Analysis of real driving data to explore travelling needs in relation to hybrid–electric vehicle solutions

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Analysis of real driving data to explore travelling needs in relation to hybrid–electric vehicle solutions

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Abstract

The paper presents a methodology and an analysis applied to a real-life dataset, which refer to an extended period that lasted more than one year, pertaining to trips undertaken in Europe by more than one thousand vehicles. The results in this paper are an example of the detailed information that can be extracted from rough data to support the decisions of stakeholders and final users (e.g. car makers, authorities, drivers) in order to understand which road vehicle will be able to comply with the actual daily usage of automobiles in the next few years.

The main scope of the paper has been to focus on variables concerning the duration and lengths of trips, the idle times, and the energy consumed by engines. These variables have been correlated and compared with the current and expected hybrid and electric ranges of autonomy, as constrained by the present and next generation of electric batteries, both in terms of autonomy and time required for their recharging. Therefore, the aim of the study has been to find answers to the following research question: considering the daily mileage, actual fuel consumption and idle time structure, can hybrid and electric powertrains represent adequate alternatives to traditional engines, considering the present battery ranges and charging alternatives?

Long distance trips have been analysed in detail to obtain a better understanding of whether they can be covered by electric cars in the same ways as they are with engine-based ones. In the extensive sample that has been analysed, in order to satisfy 99,9% of the trips, it would be necessary to raise the range to 400 km/day. This target could be reached by adopting a PHEV (plug-in) or a full-electric car with an equivalent range. This study provides a quantitative analysis of the energy needs, obtained over a wide range of usage of road vehicles, and attempts to correlate them with the opportunities of recovering energy during the idle time detected over real-life 24h driving cycles, assuming the availability of intermediate charges.

Keywords

Electric and hybrid automobiles; Real driving cycles; Private road transport; Data analysis; Driving classification; Battery autonomy; Vehicle electrification.

1 Introduction

In recent years, local authorities have been developing measures to limit road traffic in cities with various constraints, which have mainly been environmentally oriented. This is especially due to the high levels of pollution, as well as the European targets regarding the environmental impact of ICEs – *Internal Combustion Engines* – (95 gCO_2/km at 2020-21[1]), energy consumption and the concentration limits in urban contexts. In consideration of these measures, opting for a motorised private transport has become a more complex decision.

The automotive field has recently been undergoing technological innovations due to some aspects, such as: complex environmental dynamics, greater safety and higher economy savings, both for car makers and customers. All these aspects have become more important than in the past, but the engineering process results to be slower and more expensive than in the last century. Consequently, the margin of error is minimal. In particular, for the industrial sector, decisions must be taken after a detailed analysis of real premises and market conditions, because, should they be wrong, the result would lead to irreversible consequences. Recent events confirm that the automotive field needs to undergo changes, because old policies have to be up to date with the current situation. To justify the issuance of new standards, some key events, such as the traffic restrictions applied in many cities in order to reduce air pollution, the scandal of "Diesel Gate" in the USA and the European adoption of a new vehicle homologation cycle, WLTP (*Worldwide Harmonized Light–Duty Vehicle Test Procedure*), instead of NEDC (*New European Driving Cycle*), which has been considered to have discrepancies over the reality [1], [2], [3], [4], [5] ,are reported hereafter. Many studies have explored the discrepancies between ICE, especially when compared with the efficiency of electric motors, and have confirmed the advantages of the latter in relation to a higher efficiency and consequently better emissions at low loads (e.g. in cities, during stop and go motion phases, etc.).

The main purpose of this research is to show the results of an analysis regarding car driving habits, detected using a dataset obtained from automobiles in use in Europe. Some relevant travel aspects (variables) concerning the lengths and durations of journeys by car, related to their general location (urban, extra–urban and motorway), were collected. Moreover, the idle times after the journey were analysed, as they provide an opportunity to charge electric vehicles. The analysis has in particular focused on long trip data, as they represent the critical aspect for car electrification. The study has attempted to understand whether these new automotive technologies would be able to satisfy user

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[1] Source (European Commission, Horizon Programme 2020):
https://ec.europa.eu/programmes/horizon2020/en/what–horizon–2020

demand, and if so, which traction technology or powertrain would be the best choice or at least a suitable one for future mobility.

1.1 Environmental trends in the European Union

Light-duty vehicles are responsible for 13.5% of the global CO_2 emissions, and when extraction and the supply chain are considered, the percentage reaches 15%[2]. Car makers would find it difficult, or even impossible, to satisfy both the environmental constraints imposed by the European Community (Regulation (CE) no. 443/2009 and modification no. 333/2014) and the new homologation test cycle, WLTP, which was activated in 2017, but only for traditional engines. The European target for 2020-21 has been set at 95 grams of CO_2 per kilometre for passenger cars. ICCT (*International Council on Clean Transportation*)[3] reports the EU target for CO_2 according to variations of the vehicle mass, as CO_2 production depends linearly on the mass.

If a car maker does not respect the main community target of CO_2, it has to pay penalties to a European institution. In fact, starting from 2012, if a car maker exceeds – with its automobiles – the limit threshold of CO_2, considering the mass and average emissions of the whole vehicle fleet, it must pay a penalty to the EU, in proportion to its registered new cars[4]. Starting from 2019, it has been planned that the penalty will be equal to 95 €/g, even for the first grams of CO_2 over the limit imposed by the EU. On the other hand, the European Union has started to provide some eco–bonuses for car makers that equip new vehicles with innovative technologies to reduce emissions. Most car makers are investing in vehicle electrification to comply with such environmental constraints.

1.2 State of the art on vehicle usage and electrification

Innovative engines and electric motors for vehicles, in addition to conventional ICE, such as hybrid electric vehicles (HEVs), Plug–in Hybrid Electric Vehicles (PHEVs) and Full Electric Vehicles (FEVs), are becoming popular, and this has induced many authors to investigate the relationship between their features and trip needs, where the travelled distance is a relevant factor. In [6], the focus was on PHEVs, whereas [7] explored user preferences for the whole range of electric vehicles. Their study also reported some user motivations and policy implications. Many studies have recently become available

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[2] Source: European Commission Press Release "Further CO_2 emission reductions from cars and vans: a win–win for the climate, consumers, innovation and jobs", Brussels, 11 July 2012. (Online: http://europa.eu/rapid/press–release_IP–12–771_en.htm)
[3] Source ICCT: "Global Best Practices in Fuel Economy Policies", Vicente Franco, Peter Mock, June 2014.
[4] Regulation (EC) No. 443/2009 of the European Parliament and of the Council of 23rd of April 2009, Article 9 (Allowance for excess emissions), subsection 4.

concerning daily mobility and user preferences for electric vehicles, from various perspectives [8]; [9]; [10]; [11]; [12]; [13]; [14]; [15]; [16]; [17].

Moreover, fuel consumption depends on the context of use (e.g. urban, motorway) and on driving habits, and is correlated to air pollution; moreover, it introduces a social cost that should be considered when using a vehicle. Generally, the pollution cost is higher in cities than in extra–urban areas, because it affects the people who live there more directly. The effects on energy consumption and the relationship between location and household vehicle miles of travelling was studied for a dense city (Chicago) in [18]. In [19], the analysis was focused on the range, as a crucial technical feature of Electric Vehicles (EVs): many of the existing studies underestimate the range requirements, as they are generally based on one–day analyses and on the mean values of daily trip distances. These data are not appropriate neither sufficient to answer questions on user needs; longitudinal mobility data result to be more suitable.

Regarding the environmental impact, [20] compared CO_2 car emissions of both ICEs and hybrid electric powertrains; the results demonstrate that: «*the probability that a BEV (Battery Electric Vehicle) produces less GHG (Green House Gas) than an ICE vehicle is estimated at 90%, […] BEVs produce on average 15% GHG more than HEVs and the probability that BEVs produce less GHG than HEVs is estimated at 44% […] estimating a current superiority of HEVs instead of BEVs*». Moreover, as argued by [21]: «*Hybrid vehicles produce fewer emissions than traditional ICE and use less fuel*». It is obvious that FEVs produce a minor environmental impact than the other traction technologies (TTW – *Tank to Wheel* efficiency), but, in order to ensure a proper evaluation, it is necessary to introduce the efficiency of energy production and distribution (WTT – *Well to Tank* efficiency). In fact, «*Technologies that depend directly or indirectly on electric energy (e.g. BEVs, hydrogen cars) do not produce exhaust gases during their use, but they indirectly produce pollution during the energy production […] different emission values depend on the efficiency with which technology uses electricity in its life cycle […]* ».

Other studies closely related to green gases emissions, such as those of [22] and [23], state that the environmental benefits of electric drive cars also depend on the energy–generating mix. In fact, renewable energies and low carbon resources help to achieve the goal. The higher efficiency of electric vehicles than that of ICE vehicles could reverse the actual private transport energy consumption in Europe on the electric grid by one third, and thus encourage less dependency on the oil monopoly [24].

Generally, to reduce the climate effects of a car, such as reducing CO_2 gases and pollution, policy makers have to support and encourage the adoption of electric drive vehicles [25]. However, safety, reliability range and complexity for recharging when equipped spots are not available are the greatest concerns when purchasing BEVs. Moreover, the high cost of new battery vehicles and the low density network of charging infrastructures also stifle market growth [26]. Research has recently been conducted on vehicles emissions, in particular on Full and Mild Hybrid electric powertrains. The results are similar to the previous ones, that is, the longer the electric drive is, the lower the local gas emissions [27].

Although ICEs produce more gas emissions than other traction technologies, the environmental temperature should be taken into account. In fact, CO_2 production and fuel consumption are higher at lower temperatures than at other conditions [28]. Moreover, the efficiency of batteries on electric vehicles depends on the working temperature, and while the heating on ICEs, when needed, is costless, it requires more energy in BEVs. Another real–time–based analysis was carried out on private car journeys in Great Britain, and the results highlighted that cars in the London area on average covered 1000 miles more than in other countries [29]. Moreover, the inhabitants of London represent the population with the lowest number of cars.

In 2016, the share of electric traction vehicles (Full electric and hybrid electric) was 30% of the total number of vehicles in Norway. People were interviewed on their driving habits (lengths, travel times, context of use or driving cycles), and the results showed that electric car owners were on average younger than the owners of other types of cars and that they took advantage of the cheap cost of electric traction to do daily trips. On the other hand, 80% of the full-electric car owners had another Diesel or gasoline vehicle at their disposal to cover longer journeys. The purchasing of electric vehicles depends to a great extent on State subsidies, which reduce the purchase price, and allow drivers to enter into restricted traffic areas, obtain free recharging and avoid the payment of motorway tolls [30]. Moreover, [31] analysed 783 real vehicle speed profiles gathered in Texas. The average covered length was of 62.5 km per day, and a PHEV with 40 km of electric range seemed to be the best choice to satisfy both the driving habits and economic requirements of Texans.

2 Methodology and dataset description

The driving analysis has been conducted by applying two different approaches to the dataset. The first approach was focused on a recorded *single trip*, and trips were classified individually in relation to the length, duration, idle time and context, considering their frequency of use. This first part was important to comprehend what the most frequent car usages were and identify the structure of representative trips.

The second approach was focused on a more general view, considering all the trips performed each day, in order to provide an overview on the *daily usage* of the vehicle. This second step was more important for users and car makers, because it showed how different trips composed the entire daily usage, and provided the daily travelled length and duration with reference to a 24h driving cycle.

Extreme values of daily and single trips were also investigated; in order to better understand the relevance of these trips, drivers were classified according to the number of travelled days in the considered period. Two main groups emerged: the first, sporadic users who travelled fewer than 15 times in 15 months; the second, frequent users who drove more than 15 times. This preliminary step was important to classify how the dataset would be composed and to investigate whether sporadic drivers could affect the subsequent results. A flow chart of the used analysis method is reported in Figure 1 to better clarify these two approaches and illustrate the data they dealt with.

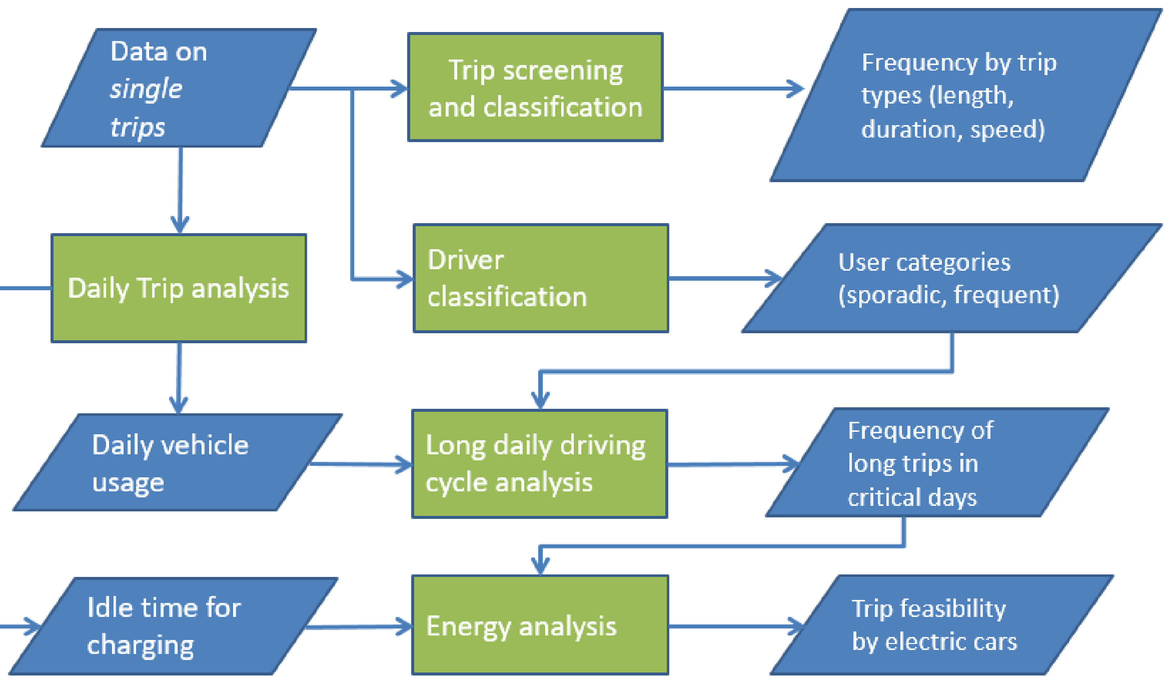


Figure 1: Flow chart of the analysis method with data and procedures

The long daily driving cycles were then analysed, since they are the main obstacle to a wide deployment of fully electric vehicles. According to the maximum length that can be covered by an electric vehicle (an average 300 km, 2017), all the users (sporadic plus frequent) were also analysed according to the single relevant trips they made. Two different scenarios were analysed:

- Single trips longer than 100 km, including days when the total covered length was more than 300 km;
- Single trips longer than 50 km, including days when the total covered length was more than 200 km.

Finally, according to the energy consumed during the daily trips (expressed as covered length), the journeys in which energy could be (or could not be) recharged during idle time after the trip, which may also depend on the available charging power, were identified. An analysis of the travel habits was conducted on some vehicles of the FCA Group (*Fiat Chrysler Automobiles*) whose models cannot be revealed for privacy reasons. Each trip record contained the following information:

- the Market;
- the user ID;
- the vehicle model and its engine;
- the presence of a Start and Stop system;
- the gear shift, with its main information on adopted technology;
- the starting trip day of the week;
- the starting and ending journey time;
- the trip duration;
- the journey type (urban, extra–urban, motorway or mixed);
- the maximum speed;
- the journey length;
- the average fuel consumption (l/100 km) and the total fuel consumed (litre).

On the other hand, since no information was available on vehicle positions, it was not possible to obtain useful data, such as the presence of slopes along the route, or to explain the possible reasons that induced users to take their cars. Each trip started when the engine was turned on; it ended when the vehicle stopped and the engine was turned off. If the vehicle was equipped with a *Start and Stop* system, and it worked regularly during a trip, the control unit considered all the eventual stops within the same single journeys. Moreover, the control unit calculated some driving parameters, such as the energy consumed, the average speed, the numbers of stops and the time spent driving over 50 km/h. Thanks to this algorithm, conceived and developed by FCA, it was possible to classify all the journeys into three categories: urban, extra–urban and motorway.

The cars were used for various types of trips and in different travel conditions: 39.2 % of the total trips were conducted in an urban context, 58% in an extra–urban one and the remaining 2.8% on motorways. A total of 1085 vehicles were analysed, and the vehicles were registered in France, Spain, Germany, the United Kingdom and Italy. A total of 223424 journeys were taken into account. The time window covered from the first day of 2015 until the end of March 2016. As can be seen in Figure 2, the trips registered by users during 2016 were from two to five time higher than the year before. In addition, there may have been a system crash during November 2015 (around week 45).

