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Connecting electrification with eco-driving: using real-world driving data for assessing potential energy savings

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Summary

Current indicators on energy and greenhouse gas emissions point towards a need to change the transport sector paradigm, particularly at urban level. In this sense, this work aims at assessing the energy impacts of two alternative solutions: experimental analysis of shifting from conventional propulsion technologies to electric vehicles and numerical simulation of eco-driving concepts. Four drivers were monitored under real-world conditions in the Lisbon Metropolitan Area, using conventional light-duty vehicles and electric vehicles, to evaluate the behavioral changes and energy use related to the technological shift. Collected 1 Hz on-road data combined with a drive cycle numerical tool was used to estimate the potential energy impacts of adopting eco-driving concepts, by adapting speed and acceleration driving profiles. The results indicate reductions in energy consumption of 62% associated to technological shift, depending on driving events; while eco-driving can lead to reductions of circa 16%, by changing the acceleration speed profiles (maintaining all other characteristics of the trip).

Keywords: electric vehicles; eco-driving; drive cycle; energy consumption; combined approach

1 Introduction

The transport sector is accountable for considerable externalities, mostly at urban level (in terms of traffic, energy consumption, air quality and noise). For example, road transport in the UE-28 was responsible in 2016 for 33% of the final energy consumption and 31.6% of greenhouse gas emissions [1]. These facts justify the need to consider alternative solutions for this sector. Two of the possible alternatives include, on a technological perspective, the shift to electric vehicles and, on a behavioral perspective, the promotion of eco-driving.

The use of electric vehicles has a high potential to reduce energy consumption, improve air quality and reduce noise. However, such technologies are still not as established as conventional ones, presenting weak points, such as purchase cost, suitability, performance, autonomy and recharging limitations [2]–[4].

Over the last years, literature has addressed several issues related to electric mobility with particular emphasis on consumer adoption considering several factors affecting the adoption of these alternative technology vehicles [5]–[11] and on the comparison of the use of EV with ICEV in different applications, using both numerical simulations and real-world cases [12].

Focusing on the later, De Gennaro et al. (2014) [13] used GPS traces from ICEVs to evaluate the potential of EVs to meet the mobility demand in two cities in Italy. Moreover, the study accounted for the electric energy demand due to the electrification of different fleet shares, aiming at understanding the impacts on the electric energy distribution grid. To accomplish the study objectives, geo-referenced driving patterns of vehicles were acquired allowing to represent the average fleet sample over one month. An e-mobility model was developed to estimate the share of the urban vehicles which could potentially be replaced by EVs while the potential electric energy demand was calculated based on fixed consumption values obtained from car manufacturers or from the US Environmental Protection Agency (EPA) tests, depending on the type of EV that was considered. Main findings showed that more than 80% of the urban trips are eligible to be covered by electric vehicles and that an urban fleet share of up to 28% could be replaced by electric vehicles without any change in their driving patterns. The analysis of the impact of the potential BEV fleet share on the electricity grid load resulted in no more than 5% of the total electricity demand in the analysed areas.

Similarly, Greaves (2014) [14] used driving data recorded by GPS technology to assess the extent to which car mobility requirements can be met by EVs. An energy consumption model based on characteristics of the vehicle and on speed was used to determine the charge depleted, while a battery recharge function was used to determine charging times. Results revealed that EVs with a range of 60 km and a simple home-charge set-up would be able to accommodate over 90% of day-to-day driving. Moreover, the authors concluded that even if EVs are not suitable for long, high-speed journeys without having recharging alternatives, they are particularly suited for the majority of day-to-day city driving trips.

As for eco-driving, the promotion of this behavioral change has several barriers namely the difficulty to properly convey the message in a way that drivers modify their behavior, as well as prevent from rebound or short terms effects [15], [16]. In more detail, drivers have difficulty in acknowledging and accepting to change their behavior, and when they do, they may come back to previous behavior, if reinforcement is not provided. For instance, Beusen (2009) [16], who monitored 10 drivers over a period of 10 months and, in the 4 months after a general eco-driving training session, found that the average fuel consumption was reduced by 5.8%, with most of the drivers showing immediate gains that were stable over time. However, 20% of the drivers were found to go back to their original driving habits. The way and type of message also has influence in the outcome that results from providing feedback. Rolim (2016) [15] performed an assessment that showed that people react differently to the feedback provided. A sample of 40 drivers was monitored for a period of 6 months to assess the impacts of delayed feedback on driving performance considering indicators such as average speed, excess speeding, extreme braking and acceleration and consequent outcomes in terms of fuel consumption and CO_2 emissions. This assessment was based on data for two driving monitoring periods of 3 months each: one without feedback (Phase 1) and another with feedback (Phase 2). The authors concluded that overall both experimental and control groups increased fuel consumption and CO_2 emissions over 5%. A deeper analysis on the effect of the type of feedback revealed that when receiving negative feedback (revealing a performance decline), behavior would improve the following week while the opposite was found for positive feedback (drivers worsened their performance after receiving information of an improvement in the previous week). Therefore, characterizing the potential energy reduction associated to the implementation of this behavior in conventional or alternative technologies is crucial, in order to provide basis for a better design of tailormade driver feedback.

