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Micromobility and smart cities: efficiency, energy consumption and range analysis for electric vehicles

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Abstract. Climate change and smart cities are topics where a large number of resources are being invested to avoid it and advance its development respectively. This paper presents a calculation procedure of the car efficiency, energy consumption and range whose efficiency has already been tested for hybrid vehicles (including plug-in) and fuel cell vehicles, as well as pure electric vehicles of category M_1. This method has been adapted for quadricycles of category L6e and L7e in order to be able to use it to accelerate the design of this type of vehicles and contribute to its introduction in Smart Cities. The reliability of the system has been verified with commercially available vehicles and prototypes taking into account their technical specifications: electric motor (e.g., permanent magnet motor), technology of energy storage system (e.g., lithium-ion battery), weight and geometry of the car for all types of drive cycles. According to the literature review, there is currently no standardized operating system or hardware abstraction layer for such methodology/application in the automotive sector. This flexible method can be easily extended for different technologies of batteries and electric motors, different standard or customized drive cycles, etc. Besides, it has high reliability for vehicles of category L since in no case does the error reach 5% and the average value is 2.5% when real data from vehicle manufacturers and outcomes are compared. Thus, results show the consistency of the system.

Keywords: Consumption / efficiency / electric vehicle / energy / micromobility / quadricycle / range / smart city / vehicle category

1 Introduction

Combating climate change through fossil fuel final reduction is the cleanest form to get energy [1]. The idea of smart and sustainable cities emerged in the 1990s [2]. Due to climate change and the growing development of Smart Cities, micromobility is becoming increasingly important, so this work can be very useful for the future. In addition, only purely electric vehicles will be treated, which makes research even more interesting for the incoming research in the field. Given the novelty of the subject, it is also difficult to find bibliography on the subject.

In addition, the large number of vehicles and prototypes could be cited as a sign of the potential of microcars, such as Renault Twizy, Seat Minimó, Peugeot BB1, Volpe Zagato (HEV (hybrid electric vehicle) and BEV (battery electric vehicle)), Honda MCβ, Volkswagen Nils, Audi Urban Concept, Opel RAKe Lightweight EV (electric vehicle) Concept, Citroën Ami One Concept, Microlino, Kia POP Concept, Melex 391, Little EBOX6, Goupil G4, Aixam eCity, Aixam eCoupé, PSA Velv, Toyota COMS EV, Tazzari Zero, Hiriko, Armadillo T, etc.

This paper provides a calculation methodology in order to find the efficiency of 4-wheel vehicles of Category L according to [3], that is, L6e (light quadricycle) and L7e (heavy quadricycle). It does not focus on vehicles with 3 or less wheels because they can become less stable, such as the "Kabinenroller 175" given to its single rear wheel has an unstable load distribution.

Current literature about quadricycles deals with fixed vehicle configurations [4–6] or calculations are made based on other parameters (for example [7] uses battery power consumption, driver comfort temperature and travel time) or is only based on a vehicle component ([8] only studies the electric motor).

More recent publications also try to make calculations by comparing different types of technology for various conditions (in [9] they deal with two different types of batteries for three urban cycles) but in this work it is delves more deeply into the architecture of the vehicle.

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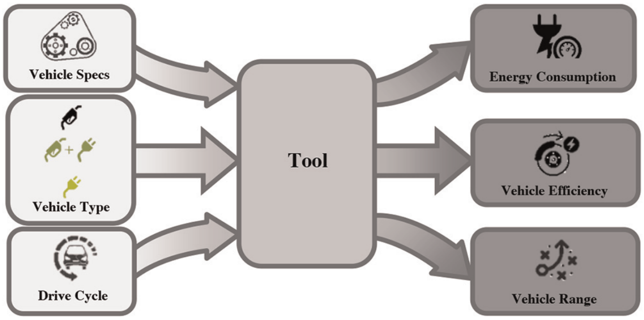

Fig. 1. Tool description.