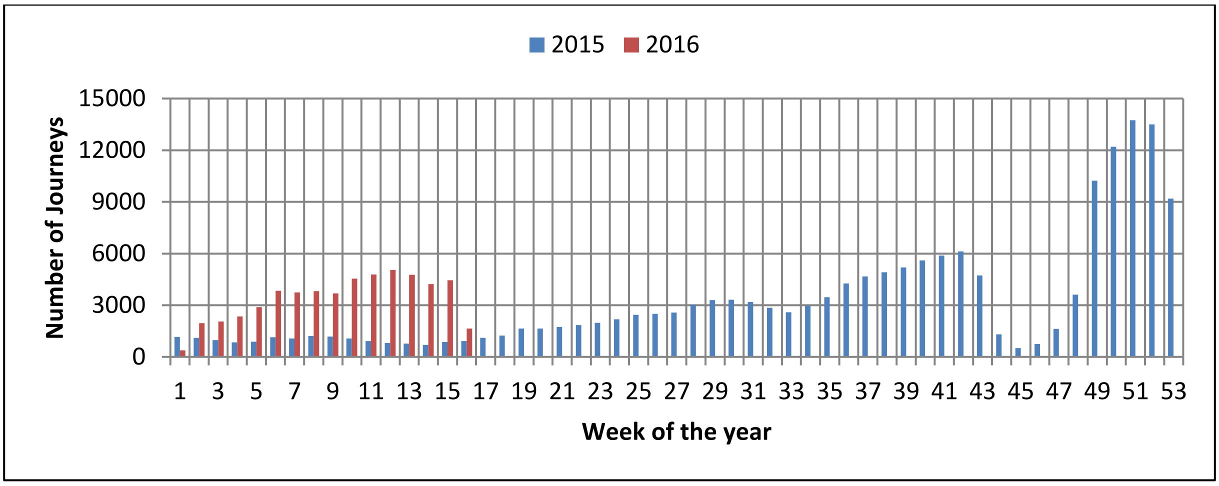


Figure 2: Number of analysed journeys, divided by the number of weeks in the year (from January 2015 to March 2016).

The users were monitored, for each day of the considered period, regarding the duration and length of their trips. As shown in the example in Figure 3, the first line identifies a user who drove eight trips on the 1st of November 2015 for a total of 4553 seconds. Other people undertook different journeys during the same day.

⊟ **1.11.2015**	**73**	**53997**
{0EBF93BE-AF99-4E26-87A9-8D5A9B455065}	8	4553
{2486BDED-0D34-48C4-8EEB-D447317517AD}	3	1792
{2CD77CE3-4A12-4A2C-8F27-838C86E6574E}	2	3808
{3AEC9FF8-E13C-4139-8480-CE08974A39E6}	8	3524
{3E6E232E-A74F-4395-B74C-6F5A020C747B}	5	5193
{4D22DECC-1C3E-494B-8B5E-E904109A8D08}	6	3693
{558F83FE-7AD4-424D-B892-A154ED9331AE}	4	2436
{7541E572-9FC1-47C4-B2BE-DCEDCA3EDBE3}	3	5148

Figure 3: Example of the duration of daily trips per user.

From the obtained data, it was possible to analyse each journey in detail for any user, each of whom was identified with an alphanumeric code. Therefore, it was possible to calculate how many trips had been undertaken and their total length for any specific day, as well as the maximum and minimum values. It was also possible to obtain more details about the individual users: it was possible to ascertain the trips covered by a user over the period together with information on the time, length and the fuel consumed on each trip.

3 Results of the dataset screening

The main results of the preliminary screening of the dataset are listed in the following sub-sections next paragraphs, and they are divided into two groups, that is, urban and all trips together. Two procedures were applied to obtain information on the private mobility structure: firstly, considering the frequencies of each single trip; secondly, aggregating all the trips undertaken in a day to ascertain the range required over 24h.

3.1 Distance travelled analysis

The first variable chosen to define how drivers used their cars, was the distance covered by each trip and globally on a daily basis. The obtained results were useful to assess the mobility ranges on average and to define some guidelines for the best solutions for the powertrains.

Figure 4 shows the frequency of the length of urban trips: 35% of urban trips are less than 5 km and 90% less than 10 km. The most frequent distance covered in a single trip (one way) is 5 km. Only trips longer than 1 km are represented in this figure in order to focus on relevant trips.

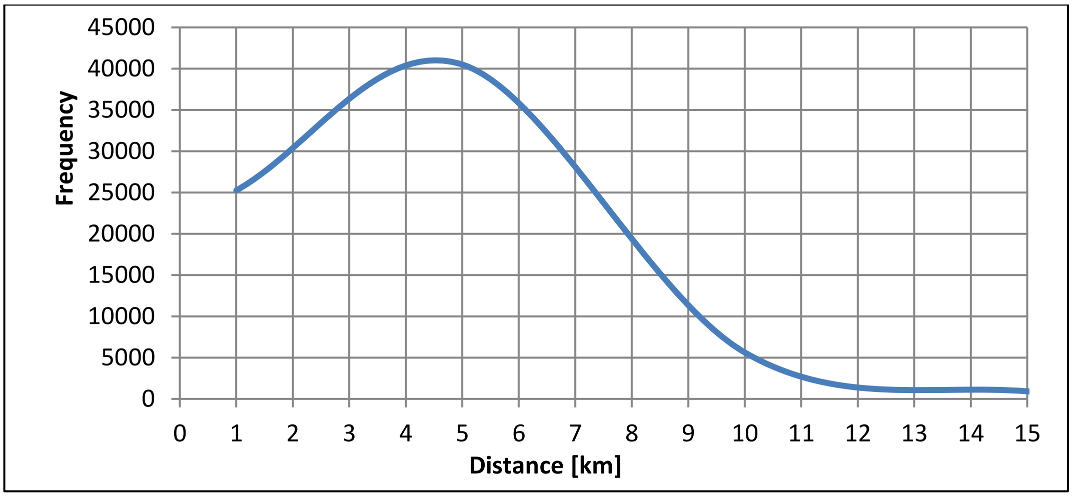


Figure 4: Frequency [#trips] of the distance covered in an urban context for one–way trips.

The relationship between the total urban daily distance and the number of days per user was also analysed. The “Days per user” variable, which is the frequency of the daily covered distance, sums the days when a daily length was observed within the established distance for bin for all the users. The obtained results are shown in Figure 5: 50% of the days per user trips refers to trips of between 0 to 5 km/day and 99.9% refers to less than 50 km/day. Only in 2% of the days is at least one trip longer than 50 km/day observed in an urban context.

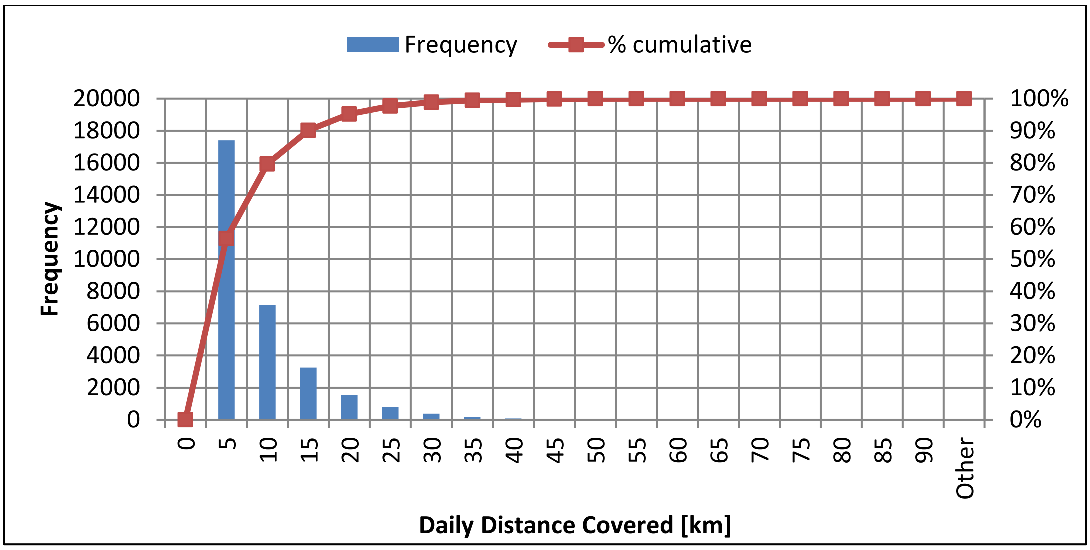


Figure 5: Frequency [#days] of the daily distance covered in an urban context.

Cars usually allow a great variety of trips to be covered: in this section, the trips performed out with the urban context are analysed in order to extend the transport mobility picture, and to identify the single trips and daily average distances covered. Figure 6 and Figure 7 show the frequency of the distance covered by a single trip undertaken in an extra–urban and motorway context: 90% of the extra–urban trips are shorter than 30 km, with one way peaks at around 10 and 30 km. On the contrary, in the motorway context, 10% of the total trips are shorter than 20 km, 35% are between 20 and 60 km long and 55% cover more than 100 km per journey. Figure 7 has intentionally been truncated at 240 km, because the sample is scattered beyond this limit; further details are given in section 4.

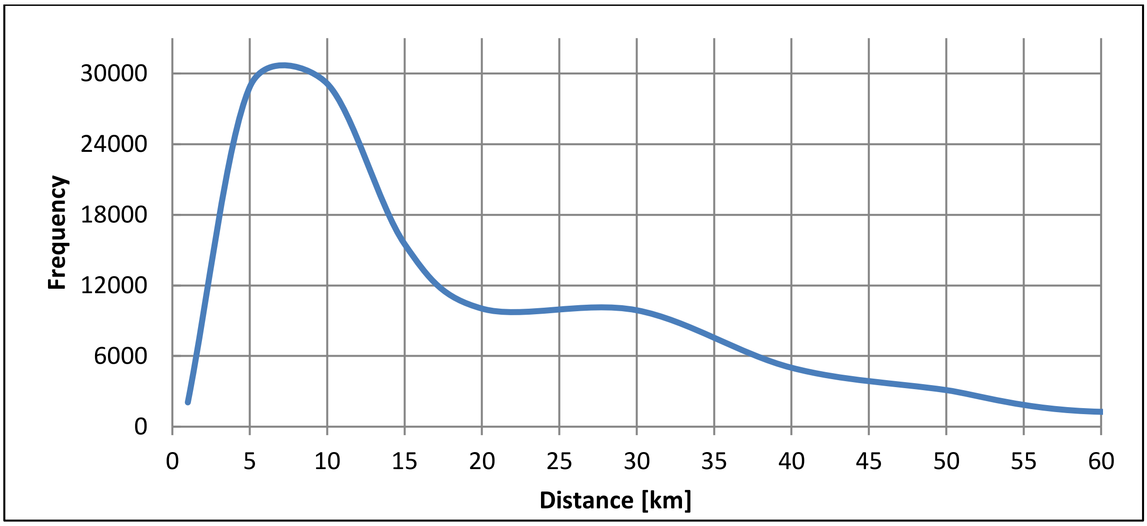


Figure 6: Frequency [#trips] of the distance covered in an extra–urban context for one–way trips.

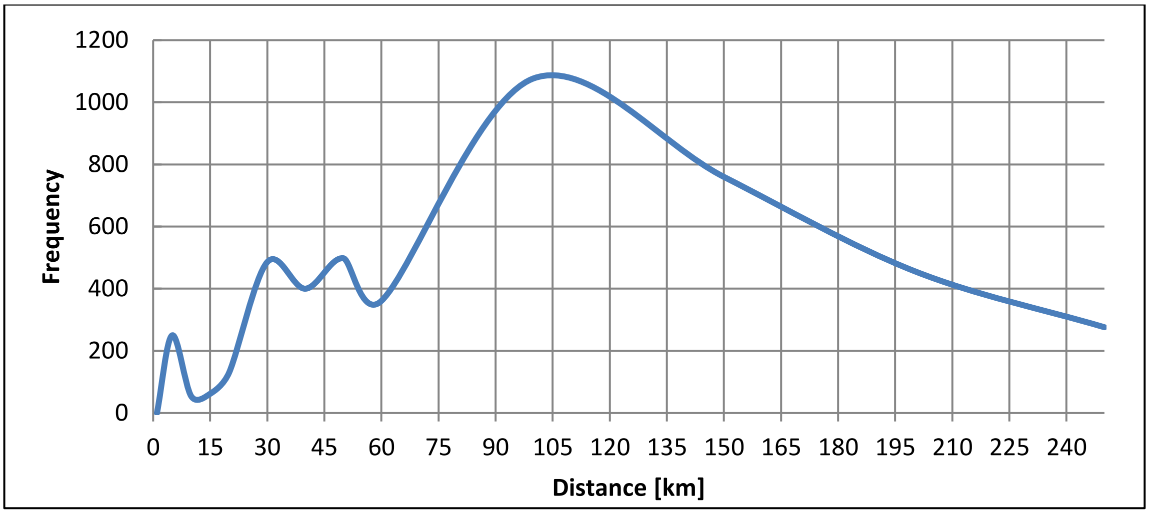


Figure 7: Frequency [#trips] of the distance covered in a motorway context for one–way trips.

The frequency of the daily distance for all the trips is shown in Figure 8. In this context, extended daily trips are relevant, because, although 99% of the days per user covers at most 400 km/day, only 60% of the days less than 50 km/day are observed, whereas this range was observed in 99.9% of the days for an urban context.

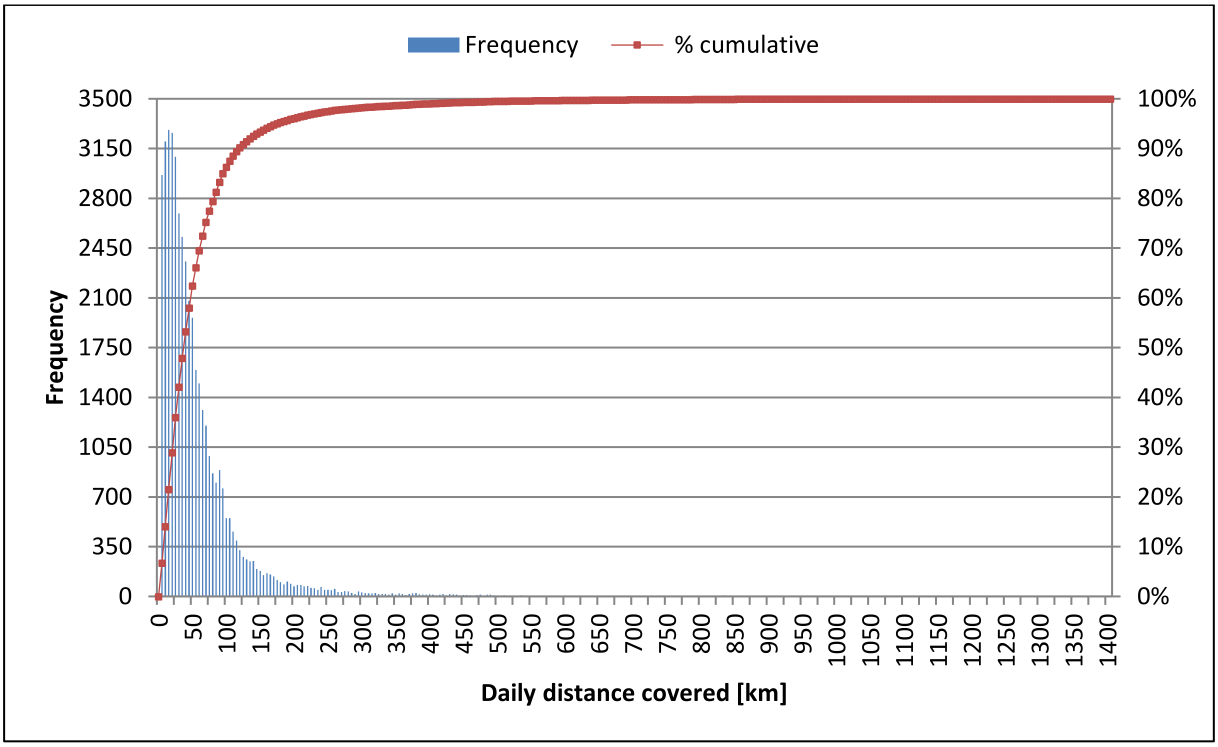


Figure 8: Frequency [#days] of the daily distance covered over all the driving cycles (contexts) for all the trips.

3.2 *Travel time analysis*

Another important variable that may affect the move to electric vehicles, in addition to the trip length is the trip duration. In fact, this directly influences the battery operations and it is crucial for the electric traction system, as auxiliary devices, such as air conditioning, radios and other on-board systems depend only on the battery power. Trip duration has therefore to be taken into consideration appropriately to design the battery size appropriately, in consideration of the power required for the auxiliaries. It has been estimated that an air conditioning system, for both cold and hot temperatures, needs from 1 to 3 kWh of continuous power to operate, and this contribution may not be negligible for extended trips.

The number of registered urban trips was 1037, and the frequency of their daily travelled time is reported in Figure 9. The results show that more than 50% of the journeys undertaken in an urban context were briefer than 16 minutes, 90% were briefer than 52 minutes and 99% were briefer than 107 minutes. The daily trip duration can be ascertained for the urban trips by considering the following statistics: average (22 minutes), median (14 minutes) and mode (4 minutes).   However, the results show that longer trips than 52 minutes were observed for 50% of the days and those longer than 107 minutes were observed for 24% of the days.