Consequently, in this context where the penetration of electric vehicles is rising, but where the need to promote eco-driving continues to exist, this paper proposes a coupled approach to quantify the impact on driving behavior of shifting to electric vehicles and of promoting eco-driving, based on real world measured data.

2 Data and methods

The overall schematic of the scientific approach used to tackle the presented objective is portrayed in Figure 1. The first step was to acquire real world driving data by monitoring both conventional and electric vehicles, enabling to quantify the impacts of shifting to electric vehicles. This data was also used as the basis to assess the impacts of eco-driving. In order to accomplish this, a model was developed allowing to test scenarios considering reductions of eco-driving (by restricting acceleration), as well as imposing a reduction in speed limits. A detailed description of the methods applied and data collected for this work is presented in the following sections.

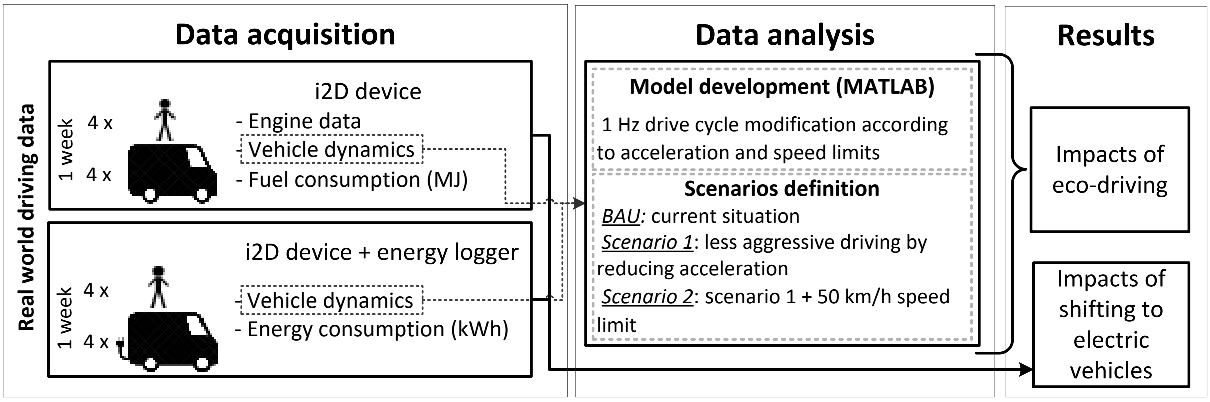

Figure 1. Schematic of data and methods used

2.1 Data acquisition and processing

To accomplish the objectives of this research work, four drivers were monitored in Lisbon, Portugal, for a period of two to three weeks, in both vehicle technologies. During the first period, drivers used a conventional internal combustion engine light-duty vehicle (ICEV), while during the second period they used an electric vehicle (EV). The monitored drivers were employees of a distribution company, thus most of the monitored data was acquired during daytime, under regular operation. Moreover, as results of the type of service performed, driving data was collected exclusively within the Lisbon Metropolitan Area, consisting mostly on urban and sub-urban roads.

Data on vehicle dynamics (EV and ICEV) and engine operation (only for ICEV) were collected at 1 Hz using an on-board data logger, the i2D device. This data logger is connected to the OBD port enabling to unobtrusively collect, measure and automatically transmit vehicle driving data such as speed, acceleration, engine rpm, throttle position, mass air flow, etc. Furthermore, it also collects data on location (GPS coordinates) and road topography (via barometric altimeter). For the EV, the energy recharged (kWh) in each recharging event was also monitored. An energy logger (Voltcraft Energy Logger 4000) was used to collect minute by minute data on voltage, current and power as provided by the electricity grid while the EV was recharging.

