutral slope (%)	Positive slope (%)
B1	−15	15	36
B2	−11	7	25
B3	−12	16	86
B4	−6	5	52
B5	−11	−7	49
Average	−11	6	49

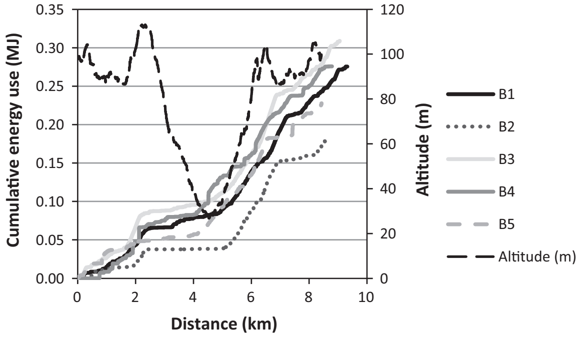


Fig. 4. EB cumulative energy use per bikers.

to have neutral slopes. As mentioned before, the use of the EB enabled significant increases in speed in sections with positive slopes, which ranged from 25% to 86%, with an average of 49% increase in average speed. In negative slopes, all the bikers rode faster with the CB (11% decrease in average speed from using EB compared to CB). In neutral slopes, only one biker did not increase his speed when using the EB. Nonetheless, the average speed increase in neutral slopes was of 6%. As previously mentioned, these low changes in speed in negative and neutral slopes can be due to the lack of a safe feeling when using the electric bicycles. Likewise, when the speed was already high with the conventional bicycle, the electric option did not allow the bikers to gain much from its use.

Generally, the use of electric energy assistance in the EB occurred in the same parts of the trip for all bikers, as shown in Fig. 4. However, it is possible to see that some bikers used the electric support system more constantly throughout the journey, even if at lower levels of electric assistance.

The total electricity used by each biker is presented in Table 5, as well as the indicator of the total amount of energy per kilometer travelled. These values correspond to the Tank-to-Wheel stage (TTW), which translates the required energy consumption associated to drive the vehicle, in this case, the bicycle. It should be noted that the energy consumption was computed using the total trip, which includes kilometers done both with and without the use of the electric assistance. The results do not show a clear relation between the increase in speed when moving from conventional bicycle to electric bicycle and the amount of energy used, which can be justified by several different factors such as the low experience with EB by each biker, the management of the electric assistance by each bikers and traffic conditions.

The electric bicycle energy consumption per kilometer has an average value of 0.028 MJ/km, which allows travelling around 46 km between battery recharges. When comparing the EB with the typical CB energy use (which rounds 0.06 MJ/km [50–52]), the electric energy share ranges from 33% to 56% of the total energy use for the 5 bikers.

Table 5
TTW energy consumption when using electric bicycles.

Parameters	B1	B2	B3	B4	B5	Average	Standard deviation
Total energy (MJ)	0.276	0.179	0.309	0.276	0.228	0.254	0.051
Energy per kilometer (MJ/km)	0.030	0.020	0.034	0.031	0.027	0.028	0.005
Average speed (km/h)	14.2	7.7	10.0	12.3	16.6	11.3	3.5
EB (MJ/km)/typical CB (MJ/km) [50–52]	50%	33%	56%	51%	45%	47%	9%
Autonomy (km)	43	65	38	42	48	46	11

Table 6
Time, distance, mean speed and maximum speed for the different transport modes.

Parameters	Bicycles		Electric vehicles		Conventional technologies		Bus
	EB	CB	L-EV	EV	ICEV-SI	ICEV-CI	
Time (min)	47.2	49.8	46.3	43.8	43.8	43.8	41.6
Distance (km)	8.9	8.3	9.8	10.2	10.2	10.2	10.2
Average speed (km/h)	11.3	10	12.7	14.0	14.0	14.0	14.7

3.2. Transportation modes comparison

A comparison between the different transportation modes was performed for the monitored route. Table 6 presents the trips results for the different transportation modes studied.

