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Indirect methodologies to estimate energy use in vehicles: Application to battery electric vehicles

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A B S T R A C T

Considering electric mobility as a viable alternative to conventional technologies, it is essential to characterize electric vehicles in terms of their real-world energy use. The objective of this work was to characterize in detail the real-world energy use of battery electric vehicles. An innovative method was developed through a calibration procedure using a group of three electric quadricycles, which were measured in real world on-road conditions for several trips by collecting 1 Hz data on vehicle dynamics (speed, acceleration and slope) and energy usage (measured directly at the battery terminals). Using this dataset, and through the adaptation of the vehicle specific power approach for quadricycles, it was possible to estimate electricity consumption with an absolute error between 1.4% and 4.5%. Due to the difficulties and risks associated to direct battery measurements of voltage and current of commercially available light-duty battery electric vehicles, this methodology was expanded and validated to this vehicle class in order to define the second-by-second electricity consumption as a function of the vehicle dynamics, based only on global recharging data per trip. The results obtained for two light-duty battery electric vehicles present similar accuracy and precision when compared to experimental results obtained for the electric quadricycles, with absolute deviations between 5.2% and 7.3%. The development of indirect methodologies to estimate the real-world on-road battery electric vehicle energy use in a prompt and simple way constitutes a powerful tool to evaluate the performance of these vehicles on any real-world trip.

1. Introduction

The transport sector is associated with an increasing trend in energy consumption and pollutant emissions. This sector is responsible for 30% of the world's energy use and 60% of the oil use, while the road transport sector is responsible for 80% of the energy used in the transport sector [1]. Furthermore, increasing motorization rates and demand for mobility are being observed [2], which justifies the need to introduce alternative solutions to reduce the energy use and diversify energy sources, promoting energy efficiency and reducing the emissions of local pollutant [3]. However, to assess the real impacts of using these alternative propulsion systems, it is necessary to analyze and compare their performance and impacts with the current propulsion technologies.

Battery electric vehicles (BEV) are known for their higher efficiency and zero local emissions, being considered as a good alternative in an urban driving context, where the pollution effects have high impacts in densely populated areas [4,5]. Studies concerning real-world use of light-duty BEV in urban applications have been performed indicating potential opportunities. A study by Baptista et al. [6] estimates a Tank-to-Wheel energy consumption reduction by a factor of 5.0 by BEV when compared with a conventional spark-ignition vehicle and 3.6 when compared with a conventional compression-ignition vehicle, while for global Well-to-Wheel CO_2 emission the electric mobility reached a reduction factor of 4.3 when compared with a conventional spark-ignition vehicle and 3.2 when compared with a conventional compression-ignition vehicle [6]. A case-study for the city of Istanbul indicates that a 10% penetration rate of electrically driven vehicles could contribute towards a reduction of almost 790,000 tons of CO_2 [7]. Regarding local pollutants such as NO_x, it was found that Well-to-Wheel emissions, in Portugal, can be reduced by a factor of 1.3 compared with a conventional spark-ignition and 3.4 comparing with a conventional compression-ignition vehicle [6]. Another particular application of electric vehicles is urban freight transportation, since electric mobility in an urban environment can be under certain situations economically viable, with

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considerable advantages concerning energy consumption, energy dependence, pollutant emissions and human health [8]. The same study also reports potential average saving of CO_2, HC, NO_x and CO emissions by a factor of 3.7, 79.7, 33.6 and 244.8, respectively, by replacing two Diesel vehicles by BEV circulating in a Belgium port. This confirms that both the environmental impacts (CO_2, air quality) can be strongly reduced with the use of BEV - from 30% to 100%, depending on the electricity production mix [9]. However, this aspect is of extreme importance since for countries with electricity production systems with high CO_2 intensities, the BEV can present little to none contribution to reduce the CO_2 associated to transportation sector [10].

An important characteristic that also contributes to high efficiency levels of electric mobility is the possibility of battery recharging during braking situations. Sterkenburg et al. [11] studied several patterns of electricity regeneration while braking on BEV, concluding that they have the capacity to regenerate from 10% to 20% of all the energy used by the electric motor during typical trips. The methodology adopted by this author was experimental, based on data measured directly from the battery terminals during on-road monitoring. Similar conclusions were found in chassis dynamometer, with regenerative braking contributing to harvest between circa 5% and 25%, for EUDC and ECE-15 driving cycles, respectively [12].

