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Analysis and assessment of the electrification of urban road transport based on real-life mobility data

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Abstract

Assessing the potential of electric vehicles against actual user needs is a key-issue to integrate individual e-mobility in sustainable transport. An extensive analysis of real-life mobility has been carried out, in view of deriving and quantifying the potential of introducing electric vehicles in urban environment. A large activity data set collected with GPS black boxes mounted on approximately 16,000 vehicles monitored for a one-month period in the Italian province and city of Modena has been purchased and post-processed in order to characterise vehicles' driving patterns. The ability of different types of electric vehicles to cover the real mobility needs of the users has been then investigated, estimating the percentage of individual trips which might be suitable to be performed by electric vehicles, as well as their potential impact on the electric energy distribution grid depending on different recharging behavioural models. The results show that more than 80% of these trips might be driven electric and that a fleet share lying between 10% and 25% can be immediately converted to battery electric vehicles, being not affected by their limited range. The quantitative key-insights based on real-life mobility data enable to address several issues, ranging from technological aspects, policy impacts and interoperability possibilities offered by the integration of electromobility with the energy distribution grid.

Keywords: electric vehicles, activity data, urban road transportation, energy distribution grid

1   Introduction

Road transport contributes about one-fifth of the EU's total emissions of carbon dioxide (CO_2), the main Green-House Gas (GHG). CO_2 emissions from road transport increased by nearly 23% between 1990 and 2010, and without the economic downturn growth could have been even bigger [1]. Being transport the only major sector in the EU where greenhouse gas emissions are still rising in spite of the efforts made in the last two decades in regulating vehicles gaseous

emissions (i.e. Euro emissions regulations), it becomes clear that new transport solutions must be investigated. This is one of the main arguments which call for the electrification of individual road transportation, notably in an urban context [2]. Under the Kyoto Protocol, the European Union (EU) is committed to reducing its emissions by 20% below 1990 levels by 2020, and by 80-95% by 2050 in order to contribute to keep the global temperature increase below 2°C [3], [4]. The European Commission (EC) White Paper [2] has set ten goals to be achieved in the

next twenty to forty years. They include the reduction of the share of conventionally-fuelled cars in urban transport to 50% by 2030, phasing them out in cities by 2050, and the shifting of 30% of the freight road transport over 300 km to other modes (e.g. rail or waterborne transport) by 2030, to be increased to 50% by 2050. According to these visions the transportation system should evolve in the next decades towards cleaner, more energy efficient and sustainable vehicles and most likely electric road mobility will play a major role. This is also strengthened by the recent initiatives, demonstrations, and strategic position papers on electromobility published by governmental and private institutions [5], [6], [7], [8] and by the increasing attention received from public as well as private investors.

In general, electric vehicles (e-vehicles) are made of several key components (e.g. battery, power conditioning system, electric engine, electric drivetrain, etc.), requiring integrative optimization. Enlarging the perspective from the e-vehicle to a future electromobility system, its success will depend on the ability to respond to people's mobility necessities (i.e. user friendliness and public acceptance), and how it is delivering on the sustainability demand called for by the governmental programmes. In practice, e-vehicles will play a substantially different role compared to conventional vehicles, demanding a high level of integration in the electric energy distribution and storage systems [9], [10]. They need availability of recharging spots distributed over the urban territory [11], and easy and attractive pricing models for the electric energy. Even though mobility is something closely related to the individual driver's life-style and habits, it is well proven that a vast majority of people behave on average in a quite predictable way [12], [13]. The monitoring of todays (conventionally fuelled) vehicles is therefore the key to derive the averaged performance parameters EVs have to cope with, in order to efficiently serve as individual means of transport at large scale. To this purpose two activity data sets have been purchased from the private company Octo Telematics [14]. This company is specialised in collecting vehicles' driving patterns for a number of different applications and the databases purchased were extracted from its data pool to represent the averaged mobility behaviour in the Italian provinces of Modena and Firenze. The databases contain the driving patterns of a large fleet share of these two provinces, acquired with GPS devices connected via GSM to a remote

storage unit. From these data it was possible to accurately estimate the number of trips undertaken in the monitored period (one month, i.e. May 2011), the distances travelled, parking durations and geographical distribution of trips. The analysis refers to an area identified by the province boundary, mainly characterised by a number of close urban conglomerates connected by an inter-urban roads network. Hence the text will refer to this as urban mobility. A large number of different analyses have been carried out [13], [15] but, for a matter of brevity, only the most relevant aspects will be discussed in this paper. The results are presented for the province of Modena only; all the findings have been compared with those of the province of Firenze, proving that the averaged mobility behaviour within similar urban and social environments result to be similar.