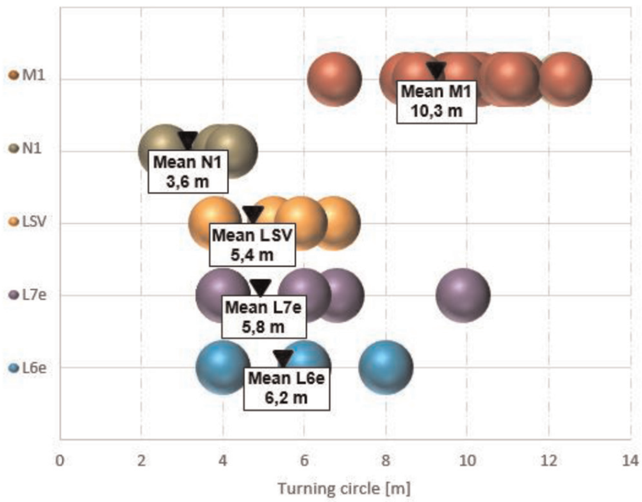

Fig. 2. Turning circle for different car categories. Source: [10].

This paper aims to present a methodology for calculating the energy consumption and driving range for microvehicles, for which a mathematical tool has been designed thanks to a computer program. Initially, the specifications and architecture of the vehicle must be known, as well as the description of the driving cycle (time and speed) as shown in the diagram in Figure 1.

2 Smart city and quadricycles

According to the European Commission, 'a smart city is a place where traditional networks and services are made more efficient with the use of digital and telecommunication technologies for the benefit of its inhabitants and business'.

A smart city goes beyond the use of information and communication technologies for better resource use and less emissions' such as smarter urban transport. For this reason, zero or low emission vehicles are essential.

Electric quadricycles do not emit CO_2 or any type of noise, they are, therefore, ideal for creating an eco-sustainable urban environment, very robust and, at the same time, compact. Depending on the case, they can be designed for high load capacities and with an autonomy that covers at least a day of work.

Fig. 3. Scaled representation of parking space of Barcelona, Stuttgart with a Nissan Leaf and three Renault Twizy. Source: [10–12].

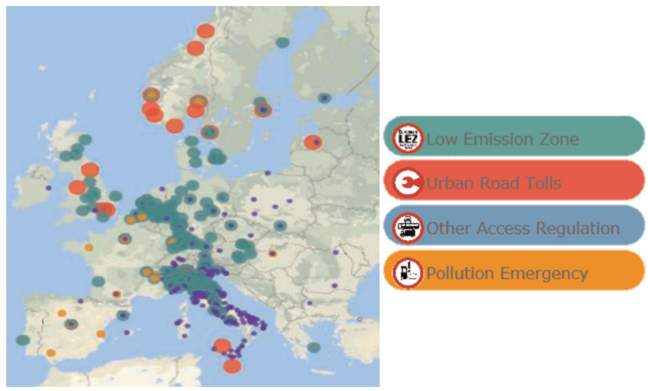

Fig. 4. Urban Access Regulations Map in Europe. Source: [13].

There are a large number of advantages and some of them make these types of vehicles more interesting than the traditional M_1 category:

√ Easy drivability:

Their small turning circle facilitates its drivability especially in the city. Figure 2 shows a comparison between several categories of vehicles.

√ Smalls dimensions for parking:

In [11] is possible to find the regulation, for example, for the city of Barcelona (Spain), where it is said the parking reserved has to be at least 5.4 m long and 2.4 m wide. According to [12] it is established the parking space, for example, for the city of Stuttgart (Germany) should be 5.0 m long and 2.3 m wide. Figure 3 shows a scaled representation of this data and a comparison with a Nissan Leaf and three Renault Twizy. A microcar occupies a third of the space that a M_1 vehicle does.

√ No emissions car:

Table 1. Energy consumption for battery electric vehicles.

Vehicle BEV	Year	Energy ESS [kWh]	Range [km]	Consumption [kWh/km]
TESLA X S90D	2016	90	402 (EPA)	0.22
	2016	90	467 (NEDC)	0.19
NISSAN LEAF	2013	24	199 (NEDC)	0.12
	2017	30	250 (NEDC)	0.12
VW e-UP!	2013	18.7	160 (NEDC)	0.12
RENAULT ZOE	2013	22	195 (NEDC)	0.11
TESLA S 85	2013	85	500 (NEDC)	0.17
	2013	85	426.5 (EPA)	0.20
VW e-GOLF	2015	24.2	190 (NEDC)	0.13
BMW i3	2013	21.8	190 (NEDC)	0.11
CHEVY SPARK	2015	18.4	132 (EPA)	0.14
			Mean [kWh/km]	**0.15**

These kind of vehicles are especially suitable for future smart cities due to the growth they are suffering and will suffer as well as the growing social awareness of the environmental care. They are ideal for short-distance trips by up to two people.