The energy performance of BEV monitored under on-road conditions has not yet been thoroughly studied and most of these studies have been performed with converted vehicles [13] or vehicles with simpler, low-power, powertrain configurations [14]. Using on-road vehicle monitoring, it is possible to assess energy use over different driving conditions. For instance, Devie et al. [14] characterized the behavior/autonomy of the batteries of an Aixam Megacity quadricycle, according with age, type of driving and climatic conditions. The methodology used included data collection on electric current and voltage, battery temperature and vehicle speed, at 1 Hz.

On converted and low-power electric vehicles, it is easier to obtain data (such as voltage and currents), providing more opportunity to access energy flows than on commercially available vehicles [13], since the mainstream vehicle manufacturers have their propulsion systems well protected and secured and do not provide standard access to the powertrain data (such as in conventional vehicles) via standard OBD (On Board Diagnostics) messages. For mainstream light-duty BEV, measuring energy use requires extreme caution to deal with the high voltages and currents involved during installation of sensors, as well as possible physical modifications on the vehicles. Furthermore, access to OBD data is not regulated for alternative technologies, which hampers a normalized, manufacturer approved use of the existing information. In this sense, alternatives to avoid this intrusive approach are worth of investigation.

The importance of correctly estimating real-world vehicle energy use, particularly for modeling the impacts of these vehicles has been shown, either for quantifying the impacts of these vehicles, as well as to forecast their footprint on the country electricity grid [15]. As a result, this work proposes a new method capable of surpassing the difficulties associated with real-world on-road monitoring, based on the Vehicle Specific Power methodology and the global trip energy recharging data.

2. Materials and methods

This work uses real-world on-road data to develop an innovative methodology for the indirect estimation of electricity consumption according with driving power. In order to acquire on-board vehicle data on both electricity consumption and vehicle dynamics of BEV, on-road test measurements were carried in the Lisbon metropolitan area (Portugal), covering both flat and hilly areas in the Autumn period. The average temperature ranged between 18 °C and 22 °C [16].

Three quadricycles (vehicles A, B and C) were tested only in urban conditions (due to traffic rules and road code limitations), while two light-duty vehicles (LDVs) from major vehicle manufacturers (vehicles D and E) were tested both on urban and extra-urban areas allowing for higher speeds (and power conditions), complementarily to the urban centers.

2.1. On-board laboratory for data acquisition

The portable laboratory used to acquire and record data from several sensors is conceptually similar to a Portable Emission Measurement System used in other studies [6,17,18]. Dedicated equipment is used to collect vehicle dynamics and road topography, as well as electricity consumption, on a second-by-second basis, while the vehicle is being operated on the road.

A distinction must be made between the equipment used on quadricycles and on LDVs. For quadricycles, electricity consumption data is acquired directly from the battery terminals using current and voltage probes, while the vehicle dynamics is measured using a GPS unit to collect speed and altitude. This setup was already used in other similar applications [6,19]. All the sensors used were connected to a laptop running software purposely developed for the integration of all equipment and data synchronization in order to get accurate results. The exception is the Energy Logger which is connected to the recharging socket and used to collect information on the electricity charged. Table 1 presents a summary of the equipment used and its characteristics.

Regarding the LDV, the access to high voltage/current cables that connect the electric propulsion components is not recommended by the vehicle manufacturers. Moreover, the tested LDV are supplied by third party users for a limited time and accessing the power cables would require damaging some of the insulation components. Therefore, the access to the battery is not possible or recommendable, consequently, on-road monitoring procedure for LDV is identical to quadricycles regarding the vehicle dynamics but, instead of monitoring the electrical consumption in a

Table 1
Description of the equipment used.

Equipment	Data acquired	Temporal resolution	Accuracy	Resolution	Used on
Garmin GPS map 76CSx	Speed (km/h), altitude (m), location	1 s	Speed: 0.05 m/s steady-state Altitude: 3 m	0.05 m/s 0.3 m	On-road, quadricycles and LDVs
Voltage and current probes (Fluke i1010)	Voltage, current	1 s	Current: 2% + 0.5 A Voltage: Negligible, directly connected to NI DAQ board	0.02 A 0–10 V scale, in a 16 bits scale	On-road, quadricycles only
Energy data logger (Voltcraft Energy Logger 4000)	Energy, Power, Current, Voltage	1 min	5–3500 W (±1% + 1 count) 2–5 W (±5% + 1 count) <2 W (±15% + 1 count)	0.1–3500 W	Household socket, quadricycles and LDVs