Similar datasets have been already used in other studies available in literature, exploring public acceptance and usability of EVs 0, [17], the power infrastructure energy demand, grid optimisation [18], [19] and market potential of EVs [20]. In this paper a fleet sample accounting approximately 16,000 vehicles has been considered, representing 2.6 million trips and 15.0 million kilometres carried out in one-month period. The main results presented aim to derive:

- urban private mobility demand;
- ability of real EVs to meet this demand;
- impact of electric energy demand of EVs on the distribution grid load;
- design parameters for the recharging infrastructure (i.e. load-capabilities and their geographical distribution).

2   Activity Data Structure

The activity data acquisition campaign carried out by Octo Telematics involved 52,834 vehicles in the province of Modena, which represent approximately the 12.0 % of the complete fleet of the province (i.e. approximately 441,600 vehicles, at 31st December 2011). The area of the province extends for 2,688 km^2, including approximately 706,000 inhabitants, therefore it is characterised by a population density of 262.7 inhabitants per km^2 and a vehicle density of 0.62 vehicles per inhabitant. Both values are in line with Italian averages [21]. Among the 52,834 surveyed vehicles only those showing predominant local mobility behaviour have been selected. They are defined as those carrying out more than 50% of their trips within the province boundary. This

filtering criterion aims to focus the analysis on the urban traffic share, considering users (i.e. identified with the vehicle they drive) who live and work in the province, driving on a daily-routine basis and mostly suitable to be served by e-vehicles in a short-to-midterm perspective. Thus the sample analysed was reduced from 52,834 to 16,263 vehicles (i.e. to 30.7 %), representing the 3.7% of the total vehicles registered in the province. The 91.6% of the analysed vehicles were registered to the name of physical persons (later labelled as "private") while the remaining 8.4% were vehicles registered to the name of a commercial activity (later labelled as "commercial"). The age distribution of the private vehicles' holders is in line with the age distribution of Italian drivers.

Each record of the GPS devices mounted on the vehicles consists of a line of numbers indicating: an anonymous ID number (private/commercial, unique for each vehicle), calendar date, time (in GMT), GPS coordinates per record (latitudinal and longitudinal coordinates and azimuthal angle), quality of the GPS signal (1: no signal, 2: poor signal, 3: good signal), engine status (0: switched-on, 1: driving state, 2: switched-off), instantaneous speed and cumulative distance, measured from the beginning of the trip, per record. The data are recorded every second, and then periodically sent via GMS to a remote storage unit. The data are released after a preliminary processing aimed to decrease the data acquisition frequency to approximately 0.01 Hz, to reduce the database size. Short trips with a length less than 30 metres and/or duration less than 30 seconds are filtered out as not being representative of real mobility necessities. In our analysis, we define a trip as a sequence of records which starts when the engine is switched-on and ends when the engine is switched-off. The downscaling of the data acquisition frequency does not lose any representative trip data, as the engine switch-on and engine switch-off states are not affected by it. After this processing the data of the 16,263 vehicles considered reduces to 16.9 million records (i.e. data lines).

At this level the data are imported in MATLAB® [22] and processed with a set of modular scripts. First, a preliminary consistency check procedure is performed. This algorithm is designed to process the database searching for non-consistent data sequences (e.g. trips which do not start with the engine status switching-on and/or do not finish with the engine status switching-off). These non-consistencies are filtered out of the database,

leading to a data line reduction from 16.9 million records to 16.0 million and to a vehicles' number reduction from 16,263 to 16,223 vehicles. Then the data are submitted to an aggregation algorithm which reduces each trip to a single data line, calculating integral values of length and duration per trip and parking. This aggregated database is then submitted to further aggregation steps, targeted to reduce all the trips performed by a single vehicle in the day, week or month to a single line. This processing is designed to derive a manageable data structure. The final databases are representative of approximately 2.6 million trips and parking events, accounting for more than 15.0 million kilometres. The aggregated data structures are the basis for the analyses described in the next paragraphs.

3   E-mobility model

The modelling of the e-mobility aims to investigate if, and in which measure, urban driving can be served by electric vehicles. As stated in the introduction of this paper, the electrification of urban mobility is a complex topic, which involves at least three aspects: e-vehicles performance (e.g. range), their ability to be integrated within electric energy distribution grid (including AC and/or DC charging facilities), and behavioural models of the drivers (intended as driving as well as re-charging behaviour). In this study the activity data are the input to derive the driving behaviour to be served by EVs. Instead the recharging behaviour is assumed variable according to a number of assumptions later described. The electricity demand arising from the recharging behaviour of the e-vehicles is applied as a passive load on the electricity distribution grid and no grid-to-vehicle interaction is considered (i.e. smart grids). However the results presented here already provide key-insights of the possible integrations of e-vehicles in urban mobility, vehicles-to-grid and smart grids applications.

