Electric vehicles and charging strategies to meet urban mobility requirements

E. Paffumi, M. De Gennaro, H. Scholz, & G. Martini
European Commission, Joint Research Centre,
Institute for Energy and Transport, Italy

Abstract

In order to integrate electric vehicles into urban mobility it is necessary to assess the usability and efficiency of hybrid, plug-in and battery electric vehicles. Despite the progress that has been made in this field over the last decade many issues still need to be addressed. These include the limited range of electric vehicles, life cycle assessment of their parts and components, integration with the electricity grid as well as long-term sustainability of Li-ion batteries. This paper analyses real urban driving data collected with GPS devices installed in vehicles. These devices enable to map typical urban mobility needs and driving patterns in detail. The data was collected in May 2011 in the Italian province of Modena. The analysis involved approximately 16,000 vehicles out of more than 50,000 surveyed. The travel data was used to quantify the capabilities of different types of electric vehicles and their ability to meet modern urban mobility needs.

This paper presents the model, the input parameters and the assumptions adopted for the analysis. It examines the relevance of different recharging scenarios against real-life mobility data. The results provide a new insight into the potential electrification of urban transport and development of recharging infrastructure.

Keywords: electric vehicle, mobility, travel behaviour, urban environment, battery, state of charge, charging strategy.

1 Introduction

According to the recent European Roadmap for the Electrification of Transport [1], electrifying individual road transport will increase energy efficiency, reduce

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Greenhouse Gases (GHGs) and noxious emissions, notably in an urban context. European GHGs emission reduction policies aim to maintain the global temperature increase below 2°C. The European Union (EU) is committed to reducing emissions by at least 20 per cent below 1990 levels by 2020, and by 80–95 per cent by 2050 [2].

Despite the recent progress of the automotive industry towards environmentally friendly solutions [3], electric passenger cars are not yet competitive with internal combustion engine (ICE) vehicle technology since the energy storage system cannot yet perform in term of range and costs as the oil tank. Battery production costs are still high, and technology is still under development to achieve higher energy storage capacities. Moreover the successful adoption of EVs will be strongly dependent on their capacity to be integrated into existing electricity network technology [4].

The results presented here analyse driving data from urban mobility behaviour collected with GPS devices in a large sample of vehicles in the province of Modena in northern Italy over a period of one month (May 2011). The analysis focuses on urban driving behaviour patterns and the ability of different EVs to meet the needs of modern car use. In this respect six different types of EVs (from the light quadri-cycle to the big size sports utility vehicle (SUV)) have been considered. The battery recharge was performed according to four different charging schemes: AC, DC, night and smart/off-peak. The behaviour of each driver has been reproduced one-to-one. This provides the numbers of users whose travel needs over one month, could be met by the EV performance and the adopted recharge strategy.

Future developments of this analysis will focus on the assessment of the impact of the electrification of private transportation on the power distribution grid, as well as on advance features such as vehicle-grid interoperability, distributed energy storage networks and smart grids.

2 Background information and methodology description

This section provides a detailed description of the database used in the analysis. It also provides a general description of the method developed to study the use of electric vehicles.

2.1 Description of the mobility databases

Car use behaviour is a crucial aspect that needs to be addressed when examining the potential impact and wide spread use of EVs. To this purpose, a large set of data representing real urban driving behaviour has been used in this analysis. These data were purchased from the private company Octo Telematics [5].

This database contains a large amount of urban mobility data of private and commercial vehicles acquired with GPS black boxes connected via GSM to a remote storage unit. The campaign to collect the data involved 52,834 vehicles (approximately 12.0% of the circulating fleet) in the Italian province of Modena, in the month of May 2011. The analysis is restricted to 16,263 vehicles (30.7%

of the original sample). This is the share of the fleet that were predominantly used in an urban context (defined as more than 50% of trips carried within the province area). The acquisition devices anonymously recorded time, GPS position coordinates, engine status, instantaneous speed and cumulative distance with a variable frequency (in the order of magnitude of 0.01 Hz), enabling a usage profile to be derived for each vehicle. Table 1 presents general data for the province of Modena.

Table 1: General data for the province of Modena.