In this way, it helps to accelerate the reduction of CO_2 emissions.

Figure 4 indicates the European cities where the access of the most polluting vehicles is prohibited or limited or it is necessary to pay a toll to access certain areas.

√ Smalls dimensions for roads to improve traffic flows:

Compact body size facilitates the access from suburbs to city centre/within the city centre.

According to [14], 'drivers have started to spend much time in traffic each day. The number of vehicles has become another issue in these traffic jams. In other words, it has become a plenty of vehicle space per person. The required volume for a passenger in a sedan type vehicle is approximately 15 m^3/person for a single occupant. This value is 5 times bigger than requirement for a person in a city bus. According to statistics, 87 % of commuters in USA travels 29 km or less daily. And the number of passengers per vehicle is around 1.6, in rush hours it decreases down to 1.4. This value is even less in European cities and is about 1.1–1.2 [15]. Now that the problem is to reduce pollution, energy consumption and area per person in traffic, small urban cars would be a strong alternative to this issue'.

√ Low weight and consumption vehicle:

Low weight is fundamental in mobility, especially in electric motor applications, where a little increase in mass affects the endurance seriously given that vehicle mass has a major impact on the total resistance acts on the automobile [14]. L6e should have a mass in running order smaller or equal to 425 kg and L7e smaller or equal to 450 kg (for transport of passengers) or 600 kg (for transport of goods).

From Table 1 to Table 6 it can be seen that cars of category L (Table 6) need less energy to operate than those of category M_1 (Table 1 to Table 5).

√ Driving license requirements:

Light quadricycles (L6e) can be driven with or without a driving license, according to the legislation of European countries. For example, according to [16], drivers do not need a drive license but must have a minimum of 14 years. Heavy quadricycles (L7e) must be driven with either a category A or B license, according to the legislation of European countries.

√ Low initial and running costs (to attract attention and to promote tourism):

Stimulate local revitalization by providing tourist mobility freely and strengthen tourist destinations.

√ Quadricycles combine the advantages of motorcycles and passenger cars M_1:

Quadricycles are as small and flexible as a motorcycle but ensure protection from the external effects for different weather conditions and stable as a passenger cars M_1 [14].

Table 2. Energy consumption for series hybrid electric vehicles.

Vehicle Series HEV	Year	Energy ESS [kWh]	Range [km]	Consumption [kWh/km]
BMW i3 Rex	2013	21.8	170 (NEDC)	0.13

Table 3. Energy consumption for parallel hybrid electric vehicles.

Vehicle Parallel HEV	Year	Energy ESS [kWh]	Range [km]	Consumption [kWh/km]
AUDI A3 Sportback etron	2014	8.7	50 (NEDC)	0.17
VW Golf GTE	2015	8.7	50 (NEDC)	0.17
FORD C-MAX ENERGI	2015	7.6	30.6 (EPA)	0.25
VW XL1	2013	5.5	50 (NEDC)	0.11
BMW i8	2013	7.1	37 (NEDC)	0.19
		Mean [kWh/km]		**0.18**

Table 4. Energy consumption for series parallel hybrid electric vehicles.

Vehicle S/P HEV	Year	Energy ESS [kWh]	Range [km]	Consumption [kWh/km]
TOYOTA PRIUS (3rd gen)	2009	1.3	8 (NEDC)	0.16
CHEVROLET VOLT	2016	18.4	85.3 (EPA)	0.22
		Mean [kWh/km]		**0.19**

Table 5. Energy consumption for fuel cell electric vehicles.