3.1   E-vehicles performance

In this study six e-vehicles have been considered. Each of them represents a different market segment, identified by performance parameters, chosen to be representative of Battery Electric Vehicles (i.e. BEVs) recently come on the market or which will be soon (i.e. before 2015) commercially available. They are: a light quadri-cycle, a small size vehicle (typical city-car, four passengers), two medium size vehicles (a typical

family car and a high-performance family car, five passengers) and two large size vehicles (a Sport Utility Vehicle, SUV, and a sport sedan). For a matter of brevity only results concerning two among these six vehicles are provided: the small city-car and the medium size car. Table 1 summarises the data from real-test-drive performed by the US Environment Protection Agency (i.e. US EPA) [23], for these two vehicles. All the vehicles are equipped with Li-Ion batteries.

Table 1. Summary of the main EVs performance data according to [23].

Vehicle Type	Curb Weight [kg]	Electric Motor [kW]	Battery Size [Wh]	Energy Consumpt. from driving Tests [Wh/km]
Small size car	1,080	47	16,000	185
Medium size car	1,520	80	24,000	210

The energy consumption given includes the auxiliaries, such as, Heating, Ventilation and Air Conditioning (HVAC) system, radio and lights. The electric energy consumption of EVs is in general higher than that specified by the manufacturer and is strongly dependent on driving and environmental conditions and use of auxiliaries. The assumed data aim to consider an averaged impact of these effects.

Concerning the typical energy storage device performance of the BEVs, the battery is characterised by a minimum and maximum State of Charge (i.e. SOC), below or above which the battery might be damaged. In this model the minimum and maximum SOC have been set equal to 20% and 95% of the nominal energy capacity of the battery. The rate of charging is also an important parameter to prevent battery damage. During the recharge of the battery the power is scaled in relation to the SOC of the battery and is mostly below the given maximum power from the grid. This study assumes the applied recharge power constant during the recharging time. The maximum power available from the grid is scaled down, to stay conservative in term of recharging time. Battery self-discharging is also considered. This happens when a battery is left to rest for a long time. Self-discharging is applied in this study when the vehicle is parked but no recharge takes place, even though it represents a small percentage of discharge. The battery self-discharging factor has been assumed to be

approximately 10% of the nominal maximum battery energy capacity per month [24], and then it is scaled according to the parking time. In addition it has been assumed that the battery of each vehicle is fully charged at the beginning of the analysis period meaning the SOC equal to the maximum allowed SOC (i.e. 95%).

3.2 Recharging behavioural model

In this study twelve possible recharging strategies have been considered, designed to reproduce the most widespread recharging behaviour, depending on the individual behaviour of the driver and on the recharge infrastructure available. They are based on data quoted in the literature [25] and include:

- non-aggressive/aggressive recharge (i.e. the vehicle recharges only when a long parking happens or whenever/wherever it is possible);
- on-peak/off-peak recharge (i.e. the vehicle charges according to the grid load);
- indirect price-based/direct smart-grid recharge (i.e. the vehicle charges when price constraints set by the owner are met, or when the grid decides to supply the energy according to its infrastructure optimisation).

According to these guidelines different recharge strategies can be defined, by changing the parking duration constraint or the electric power of the recharge infrastructure. Among the twelve strategies applied, three have been selected to be presented in this paper, and they are summarised in Table 2. More details about the other strategies can be found in [15]. These three strategies have been selected because they are the less aggressive, in term of recharge constraints and grid requirements, among the twelve considered. For this reason they can be considered the most suitable to be implemented in the short-to-mid perspective. Strategy 1 (Long-Stop Random AC) represents a scenario when a long stop of the vehicle must be met (i.e. longer than 120 minutes) to apply the recharge. It is applied with a conventional Italian recharge infrastructure (i.e. AC, single-phase at 3.3 kW, Mode 1/2 [26]), and it is representative of the recharge which can be made at home or wherever the vehicle is subjected to a long parking event (e.g. office, airport or train station parking lots, etc.). The recharge power is set constant and equal to 2 kW, and the recharge is subjected to a random-generated threshold parameter. In practice each time a vehicle meets the recharge time-constraint a random number generator algorithm produces a value between 0

and 1. Each value in this interval can be generated with the same probability; therefore this algorithm provides a flat probability function. Only if this number is higher than 0.6 (i.e. 40% of the probabilities) the recharge applies. This random threshold is representative of two possible effects: the recharge station is not available at the parking lot or the driver forgets to recharge.