Regarding the monitored vehicles, the conventional and electric models of the Renault Kangoo van were monitored. The Renault Kangoo is a light commercial vehicle, with both the ICEV and the EV models having the same dimensions and identical cargo capacity. The ICEV vehicle was diesel-powered, compliant with Euro 5 standard, 55 kW of maximum power and an engine displacement of 1.5 l. The battery electric vehicle was powered by a 44 kW synchronous motor with a lithium-ion battery with a nominal capacity of 22 kWh.

Table 1 presents a characterization of the mobility patterns for each driver using both conventional and electric vehicles. This dataset enabled the comparison of driving behavior when shifting to electric vehicles.

Table 1. Characterization of the mobility patterns for ICEV and EV

Type of vehicle	Driver	Number of days	Number of trips	Distance travelled (km)
ICEV	1	14	265	337
	2	12	269	502
	3	14	534	619
	4	15	487	740
EV	1	15	93	302
	2	15	138	395
	3	14	209	357
	4	15	231	732

The 1 Hz acquired data was processed using the Vehicle Specific Power (VSP) methodology. In this methodology, vehicle energy consumption obtained from measured data are grouped into bins, according to the power requirements per unit of mass of the vehicle, on a second by second basis [17]. In the case of light-duty vehicles, VSP is divided in 14 modes. Modes 1 and 2 represent negative values of VSP and concern deceleration or negative road slopes. Idling is represented in mode 3. Beyond this mode, the higher the speed and accelerations the vehicle reaches, and consequently the power demand, the higher the mode. Even though each mode presents statistically different fuel consumption, none is dominant in the estimation of the trip's fuel consumption.

2.2 Model development and scenario definition

To quantify the potential impacts of promoting eco-driving on both vehicle technologies, a road load model (based on VSP) was developed in order to modify real world drive cycles according to the eco-driving principles (namely in terms of speed and acceleration). Using the original 1 Hz driving data (speed, altitude) and assessing the vehicle power requirements on a second-by-second basis, specific eco-driving criteria on speed and acceleration were imposed, resulting in adjustments of the driving cycle to fulfil the defined criteria by maintaining total distance and stops along road infrastructure.

The drive cycle adjustment model was implemented in MATLAB (version R2014a), by imposing an aggressiveness limit or cut-off point. This was accomplished using the definition by Faria et al. [18] of aggressive driving when a combination of speed and acceleration is achieved. In this case, the average acceleration limit was tested to establish an aggressive behavior. Points with higher acceleration would be limited to the maximum limit, resulting in adaptions in speed. Also, the possibility of imposing a maximum circulation speed was also included.

This model enabled to test a range of scenarios to determine the impacts of eco-driving on energy consumption. Three scenarios were considered, namely:

- Business-as-usual (BAU) – This corresponds to the current situation enabling the quantification of the impacts of the mobility patterns;
- Scenario 1 – In this scenario less aggressive driving was imposed by using an acceleration threshold. This threshold is variable according with speed and was defined based on real world driving data from 47 drivers (for further details see previous publications). In more detail, for a given speed whenever the acceleration was higher than the defined threshold it was set to the threshold value with driving cycle speed profile being adjusted accordingly. This scenario aims at assessing the impacts of promoting a more eco-driving behavior, which may result in reducing acceleration and braking profiles; and
- Scenario 2 – This scenario combines scenario 1 with a speed limit of 50 km/h. This corresponds to a more restrictive scenario by imposing less aggressive driving coupled with a maximum speed of 50 km/h. In a context where urban center circulation is increasingly regulated and restricted, with the implementation of lower speed limits mainly due to safety reasons, this scenario combines a behavioral and regulatory enforcement on the urban scale.

The impacts of implementing such scenarios were analyzed in terms of vehicle dynamics but also by accounting the energy consumption associated to such behaviors.

3 Results and discussion

The comparison of the mobility patterns associated to the four drivers in the two technologies was performed first, as is presented in Table 2. In spite of some differences in the mobility patterns indicators that may be justified by differences in the type of service performed in each period (and could not be controlled), the drivers opinion was that EV technologies were suited to perform this type of service and few operational constraints were observed, mainly associated to the recharging needs but not to the driving experience itself.