Population (total)	**Population (density)**	**Registered Vehicles Vehicles per Person**	**Surveyed Vehicles (% of the total)**	**Analyzed Sample (% of the surveyed)**
706,509 (31/03/2012)	262.77/km^2	441,609 – 0.62 (31/12/2011)	52,834 (12.0%)	16,263 (30.7%)

The age distribution of the car users reflects the typical age distribution of the Italian drivers, and the data are assumed to be representative of the Italian population mobility needs and driving behaviour. In support of this the results of our analysis have been compared with the results from other surveys available in literature for other EU countries as well as for the USA [6]. Aside from the effect on the results of the type of survey carried out (face to face or written surveys) the values reported in literature are very similar with those computed in this study.

Table 2: Database sizes at the different steps of the analysis.

Database lines (after cleaning) [$\cdot 10^6$]	**Database size reduction after cleaning**	**Database lines (aggregated per trip) [$\cdot 10^6$]**	**Database lines (aggregated per day) [$\cdot 10^6$]**	**Database lines (aggregated per week) [$\cdot 10^6$]**
15.998	- 5.44%	2.642	0.397	0.0870

In order to analyse only the data representative of real trips, a preliminary filter has been applied to the supplied data: trips with length less than 30 metres and/or duration less than 30 seconds have been filtered out. In addition in order to eliminate spurious records, the data have been submitted to a cleaning and consistency check procedure. This procedure is targeted to filter the trips affected by non-consistent series of engine status (e.g. trips that are not starting with an engine switch-on or ending with an engine switch-off status) causing a reduction in the number of car to 16,223 (-40 respect to the original sample), with a database lines reduction of -5.44% respect to the original size. The data have been then submitted to an aggregation procedure (per trip, per day, per week and per month) to improve the effectiveness of the post-processing. Table 2 summarises the results of these procedures. The number of aggregated lines per month is equal to the number of car users.

2.2 Description of the electric vehicles study method

To better evaluate the ability of EVs to meet daily urban driving needs a tool has been developed based on the available data. The input data for this tool are: battery and vehicles parameters (e.g. battery size and specific energy consumption of the vehicles considered) recharge strategies (defined as recharge constraints, e.g. minimum parking duration to recharge) and the energy consumption of vehicle auxiliaries.

2.2.1 Battery and vehicles parameters

Table 3 summarises the data for the six EVs selected as reference in this work from a real test-drive, Environmental Protection Agency (EPA) [7] and related battery characteristics. The energy consumption for these vehicles already includes use of auxiliaries such as heating, ventilation and air conditioning (HVAC) system, radio, lights, etc. The battery is also characterised by a minimum and maximum allowed State of Charge (SOC), below or above which the battery will be damaged. In this model the minimum and maximum SOC are set at 20% and 95% of the nominal energy capacity of the battery. In daily life this is not visible to the EV user since the usable SOC window is set by the manufacturer in the battery-vehicle performance control electronics to prevent unwanted damage to the battery.

Table 3: Summary of the main EVs data used in the analysis, and from drive tests [EPA, 2012].

Vehicle Type	Curb Weight [kg]	Electric Motor [kW]	Battery Size [Wh]	Energy Consumption from Driving Tests [Wh/km]
Light quadri-cycle	450	13	13,000	70
Small size car	1,080	47	16,000	186
Medium size car	1,521	80	24,000	210
Medium size car (high performance)	1,815	125	32,000	205
Large size car	2,108	310	85,000	236
Large size SUV	2,600	300	85,000	265

The self-discharge of the battery is also considered. This is when a battery is left to rest for a long time. Self-discharge is applied when the vehicle is parked and 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 battery energy capacity per month [8]. This

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value is then scaled to the time of parking of the vehicle, when no recharge takes place.

2.2.2 Recharging strategies

In this study four possible recharge strategies have been introduced, based on charging scheme quoted in the literature [9]. In a future scenario with a widespread diffusion of EVs, it is easy to imagine that the electricity market will adapt to serve the increased energy demand. Therefore the EVs will not be just a passive load on the grid but they will probably interact with grid in a smart way. In this analysis these effects are not considered. It is assumed that the recharge event is only submitted to selection criteria based on the strategy constraints with the same probability to occur for each strategy.