Table 2: Details of the recharge strategies

Strategy ID - Name	Recharge Constraint	Power [kW]	Recharge Model Inputs
1 - Long-Stop Random AC	Stop > 120 min and Random > 0.6	2	Parking duration and random threshold
2 – Short-Stop Random DC	Stop > 20 min and Random > 0.6	40	Parking duration and random threshold
3 - Smart AC	Off-peak 4 hours (±2 h) time window	2	Parking duration and smart time window

Strategy 2 (Short-Stop Random DC) is very similar to strategy 1, but the time threshold is set to 20 minutes (i.e. short-stop) and the recharge is applied in DC (55 kW, Mode 4 [26]). The random threshold is the same as above. It is representative of the recharge which might happen in dedicated parking lots, equipped with fast-charging devices (e.g. shopping areas). Also in this case recharge power is scaled down to a constant value of 40 kW. Instead strategy 3 (smart AC) is quite different; in this case the recharge is applied only in a time window of 4 hours (± 2 hours) around the minimum of the electric energy grid load. The Italian electric energy consumption for May 2011 [27] is provided as an input to define the smart window of possible recharging time. The minimum grid load happens around 4 a.m. from Monday to Saturday and around 7 a.m. on Sunday. Hence in this case the recharge is imposed only if the vehicle is parked between 2 a.m. up to 6 a.m. during the week and between 5 a.m. and 9 a.m. on Sunday. It is representative of the recharge which might happens at home and it might be associated to a lower electricity fee.

The charging efficiency in all cases has been set equal to 95% [15]. No effect of the temperature conditions has been considered, nor the seasonal variation of the habits of the drivers and of the electricity energy consumption profile.

4   Results

4.1   Mobility Results

In this paragraph the attention is focused on the results of the mobility analysis of the activity data of the province of Modena. Among the several analysis performed a selection of the most meaningful quantities to be taken into account is presented. In Figure 1-(a) the portion of the fleet in motion at the same time is depicted, with distinction between private and commercial vehicles. The values provided are averaged in time for the four weeks of May 2011. Three traffic peaks can be seen from Monday till Friday, in the morning (approximately at 7.30), in the mid of the day (approximately at 12.00) and in the evening (approximately at 18.30). In contrast, at the weekend (Saturday and Sunday) the shape of the curve is different, showing only two peaks: approximately at 12.00 and approximately at 19.00. A periodical behaviour can be noticed in the working days, with a maximum at 11.5% for private vehicles and at 15.2% for commercial vehicles. The continuous and the dashed curve depicted are quite different, highlighting a more intense use of the captive fleets during the working days. The remaining percentage to 100% in Figure 1-(a) represents the averaged share of the fleet parked in the week. Therefore it can be noticed that more than 90% of vehicles are parked for the most of the time, with a nearly 100% of the vehicles between 1.00 a.m. and 5.00 a.m. Figure 1-(b) and 1-(c) depict trip length and parking duration, averaged in time for the four weeks of May 2011. The results show that:

- the averaged trip for a private vehicle has a mean length between 5 and 20 km;
- the averaged parking for a private vehicle has a duration between 2 and 12 hours.

From these results it can be concluded that the average urban mobility demand is made of relatively short trips with relatively long parking events. A large deviation from these results can be seen for commercial vehicles, especially concerning the average trip length. Long trips (more than 50 km, on average, from Monday to Thursday) are registered in the morning, most probably due to delivery vans. Driving activity of the commercial vehicles appears to be reduced in the weekend, while parking duration is in general shorter compared to private vehicles.