Table 2: Mobility patterns characterization for the selected sample

Type of vehicle	Driver	Trips per day (avg.)	Trip distance (km)	Distance per day (km)	Average speed (km/h)
ICEV	1	18.9	1.3	24	29
	2	22.4	1.9	42	32
	3	38.1	1.2	43	20
	4	32.5	1.5	49	32
EV	1	6.2	3.2	20	29
	2	9.2	2.9	26	27
	3	14.9	1.7	26	27
	4	15.4	3.2	49	20

As for the energy consumption characterization of both ICEV and EV, the experimental procedure and applied methods [19], [20] enabled the quantification of energy consumption by power requested to move the vehicle (VSP mode) for both vehicle technologies (considering each technology average), as is presented in Figure 2. As expected, EV are 3 to 4 times more efficient in energy consumption, independently of the driver, mainly due to the higher efficiency of the electric motor and the presence of regenerative braking.

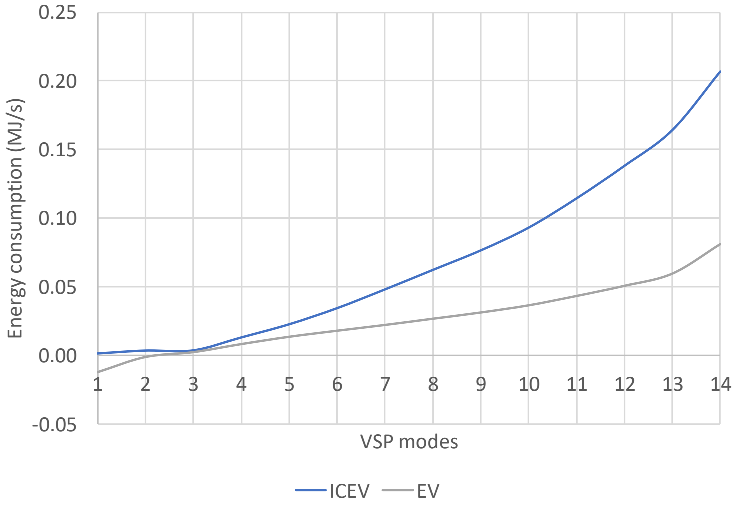

Figure 2: Energy consumption per VSP mode for both technologies

Regarding the analysis of driver performance between the ICEV and the EV in specific events, EV had slightly lower speeds than the ICEV, maintaining similar acceleration and vehicle specific power (VSP) profiles overall, while substantially reducing energy consumption in all events: 67% on the high-speed road, 62% for traffic lights, 59% on roundabouts, 60% on a steep uphill and 158% on steep downhills.

The results of promoting the scenarios tested are presented in Figure 3. On average, the implementation of Scenario 1 resulted in a 0.1% increase in travel time for ICEV and 0.3% for EV, which corresponds to a maximum of 6 minutes increase in the total time of driving which may be considered negligible. As for Scenario 2, that combines eco-driving with speed limit reduction, it results in a 3.2% increase in travel time for ICEV and 1.8% for EV, corresponding to an average 47 minutes increase in total monitored travel time over the full studied period, which may not be disregarded. The opposite trend is observed for average speed, with a 0.1% and 0.4% decrease in average speed in Scenario 1 for ICEV and EV respectively, while for Scenario 2 these reductions are of 3.1% and 1.6% for ICEV and EV respectively.

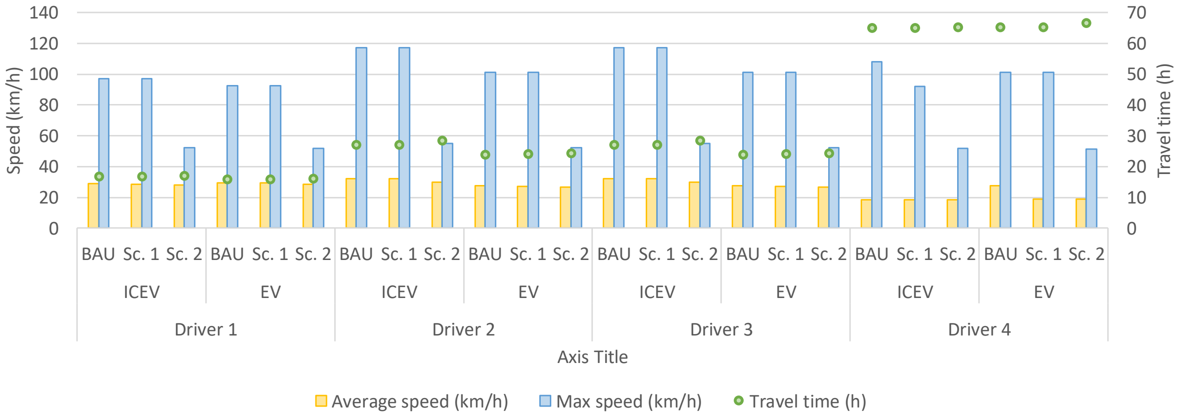

Figure 3: Scenario results considering travel time and speed variables

The aggressiveness profiles of the four drivers are also affected. For simplification purposes, Figure 4 presents the average positive and negative accelerations obtained from the implementation of the two scenarios, with an average 13% reduction in aggressiveness.