Vehicle FCEV	Year	Energy ESS [kWh]	Range [km]	Consumption [kWh/km]
TOYOTA MIRAI	2015	166. 7	550	0.30
		166. 7	502	0.33
HONDA CLARITY FC	2016	182	585.6	0.31
HYUNDAI ix35 FCEV or TUCSON FCEV	2013	194. 7	589	0.33
MERCEDES-BENZ GLC F-CELL	2017	146.7	437	0.34
		Mean [kWh/km]		**0.32**

Table 6. Energy consumption for battery electric vehicles of category L.

Vehicle Category L BEV	Year	Energy ESS [kWh]	Range [km]	Consumption [kWh/km]
RENAULT TWIZY (45)	2018	6.1	100	0.06
LITTLE EBOX 2WD	2013	9.6	60	0.16
RENAULT TWIZY (80)	2018	6.1	100	0.06
LITTLE EBOX 4WD	2013	9.6	50	0.19
LITTLE EBOX6 2WD	2013	9.6	60	0.16
LITTLE EBOX6 4WD	2013	9.6	60	0.16
AIXAM eCITY	2019	6.1	110	0.06
AIXAM eCOUPÉ	2019	6.1	110	0.06
AUDI URBAN CONCEPT	2011 proto	7.1	73	0.10
VW NILS CONCEPT	2011 proto	5.3	65	0.08
MICROLINO	2019	8.0	125	0.06
	2019	14.4	200	0.07
		Mean [kWh/km]		**0.10**

3 Technical work preparation

3.1 Calculation basis

The calculation method has been tested and presented in works [17,18] for vehicles of category M_1 with the architectures of EV, HEV and PHEV (series, parallel and series-parallel) and FCEV (fuel cell electric vehicle). Given the characteristics that make light and heavy quadricycles unique, certain adjustments to the calculations have been made with the help of the literature and according to [19].

In addition, due to the novelty of the subject, calculations with more vehicles of category M_1 and N_1 have been made, in order to ensure that the results of the methodology are reliable and viable.

The longitudinal dynamics equations to determine automobile total Running Resistance (F_T) will be used:

$$F_T = m{\cdot}a + F_{R0} + F_L + F_{Si} \tag{1}$$

where m is the mass of the vehicle in kg, a is the acceleration of the vehicle in m/s^2, F_{R0} is the Rolling Resistance, F_L is the Drag Resistance and F_{Si} is the Climbing Resistance (which in this work is considered to have a value of zero because all the drive cycles included in this work are in flat surfaces).

It is necessary to calculate the power (P) in order to measure the necessary acceleration power:

$$P = \frac{F_T}{\eta}{\cdot}\upsilon \tag{2}$$

where η is the power loss of vehicle parts and υ is the speed of the vehicle in m/s.

With these data, consumed energy of the vehicle can be calculated (E):

$$E = \int_{traction} P_{out}\,(t)\,dt + \int_{braking} P_{in}\,(t)\,dt \tag{3}$$

where is the cycle time in s. Since vehicles can be equipped with electric motors that acts as a power generator, this aspect should be taken into account.

3.2 Vehicle architecture

In the present paper only the architecture of pure electric vehicle will be discussed. The components that will be taken into account are shown in Figure 5.

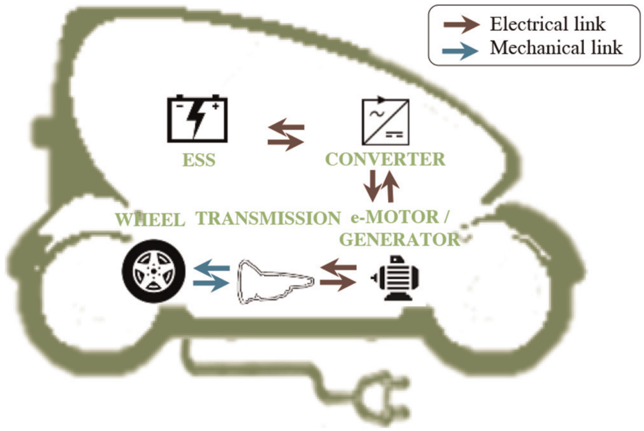

Fig. 5. Architecture of EV.