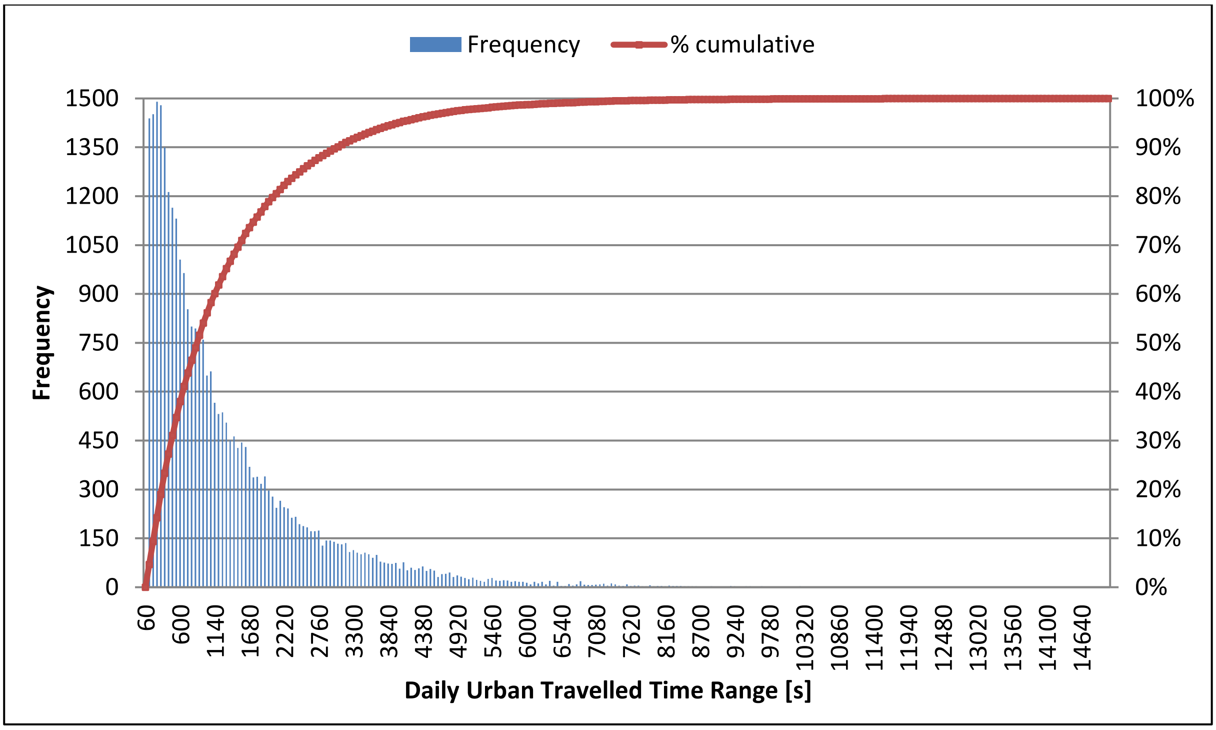


Figure 9: Frequency [#days] of the daily time for travelling in an urban context.

The travel analysis shows that the duration of more than 40% of the urban trips was less than 5’, the duration of more than 50% of the extra–urban trips was shorter than 30’ and the duration of nearly 80% of the motorway trips was longer than 30’ (Figure 10).

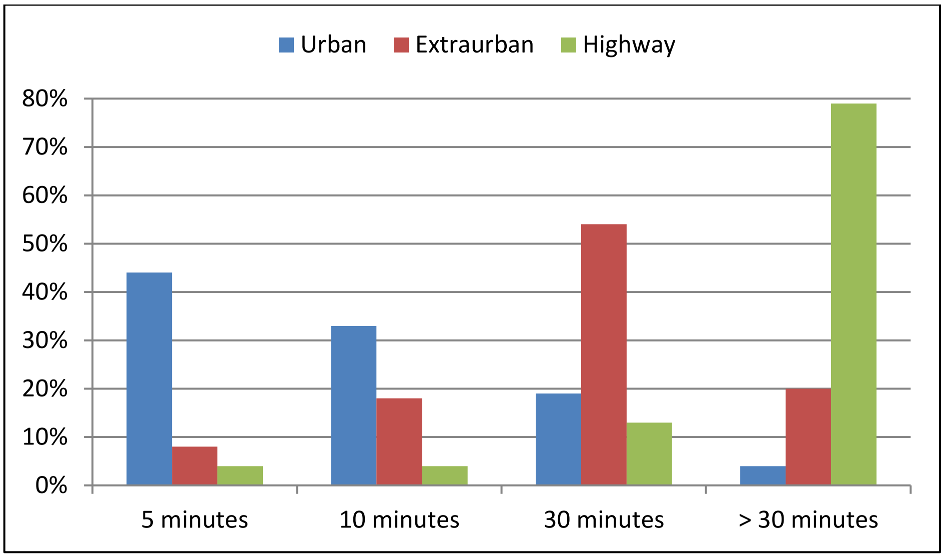


Figure 10: Trip duration of each journey (one–way) divided by the use context.

Regarding the overall number of performed trips, more than 50% had a duration of less than 64’, 90% of less than 2.5 hours and 99% of less than 5.2 hours (Figure 11). Considering the users involved for the same time duration, the results show that 89% of them undertook a trip for more than 64 minutes, 69% for more than 2.5 hours and 22% for more than 5.2 hours. The daily trip duration can be described for all the trips considering the following statistics: average (77 minutes), median (63 minutes) and mode (49 minutes).

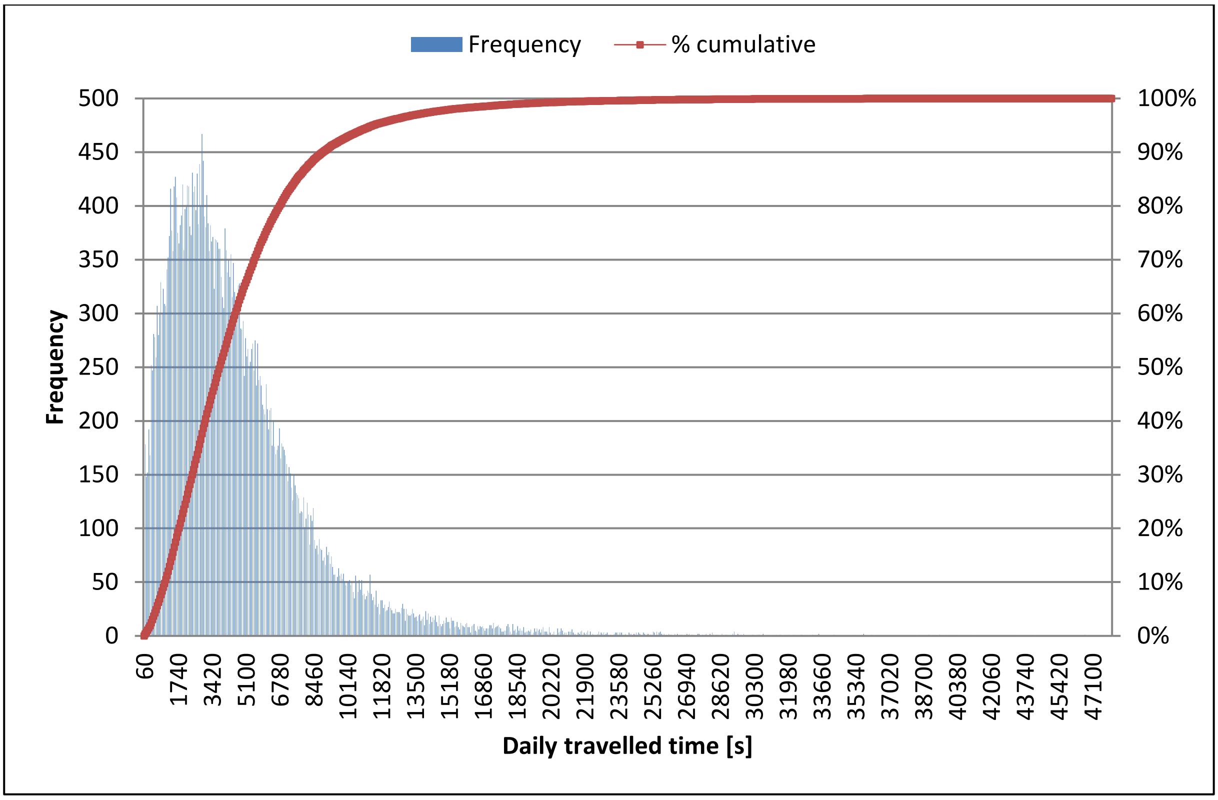


Figure 11: Frequency [#days] of the travel time for all the driving cycles (contexts) and for all the trips.

3.3 Average speed

Another important variable, regarding the average speed of the trips, was extracted to complete the screening of the dataset. In order to avoid the influence of the different national traffic rules on the speed limitation, only the trips pertaining to the Italian market, which, however, represents approximately 66% of the total journeys, were selected for the analysis. The average speed was divided into three groups: urban, extra–urban and motorway. All the very short trips were excluded from the data analysis in order to obtain results about relevant trips, and the entire dataset was filtered considering the following settings:

- Urban: trips >2km and >120 s;
- Extra–urban: trips >5 km and >300 s;
- Motorway: all trips.

Each point in Figure 12, in Figure 14 and in Figure 16 represents a single journey and its covered length and time duration. The upper limit of the urban average speed is approximately less than 40 km/h (red line in Figure 12). The upper extra–urban limit average speed is approximately 80 km/h and a great number of trips are performed with a lower average speed: a small group of journeys are covered faster than the others, but these were considered as non-representative outliers. Almost all of the overall motorway journeys were travelled at an average speed, with a lower limit of approximately 70 km/h (red line in Figure 16) and an upper limit of approximately 130 km/h (green line). The maximum and minimum average motorway speeds were 154.63 km/h and 2.86 km/h, respectively.

Figure 13, Figure 15 and Figure 17 represent the frequency of the average urban speeds. It is important to outline that approximately 50% of the urban journeys show a lower average speed than 20 km/h and approximately 46% fall in the range between 20.1 and 30 km/h. A total of 70% of the extra–urban journeys have a lower average speed than 50 km/h and more than 90% of less than 70 km/h. Finally, more than 50% of the motorway journeys have a lower average speed than 90 km/h and approximately 90% have a lower speed than 110 km/h.

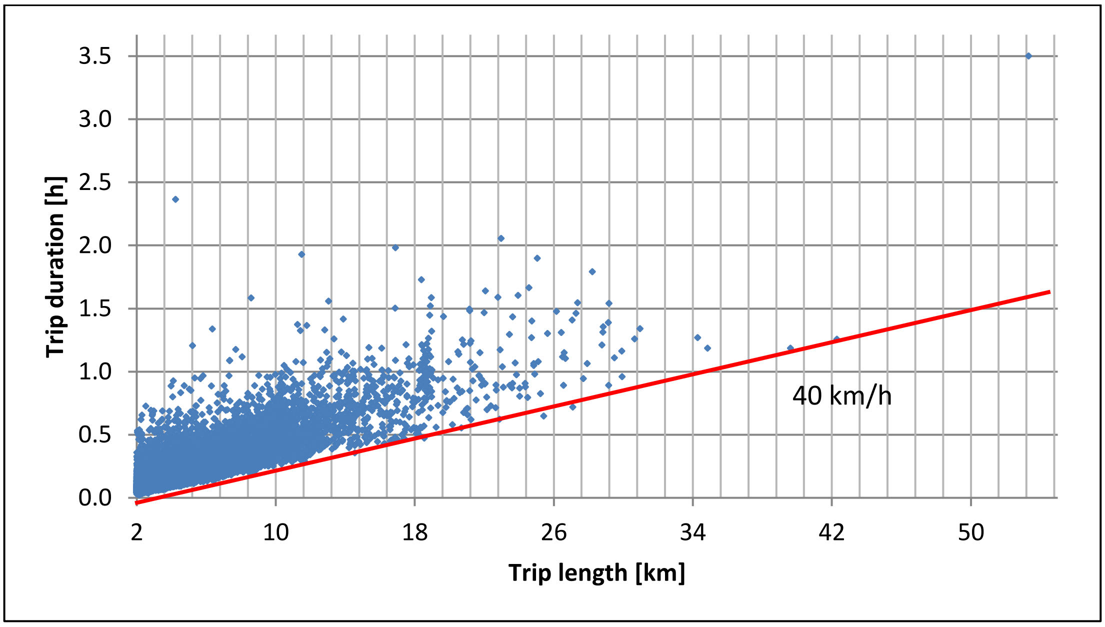


Figure 12: Average speed [length/duration] of the Italian urban trips.

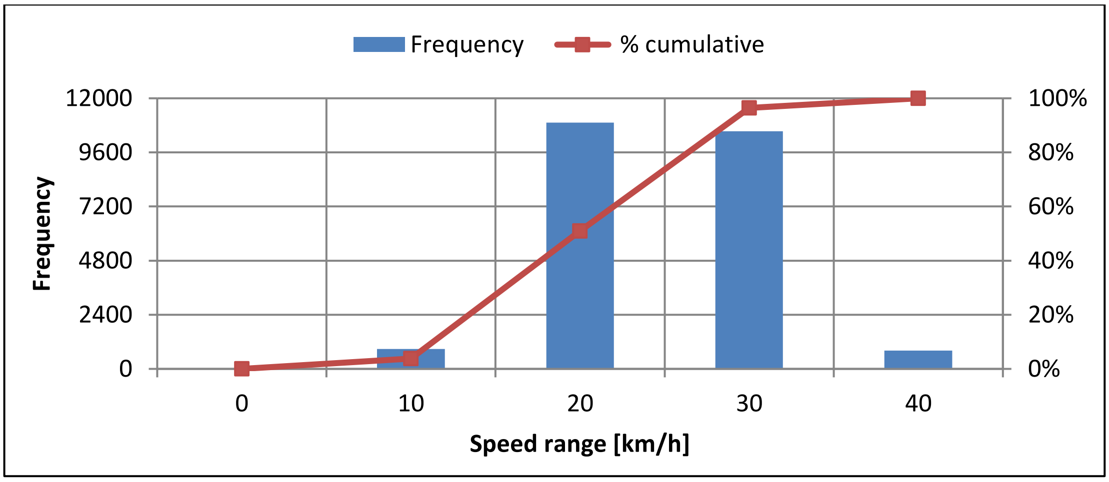


Figure 13: Frequency [# trips] of the average Italian speed in an urban context.

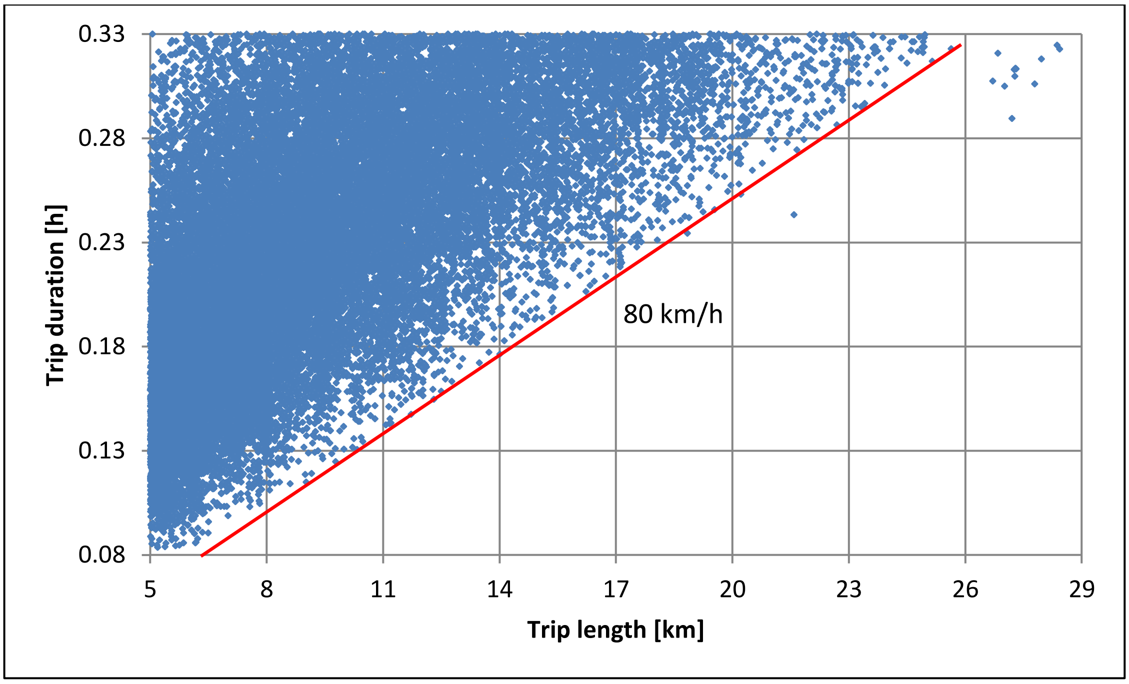


Figure 14: Average speed of Italian extra–urban trips.