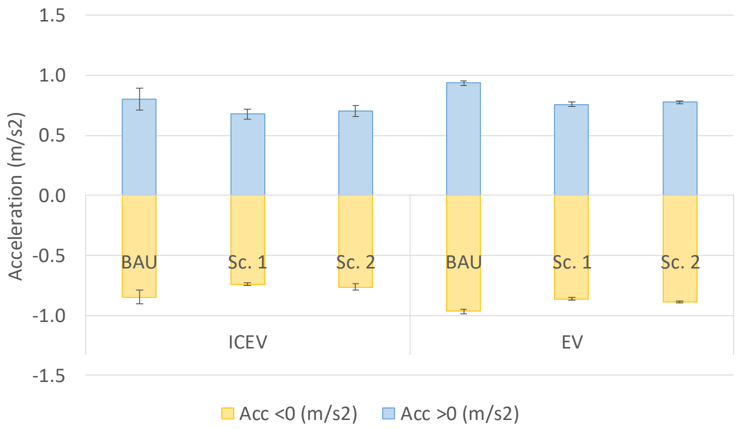

Figure 4: Scenario results regarding acceleration profiles in both technologies for the considered sample

The implementation of these scenarios including eco-driving behaviors also results in modifications of the VSP profile, as presented in Figure 5. The improvements of shifting technology are visible, passing from an average of 2.8 MJ/km to 1.1 MJ/km in EVs. Also, the implementation of the scenarios results in requiring less power to the vehicle (-12% for Scenario1 and -21% for Scenario 2). Typically, we can also observe that the potential of reduction associated only to eco-driving (Scenario 1) is slightly higher for ICEV than for EV, both for acceleration and energy consumption outputs.

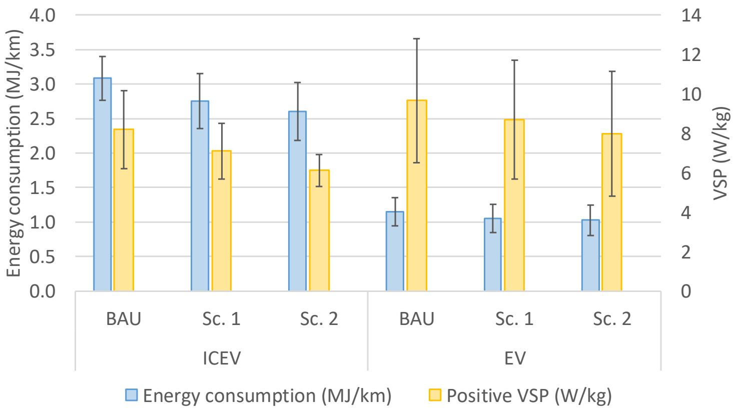

Figure 5: Energy consumption per VSP mode for both technologies

4 Conclusions

This work presents a novel approach that combines real-word data with a numerical simulation approach, enabling the assessment of the individual and combined impacts of shifting to electric mobility and of inducing changes in driving behavior. It enabled the quantification of possible gains of adopting more eco-driving behavior (of up to 16% in energy consumption, on ICEV and up to 4% in EV), without sacrificing travel time (differences below 3.2% in travel time). Therefore, results reveal that improving driving behavior can lead to important benefits on a shorter term, while maintaining vehicle technology. Nonetheless, over a longer period of time, the technological shift to electric vehicles might be a higher leap towards the decarbonization and air quality improvement on urban centers. The combination of both measures proves to be a good approach to reduce the impacts associated to this sector in a sustained manner.

In an automotive market that is thriving for change, as electric vehicles start to gain higher market shares, the promotion of eco-driving continues to be essential in the promotion of energy efficiency, even if a much more efficient technology is under consideration. The topic of eco-driving will continue to be relevant while the driver has an active role within the vehicle. In a long-term future, when autonomous driving gains terrain, eco-driving information will also be crucial in drive cycle algorithm design for road network efficiency optimization.

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