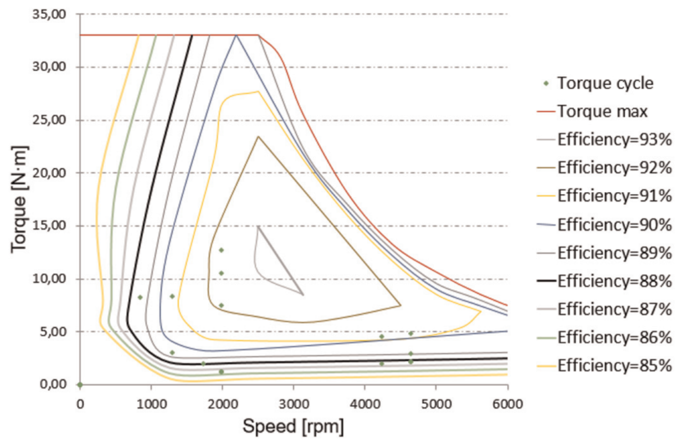

Fig. 6. Motor Efficiency Map For Twizy in ECE-15.

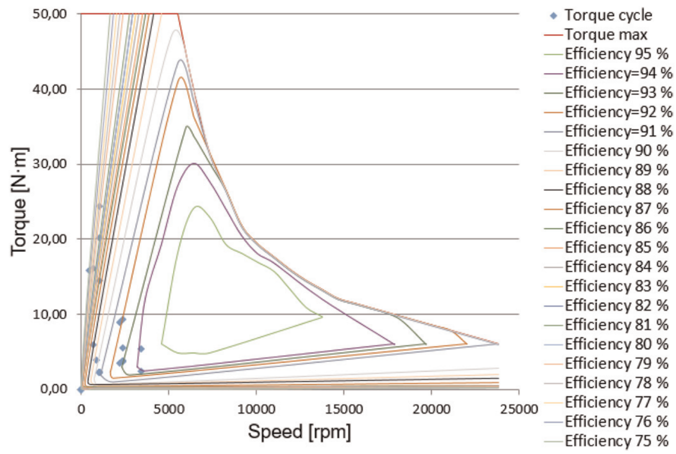

Fig. 7. Motor efficiency map for both Aixams in ECE-15.

In this case, in relation to the ESS (electric storage system), calculations will be verified with vehicles whose energy is stored in batteries whose cathode is a lithium compound.

Electric motors to be taken into account are going to be IM (induction motor) and PM (permanent magnet motor) technologies.

Converter, when connecting the battery and the electric motor, works as an inverter (DC (direct current) → AC (alternating current)) and, when connecting the generator (AC) with the ESS (DC), it works as a rectifier.

The drive system is connected to the wheels by means of a transmission that can give traction to both the front and rear axle or both.

4 Evaluation and hypotheses

In the present document, efficiency, consumed energy and range have been calculated and programmed by means of a software to generalize the calculation of any vehicle.

The checked drive cycles are those declared by the car brands and the calculation method is prepared to adapt to any type of route, provided that its speed (m/s) and time (s) are defined.

As mentioned, calculations have been prepared to be applied to any type of surface, including non-planar ones.

At the time of starting calculations, the ESS must be at 100 % of their nominal capacity.

All presented results have been done in electric mode and are based on official commercial information provided by car manufacturers.

Regarding the calculation of the efficiency of electric motors, real maps are considered, that is, the map shown in [20] for IM and the map of Toyota Prius 3rd generation for permanent magnet motor.

This procedure has been designed for TtW (tank to wheel energy) pathway, so, in this case, calculations involving the production, transport and distribution of electricity are not taken into account.

Efficiencies have been contrasted with the current literature and tested with the technical data of vehicles currently available in the market. Furthermore, in this case, quadricycles prototypes have been used, due to the lack of vehicles, to check the feasibility of the calculations.

5 Results

5.1 Renault Twizy 45

As a standard bearer for L6e vehicles, the efficiency of this vehicle has been calculated to obtain the consumed energy and its available range.

Efficiency of components showed in Figure 5 have to be found.

In relation to battery efficiency, according to [21], it depends on the cells' capacity and whose values range from 96.3 % to 88.9 %. However, it can vary depending on the cycle. According to [22], for the ECE-15 cycle the efficiency varies. In [22] is showed that the efficiency in urban cycles (UDDS [Urban Dynamometer Driving Schedule]) is lower than in non-urban (HWFET [highway fuel economy test cycle]) or mixed (NEDC [new European driving cycle]). The battery configuration is a 2s21p of 43 Ah LMO ($LiMn_2O_4$) cells at the cathode and graphite at the anode, so the efficiency is 86 %.

