**Universidad de Cádiz**

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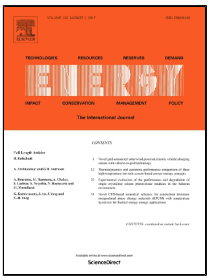

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## Abstract

Electric vehicles are the most promising sustainable transport technology for solving problems linked to the internal combustion engine vehicles. Wireless charging reduce the main problems associated with electric vehicles, driving range, charging time and size and cost of the battery. Inductive power transfer is the most promising technology for dynamic wireless charging of electric vehicles, which can be used to supply the motors and charge the battery while moving. This paper presents a comparative study of a

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dynamic wireless power transfer system for charging electric vehicles driving on three stretches of traffic road (motorway, highway and urban stretch) in Cádiz (Spain). The study analyses the electricity consumption demanded by the dynamic wireless power transfer system and the battery state-of-charge of the electric vehicles that travel the stretch to evaluate the increase of autonomy, the length of the stretch or speed of the vehicle for achieving a specific increase of state-of-charge. The results show a great dependence on stretch of road, with large fluctuations in the urban stretch and more stability in the highway and motorway. This study could help to design stretches of roads with dynamic wireless power transfer and to quantify the power and energy demanded by the system.

**Keywords:** Electric vehicle; wireless power transfer; battery; dynamic charging.

## 1. Introduction

Transport is one of the fastest growing sectors in the world. Internal combustion engine vehicles (ICEVs), based on liquid fossil fuels that supply 95% of the total energy consumed by world transport [1], is the largest technology currently in use in the road vehicles worldwide. This heavy dependence on fossil fuels is causing environmental problems (high air pollution and greenhouse gases emissions) and issues of economic and social sustainability [2]. This makes there is a need for new sustainable transport systems [3].

In this scenario, electric vehicles (EVs) are viewed as a viable, attractive and sustainable transport technology for solving the problems linked to ICEV [4]. In fact, the global EVs stock at the end of 2014 (665,000 units) represented 0.08% of the total passenger cars. The International Energy Agency estimates that the EVs stock will be

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over 20 million (2% of total passenger cars) including plug-in hybrid EVs and fuel cell vehicles by 2020 [5], and almost 80% of automobiles sold in 2050 will be EVs [6]. The conditions for the successful deployment of EVs were analysed in [7], where different scenarios of car technology deployment, particularly battery EVs, were studied. Plug-in hybrid EVs (ICEs with rechargeable battery or supercapacitors) enable downsized ICEs with high operating efficiency and facilitate the grid integration of intermittent renewable energy sources by using distributed electricity energy storage [8]. Fuel cell vehicles assisted by batteries and/or supercapacitors represent another interesting option of power source integration in hybrid EVs [9].

However, several barriers are hampering further development and use of EVs [10]. The battery is the most important component of an EV and is also the main limitation of current EVs. The current batteries of EVs present high cost, short lifetime, short driving range and excessive charging time when compared with ICEV [11]. Furthermore, batteries are still usually oversized and underused, which evokes augmented weight, volume, and purchase cost [12]. The use of efficient battery management systems can help to improve battery durability [12], and energy efficiency and cost-effectiveness [13].

These obstacles need to be solved and new technological solutions must be developed in order to achieve a further integration of EVs in transport sector. The current research is focused on developing new batteries and new charging methods [14]. Lithium-based battery technology, which is not fully matured, hold the potential to be the perfect rechargeable battery for future EVs [14]. There are other battery technologies in the experimental phase, such as lithium–sulfur (Li–S) and metal-air, which need more research to be extensively commercialized [15]. Bio-batteries, systems relying on biological components (enzymes and biological systems) for the generation of low electric currents, can be another promising technology for future EVs [16]. A review of

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the stage-of-the-art charging technologies of EVs (power levels, types, and standards) was carried out in [17]. To ensure the appropriate charging of EVs and grid integration and operation, the development of smart charging methods and solutions is needed [18]. A battery-assisted charging system was developed to improve the charging performance of a quick charger for EVs [19]. An integrated optimization framework for battery sizing, charging, and on-road power management in EVs was presented in [20]. A novel optimal charging scheduling strategy was proposed for different EVs in [21].