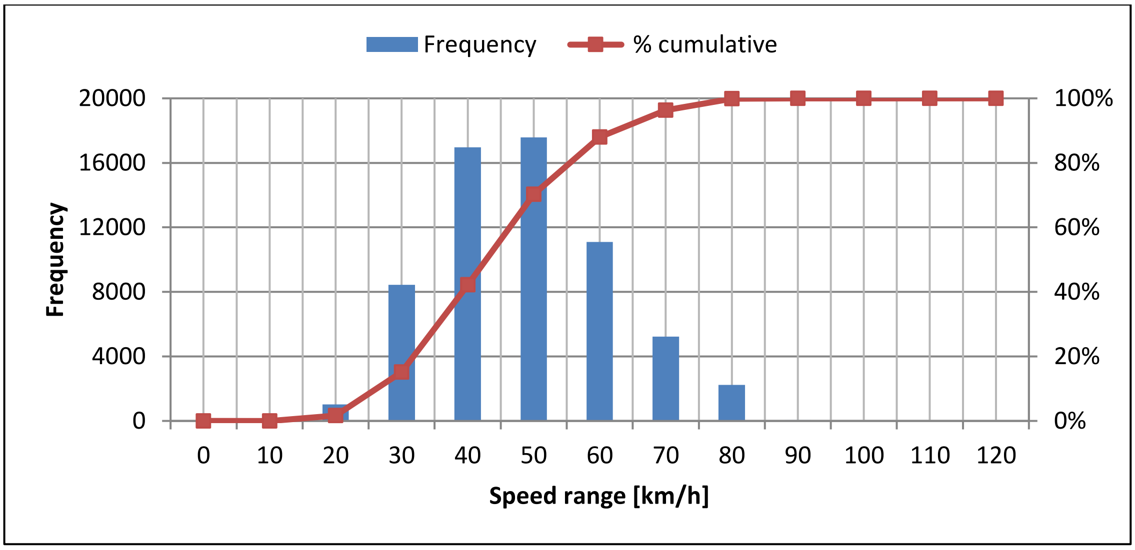


Figure 15: Frequency [# trips] of the average Italian speed in an urban context.

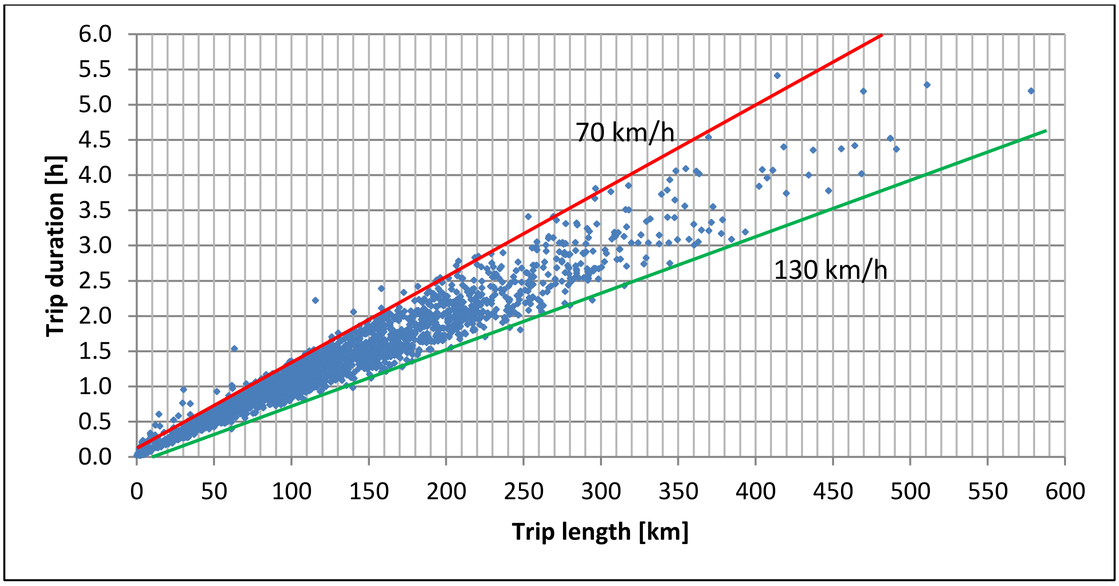


Figure 16: Average speed of Italian motorway trips.

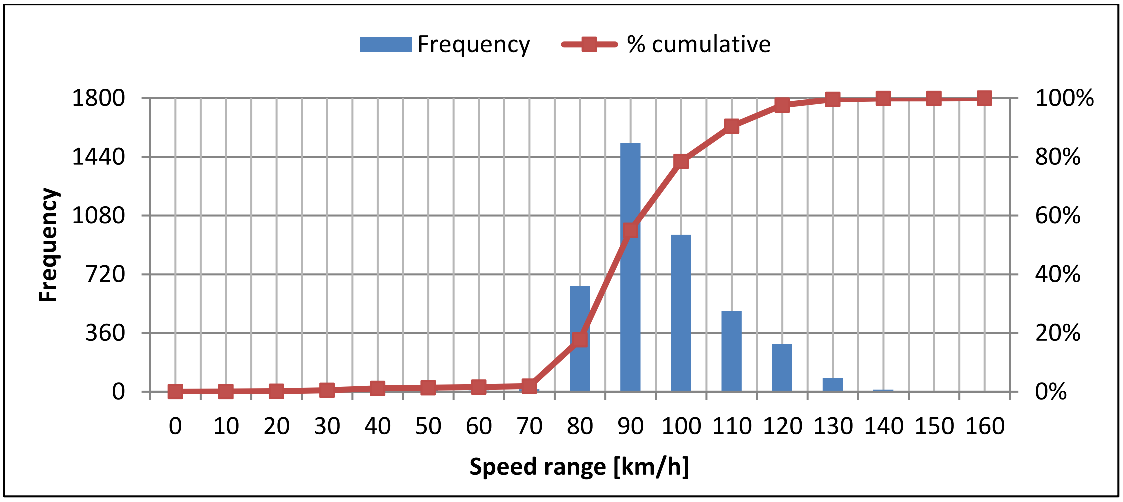


Figure 17: Frequency [# trips] of the average Italian speed in an urban context.

4 Analysis of the longer daily driving cycles

In this section, a specific analysis has been carried out on the same dataset to ascertain whether electric vehicles equipped with batteries that can provide a limited and well-defined range could also be used for long trips. For this reason, this data subset was further explored considering a driver classification, the available BEVs on the market and the opportunities for recharging during the idle time periods after long trips.

4.1 Driver classification

In order to analyse the longer daily trips, it was considered useful to know more about how the sample was composed. The study focused on the daily history of trips over the observed period and the length covered by automobiles. Figure 18 represents the number of days each user travelled with a bin of 10 days over the considered period (1 year and 3 months) and the frequency, expressed as the number of users detected in each bin. Only one user travelled for 280 days over the 15 months, less than 30% travelled from 0 to 10 days, 15% travelled from 10 to 20 days and a decreasing percentage travelled more frequently.

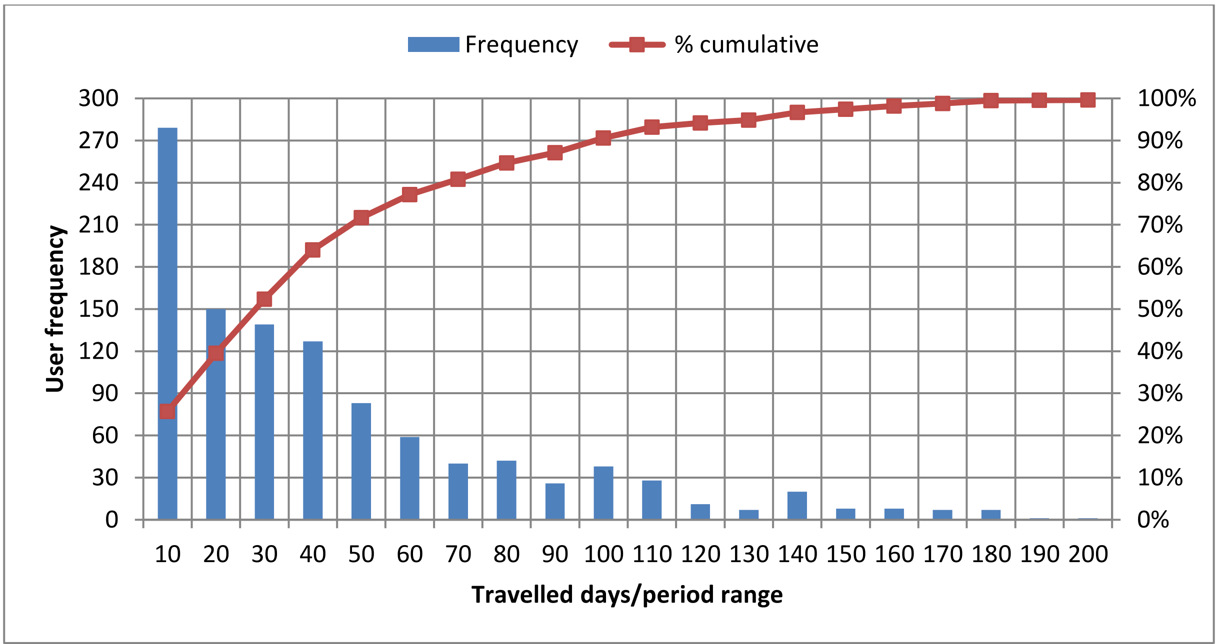
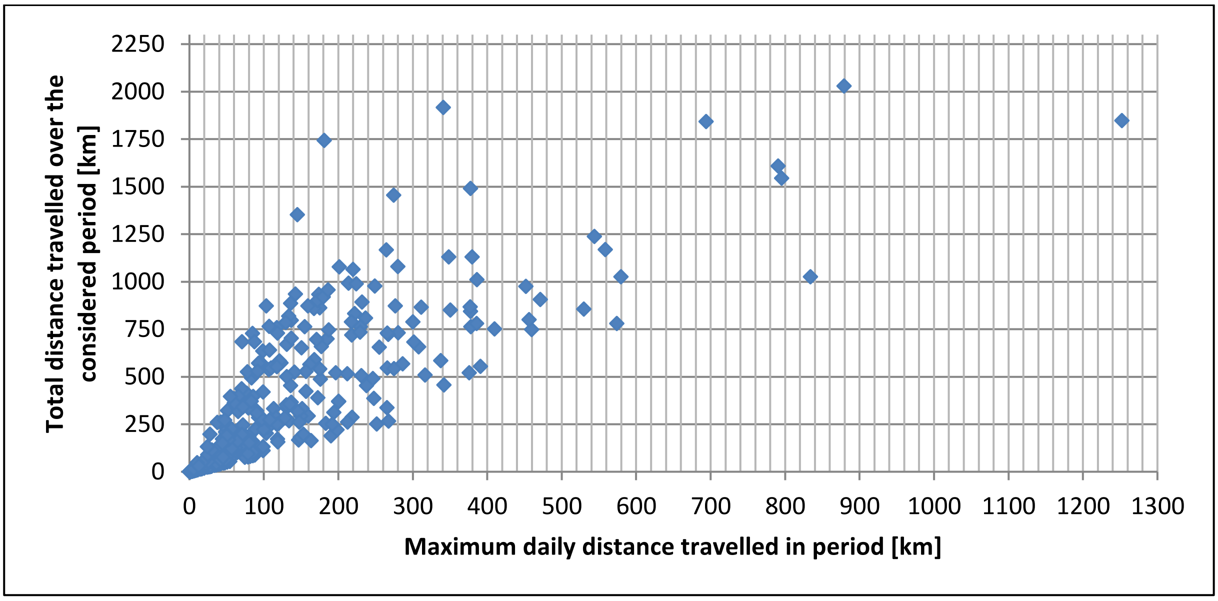


Figure 18: Frequency [#users] of the travelled days over the observed period for all the driving cycles (contexts) and for all the trips.

Considering the heterogeneity of the usage frequency, a classification was proposed to better describe the features of the sample, in which those users observed only for a limited number of trips were separated from those who made more frequent trips. Therefore, a limit of 15 days was assumed below which users were considered "sporadic" (at least one trip each month on average during the considered period). As regards the classification of these drivers, 353 sporadic users completed less than one journey per month (approximately 30% of the total analysed users). The limit value of 15 was decided on considering that the yearly fees for renting a car are cheaper than car taxes and assurances, while the purchasing of a vehicle itself was neglected. According to this assumption, sporadic users may rent a car instead of buying one. A detailed representation of the maximum daily covered distance and the total travelled distance over the considered period for each user is reported for both sporadic and frequent drivers in Figure 19 and Figure 20. Sporadic users did not drive for more than 14 days and travelled a maximum 2000 km (approximately 350 km on average was the distance covered by each user). In addition, as they represent approximately 30% of the total users, the amount of distance they covered was only 5% (approximately 123550 km covered by sporadic users versus 2527769 km covered by all the users).



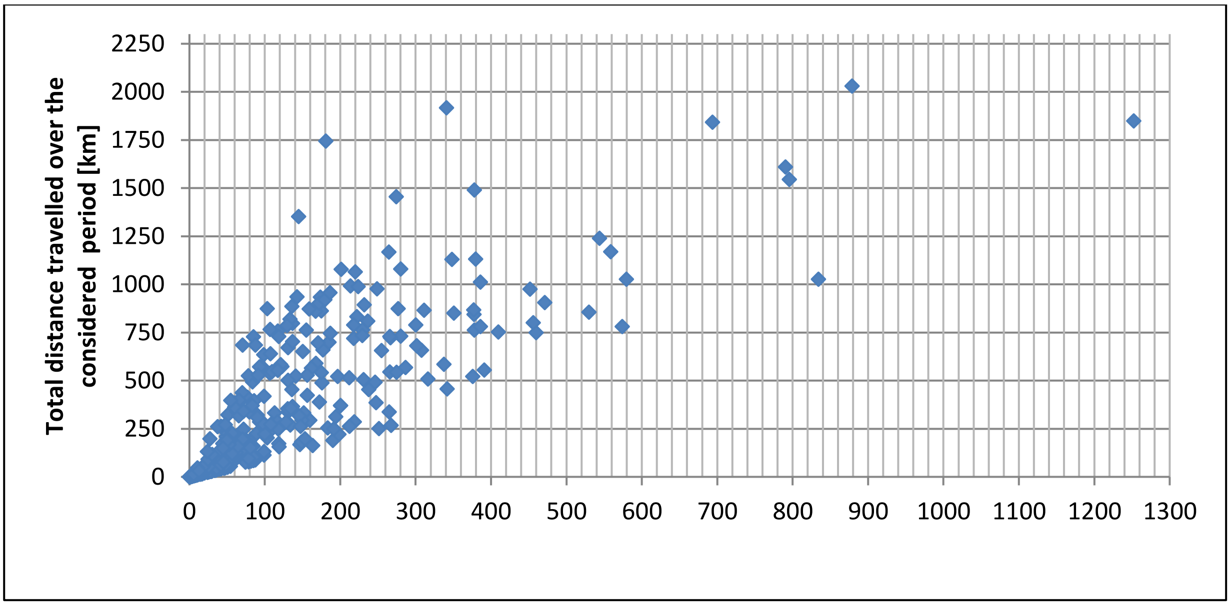


Figure 19: Sporadic users, total length travelled versus maximum daily trips.

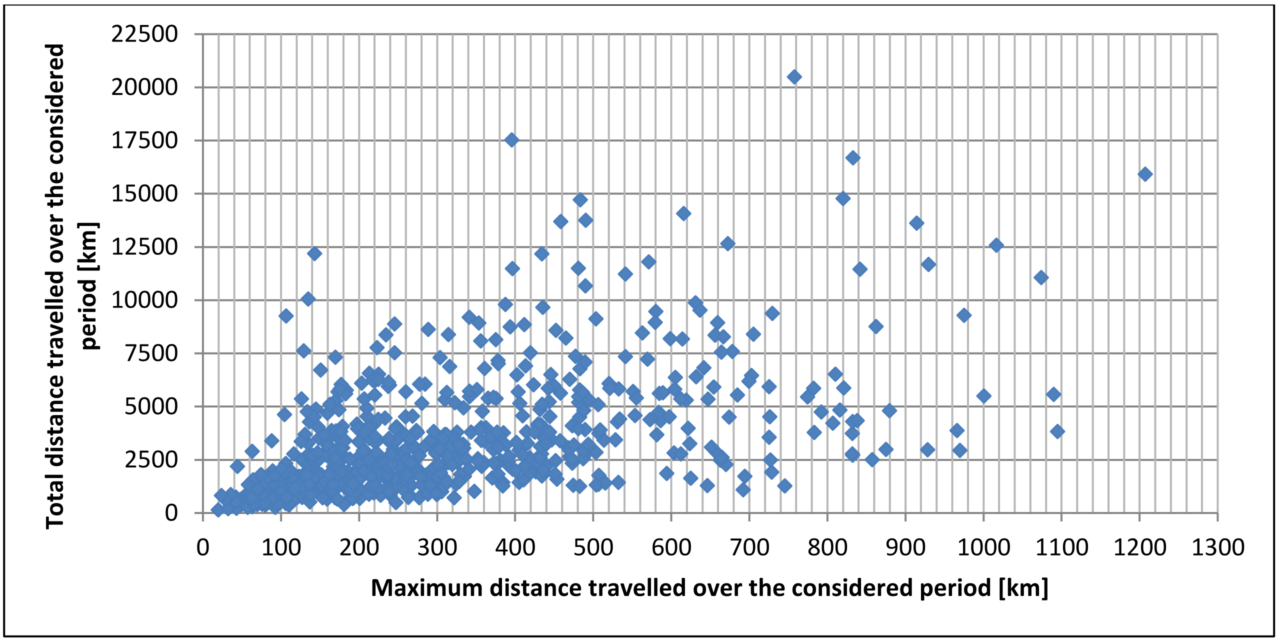


Figure 20: Frequent users, total length travelled versus maximum daily trips.