The four recharging strategies chosen are based on time constraints of the parking of the vehicle plus additional optional conditions. Strategy 1 and 2 select as a recharging window each parking event with duration more than 120 minutes. The strategy 1 recharges the vehicle at a nominal power of 2 kW (e.g. house-built electricity grid, alternate current AC), while strategy 2 recharges the vehicle at the nominal power of 40 kW (e.g. fast-charging columns, direct current DC). Strategy 3 has been designed to take into consideration home-charging devices in night time. The recharge is performed at 2kW, only between 10 p.m. and 7 a.m. and only if the parking has a minimum duration of 4 hours. Finally strategy 4 is similar to strategy 3, allowing the recharge only in a time window of 4 hours centred on the minimum of the energy request (around 4 a.m. of each day except on Sundays where it occurs at around 7 a.m.).

Table 4 presents the details and the constraints of the considered recharging strategies

Table 4: Details of the recharge strategies defined in the algorithm.

Strategy number and name	Time constraint	Power, kW	Input Parameters
1 = Long-Stop AC	Stop > 120 min	2	Parking duration
2 = Long-Stop DC	Stop > 120 min	40	Parking duration
3 = Night-charging AC	Stop between 10 p.m. and 7 a.m. of day after AND Stop > 4 hours	2	Parking duration and night time window
4 = Smart AC	Min – 2h < Stop < Min + 2h, where Min = minimum of the energy request from the grid	2	Parking duration and smart time window

The EV driving possibilities are evaluated according to the driving patterns from the databases and related charging at charging spots, considering each trip as a discharge event and each parking as a recharge opportunity. At the beginning of the single vehicle trip sequence the SOC of the battery is set to its maximum (95% of the nominal energy capacity), and then it discharges and recharges according to the user's profile. The energy needed to cover the distance of the trip is calculated, considering the energy consumption per km of the vehicle and battery type defined. If the SOC allows the trip because it is higher or equal to the energy needed to cover that trip, plus the eventual energy of the auxiliaries in operation during the trip, then the trip is counted as "done" and the SOC of the battery is updated subtracting the total energy of the trip. If instead the SOC does not allow the trip, the trip is marked as not done and the SOC is not updated, but left equal to that at the end of the previous trip. The conditions needed to perform a recharge are then verified and in case they are satisfied, the SOC is updated with the energy stored during the recharge. The recharge is performed for all the duration of the parking up to the maximum of energy allowed for the battery and the SOC updated correspondently. When the maximum SOC is reached the recharge is discontinued even though the vehicle is still parked. The self-discharging of the battery is imposed when the recharge does not take place and the vehicle is parked.

3 Results and discussion

This section describes the results obtained with the developed method. Before discussing in detail the EV results, about successful trips per EV and recharge strategy, a brief summary of the characteristics of the driving pattern, such as duration and length of the trip and parking time from the Modena database, will be presented.

3.1 Driving behaviour studies

Table 5 presents selected average results obtained with the analysis of the urban driving behaviour. This table shows a mean number of 6.6 trips per day, a mean distance of about 8 km for trip, an average time of the trip of nearly 12 minutes and an averaged parking time of approximately 4 hours. These numbers have been calculated for the province of Modena, but they have been verified to be in line with a further test-case study conducted for the province of Firenze [10] and more studies available in literature [6].

Table 5: Results from the analysis of the database of Modena.

Province	**Number of vehicles**	**Number of trips per day (average)**	**Mean trip distance [km]**	**Mean trip duration [min]**	**Mean parking time [h]**	**Mean trip velocity [km/h]**
Modena	16,223	6.6	7.8	11.7	4.0	29.0

Figure 1 shows the percentage of the total fleet in motion at the same time, averaged over the values calculated for the four weeks of May 2011. Three traffic peaks can be observed from Monday till Friday, in the morning (approximately at 7.30am), in the middle of the day (approximately at 12 noon) and in the evening (approximately at 6.30pm). During the weekend (Saturday and Sunday) the shape of the curve looks quite different, with two peaks only: a first approximately at 12 o'clock and a second in the evening, approximately at 7 o'clock. The mobility patterns are periodically repeated in the working days, and they never exceed the 11.73% of the total, with a mean value equal to 4.29%.