Wireless charging can help overcome the problems linked to the driving range and charging time of EVs. The most promising technology for wireless charging of EVs is based on Inductive Power Transfer (IPT) [22]. It uses primary coils located in the charging station to transfer induced power to the secondary coils of the EVs [23], which can be used to supply the motors and/or to charge the battery of the EVs. This charging system allows to transfer high power, presents high efficiency, and is reliable and maintenance friendly [24].

Wireless charging can be stationary or dynamic [25]. Stationary charging is performed with the EV stopped at public or private parking areas, while dynamic charging is carried out when the EV is moving on sections of road. Stationary charging presents lower cost, but it needs larger size of battery to store more energy and to increase the driving range when compared with dynamic charging. Dynamic charging, which uses several primary coils embedded in the track to transfer induced power to the secondary coils of the EV while it is moving, can help to reduce the size and cost of the battery, and increases the driving range [25]. Stationary charging is the most highly developed wireless technology for EVs, so that there are currently various commercially available static wireless chargers. On the contrary, more recent is the interest in dynamic wireless charging of EVs, and therefore, the level of development is much smaller and it requires

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further research. In fact, due to the early developmental stage, there are relatively little studies on dynamic wireless charging of EVs in the scientific literature. The existing technological solutions for wireless power transfer used in EVs were analysed in [26] and [27]. Modern trends in wireless power transfer for transport applications were presented in [28], where the roadway challenges, the problems that still exist and the possible solutions were analysed. An efficiency analysis and design of wireless power transfer was performed in [29] by simulations and experiments. The results showed that the efficiency strongly depended on the resonance frequency, and consequently, an algorithm was developed to determine the optimal system resonance frequency. Korea Advanced Institute of Science and Technology has developed a commercially available dynamic charging transportation system, whose optimal design was described in [30] and economic analysis was performed in [31]. Oak Ridge National Laboratory provided in [32] its experience and challenges facing dynamic wireless charging of EV. The costs associated with the implementation of a Dynamic Wireless Power Transfer (DWPT) infrastructure for EV were analysed in [33].

However, only a few papers have analysed and evaluated DWPT systems for EVs driving on stretches of traffic roads. The potential for wireless dynamic charging to address range and recharge issues of EVs by considering travel to regional destinations in California was analysed in [34]. This study made it possible to evaluate where and to what extent dynamic infrastructure would be needed, and it included a cost analysis by varying dynamic charging power level and vehicle range. A traffic model was developed in [35] for analysing the wireless dynamic charging of EVs from both traffic and energy points of view, which was applied to the case of a freight distribution service in Turin. The study presented in [36] evaluated the feasibility of powering EVs by wireless dynamic charging on England's major roads, in which aspects such as configuration,

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necessary equipment, power requirements, costs, benefits and impacts were analysed. Finally, the FABRIC research project [37], which is currently being developed, claims to conduct feasibility analysis and development of on-road charging solutions for future EVs, including the analysis of EVs driving on stretches of roads. The main contribution of this paper is to compare the dynamic wireless charging of EVs driving on three stretches of traffic road (motorway, highway and urban stretch), which present different traffic flow (intensity and speed) and length. The main variables analysed in this study are the power and energy requirements in order to evaluate the infrastructure needed for the electricity supply of the DWPT system, and the EV battery state-of-charge (SOC), which is evaluated from the points of view of the increase of autonomy, or the length of the stretch or speed of the vehicle for achieving a specific increase of SOC.

The remainder of the paper is organized as follows. Section 2 reviews the concept of DWPT for charging of EVs. Section 3 describes the technical characteristics of the EV (Nissan Leaf) and DWPT system under study. In Section 4, the three stretches of roads under consideration (motorway, highway and urban stretch) are defined and the traffic data (intensity and speed) are discussed. Section 5 details the methodology applied in the assessment of the three case studies, and how the main variables (power required by the entire DWPT system, energy transferred to the EV, consumed by the EV and stored in the battery of EV) are calculated. Section 6 shows and analyses the results obtained in the three stretches of roads under consideration. Finally, Section 7 outlines the conclusions that can be derived from this work.