Table 7. Results for quadricycles.

Vehicle	Category	Year	e-Motor	Energy [kWh]	Total Efficiency [%]	Range [km]	Cycle	Range Calculated [km]	Error [%]
RENAULT TWIZY (45)	L6e	2018	IM	0.04	59.2	100	ECE-15	96.1	3.9
LITTLE EBOX 2WD	L6e	2013	IM	0.01	67.3	60	25 km/h	57.2	4.7
RENAULT TWIZY (80)	L7e	2018	IM	0.04	59.2	100	ECE-15	96.1	3.9
LITTLE EBOX 4WD	L7e	2013	IM	0.01	65.1	50	25 km/h	51.3	2.5
LITTLE EBOX6 2WD	L7e	2013	IM	0.01	66.6	60	25 km/h	58.5	2.6
LITTLE EBOX6 4WD	L7e	2013	IM	0.01	65.1	50	25 km/h	47.9	4.1
AIXAM eCITY	L7e	2019	PM	0.03	60.1	110	ECE-15	109.8	0.2
AIXAM eCOUPÉ	L7e	2019	PM	0.03	60.1	110	ECE-15	109.8	0.2
AUDI URBAN CONCEPT	L7e	2011 proto	PM	0.71	63.9	73	NEDC	70.7	3.2
VW NILS CONCEPT	L7e	2011 proto	PM	0.60	66.2	65	NEDC	64.0	1.6

Converters have an efficiency of 98 % [21,23–25].

According to [26], drivetrain efficiency is 90 % for this type of vehicles, but it should be taken into account that the efficiency decreases with the dimensions and structure of the vehicle [19].

As said before, for this type of motors, an IM, a generic motor map extracted from [20] has been used. To calculate efficiency of the electric motor (and generator too), its efficiency map must be taken into account (see Figure 6). Results depend on the technical specifications of the vehicle and the drive cycle. In this case, Renault declares that it complies with Regulation as reported in [27] for which an efficiency of 88.8 % is obtained for its IM.

Since the efficiency of the generator is lower than that of the electric motor, according to [19], 5 % is subtracted from the value.

The total efficiency is 59.2 % and, with the help of equations (1), (2) and (3), it can be concluded that the calculated range is 96.1 km. Comparing this value with the brochure's range (100 km) the calculation's error is 3.9 %.

5.2 Little EBOX 2WD

Again it is a light quadricycle (L6e) with an IM. Taking into account that the homologation tests have been carried out at a constant speed of 25 km/h and, with the help of the efficiency map of its electric motor (with the same procedure as by the Renault Twizy in Figure 6), it is concluded that the motor efficiency is 90 %.

The rest of the efficiencies have been calculated using the same procedure as detailed before.

The calculated total efficiency is 67.3 %, consequently the calculated range is 57.2 km, with 4.7 % deviation in relation to the official range declared by the brand (60 km).

5.3 Renault Twizy 80

The electric motor/generator of this vehicle is the same as the Twizy 45, but its specifications are limited to be able to sell it as a "license-free" vehicle that can be driven by young people aged 14 or 16 (depending on the European country). In this case it is a vehicle of category L7e.

On this occasion the efficiency of the IM is also 88.8 % (Figure 6).

A final efficiency of 59.2 % is obtained, so the results are analogous to Twizy 45.

5.4 Little EBOX 4WD

This time the car has the same electric motor as in the EBOX 2WD (two-wheel drive) but, being a 4WD (four-wheel drive) vehicle, the power and torque are twice as high.

The electric motor efficiency is 87 % at a constant speed of 25 km/h.

With all data, a total efficiency of 65.1 % is reached, a calculated range of 51.3 %, that is, a deviation of 2.5 %.

5.5 Little EBOX6 2WD

Again, it is a vehicle with an IM in a constant speed cycle (25 km/h), which it is found to have an efficiency of 90 %.

A result of 59.1 km calculated with an efficiency of 67.3 % is got. Taking into account that the official range is 60 km, the error obtained is 1.5 %.