In Figure 2 the histograms of the Probability Distribution (PDs) of the number of trips,

cumulative trip length and cumulative parking duration (referring to the total fleet), aggregated per day and per week are depicted. These distributions show that more than half of the vehicles make less than 6 trips and 20 km per day and 30 trips and 200 km per week, being parked for more than 90% of the time. Approximately 75% of the vehicles drive for less than 60km per day and 300 km per week. Comparing these results with the average performance of the earliest EVs available on the market, it is clear that hybrid and electric vehicles could already meet a large portion of urban mobility demand without major adaptation or technical improvements, with the added benefit for a reduction in fuel use and emissions of urban air pollutants. Approximately 9% of the vehicles in the sample exceed 100 km in per day, reducing to 3% exceeding 150 km per day.
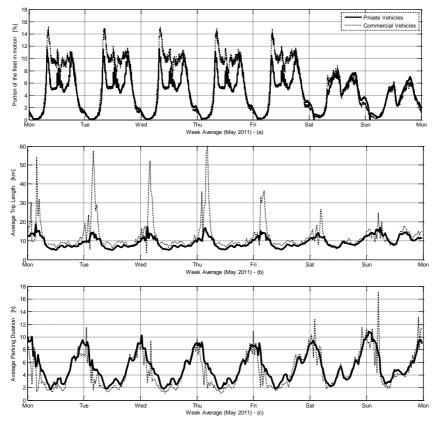

Figure 1: Portion of the fleet in motion (a), trip length (b) and parking duration (c) for the private and commercial vehicles in the province of Modena. Results are averaged over the weeks of May 2011.
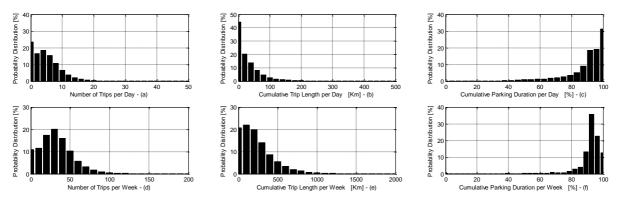

Figure 2: Probability Distribution (PD) histograms of the number of trips, cumulative trips length and cumulative parking duration per day, from (a) to (c), and per week, from (d) to (f) for the Modena province.

4.2   EVs performance results

The EVs model presented in this paper is targeted to evaluate the share of the driving urban mobility demand which might be suitable to be driven electric. This fleet share is defined as the percentage of vehicles whose trip sequence is not interrupted by a critical SOC event (i.e. SOC less than the minimum allowed, equal to 20%).

The trips and parking sequence of each vehicle are followed, considering each trip as an energy consumption event and each parking as a possible recharging event. The recharge happens during the parking time if recharging strategy constraints are met. Figure 3 depicts for the two vehicles and for the three recharging strategies considered the percentage of the trips which are suitable to be driven electric (black bars) and the share of the fleet capable to perform all the trips of the month by an electric vehicle (white bars). It can be noticed that the vast majority of the trips (more than 80%) can be driven electric. This is in line with the average driving behaviour described in the paragraph above, being the driving patterns characterised by frequent short trips. Instead white bars show that a percentage between 10 and 25% of vehicles are capable to drive only electric. These results can be interpreted in a double way: they means that most of the urban mobility demand can be covered with the performances of current BEVs, while the remaining part can be covered with other meaning of transportation (e.g. public transport). In addition they mean that a non-negligible part (i.e. more than 10%) of the urban fleet can be immediately driven electric,

without major improvements of the vehicle's performance or adaption of the recharge infrastructure. If we remove some of the constraints imposed, for instance the random threshold in strategy 1 and 2, the percentage of trips that can be made electric increases to more than 95% while the share of the fleet which can make all the trips electric increases to a value between 30% and 50%. If we consider larger battery size (e.g. about 35 kWh) it increases up to a value between 50 and 70%, depending on the recharge strategy [15]. These results mean that EVs can be successfully implemented in the urban mobility in a short-term scenario, and that their penetration level can be realistically set to the target value of the EC White Paper (i.e. 50% of urban mobility by 2030) in a mid-term scenario [2]. In addition, besides the fact that this model assumes as frozen the driving patterns, these results prove that the urban mobility demand is suitable to be satisfied by a new generation of vehicles whose environmental footprint is much lower compared to that of the conventionally fuelled vehicles.

In Table 3 the mean daily and monthly number of recharges estimated for the vehicles and for the recharge strategies considered are provided. The long-stop random AC strategy (i.e. strategy 1) shows approximately one recharge every two days, resulting to be the more restrictive among the three considered in term of recharging constraints. Instead short-stop random DC and smart AC (i.e. strategy 2 and 3) show approximately one recharge per day.
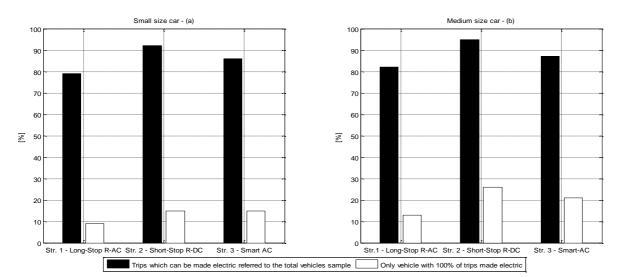

Figure 3: Percentage of the trips which can be made electric (black bars). Fleet share capable to make all the trips electric in the analysed period (white bars). Modena province, May 2011.