4.2 Matching long driving cycles and BEV ranges

A matching between the driving demand, in our case described by the recorded trips in the dataset, and market supply, represented by the available full electric vehicles, is useful to understand whether the current electric vehicle range could satisfy the users' needs.

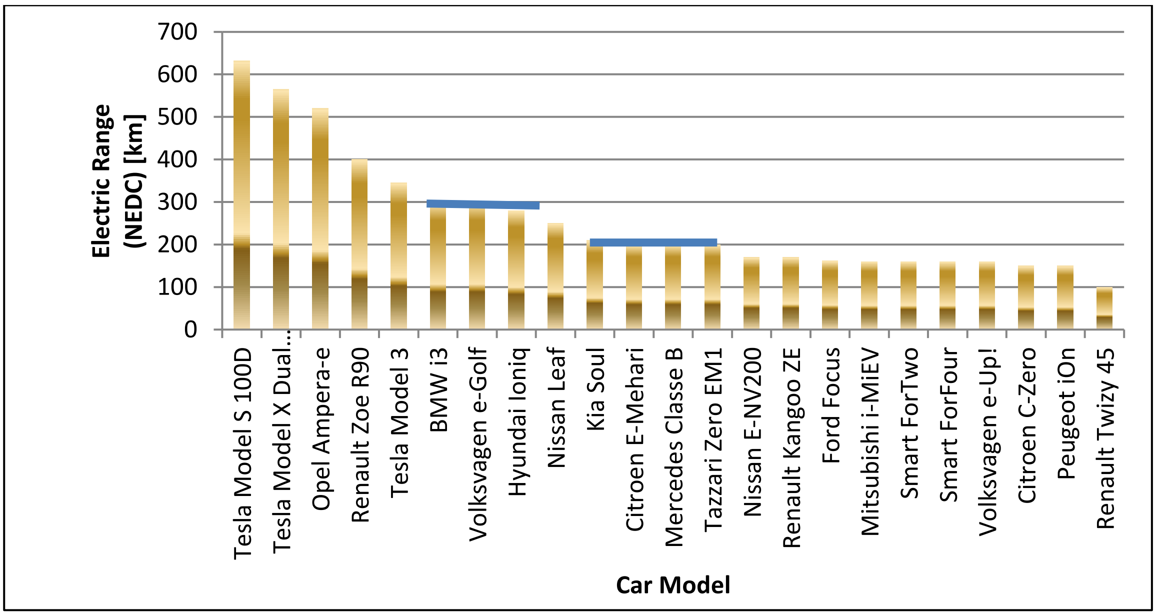


Figure 21: Electric cars on the market with the specifications of the ranges they obtained during an official homologation with the NEDC cycle (market updated until first quarter of 2017).

Figure 21 shows that the maximum electric range is close to 620 km, and the minimum one is at around 100 km. The point in the chart where the rate changes is represented by two main values: 200 km and 300 km. These values were taken as representative of the average maximum distance that can be covered by an electric vehicle.

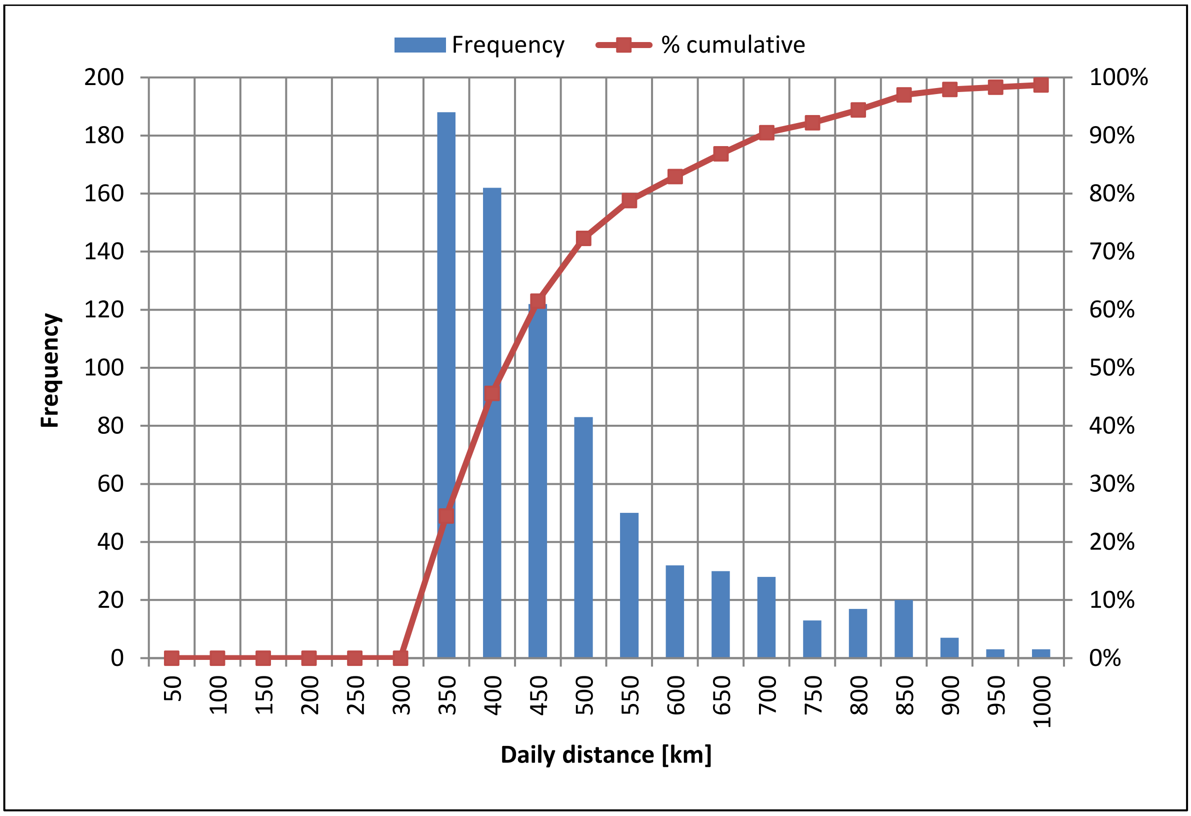


Figure 22: Frequency of longer daily trips (>300km).

All the trips made by users (classified as either sporadic or frequent) were analysed considering the maximum length that can be covered by an electric vehicle and the single relevant trips they are composed of. Two different scenarios were analysed according to the thresholds established for the daily trip length (300 or 200 km) and the single trip length (100 or 50 km):

- Days with a total covered length greater than 300 km, which represents 769 day*users and 1.75% of the total days (Figure 8), in which 1467 trips were longer than 100 km;
- Days with a total covered length greater than 200 km, which represents 1728 day*users and the 3.94% of the total days (Figure 8), in which 3593 trips were longer than 50 km.

We can assume, as the best favourable reference case, that after longer single trips (which exceed the threshold), a driver can charge the battery with a rapid charger over a negligible time slot. This approximate approach was adopted to compare the two frequently used battery sizes (range of 300 km and 200 km).

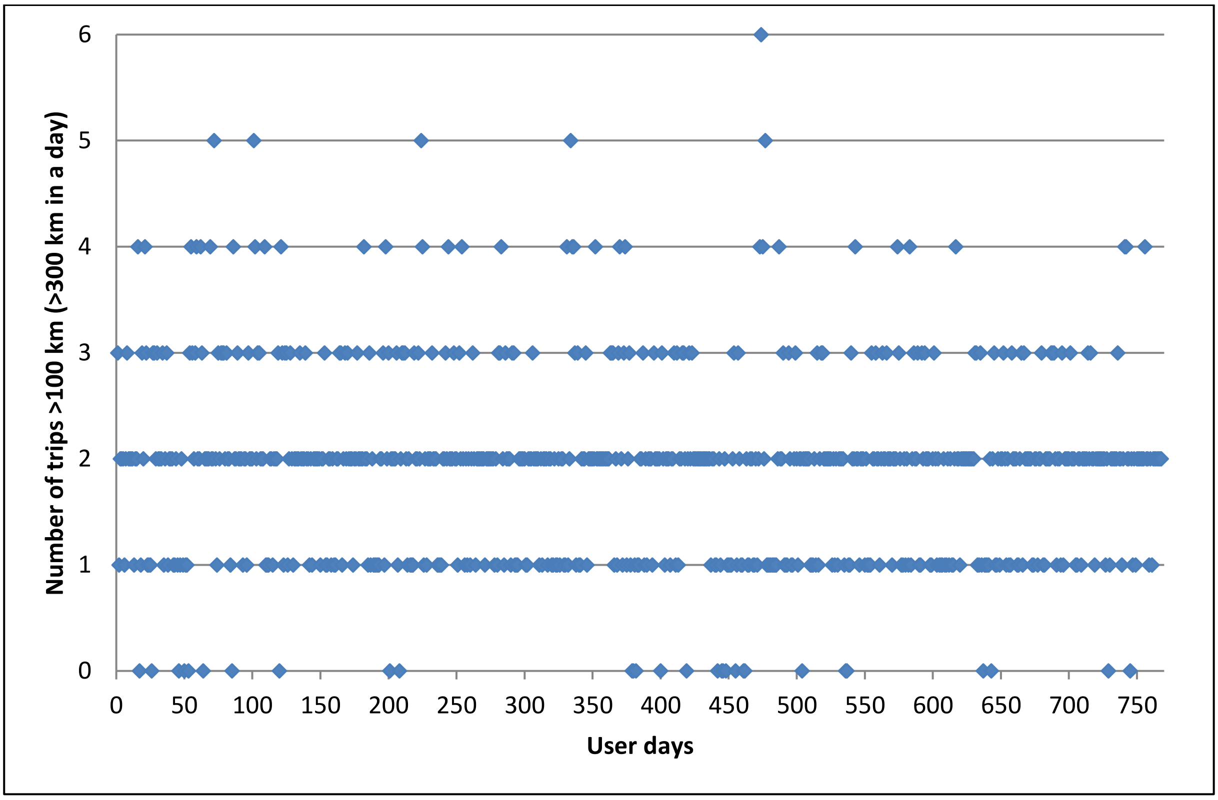


Figure 23: Features of longer trips than 100 km executed in a day with a minimum 300 km covered per user.

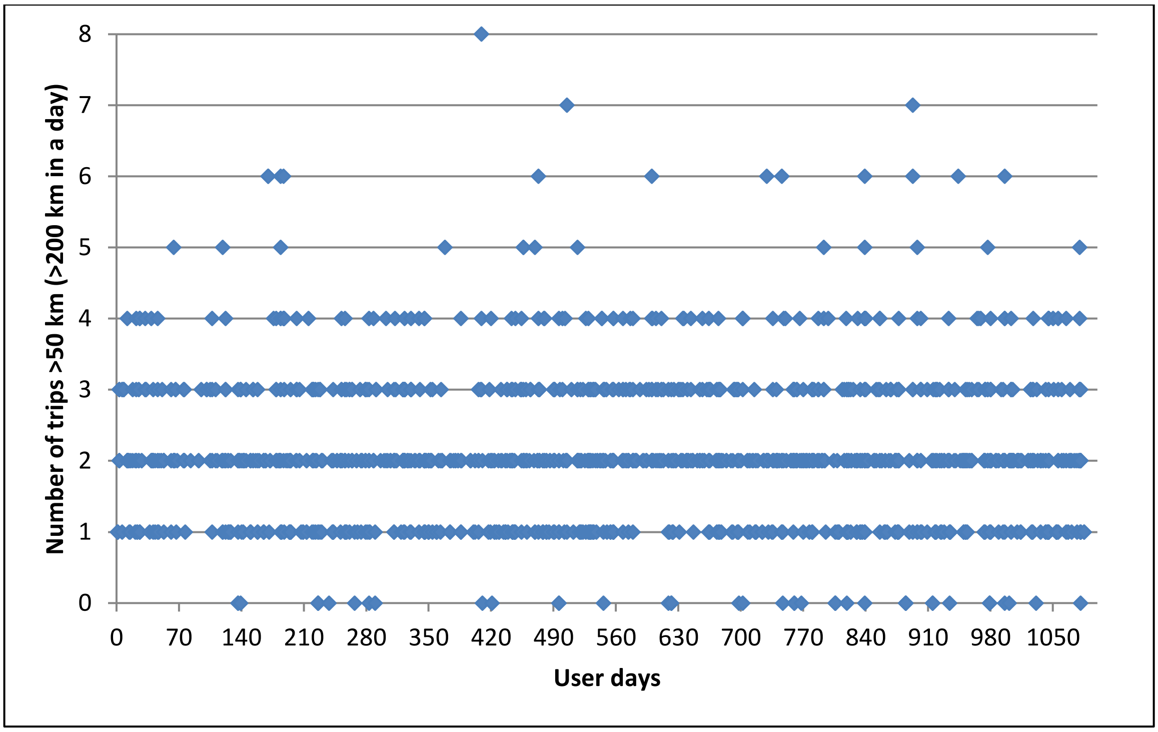


Figure 24: Overview of trips longer than 50 km undertaken in a day with minimum 200 km covered divided by the users.

The results shown in Figure 23 and Figure 24 represent the number of the longest single trips for the two cases (100 and 50 km) and the number of days in which the trips were made over the period. The number of trips longer than 50 km made within a single day covering a minimum 200 km appears denser than in Figure 23, because users usually make most of their trips over a restricted range in urban and extra–urban driving cycles (contexts). However, a battery with a range of 300 km can be used for longer daily trips than 300 km, if intermediate charging operations are available. In this first approach, a rapid charging was assumed to only have been used for longer trips than 100 km. Nevertheless, the remaining daily trips needed to be identified to ascertain whether their total length could be covered by the battery range, since they were excluded from the assumption of electric recharging. These cases are represented in Figure 25 and Figure 26, in which only 2 days out of 769 (0.26%) were detected for sporadic users, whereas 4.7% was detected for frequent users.

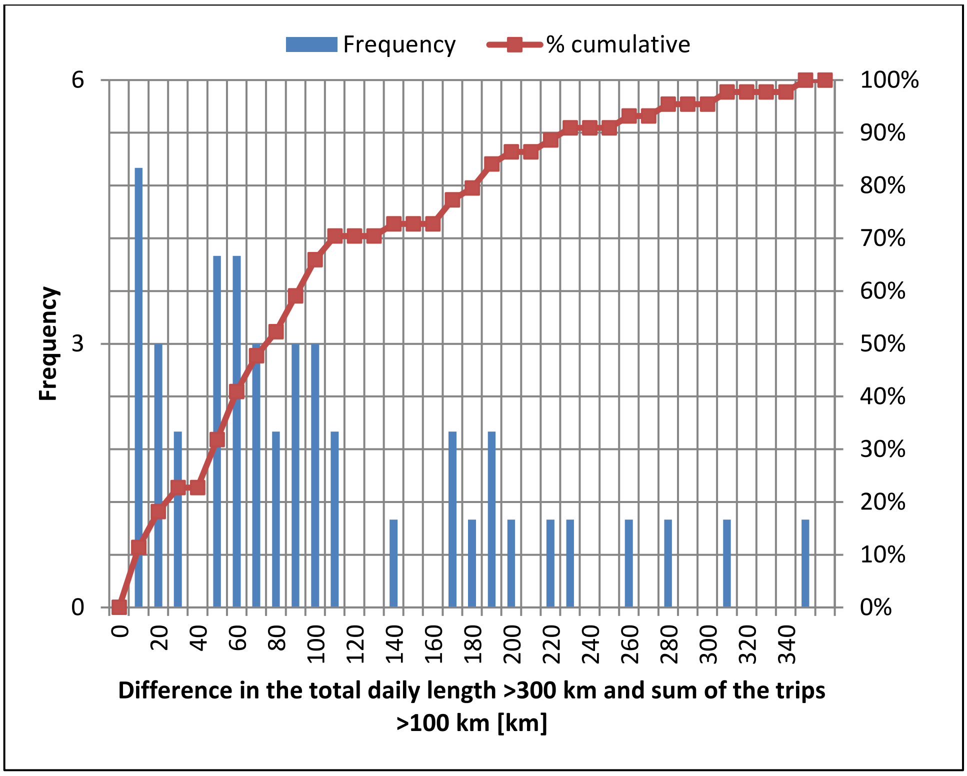


Figure 25: Sporadic users, frequency [# days] of the difference between the sum of longer trips than 100 km and the total daily length greater than 300 km.