## 2. Dynamic wireless power transfer for electric vehicles

IPT is the wireless power transfer technology most used in EV charging [24]. Essentially, IPT is based on inductive coupling process between two coils with air core.

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Fig. 1 shows a typical block diagram of an IPT system. Transmitter coil (L1) is driven by a high frequency oscillator. According to Faraday's law of induction, time-varying magnetic fields produced by transmitter coil induce a voltage in the receiver coil (L2) which is placed closer to L1. Electric power in direct current form is applied to the load (the battery) by using a rectifier. In order to reduce the leakage flux due to the air gap, compensation capacitors are connected to both coils (primary and secondary). When compensation capacitors are used, the IPT system is called Inductive Coupled Power Transfer (ICPT). Furthermore, two LC circuits appear in the system. Both LC circuits are designed to work at the resonant frequency, in order to improve the transferred energy.

**Fig. 1.** Block diagram of an IPT system

Compensation capacitors can be placed in Parallel (P) or Series (S) with their respective coils. Taking into account the type of connection of the capacitor in each winding, four topologies of ICPT systems arise: Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP). It can be probed that if parallel compensation is used, the proper capacitance value for resonant operations depends on the coupling coefficient between coils [27]. It is known that the value of coupling coefficient between coils depends on both, axis orientation of each coil and distance between them. Magnetic permeability also influences on the value of this parameter. Consequently, it is easy to conclude than in EV charging applications, coupling coefficient is not a constant, so that SS compensation is preferred.

Kirchhoff's voltage law applied to the equivalent lumped circuit of the system can be used to calculate adequate values of the components in order to obtain the Maximum Power Transfer (MPT) operation point of the system [38]. The MPT always occurs at the

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resonance frequency of both coils. In the transfer efficiency analysis of this system, both the power transferred to the load and the efficiency have been used as the figure of merit.

The charging process in DWPT is carried out while the vehicle is moving on roads [39]. One of the main advantages of this system is that the battery SOC is not a problem, or is a secondary problem, in long driving distance. On the other hand, it requires an expensive infrastructure. In addition, the energy transferred to the battery depends on several factors: speed of the vehicle, size of the charging system, etc.

DWPT charging systems can be divided into two categories based on the topology of the transmitter side: single transmitter track and segmented transmitter array.

Each system has advantages and disadvantages [40]. In the case of DWPT with single transmitter track, the primary power source is connected to a long transmitter coil buried in the track. The receiver coil, installed in the bottom of the vehicle, is much smaller than the length of the track. The main advantages of this system are: (1) Only one source is necessary to be connected to the transmitter, and therefore, the control system of the source is easier; and (2), when the vehicle is moving along the track, coupling coefficient between coils is nearly constant, and the movement of the vehicle fairly affects to the coupling parameters. Due to the different lengths of the primary (track) and secondary (vehicle) coils, three important drawbacks appear: (1) there are electromagnetic fields radiated outside the coupled region that can be harmful; (2) compensation capacitor on the primary must be distributed along primary coil length; and (3) the coupling coefficient is low so that the efficiency of the transfer of the energy decreases.

In the second case, where segmented transmitter array is placed in the road, the DWPT system has several coils buried in the track that can be connected to the primary power source. The closest coil, or group of coils, to the vehicle is connected to the power source, then, in this topology, it is necessary to know the exact position of the vehicle relative to

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the track. Furthermore, electromagnetic field radiated outside is minimized because only the coil under the vehicle is active and distributed compensating is not necessary. On the other hand, the control of the feed of the primary coil is more complex because it is necessary to know the relative position of the vehicle to the track, and to switch on the adequate coil with the source. Additionally, another drawback arises in this system, the distance between coils must be optimized in order to achieve a fairly constant charging process. Although both configurations have advantages and disadvantages, it has been decided to use the latter. The use of a segmented transmitter array has a greater complexity in operation, but can be resolved technically. In case of using a single transmitter, the simplicity of operation is accompanied by radiated field problems harmful to health, and low-efficiency operation of the system. There are several possible configurations of DWPT systems with segmented transmitter array. Among them, the "combination scheme" [41] has been chosen in this work, in which several successive coils are connected to the same power source (electronic power converter) forming a segmented transmitter array. This structure is repeated throughout the section. This type of configuration combines the advantages of other types of segmented DWPT systems and is suitable for large-scale applications.