Therefore we derive approximately 15 recharges per month (i.e. approximately 180 per year) with the strategy 1 and approximately 30 recharges per month (i.e. 360 recharges per year) with the strategy 2 and 3. Comparing these results with other recharge strategies [15] we derive a maximum number of recharge per day lying between 0.5 and 2, with a consequent number of battery cycles per year lying between 200 and 700, depending on the vehicle's battery size and recharge strategy.

Table 3: Average number of daily and monthly recharges, per vehicle, per strategy.

Strategy / EV type		Averaged number of recharges		
		Str. 1 Long-Stop R-AC	Str. 2 Short-Stop R-DC	Str. 3 Smart-AC
Small size car	d:	0.44	0.95	0.64
	m:	13.51	29.31	19.60
Medium size car	d:	0.52	1.09	0.68
	m:	16.24	33.64	20.97
d: per day m: per month				

It is interesting to notice how the smart AC strategy imposes approximately one recharge per day overnight, being the fleet share parked in the grid off-peak time window nearly 100% (see Figure 1-(a)).

In Table 4 the monthly mean SOC and energy stored in the battery, per vehicle, per strategy is provided. In all the analysed cases the SOC is nearly the 80%, corresponding to a value of energy stored of approximately 12 to 20 kWh depending on the vehicle's battery size. In addition in Table 5 the mean variation of the SOC before and after a recharge and energy stored in the battery, per vehicle, per strategy is provided. In all cases the SOC variation lies between 8% and 19%, corresponding to an energy demand applied to the grid which lies between 2.3 and 3.8

kWh, depending on the vehicle's battery size and on the recharge strategy. The results proposed in these tables gives an important insight about the distributed energy storage capabilities provided by a potential fleet of EVs, as well as on the energy demand applied to the electric grid. In Figure 4 the probability distribution (PD) of the SOC of the battery before and after the recharge is depicted for the three strategies considered. Only the medium size vehicle results are reported and they only refer to the fleet share capable to make all the trips electric (i.e. white bars in Figure 3). Bin size of the bars is 10% of the SOC, except for the first bar which reduces to 5%.

Table 4: Average SOC and energy [Wh] of the vehicle's battery, per vehicle, per strategy.

Strategy / EV type	Data	Str. 1 Long-Stop R-AC	Str. 2 Short-Stop R-DC	Str. 3 Smart-AC
Small size car	SOC	0.81	0.84	0.82
	En. [Wh]	12911	13398	13163
Medium size car	SOC	0.81	0.84	0.83
	En. [Wh]	19481	20261	19809

Table 5: Average SOC and energy [Wh] variation of the vehicle's battery before and after the recharge, per vehicle, per strategy.

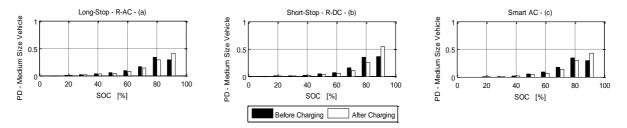| Strategy / EV type	Data	Str. 1 Long-Stop R-AC	Str. 2 Short-Stop R-DC	Str. 3 Smart-AC
Small size car	ΔSOC	0.173	0.144	0.189
	ΔEn. [Wh]	2764.6	2304.4	3016.5
Medium size car	ΔSOC	0.159	0.133	0.160
	ΔEn. [Wh]	3816.0	3192.0	3840.6

Figure 4: Probability distribution of the percentage of the state of charge values of the battery, before and after the recharge per strategy. The data refers to the medium size vehicle (see Table 1) and it considers only the fleet share of vehicles capable to make all the trips electric (see Figure 3).

These distributions show that the probability to achieve a SOC greater than 85% is approximately 40% for both AC recharge strategies, and approximately 55% for the DC recharge (because of its higher power).This probability reduces to approximately 30% in all cases before the recharge. Instead the event of driving with low SOC (i.e. less than 45%) results to occur with a minor probability, lying in a range of some percentage points. These results confirm those reported in Table 4, highlighting how, among the fleet share suitable to be driven electric, the vehicle SOC is generally characterised by a high value. From a driving path perspective, this implies that the trips and parking sequence of the fleet share is predominantly made of short trips and limited daily range (as already discussed in paragraph 4.1). This analysis can be extended to other recharge strategies and other vehicles types showing similar results [15], proving how the limited range which characterises the EVs is not a limitation in term of real usability of the vehicle in urban driving conditions.