5.6 Little EBOX6 4WD

This time, the IM at 25 km/h has an efficiency of 87 %. Again it is a vehicle with all-wheel drive so its power is twice the previous vehicle.

With a total car efficiency of 65.1 %, according to the methodology presented, the vehicle can travel 47.9 km which, compared to the 50 km declared by the brand, the deviance of the results is 4.1 %.

5.7 Aixam eCity and Aixam eCoupé

Both vehicles have the same technical specifications (those that affect the characteristics showed in Figure 7), so they have the same graphic. This time it is a permanent magnet motor. In this work, as it is said before, the efficiency map of the Toyota Prius 3rd generation is used in order to describe the behaviour of the Aixams' motor/generator. In this way, it can be concluded that the efficiency of such motor, in the cycle described in [3], is 89.0 % (see Figure 7).

To sum up, the calculated range is 109.8 km taking into account a general efficiency of 60.1 %, so the deviation of the 110 km declared by the brand is 0.2 %.

5.8 Audi urban concept

In this case, it is a prototype with a permanent magnet motor too. An electric motor efficiency of 88.2 % can be considered according with its map.

All this means the total efficiency is 63.9 % with a calculated range of 70.7 km (compared to the official 73 km) according to the NEDC. In other words, the calculation error is 3.2 %.

5.9 Volkswagen Nils concept

As well as in the case of the previous vehicle, it is a prototype, whose permanent magnet motor in the NEDC cycle has a 91.2 % efficiency.

Thus, the total efficiency is 66.2 % with a range of 64 km according to the calculations. If it is compared with the 65 km that have declared Volkswagen, the calculations are misaligned by 1.6 %.

Table 7 shows the results that have been explained in detail in this section.

6 Conclusions

As it can be seen in the results shown, the calculation method has high reliability for vehicles of category L. The results obtained after applying the method to 10 different vehicles belonging to categories L6e and L7e and, in no case, does the error reach 5 % and the average value is 2.5 %. Despite some simplifications, results show the consistency of the system.

Likewise, in previous works it has already been possible to demonstrate its accuracy for all the architectures of electric vehicles (EV, HEV and PHEV (plug-in HEV) (series, parallel and series-parallel) and FCEV). With some adjustments, all of them contrasted with the results and the bibliography, it has been found that the same methodology can also be applied to smaller vehicles with more modest specifications and performance.

It is a very simple method that uses widely known and contrasted equations. It also deals with a very interesting topic. This progress in electrical micromobility must be built on in order to continue developing new technologies to finish making the leap to Smart Cities and collaborate on the brake of climate change.

Nowadays, due to the growing environmental awareness, to the evolution of changing customer needs and the higher concentration of vehicles in cities, the presented methodology is even more interesting in order to reduce the development time of new micro-vehicles of categories L6e and L7e and, consequently, also optimizing development and research costs for manufacturers and users of the tool.

No similar or comparable methodology has been found in the literature. In addition to being able to be applied to vehicles of the traditional categories (M_1 and N_1), this methodology can also be adapted for the promising micromobility, so that existing technology can be adapted.

The future research work is going to be focused on expanding the casuistry in relation to vehicle configurations and the number of components that make up the drive train of an EV, (P)HEV, and FCV. It is also planned to develop an application with the procedure and developed software.

Nomenclature

2WD	Two wheel drive
4WD	Four wheel drive
AC	Alternating current
BEV	Battery electric vehicle

DC	Direct current
ESS	Electric storage system
EV	Electric vehicle
FCEV	Fuel cell EV
HEV	Hybrid EV
HWFET	Highway fuel economy test cycle
IM	Induction motor
L6e	Light quadricycle
L7e	Heavy quadricycle
LMO	$LiMn_2O_4$
NEDC	New European drive cycle
PHEV	Plug-in HEV
PM	Permanent magnet
TtW	Tank to wheel energy
UDDS	Urban Dynamometer Driving Schedule

Conflict of interest

The authors declared that there is no conflict of interest.

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Authors contributions

Désirée Alcázar-García: Investigation, Conceptualization, Methodology, Validation, Writing. **José Luis Romeral Martínez**: Supervision.

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