In Figure 2 the results concerning averaged trip length (2-a), and parking duration (2-b) are provided for the analysed fleet. The results show that the averaged trip has a mean length between 5 and 20 km for daily and nightly values respectively. Moreover the averaged parking time is approximately between 2 and 12 hours.

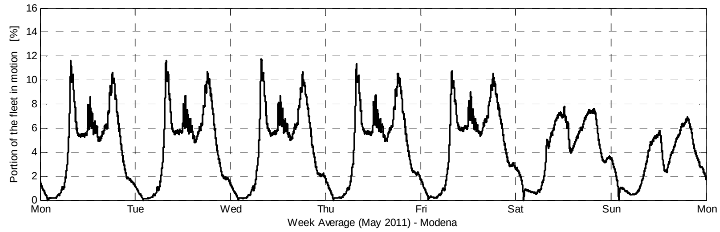
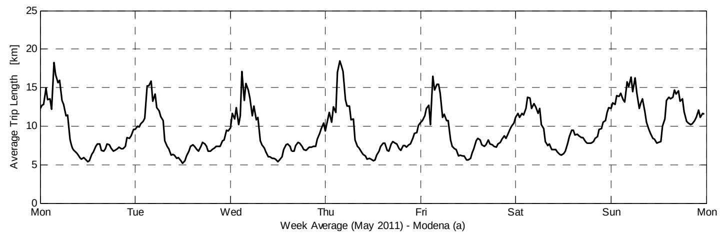


Figure 1: Averaged percentage of vehicles in motion (total fleet) during the week for Modena).



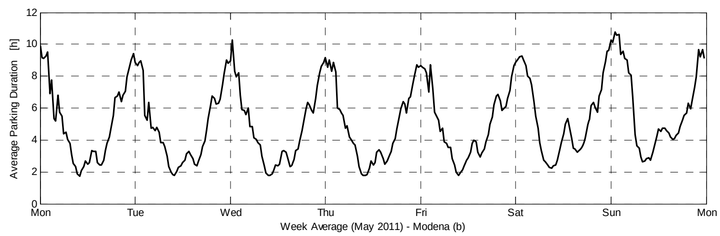


Figure 2: Averaged trip length (a), and parking duration (b) during the week for Modena.

In Figure 3 the histograms of the Probability Density Function (PDF) of the number of trips, cumulative trip length and cumulative parking duration are provided as percentage of the total and aggregated per day, from (a) to (c) and per week, from (d) to (f). These distributions show that more than half of the users make less than 6 trips and travel less than 20 km per day and 20 trips and travel less than 200 km per week, being parked for more than 90% of the time. Comparing these results with the average performance of the earliest EV available on the market, it is clear that a large part of the urban vehicles are suitable to be hybridized or electrified, with the associated benefits of reduced oil demand and polluting emissions.

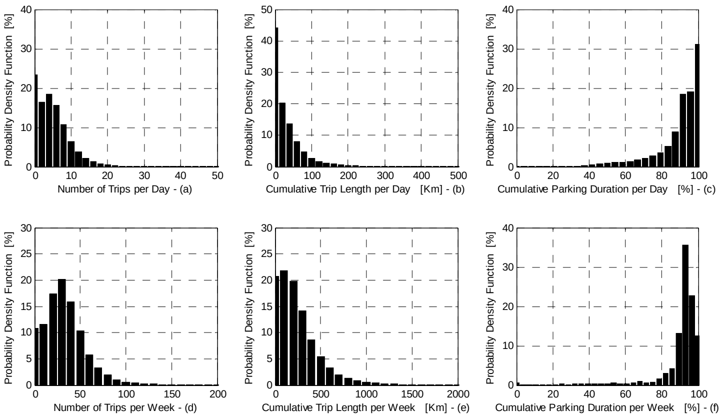


Figure 3: Probability Density Function (PDF) histograms of the number of trips, cumulative trip length and cumulative parking duration per day and per week for Modena, from (a) to (f).

3.2 Electric vehicles studies results

3.2.1 Successful trips by vehicle type and recharging strategy

The percentage of successful trips in the month for all users, together with the percentage of the users that can cover all their trips in the month, can be derived if all the vehicles in the databases are considered electric and of a given type.