4.3   Impact on the electric energy distribution grid and data geo-mapping

In Figure 5 the electric power demand distribution versus time for the medium size vehicle is depicted for the three strategies considered. The results refer only to the share of the fleet which can be driven electric (i.e. white bars in Figure 3) and are averaged over the four weeks of the analysis period (i.e. May 2011). Power demand depicted in Figure 5-(a), (c) and (e) refers to the vehicles sample considered in this study, while power grid load depicted in Figure 5-(b), (d) and (f) are scaled-up to the Italian fleet size. The range of the peak of power demand is approximately 0.4 MW for the long-stop random AC strategy (i.e. strategy 1) and approximately 2 MW for the short-stop random DC strategy (i.e. strategy 2). This increase is due to the higher power load applied by the vehicle with the second strategy (i.e. 40 kW) compared to the previous one (i.e. 2 kW). Instead the smart-AC strategy (i.e. strategy 3) provides a grid load which lies between 3 and 5 MW, depending on the day of the week, even with a power load per vehicle of 2 kW. This is due to the fact that the smart strategy concentrates the recharges in a specific time window (overnight) designed to be centred on the minimum of the grid load, taking

benefit of the fact that nearly 100% of the fleet is parked in this time window.

Three peaks per day are visible for the strategies 1 and 2 from Monday to Friday: one in the morning (approximately at 8.00 a.m.), one in the mid of day (approximately at 12.00 a.m.) and one in the early evening (approximately at 6.00 p.m.). On Sunday and Saturday the peaks reduces to two, one in the late morning (approximately at 11.00 a.m.) and one in the early evening (approximately at 6.30 p.m.). The peaks found correspond to the peaks of traffic (see Figure 1-(a)) and therefore to the peaks of subsequent parking events. The peaks of strategy 1 are slightly delayed compared to those of strategy 2 because of the lower recharge power applied. Instead in strategy 3 only one peak per day is found as expected, in correspondence of the beginning of window around the minimum electricity demand, i.e. 3.00 a.m. from Monday to Saturday and 5.00 a.m. on Sunday. As further improvement a distribution of recharges can be designed by the smart grid to avoid the vertical peaked load in Figure 5-(e), but this is not addressed in this study. The values of electric power given above could be extrapolated to the whole fleet of the province area to address the impact of the recharge power demand on the electric power grid. Moreover, assuming a uniform average mobility pattern for Italy, they can be scaled up to the size of the national fleet. The vehicles registered in Italy amount to approximately 36.3 million according to [21]. Assuming the amount of fleet share predominantly driven in urban conditions to be approximately 30% (as derived from the province of Modena, see section 2) and assuming all the percentage of vehicles that can be driven only electric (see Figure 3) the impact on the electric distribution grid of EVs has been estimated. For example in the case of the medium size car and strategy 1, the 12% of the 30% of the total fleet is assumed to be suitable to be electrified, resulting in approximately 1.3 million vehicles in Italy. Italian national grid load has been derived from [27] and reported in black in Figure 5-(b), (d) and (f). The grid load modified by summing the load applied by EVs is instead reported in grey. Results are only reported for the medium size vehicle, averaged over the week. We can notice that for strategy 1, being the averaged power load applied low compared to the other strategies (see Figure 5-(a)) the grey curve is nearly not visible compared to the national grid load. Instead for strategy 2

and 3, being the power load higher (see Figure 5-(c) and (e)), it results with an effect which is visible on the national scale. The benefits achieved applying the smart off-peak strategy is clearly visible, concentrating the energy demand arising from a potential EVs fleet in correspondence of the grid demand valley.

Table 6: Monthly EV energy demand [GWh] as derived by integrating power demand curve.

Strategy / EV type	Str. 1 Long-Stop R-AC	Str. 2 Short-Stop R-DC	Str. 3 Smart-AC
Small size car monthly energy demand [GWh]	35.49	120.29	98.39
Medium size car monthly energy demand [GWh]	96.613	331.38	186.15

Table 6 shows the global electric energy demand in the month for Italy for each vehicle type and recharge strategy, derived as described above. The values reported range from 35 to 331 GWh, depending on the recharge strategy and vehicle type. Strategy 1 result to be the less demanding, as already discussed for the Figure 5-(a), while strategy 2 and 3 have a larger impact in terms of energy demand on the grid. However comparing these numbers with the monthly Italian energy demand registered in May 2011 [27] which equals to approximately 27 TWh, we notice that in any case the electric energy demand of the 0. More results can be found in [13], [15].