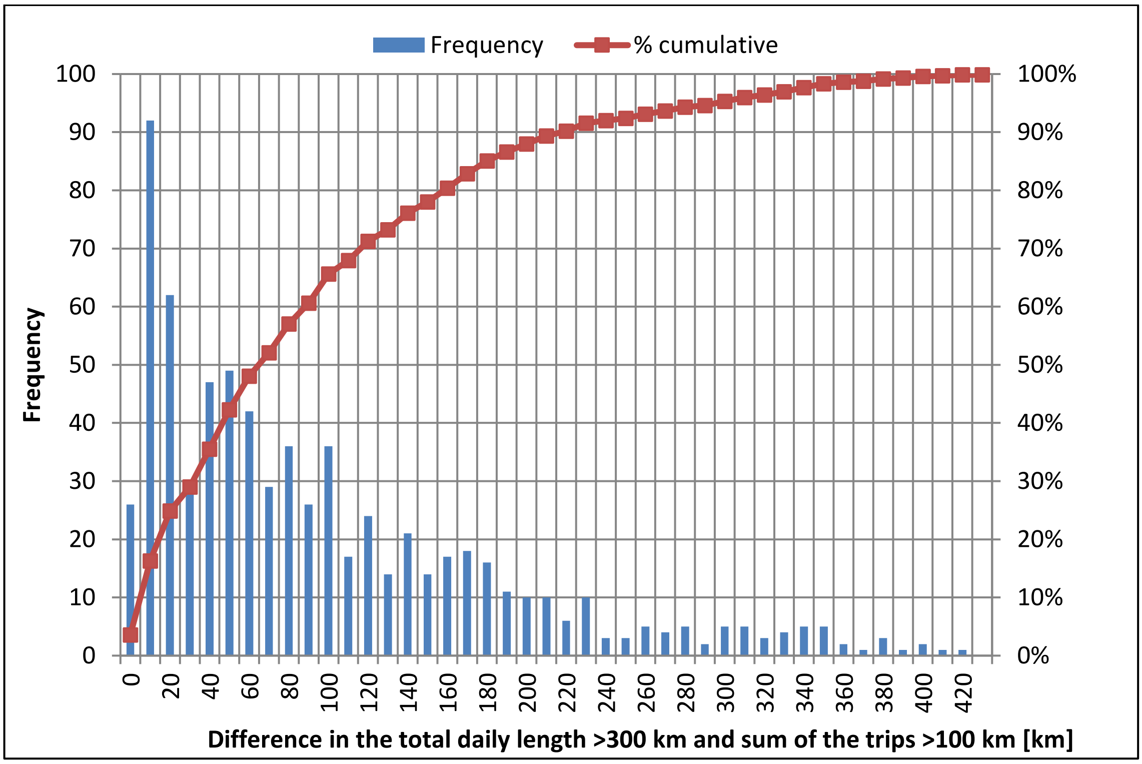


Figure 26: Frequent users, , frequency [# days] of the difference between the sum of longer trips than 100 km and the total daily length greater than 300 km.

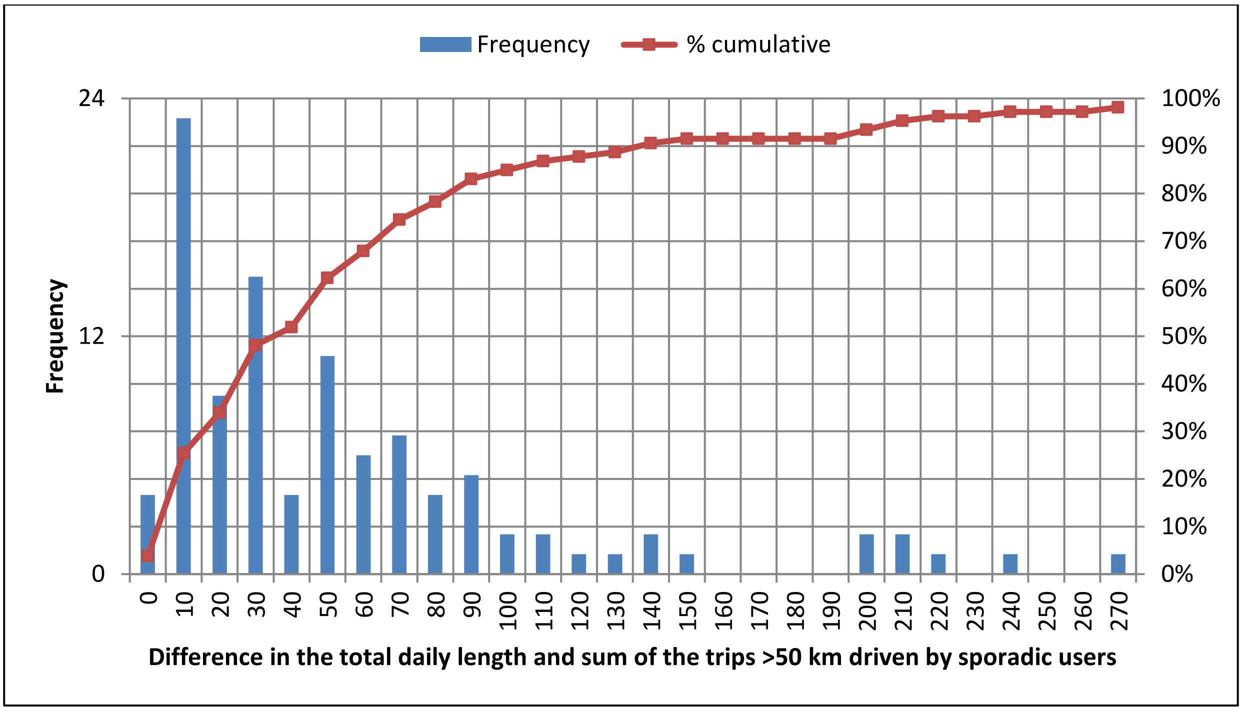


Figure 27: Sporadic users, , frequency [# days] of the difference between the sum of longer trips longer 50 km and the total daily length greater than 200 km.

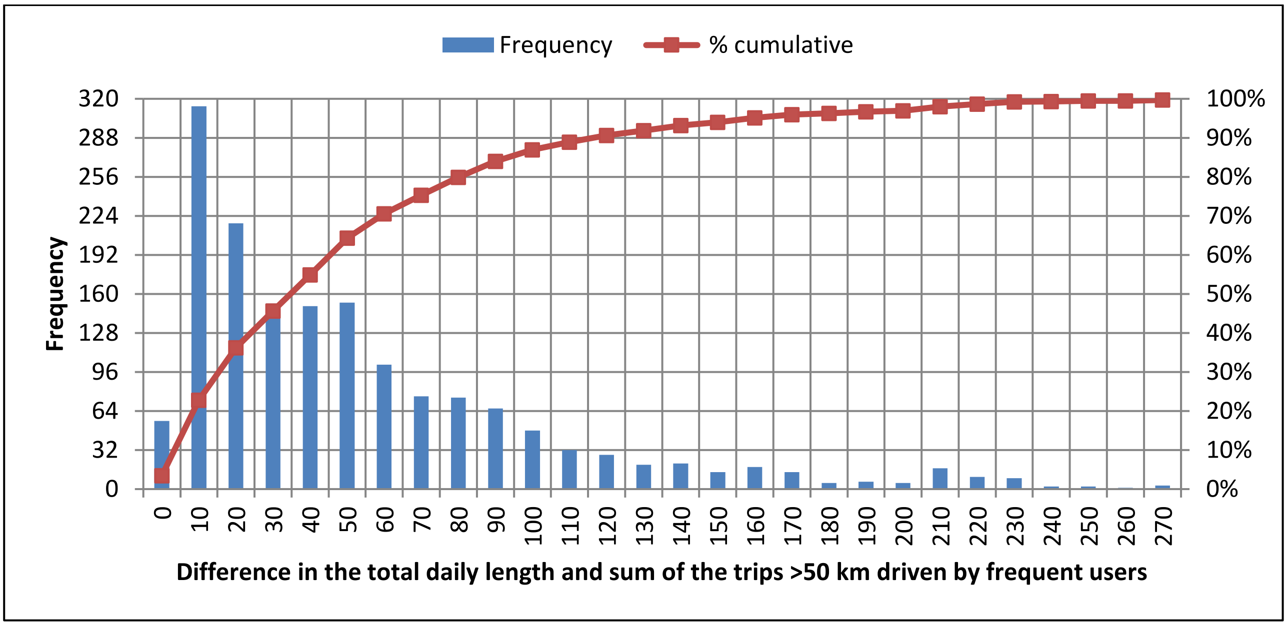


Figure 28: Frequent users, frequency [# days] of the difference between the sum of longer trips than 50 km and the total daily length greater than 200 km.

Figure 27 and Figure 28 show, for the case of the 200 km battery range, that 6.6% of the days could not be performed by sporadic users, whereas 3.02% of the days could not be performed by frequent users.

Since it is difficult to predict the actual availability of rapid charging spots along paths and at the arrival destinations for the future, long trips that could not be performed with electric batteries could be assumed to be replaced by the ICE (longer trips than 50 and 100 km in the here considered scenarios) of a PHEV. Moreover, considering a PHEV with a range of 50 km, 68.18% of the days could be performed with ICE for sporadic drivers and 57.73% for frequent drivers (Figure 25 and Figure 26), whereas 37.74% of the sporadic drivers and 35.70% of the frequent ones could use ICE for single trips longer than 100 km for days in which the total distance were higher than 300 km (Figure 27 and Figure 28).

Other results can be obtained from Figure 25 to Figure 28, by varying the total daily covered length (now higher than 200 km) and each trip undertaken on the same day (now higher than 50 km). By comparing the behaviour of the sporadic users in Figure 25 with their behaviour in Figure 27 and the behaviour of the frequent users in Figure 26 with their behaviour in Figure 28, the following considerations can be made:

- There is a difference of less than 75 km between the total daily length greater than 300 km and the sum of trips longer than 100 km for approximately 50% of the days of the sporadic users; the same percentage applies to the difference below 35 km for the users who had done more than 200 km daily and trips longer than 50 km each;
- Similar results were obtained for frequent users, that is, approximately 50% of the days showed less of a difference than 70 km between the total daily length greater than 300 km and the sum of the trips longer than 100 km; the same percentage applies to the difference of less than 35 km for the users who had done more than 200 km daily and trips longer than 50 km each.

Therefore, there were no relevant differences between frequent and sporadic users as far as this aspect is concerned. However, reducing the daily travelled distances (from 300 to 200 km) and considering shorter single trips (from 100 to 50 km) to be recharged after the trips are performed, the remaining daily trips, using only the energy stored in the battery, were less extended. These are clear indications of how the cars were used, in relation to the energy they consumed during the day, which was divided according to the length of the trips and the related idle time.

4.3 *Energy recovery opportunities during idle time*

The analysis of the idle time is reported in this section in order to enhance the aforementioned results, including the available options for electric recharging according to the actual usage of a vehicle. In fact, as the travelled time and distances provide a measure, with some approximations, of the energy used for travelling, the idle time available after the trip, if it were adequate, could be used to recharge the battery, that is, to recover the previously consumed energy.

4.3.1 *Idle time analysis for the entire dataset*

The idle time after finishing a journey has been depicted first for the entire dataset; all the contexts: urban, extra–urban and motorway have been included (Figure 29). In approximately 50% of the cases, the total idle time after finishing a journey is less than 1 hour, 10% is between 1 to 2 hours, 10% is between 2 to 4 hours, 10% is between 4 to 9 hours and it is more than 9 hours for the remaining cases (20%).

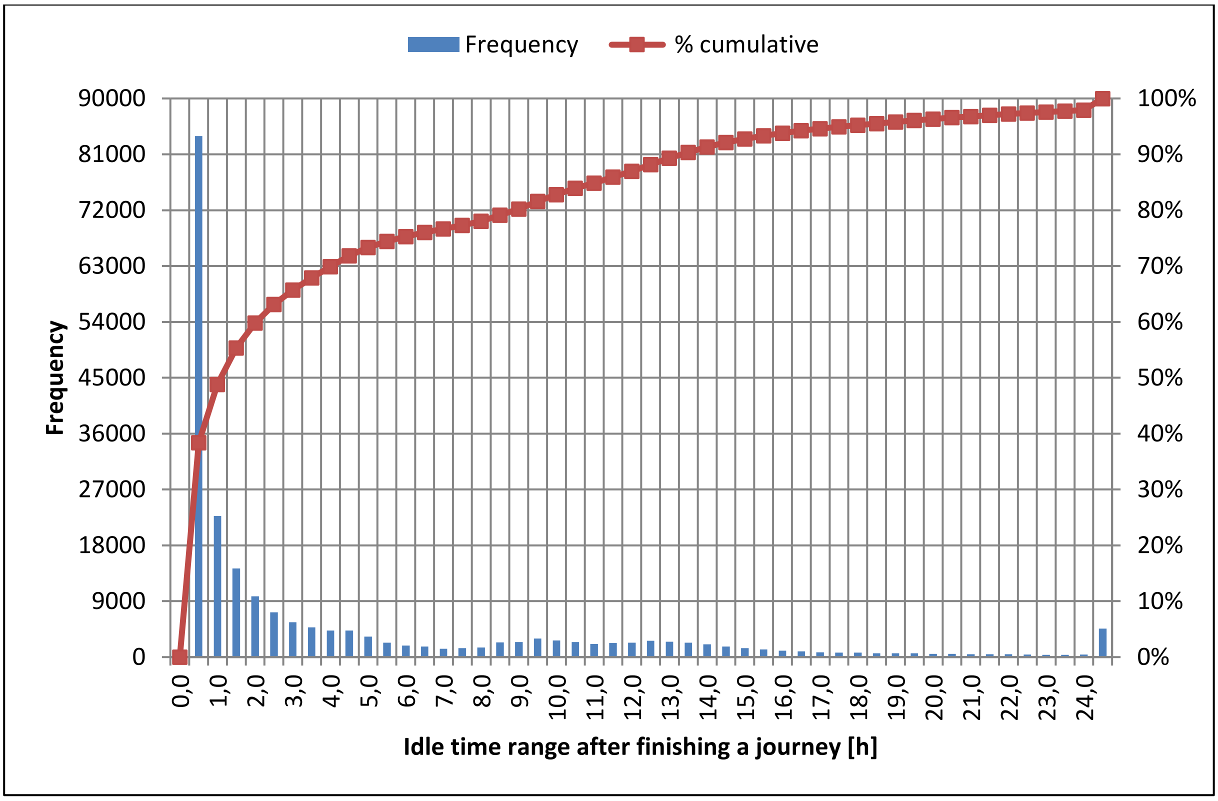


Figure 29: Idle time after finishing a trip for all the driving cycles.

Results in Figure 30 confirm that approximately 50% of the urban trips present a shorter idle time, after the conclusion of the journey, than 30'. Another 10% is between 30' and 1 h, and approximately 20% falls between 30' and 2.5 h. In relation to the night-time break, another 10% of journeys show a rest time of between 9 and 15 hours.

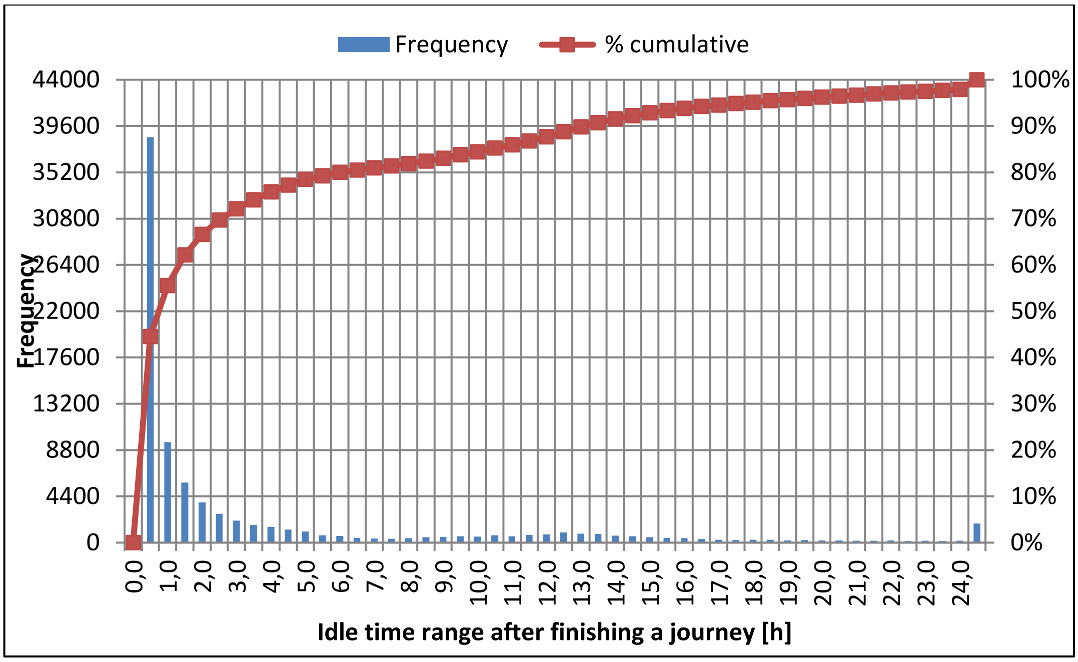


Figure 30: Idle time after finishing a trip in an urban driving cycle.

Results in Figure 31 and Figure 32 demonstrate that a longer stop can be associated with extra–urban trips, after finishing a trip, than with urban trips . Approximately 55% of the trips present an idle time of between 0 and 2 h of parking after finishing a trip, 20% of between 2 and 4 h, 6% from 4 to 8 h and 16% of the trips show an idle time of between 8 to 14 h. These results indicate that extra–urban trips could take advantage of longer breaks to slowly recharge the consumed energy.