Figure 4 shows these results for the six different vehicle types and for the each of the four recharging strategies (Table 4). In this graph black bars represent the percentage of the trips covered by EVs in the month (referred to the total amount of trips contained in the database, per vehicle, per strategy), while the white bars represent the percentage of EVs that could covered 100% of their trips in the month (referred to the total amount of vehicles contained in the database, per vehicle, per strategy).

The percentage of successful trips in the month considering all the users (black bar) is rather high, more than 90% for all the vehicle types, despite the battery size and car consumption per km. The smart recharge, (d), has a lower percentage of successful trips in the month. This is due to the conditions for the smart recharge itself that imposes a recharge only in 4 hours around the minimum of the energy request from the grid; hence lower amount of energy will be stored in the battery. Moreover, the vehicle should be parked in this time window and not all the vehicles satisfied this condition. However, more than 80% of the trips were done by all car users in the month, regardless the vehicle type. These results can bring that most of the urban trips, from the database could be covered by EVs and only 10-20% would not. Probably these trips are characterised by long distances and/or short parking durations, and therefore the battery cannot provide the range required to perform the trip. Further analyses, focused on the characterization of these trips, could give the possibility to derive some suggestions for a possible electrification of the urban mobility and deployment of charging infrastructures.

Concerning the car users that could make all their trips in the month with an EV (white bars) the results are more dependent on the type of vehicle. The light quadri-cycle has a high successful rate, between 50 and 75% for the different recharge strategies, being it light (~450kg) and having low energy consumption per km (~ 70Wh/km). Comparing the small and medium size cars this percentage is higher for the high performance medium size vehicle, in respect to the other two types, being the battery capacity higher (32kWh): about 15-30% for the small vehicle, 20-45% for the medium size and 30-60% for the medium high performance. Lower percentage of car users is found for the night recharging strategy (c), scenario commonly foreseen for a widespread use of EVs: approximately 15% for the small vehicle (~16kWh battery), more than 25% for the medium size vehicle (24kWh battery) and 40% for the medium high performance vehicle. It has to be noted however that in this scenario at least a minimum parking of four hours is foreseen, additional condition to be satisfied, rather than only parking between 10 p.m. and 7 a.m. of the day after. Also the smart strategy (d) has a low percentage of car users that can make all their trips in the month, 15, 20 and 30% respectively for the small, medium and medium high performance vehicle, again due to the short time window of recharge (4 hours only). This time does not allow to fully charge the battery as it can happen for instance with the recharge in DC (40kW).

In general it is possible to conclude that approximately 30-40% of the car users could make all their trips in the month with a medium size EV and these users are the possible target for a short-to-midterm electrification of urban transport. With a medium size high performance EV this percentage varies between 40 and 50%. These percentage of users is much higher for the large size vehicle, reaching 70-80% or even 90% with DC charging (strategy (b)) being the battery size (~85kW) and range higher, but the cost of these vehicles limits their possible widespread use in the market in a short-to-midterm. The percentage for the large size SUV is also high but slightly lower due to its higher weight.

Besides the specific mobility needs in urban areas, where travel is often undertaken in congested conditions and with limited range, other transport needs covering longer daily driving distances at higher speeds will continue to remain [1]. These diverse transport needs will probably lead to further diversification of future vehicle types. The results underline the importance of the battery capacity and specific energy consumption for a possible large widespread use of EVs to meet urban transport demands.

3.2.2 Number of recharges

Table 6 gives the mean daily and monthly number of recharges obtained in the analysis for the six vehicles in relation to the four recharging strategies, only for the car users that could make all their trips in the month in electric mode (white bars of Figure 4). The values are slightly higher for the larger cars with higher

Table 6: Mean number of daily and monthly recharges for the six different vehicle types and the four recharge strategies.