Some preliminary results concerning the activity data geo-mapping are presented. The geo-referenced data have been mapped on digital maps of the Modena province retrieved from the Google Maps server [28]. In Figure 6 the parking events associated to the recharge strategy 2 and to the medium size vehicle are depicted. Each black dot located on the map in Figure 6-(a) represents a charging event, while the blue line corresponds to the border of the province of Modena. Approximately 140,500 charging events are estimated to happen for strategy 2, while 33,800 and 99,000 are estimated for strategy 1 and 3 respectively (medium size vehicle). The red circles reported in Figure 6-(a) represent equal distances measured from the Modena city center (latitude = 44.6471 deg and longitude = 10.9251 deg), indicating, from the inner to the outer: 5, 10, 15, 20 and 30 km. The surface distances are calculated approximating the Earth geoid to a smooth sphere with a radius of 6371 km. In Figure 6-(b) the geographical distribution of these events is reported as function of this distance, showing how the large majority (approximately 80%) occurs within 20 km from Modena. Further developments, including estimation of the space distributed electric energy demand and grid design, are foreseen.

5   Conclusions

In this paper the results of the analysis of activity data containing driving patterns of approximately 16,000 vehicles (representative of 2.6 million trips and 15.0 million kilometres) recorded by GPS in May 2011 in the Italian province of Modena are presented. The averaged mobility behaviour is characterised by the average trip length ranging between 5 and 20 km and the average parking duration ranging between 2 and 12 hours (daily and nightly values, respectively).
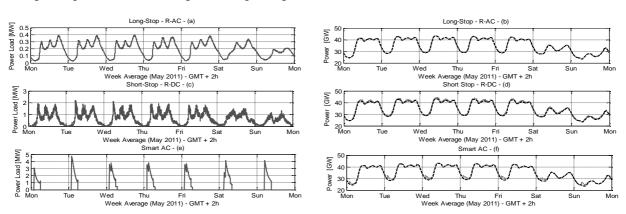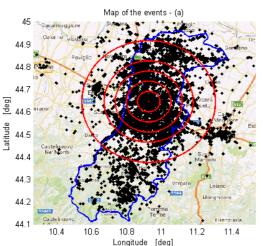

Figure 5: Mean week power demand (left column) and impact of this demand on the Italian electric energy grid load (right column). The data refers to the medium size vehicle (see Table 1) and it considers only the fleet share of vehicles capable to make all the trips electric (see Figure 3). Power demand depicted in (a), (c) and (e) refers to the fleet sample considered in this study while grid load results depicted in (b), (d) and (f) are scaled on the Italian fleet size.

The urban mobility demand result to be made by a sequence of relatively short trips and relatively long parking events, with more than half of the fleet share driving for less than 6 trips and 20 km per day and less than 30 trips and 200 km per week. Two BEVs, identified with their performance parameters (i.e. battery size and specific energy consumption), and three recharging behavioural model (i.e. long/short-stop AC/DC and smart AC) are then applied to the data, showing that a fleet share between 10% and 25% is already suitable to be driven electric. Average SOC of the battery results to be about 80% in all the cases considered, with a predicted number of recharges per day between 0.5 and 1. Maximum electric power grid load for the EV fleet of the province of Modena is forecasted to be between 0.4 MW and 5 MW, depending on the strategy, scaled up to a national electric energy demand lying between 0.1% and 1.2% of the Italian monthly energy demand in May 2011 (i.e. 27 TWh), given the electric fleet share mentioned above. Preliminary results concerning the geo-mapping potential of the data are also presented. These results provide a useful insight to address the technological and market impact of the electrification of vehicles in urban areas in the short-to-midterm scenario, based on a large amount of real-driving data. Future developments are foreseen, enhancing the geo-mapping data analysis and the grid-to-vehicle applications.

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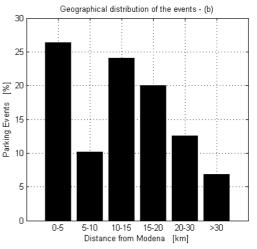
Figure 6: Geographical distribution of the parking events associated to a recharge (a) and distribution of their distance from the centre of Modena (b) for the medium size vehicle (see Table 1), and recharge strategy 2 (i.e. short-stop DC, see Table 2). Red circles in (a) are associated to the distances given on the x-axis of (b) (i.e. 5, 10, 15, 20 and 30 km from the centre of Modena). The blue line in (a) indicates the province border.

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