The higher flexibility of bikers to adapt their route along the trip makes this transportation mode comparable with motorized ones in terms of total trip time, since it enables them to travel a lower distance. Between the fastest (Bus) and slowest (CB) transport option, approximately 8 min of difference in trip duration is observed. The EB presents an increase of 13.5% on travel time over the Bus, while for the CB this increase is of 19.7%. It must be pointed out that the average bus speed considered for this route was provided by the bus operator, since the objective was to provide a general indication of the typical speeds in Lisbon with the different transportation modes. However, a more precise speed Bus value for this specific route may be different due to traffic or traffic lights.

When compared to the L-EV, the EB and CB present a 1.9% and 7.6% increase on travel time, respectively, which is quite a small difference between a non-motorized and motorized modes, but justified by the power limitation of the L-EV.

Concerning the vehicles considered (EV, ICEV-SI and ICEV-CI), EB and CB present an increase on travel time of 7.8% and 13.7%, respectively.

Regarding speed analysis, the L-EV (with speed limitation to ≈40 km/h) presents a maximum speed comparable to those of the EB and CB (39 and 41 km/h respectively) and an average speed that is similar to the EB (+12.5%), but 27.6% higher the CB. The ICEV-SI, ICEV-CI and EV present a maximum trip speed of 52 km/h and an average speed that is 24% higher than the EB and 41% higher than the CB.

Table 7 summarizes the WTW energy and pollutant impacts of using the transportation modes considered in the selected route. As expected, the EB presents the lowest results for energy consumption, CO_2 and NO_x.

In the TTW stage, the energy requirements of an L-EV are 9 times higher than the results of the EB. The EV, ICEV-SI and ICEV-CI present a factor of 29, 146 and 104 respectively over the energy requirements of an EB. Within this work a vehicle occupancy rate of one person was assumed, even though the other vehicles addressed can have larger occupancy rates, so that the comparison with the bicycle could be considered realistic. However, a bus typical maximum occupancy is 85 people with an average occupancy rate of 19% [33]. Consequently, the bus energy consumption for one individual is 2.8 times lower than the conventional vehicle technologies estimates, but it is 44 times higher than the EB in the TTW stage.

The bicycle can be considered a very interesting option for urban mobility, since it has no local impacts and, in a WTW analysis, its energy use is only 11% and 3% of the energy requirements of using an L-EV or an EV, respectively. A pollutants WTW analysis indicates 13% and 4% CO_2 emissions and 12% and 4% NO_x emissions for the EB when compared to the L-EV and the EV, respectively. Regarding ICEV-SI and ICEV-CI, their impacts are significantly higher, particularly since they have much higher NO_x TTW emissions. The ICEV-SI TTW emissions of NO_x reached 0.4 grams, while the ICEV-CI reached 4.5 g. The bus presents a total NO_x emission value of 8.5 g, representing the worst option when analyzing local pollutants emissions.

Table 7
WTW energy consumption for the different transport modes.

Parameters		Electric bicycles	Electric vehicles		Conventional technologies		Bus
			Low	Standard	ICEV-SI	ICEV-CI	
Energy consumption (MJ/user)	TTW	0.25	2.29	7.30	36.41	26.00	11.19
	WTT	0.27	2.40	7.67	5.10	4.16	1.79
	WTW	0.52	4.68	14.97	41.50	30.16	12.98
CO_2 emissions (kg/user)	TTW	0.00	0.00	0.00	2.65	1.94	0.83
	WTT	0.03	0.23	0.73	0.47	0.36	0.16
	WTW	0.03	0.23	0.73	3.13	2.30	0.99
NO_x emissions (g/user)	TTW	0.00	0.00	0.00	0.44	4.46	8.46
	WTT	0.06	0.50	1.59	1.57	0.96	0.41
	WTW	0.06	0.50	1.59	2.01	5.42	8.88

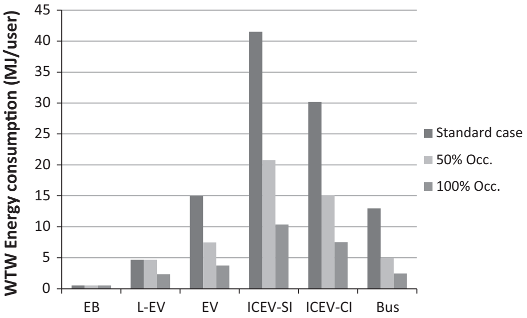


Fig. 5. WTW energy consumption impacts as function of occupancy rate (standard case, 50% and 100% occupancy for all vehicles).