Strategy / EV type		**Str. 1 Long-stop AC**	**Str. 2 Long-stop DC**	**Str. 3 Night AC**	**Str. 4 Smart AC**
Light quadri-cycle	**d:**	1.79	1.79	0.72	1.19
	m:	55.36	55.44	22.43	36.74
Small size car	**d:**	1.56	1.57	0.59	0.89
	m:	48.23	48.70	18.35	27.68
Medium size car	**d:**	1.66	1.68	0.65	0.95
	m:	51.41	52.18	20.31	29.30
Medium size car (HP)	**d:**	1.74	1.77	0.70	1.01
	m:	54.00	54.73	21.66	31.17
Large size car	**d:**	1.82	1.84	0.74	1.05
	m:	56.40	57.01	22.82	33.69
Large size SUV	**d:**	1.81	1.84	0.74	1.05
	m:	56.10	56.96	22.52	31.43
d : day; **m:** month					

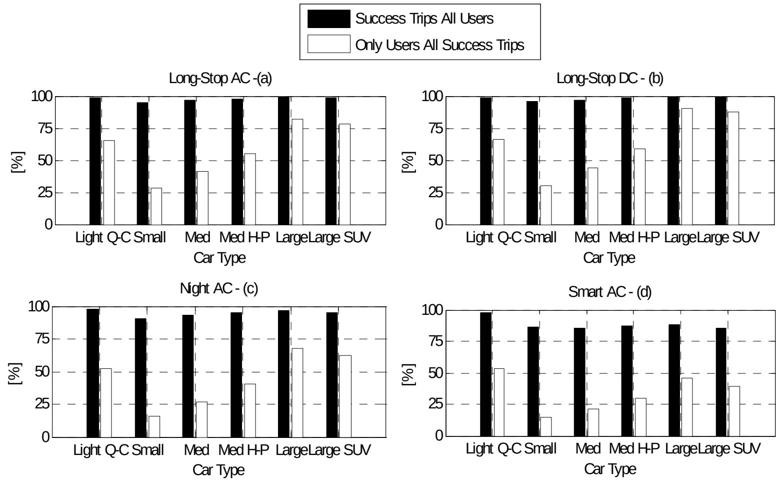


Figure 4: Percentage of successful trips for all users for each EV type and each recharge strategy (from a) to d)) compared with the percentage of users that can cover all their trips in the month by the given EV and recharge strategy (white).

consumption per km. The mean number of monthly recharges for the scenarios examined is approximately 50 recharges a month. In one year the battery could be recharged approximately 600 times in this conservative scenario of more than one recharge a day. In the less conservative scenario, for instance considering the night recharge, once a day, the battery number of recharges in the year are half. Human behaviour is also important in the recharging behaviour so as the practical aspects of being able to make the trip with the remaining energy stored in the battery. In this analysis the behaviour of the drivers was not considered. Only the conditions of recharges were verified.

4 Conclusions

This study developed a methodology to determine the potential of EVs to meet the urban drive needs of a mid-size province. The method relies on real driving data collected by GPS black boxes installed in approximately 16,000 vehicles in the province of Modena. Predominantly urban car use data were used therefore this analysis is limited to individual urban road transport only.

The results show that the portion of the fleet which is contemporary in motion is always below 12% of the complete fleet.

The time analysis of the traffic shows three peaks (morning, noon and evening) in the working days and two peaks in the weekend (noon and evening only).

The mean number of trips per day of each vehicle results is approximately 6.6, with an averaged trip length which lies between 5 km (day) and 20 km (night) and an averaged parking duration between 2 hours (day) and 12 hours (night). More than 90% of the fleet is parked for more than 80% of the time.

On the basis of these results, the possibility of introducing EVs in urban areas has been addressed. This analysis is targeted to assess the ability of six different types of EVs and four different recharging strategies to meet real urban mobility necessities. Applying this methodology, an estimate of the percentage of trips that all the users of the database can cover in a month, together with the number of all users that could cover all their trips in the month have been derived.

Approximately 30-40% of the car users could cover all their trips undertaken in one month with a medium-sized EV, depending on the selected recharging strategy.

The percentage of total number of trips, covered in the month by all users, is approximately 90% for a small-and medium-sized EV.

The scenarios of more than one recharge a day equates to approximately 50 recharges a month and 600 recharges a year.

Future research could focus on the seasonal variation in EV use, addressing more specifically the aspect of the human behaviour, together with an extension of the analysis to other cities or European countries.

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