## 3. Electric vehicle and dynamic wireless power transfer system under study

This section presents the EV and DWPT layout considered in this work to evaluate the power and energy requirements for the dynamic charging of EVs moving along a motorway, a highway and an urban stretch.

### *3.1. Electric vehicle: Nissan Leaf*

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Among the wide variety of EVs, the Nissan Leaf, which is a typical modern family car, has been considered as representative light EV and used in this study.

The Nissan Leaf is equipped with a 24 kWh Lithium-ion battery, with a capacity of 66.2 Ah and a quick charger up to 50 kW.

The Nissan Leaf power requirements were taken from the Advanced Vehicle Testing Activity of the Idaho National Laboratory (AVTA-INL) [42], where a summary of the on-road usage and performance was given. In this test, 26,000 kilometres were covered, where 83% corresponded to city trips; and 17% to highway routes. Fig. 2 shows the energy consumption at different speeds in this test, with a percent over 94% of time driven with air conditioning selected. The data wd.2ere calculated from on-board electronic data logged during a reporting period from May 2013 through September 2015.

Although the energy consumption at low speed is high, it decreases with the speed until 48.3 km/h and remains constant below 80.5 km/h. From this value, the consumption increases linearly with the speed.

**Fig. 2.** Energy consumption versus speed for the vehicle under consideration (Nissan Leaf).

An additional consideration is the energy recovered by the battery during regenerative braking. It happens more frequently in city stretches than in highway and motorways, because of the continuous changes of speed. Since the data shown in Fig. 2 were measured on-road, the effects of energy recovered by the battery, due to regenerative braking, were considered in the test.

### *3.2. Dynamic wireless power transfer system layout*

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Based on the available information, there are different topologies that can be used in the layout of DWPT systems with segmented transmitter array [36]. The selected layout is based on one of the layouts proposed in [36]. In this report two types of DWPT system layout were analysed, and their influence on different aspects of its operation. The design selected is the one with shorter segments (of a distance similar to the length of the vehicles). According to the report, both configuration studied have similar average power demand, but the configuration selected makes the DWPT system more suitable to meet high levels of demand (high traffic levels) and presents more flexibility when the system is used. The layout selected consists of a lane with consecutive power transfer segments. Each one is composed by three coils of 8 meters' long spaced by a 5 meters' gap. The distance between segments is the same as the gap. This configuration provides a segment with a total length of 39 metres. Fig. 3 shows the DWPT layout considered in this study, the same for all the stretches.

Due to the minimum speed limit in some of the roads under study (60 km/h), a considerable safe distance from the vehicle ahead (at least 36 m) is required. For this reason, only one EV can be energised in the same segment.

The secondary coil, mounted beneath the vehicle chassis, can receive up to 40 kW from the primary coil. Some of this power is used for traction and the rest would be used to charge the battery.

Each roadside segment is supplied by a high frequency inverter.

**Fig. 3.** DWPT layout of the segmented transmitter array.

## 4. Motorway, highway and urban stretch under study

In this comparative study, three types of traffic roads were considered in order to analyze the dynamic wireless charging of EVs. All of these traffic roads are located in an

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area around the city of Cadiz (Spain). Descriptions of these roads are given in the following sections.

### *4.1. Motorway and highway stretches*

Several sections of highways and motorways of the above mentioned area were considered in this study.

*A. Traffic data*

Traffic control of Spanish highway and motorway roads is carried out by the General Directorate of Traffic ('Dirección General de Tráfico, DGT') [43]. The traffic data were taken from Traffic Measurement Stations (TMS). From these set of data, TMS can compute traffic parameters in real time, or over a period.

These data do not only depend on the time of the day but also the day of the week and the month. For this reason, data used in this work were taken by these TMS during the year 2015, and were available per hour.

*B. Highway*

The highway selected for this study is CA-33 (purple road in Fig. 4) and connects the cities of San Fernando and Cadiz. It is an 11.3 kilometers-long stretch highway, and traffic data are provided by two TMS of DGT, which are named 33.1C and 33.1D. On weekdays, this highway is used by commuters between both cities.