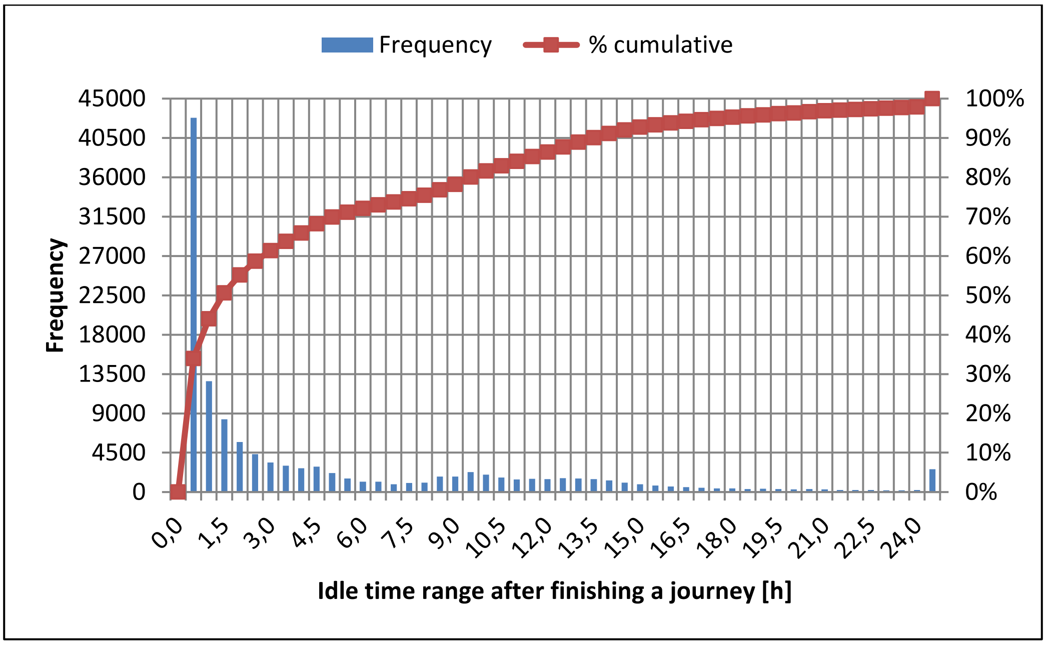


Figure 31: Idle time after finishing a trip in an extra–urban driving cycle.

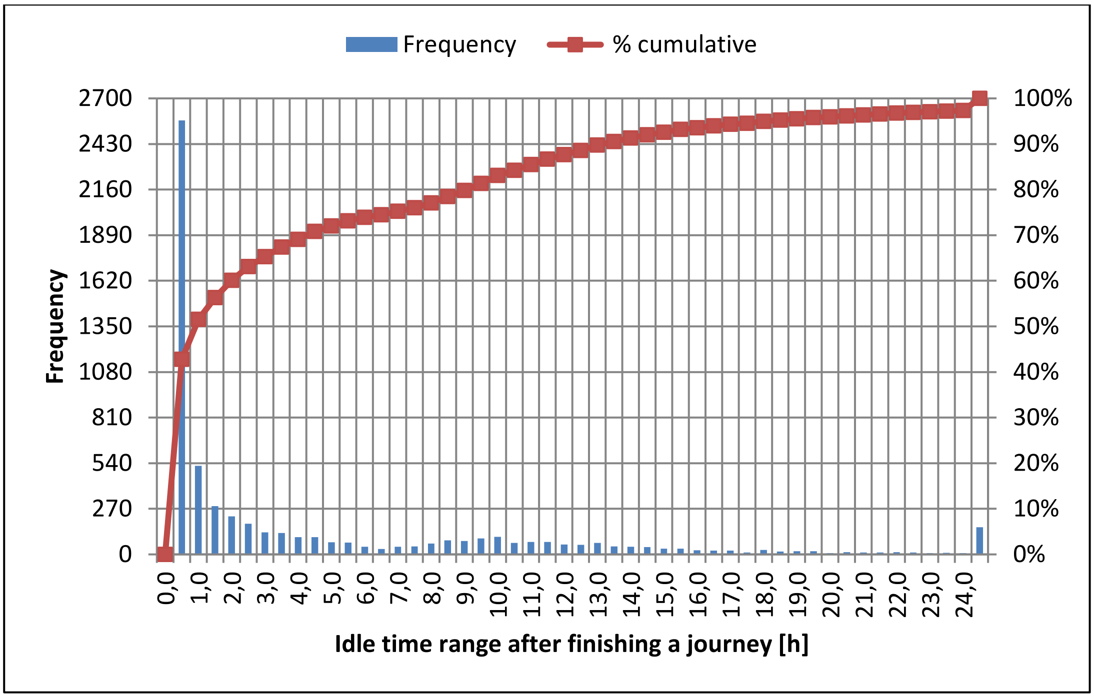


Figure 32: Idle time after finishing a trip in a motorway driving cycle.

Results in Figure 32 show that the idle time after finishing a motorway journey is less than 1 hour for approximately 50% of the trips, between 1 to 4 hours for 20% of the total trips, between 4 and 8 hours for 8% of the total trips, between 8 and 14 hours for 10% of the total trips and between 14 to 24 hours for the 6% of total trips.

4.3.2 Idle time analysis for longer daily trips

Some of the most important issues that can limit the usage of electric cars are the battery capacity, which is known as "range anxiety", the way it can be recharged, recognisable as "recharge anxiety", and the related time available after the journey for recharging the already consumed energy at the available charging points. Two scenarios, which may help to estimate to what extent the energy used after extended trips could be recovered during the parking periods, are presented in Table 1 and Table 2. Attention was focused on long journeys, since they are evidently more relevant, in relation to the "range anxiety" aspect for drivers, and may influence decisions on purchasing fully electric vehicles. On the other hand, short trips do not need to be recovered promptly with charging operations, since less energy is consumed by vehicles and more energy can be assumed to be available in the battery.

Table 1: Idle time after journeys of more than 20 km (total daily travelled distance longer than 100 km). Each box corresponds to the percentage of the total trips.

		Idle Time after journey [h]													
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Journey Length [km]	**30**	11%	3%	1%	1%	1%	0%	0%	0%	0%	1%	0%	0%	0%	**19%**
	40	7%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	**14%**
	50	6%	2%	1%	1%	1%	0%	0%	0%	1%	1%	0%	0%	0%	**13%**
	60	4%	1%	1%	1%	0%	0%	0%	0%	1%	1%	0%	0%	0%	**10%**
	70	3%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**7%**
	80	2%	1%	0%	0%	0%	0%	0%	0%	0%		0%	0%	0%	**4%**
	90	2%	0%	0%	0%	0%	0%							0%	**3%**
	100	2%	0%	0%	0%	0%	0%							0%	**3%**
	110	1%	0%	0%	0%	0%	0%							0%	**2%**
	120	1%	0%	0%	0%										**2%**
	130	1%	0%	0%	0%										**1%**
	140	1%	0%												**1%**
	150	1%	0%												**1%**
	160	1%	0%												**1%**
	170	1%	0%												**1%**
	180	1%	0%												**1%**
	190	0%	0%												**1%**
	200	0%	0%												**1%**
Total		**44%**	**11%**	**6%**	**4%**	**3%**	**2%**	**2%**	**2%**	**3%**	**3%**	**2%**	**2%**	**2%**	

Table 2: Idle time after journeys of more than 50 km (total daily travelled distance longer than 200 km). Each box corresponds to the percentage of the total trips.

		Idle Time After Journey [h]						
		0	1	2	3	4	5	
Journey Length [km]	60	8,5%	0,1%	0,1%				8,7%
	70	6,9%	0,1%	0,1%				7,1%
	80	6,6%	0,1%					6,7%
	90	6,4%	0,1%	0,1%				6,5%
	100	7,7%	0,2%					7,9%
	110	8,0%	0,3%	0,1%				8,3%
	120	6,6%	0,1%	0,1%	0,1%			6,8%
	130	4,7%	0,1%	0,1%				4,9%
	140	4,5%						4,5%
	150	3,6%	0,1%					3,8%
	160	4,0%						4,0%
	170	3,2%						3,2%
	180	2,5%	0,1%	0,1%				2,7%
	190	2,3%	0,1%	0,1%				2,4%
	200	2,6%		0,1%				2,7%
	210	3,0%	0,2%	0,1%				3,3%
	220	2,1%	0,1%	0,1%				2,2%
	230	1,8%	0,1%	0,1%				1,9%
	240	1,2%	0,1%					1,3%
	250	1,0%						1,0%
	260	1,2%	0,1%	0,1%				1,3%
	270	0,8%	0,1%					0,9%
	280	1,0%	0,1%					1,0%
	290	0,8%						0,8%
	300	0,9%	0,1%					1,0%
Total		92%	2%	1%	0%	0%	0%	

Table 1 shows the results of a specific analysis carried out on single trips that were longer than 20 km, during days when the total travelled distance was longer than 100 km; a relationship with the idle time after the journey emerges. The idle time after a journey is less than 1 hour for 44% of the total trips, between 1 and 2 hours for 11% of the total trips and between 2 and 3 hours for 6% of the total trips. A great part of the long trips only has a short time for recharging the battery. Table 2 shows only single trips that are longer than 50 km and than 200 km on a daily basis and it also reports the idle time after the journeys; 92% of these trips leave an idle time after the journey of between 0 and 1 hour, 2% between 1 and 2 hours and1% between 2 and 3 hours. In these conditions, the batteries could not be recharged for the total amount of energy consumed over the trip during the break time with 3 kW power stations. Only with fast charging (minimum 12 kW of power) could the cars probably recover all the consumed energy. Considering the range of the electric power at the charging points available in Europe (web sites, such as Nextcharge, with charging points for slow, fast and rapid chargers, are available on line) we assumed three reference values: 3 kW for low (2 – 6 kW), 22 kW for fast (7 – 22 kW) and 43kW for rapid (23 – 135 kW), according to their frequency of installation.

Since the journeys had been covered with traditional engines, it is quite difficult to estimate the equivalent electric energy consumption, unless we introduce some approximations. The energy efficiency of an ICE depends on several factors: the conditions of use (e.g. urban, motorway, etc.), fuel (e.g. Diesel or gasoline) and driving behaviour. The maximum engine and powertrain efficiencies were taken from literature [32] and [21], as reported in Table 3 and Table 4.

Table 3: Diesel and gasoline energy efficiencies TTW for the different contexts of use considered.

	Urban	Extra–urban	Motorway
Gasoline	0,16	0,25	0,35
Diesel	0,18	0,30	0,38

Table 4: Electric efficiencies of inverters, battery and electric traction motor.

	Inverter (AC/DC)	Traction battery	Inverter on board	Electric motor	Battery to wheels
Efficiency	0,95	0,90	0,95	0,90	0,77

Moreover, the conversion from fuel to electric energy is variable [33]: 1 litre of gasoline corresponds to 34MJ (approx. 9.4 kWh) and 1 litre of Diesel corresponds to 41MJ (approx. 11.5 kWh).

Gathering together all the previous information and analysing the trips with longer lengths than 20 km, it is possible to estimate the energy for each trip (Figure 33).The obtained normalized values [kWh/km] are analysed in Figure 34, with respect to their frequency.

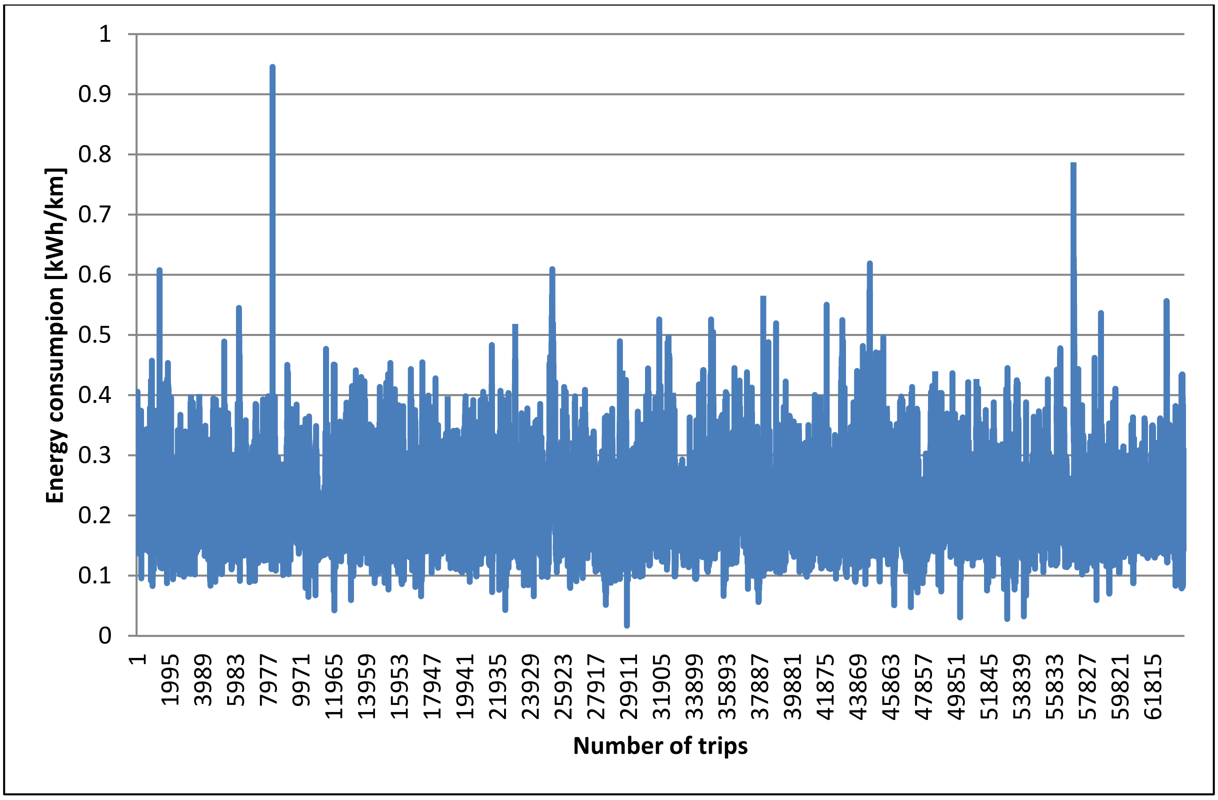


Figure 33: Energy consumption for the trips longer than 20 km.

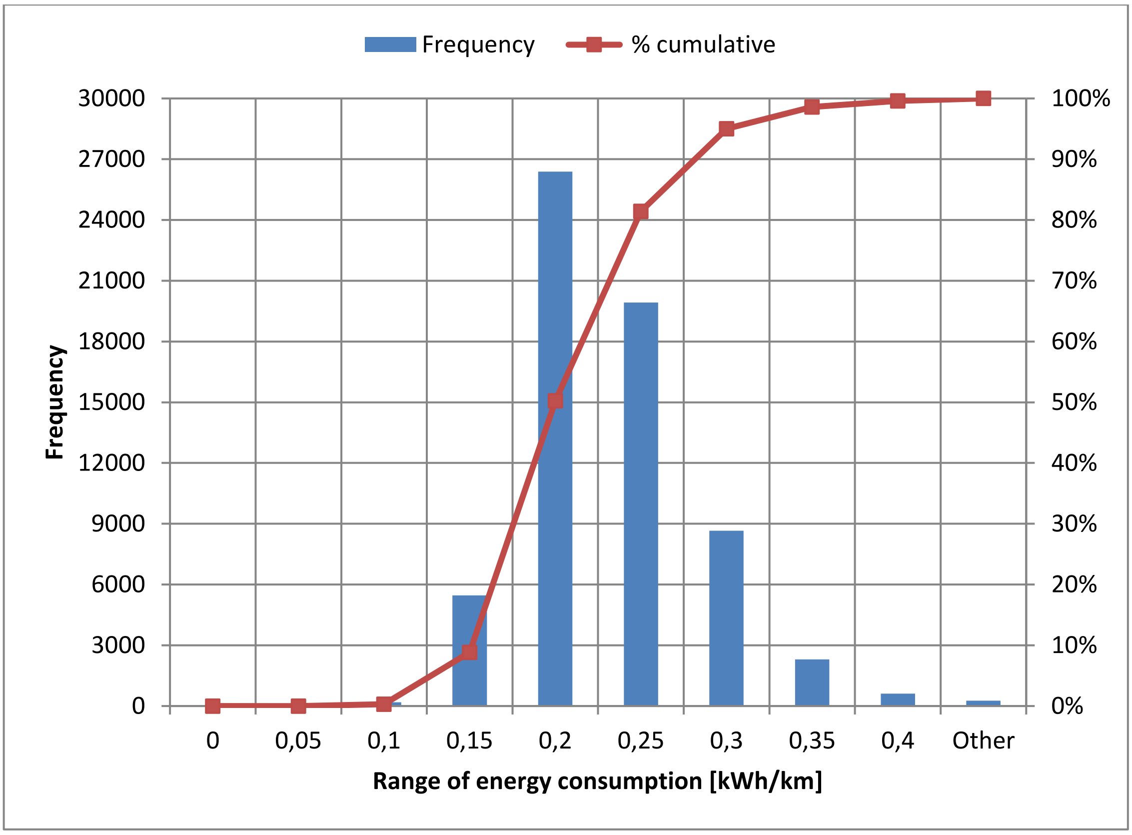


Figure 34: Frequency of the energy consumed by vehicles for which the trip distance covered was longer than 20 km.