NO_x affects essentially the lung function, causing lung and mucous membranes irritation and tissue damages [53]. Regarding environmental effects, NO_x tends to react with other atmospheric elements causing smog and acid rain. The combination of NO_x, hydrocarbons, sunlight and heat causes atmospheric ozone formation, so these results confirm the benefits of using cleaner mobility solutions in urban environment.

It is also relevant that in a WTW approach the bus presents a lower energy requirement per user than the standard electric vehicle (13% lower). Furthermore, two other vehicle occupancy scenarios were tested, one of 50% occupancy and another of full occupancy, as is presented in Fig. 5. Even if a full occupancy rate is considered for all the other vehicles, the EB would still be more energy efficient.

4. Conclusions

This research work analyzed the use of CB and EB as a means to a more sustainable mobility, when compared to other transportation solutions. Identifying and comparing different transport modes in their time and environmental efficiencies is a crucial step to influence user's choice, since it presents to the user the real impact of the trips performed. Therefore, an evaluation of speed, travel time and the use of electricity for a CB and an EB was performed with a portable laboratory collecting second-by-second trip data (including, speed, location, altitude, energy use, etc.). This was performed in a specific route in the city of Lisbon, Portugal, which was selected since it connects two major commuting areas and includes several road grade conditions, as well as driving conditions. The on-road second-by-second monitoring performed on both conventional and electric bicycles revealed that the use of an EB increases the biker average speed (8–26% increases), especially if the route includes sections with positive slopes. In sections with negative slopes the average speed decreased by 11% when using the EB, whereas it increased in neutral slopes by 6% and in positive slopes by 49%, when compared to the CB. Regarding the energy use of EB, the average value observed was of 0.028 MJ/km, which translates into a range of 46 km between recharging. For the sample studied, this value changed from 38 to 65 km, according to the level of electric assistance used by the bikers.

The analyzed route was also evaluated for other transportation solutions, including: L-EV, EV, ICEV-SI, ICEV-CI and Bus. Regarding the trip characteristics, the results show that both EB and CB can provide an interesting mobility alternative, since the travel times for this route are comparable with motorized ones (only up to 8 min higher travel time), mainly due to a higher flexibility associated with bicycles that enables them to have a reduced travel distance. The EB presents a higher travel time of 13.5%, 1.9% and 7.8% over the Bus, L-EV, and EV/conventional technologies, respectively. Similarly, the CB presents an increase in travel time of 19.7%, 7.6% and 13.7%.

In terms of the TTW energy consumption, the usage of an L-EV leads to 9 times higher results than the EB. The EV, ICEV-SI, ICEV-CI and Bus present 29, 146, 104 and 44 higher TTW energy requirement factors than the EB. The WTW energy consumption of an EB showed a use of only 11%, 3%, 1%, 2% and 4% of the energy required when using the L-EV, EV, ICEV-SI, ICEV-CI and bus, respectively. Increasing the occupancy rates of all vehicles considered would still result in a higher energy efficiency of the EB.

The WTW emissions analysis indicates 13% and 4% lower CO_2 emissions and 12% and 4% lower NO_x emissions for the EB when compared with a L-EV and an EV, respectively. Vehicles with internal combustion engines (ICEV-SI, ICEV-CI and Bus) are much more penalized, particularly on the TTW stage with 0.44 g/user emitted by the ICEV-SI, 4.5 g/user emitted by the ICEV-CI and 8.4 g/user emitted for the bus.

This research work demonstrates and quantifies that bicycles provide an interesting solution for urban trips, with comparable trip times to other transportation modes. In particular, EB can enable bikers to travel for longer distances and overcome hilly paths with less effort and higher speeds. Another benefit is the low energy requirements (in the TTW stage and also in a WTW analysis), as well as zero local emissions and reduced WTW pollutant impacts, which contribute significantly to improve the overall urban air quality.

The obtained results are case-specific but indicative of the global impact of shifting to other transport modes or using alternative technologies such as electric mobility. Future work is required to generalize this type of results, such as using a larger sample of bikers and considering its socio-demographic characteristics, using different route trips focusing more in some aspects that might have a larger impact on energy consumption and emissions (e.g. positive slopes) and the performance of a comparison with other popular public transport systems (e.g. the subway).

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