Considering that the feature of the trip that affects the energy consumption the most is its length, the obtained results were used to map the energy necessary for the travelled length in order to identify the trips that could recover the energy consumed during the idle phase after the trip.

The single trips longer than 20 km, carried out in days when the total travelled distance was longer than 100 km, are analysed in Figure 35 to Figure 38, in relation to the ability of recovering all the energy consumed during the last trip undertaken at different power charger points.

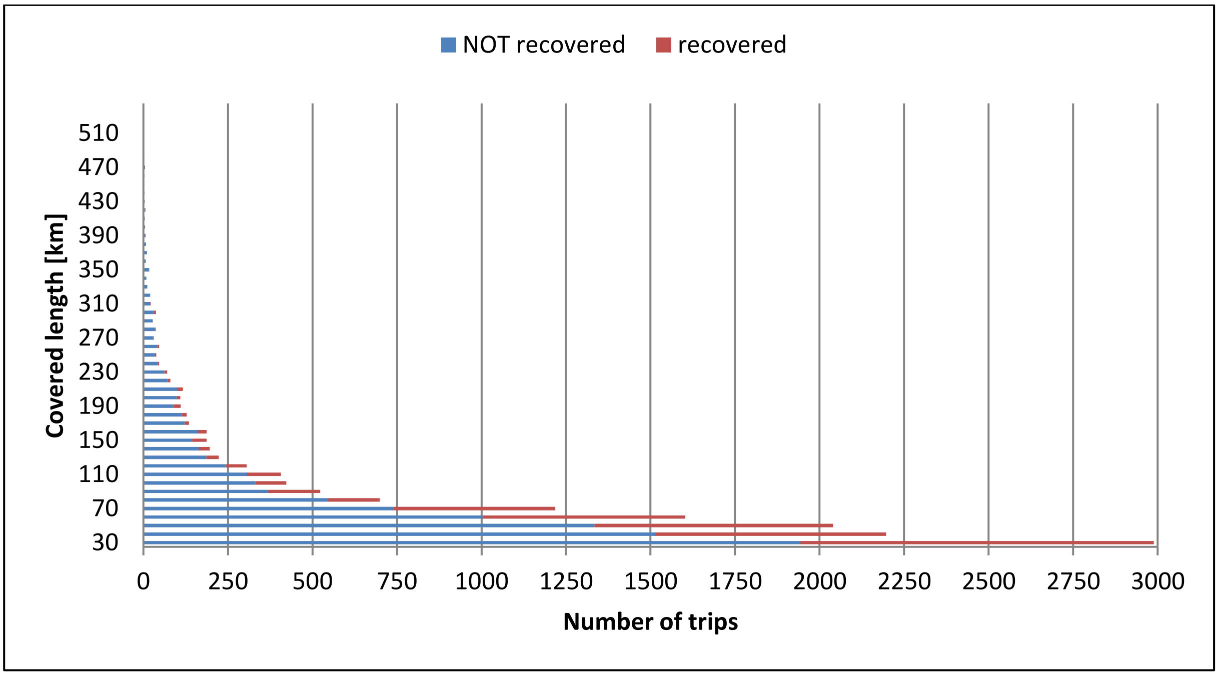


Figure 35: Number of trips for which the subsequent idle time was enough to recover the energy consumed with an availability of 3 kW of power supply.

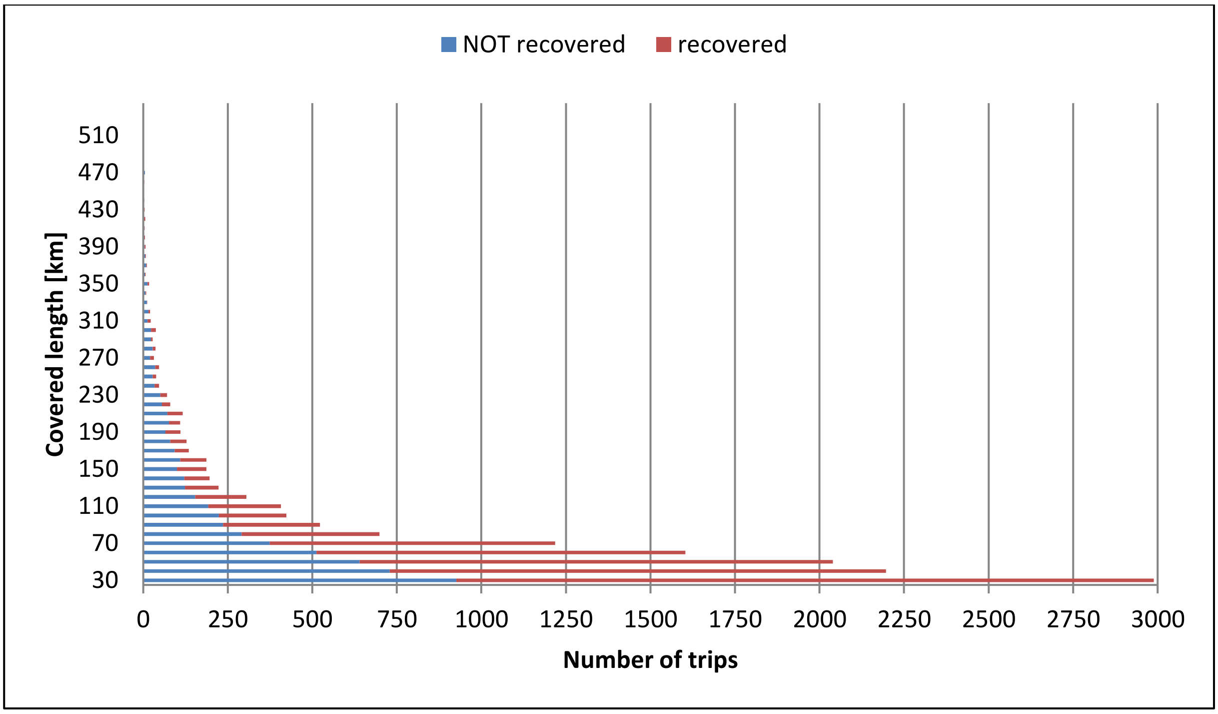


Figure 36: Number of trips for which the subsequent idle time was enough to recover the energy consumed with an availability of 22 kW of power supply.

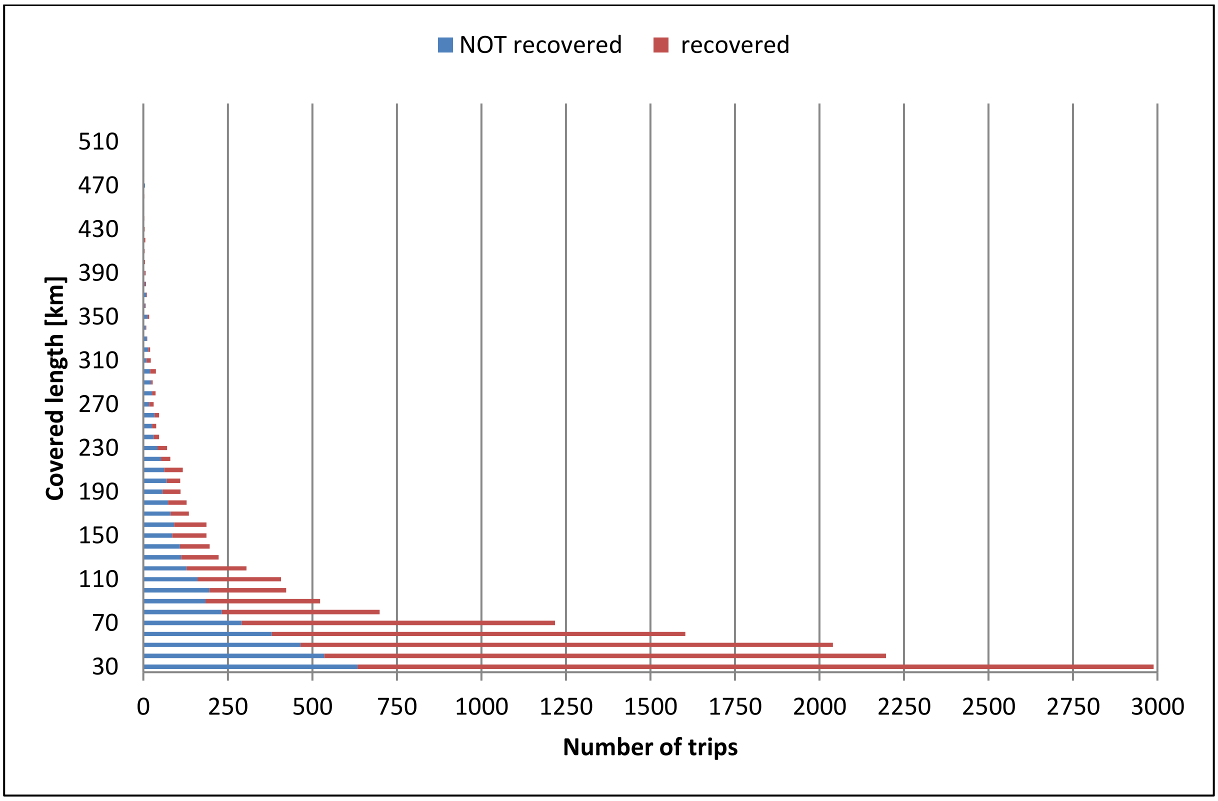


Figure 37: Number of trips for which the subsequent idle time was enough to recover the energy consumed with an availability 43 kW of power supply.

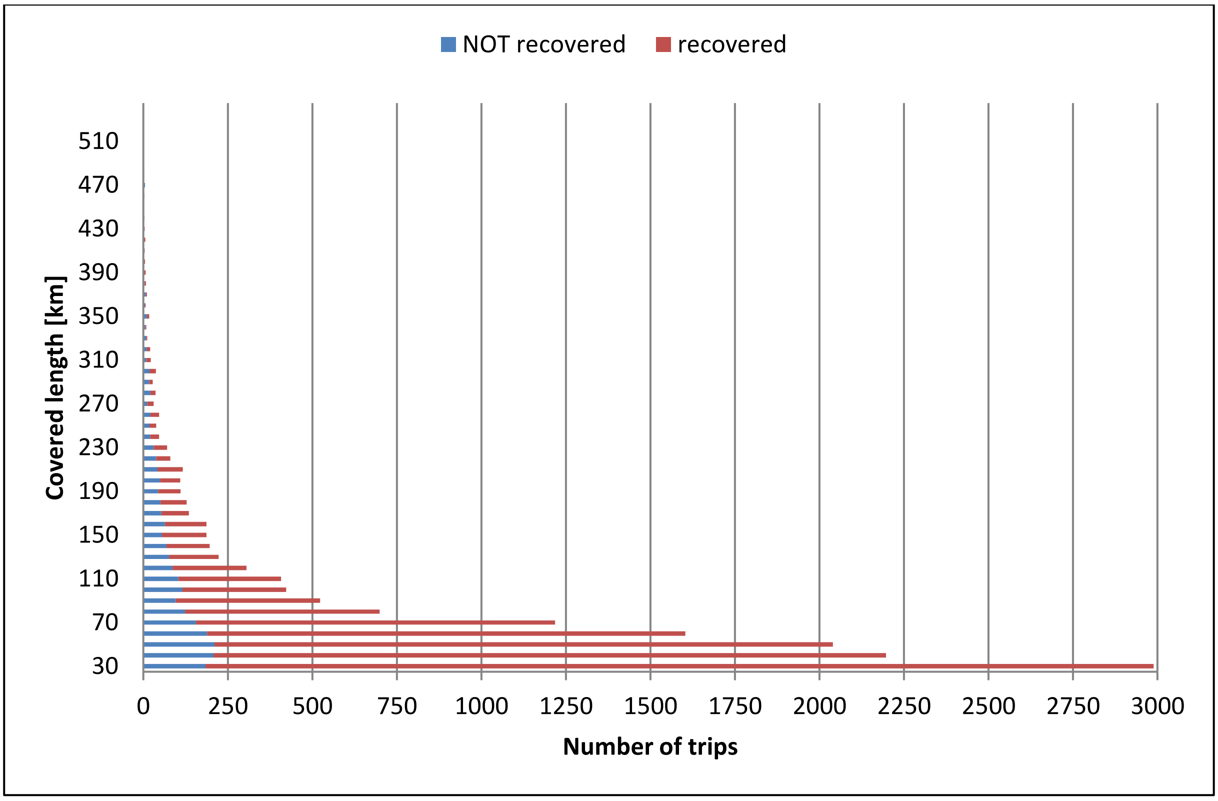


Figure 38: Number of trips for which the subsequent idle time was enough to recover the energy consumed with an availability of 135 kW of power supply.

As can be seen, a large part of the trips longer than 20 km (100 km daily) could not recover the energy consumed during the last trip with a power supply of 3 kW. However, with 22 kW or higher power, more than 50% of these trips would allow the consumed energy to be restored. Some problems arose for short journeys for which fast recharges were found to be inadequate for the time available after the journey.

5 Conclusions

Driving habits can help to evaluate the most suitable electrification options for the future automotive market, including hybrid powertrains for road vehicles; a method has been proposed to analyse data obtained from on-board devices, with which the relevant features of real-life driving cycles, related to trip distance, travel duration, daily usage and idle time after single trips can be investigated.

The original outcomes of the paper concern the proposed methodology with related results; this has been applied to a quite extended real-life dataset provided by the mentioned car maker, related to a period that lasted more than one year and which covered more than one thousand vehicles. With respect to the literature, not only the trip lengths and durations were analysed, but also the consumed energy and the option of recovering it by electric charging during the idle phases were investigated. The results obtained in this paper are an example of the detailed information that can be extracted from rough data to support the decisions of stakeholders (e.g. car makers, authorities, drivers) in relation to the present and next generation of automobiles. The European emission target for 2020/21 will be 95 grams of CO2 per kilometre for passenger cars. In order to reach such a stimulating goal, from the engineering viewpoint, the majority of car makers will have to electrify their cars, and this will include the hybridisation of powertrains, since supporting or alternating an ICE with an electric motor can increase the overall performance and reduce the local emissions.

This study has focused on some scenarios, based on the actual driving habits and possible ranges in which electric vehicles could effectively be competitive. On the basis of a collection of driving cycle data, pertaining to a period of one year and three months, it results that almost the whole urban demand could be satisfied by full electric or, preferably, (plug-in) hybrid-electric automobiles, in terms of autonomy. In fact, the data show that 99,9% of the covered urban daily distances is less than 50 km, whereas only 60% considering the overall driving cycle contexts. The aforementioned autonomy is associated with “range anxiety”, while it is worth underlying the existence of the “recharge anxiety” associated with full-electric vehicles, which implies that there is no way to recharge a BEV (Battery Electric Vehicle), unless at a charging point.

Long distance trips were further analysed, to better understand whether they could be covered by electrification. However, in order to satisfy 99,9% of the demand detected on the basis of the trips included in the dataset, it would be necessary to raise the range to 400 km/day. This target could be reached by adopting a PHEV or a full electric car with at least an equivalent electric range, not considering the battery reserve. In this study, it has been proved that car drivers cannot always recover all the energy consumed during the idle times after a journey, in particular on days with long trips, unless the charge power were increased to 135 kW. However, full electric vehicles with a range of 300 km can satisfy almost all the longer trips (99.74% of sporadic and 95.3% of frequent users), excluding the air conditioning needs (heat or fresh air production), if a rapid charging operation were performed at the end of each single trip longer than 100 km. In the case of a 200-km range, considering a rapid recharge after each 50-km trip, 93.4% and 97% of long daily trips would be guaranteed for sporadic and frequent users, respectively. In these scenarios, the results are not only affected by the battery capacity, but also by the frequency of rapid charging operations during the idle time after longer journeys. In addition, the idle time analysis, pertaining to after the completion of a trip, shows that 70% of the users have on average from 0 to 4 h available to charge their vehicles. This time could be used to charge the battery with a power supply of 3 kW at a rate of 15 km per charging hour, or to charge with a power supply of 22 kW at a rate of 110 km per charging hour. However, the link between the trip and the consecutive idle time needs to be evaluated, and this has been performed in the last part of our research. Most of the trips longer than 20 km, executed during days with more than 100 km covered, could not recover the energy consumed using a 3 kW power supply. However, with a 22 kW power supply, or even higher, more than 50% of these trips could restore the energy consumed during the previous trip.

Further researches should be carried out to provide economic indications on the various automotive solutions (e.g. BEV, PHEV, etc.), with the aim of quantifying the savings and costs for car makers (e.g. battery size), drivers (e.g. vehicle total cost of ownership), local authorities (e.g. traffic management and energy charging points; wireless power transfer systems, whether static or dynamic; etc.) and electric energy providers (e.g. electric grid and generation plant sizing). The management of the electric grid should be able to take into account fluctuations of the daily electric energy demand in function of the users' needs and their trip patterns (e.g. length, idle time, duration). Electric grid companies should probably include V2G (*Vehicle to Grid*) strategies and integration with other power centres (solar panels, etc.) to limit the over-sizing of electric power generation plants in order to satisfy the demand peaks.

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Sitography

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