**Fig. 4.** Motorway and highways under study.

Fig. 5 shows the average values of intensity and speed in this highway. On the left side, monthly average values are shown. On the right side, annual average values are given. The monthly average values of intensity (vehicles per hour) on weekdays are shown in Fig. 5.a.1, and on weekends on Fig. 5.a.2. It is noted that on weekdays, intensity have a maximum centered at 08:00 in the direction from San Fernando to Cadiz. On the

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other direction, from Cádiz to San Fernando, the maximum appears at 15:00. During the night, intensity takes very low values in both directions. On weekends, the pattern of the intensity on each direction is very similar. This behavior is also shown in annual average figures on the right hand side (Fig. 5.c.1 and 5.c.2).

Monthly average values of speed are shown in Fig. 5.b.1 (weekdays) and 5.b.2 (weekends). Annual average values are depicted in Fig. 5.d.1 (weekdays) and 5.d.2 (weekends). These figures show that the values of average speed on this highway take slightly lower values than the speed limits (100 km/h where the TMS is located) during the whole day, and during the whole year.

**Fig. 5.** Average values of intensity and speed in the highway CA-33.

*C. Motorway sections*

E5-AP4 is the motorway considered in this study that connects metropolitan area of Cadiz with metropolitan area of Seville. This motorway is a 75.3 kilometers-long road, and has been divided in three sections. Each of these sections has been depicted with different color in Fig. 4.

Section one (blue section in Fig. 4), between the cities of Puerto Real and Jerez, is 16.2 kilometer-long. On this stretch of motorway there is no toll. Traffic data is capture by two TMS, named as 85.7C and 85.7 D, located in each direction of traffic.

Section two of this motorway (green section in Fig. 4), between the cities of Jerez and Las Cabezas de San Juan, is 32.1 km-long. This stretch of motorway is toll. Traffic data are provided by two TMS, named as 76.82C and 76.82D, in each direction of traffic.

Third section of this motorway (red section in Fig. 4) is between the cities of Las Cabezas de San Juan and Dos Hermanas, where the motorway ends. This stretch is 27

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kilometers-long and it is also a toll section of motorway. Traffic data are provided from two TMS: 40.5C and 40.5 D, one for each direction of traffic.

As mentioned above, E5-AP4 motorway connects two metropolitan areas (Seville and Cadiz cities). But along this motorway there are two important points where vehicles can leave and / or enter this motorway, near the cities of Jerez and Las Cabezas de San Juan. This circumstance forces to divide the motorway into three sections, where traffic has not exactly similar behavior. It would be very extensive to explain here the behavior of the traffic in each section. One of these has been chosen here for description purposes: section one between the cities of Puerto Real and Jerez whose main characteristics have been mentioned above.

**Fig. 6.** Average values of intensity and speed in the section 1 of the motorway E5-AP4.

Fig. 6 shows traffic intensity and speed in this section of motorway. The layout of plots in this figure is the same as used in Fig. 5. On weekdays, the intensity is steady (slightly less than 500 veh/h) from 08:00 to 21:00. After 21:00 the intensity decreases and it is very low during the night. This behavior is similar during the whole year except on July and August, where a maximum appears during the mornings. On the contrary, on weekends the behavior of traffic is different. From May to September the intensity average value increases and a differentiated behavior occurs in both direction of traffic. Maximum values appear in the morning from Jerez to Puerto Real (red line), and on the other direction (blue line) in the evenings. This particular behavior of traffic can be explained because the metropolitan area of Cadiz is well known by its beaches and summer leisure places.

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It can be also observed that the average speed is located slightly below the speed limit where the TMS are located (120 km/h).

### *4.2. Urban stretch*

An avenue of Cadiz city was selected as the urban stretch under study.

*A. Traffic data*

Traffic control in the city of Cadiz is carried out by the Traffic Control Department of the City Hall [44]. The data have been taken from traffic cameras located on several traffic lights in the city. Data are available every 15 minutes.

*B. Avenue description*

Juan Carlos I Avenue is the selected urban stretch. As shows Fig. 7, this avenue crosses the city, and it has 2.4 kilometers-long. Its speed limit is 50 km/h, and the traffic data are given by two traffic cameras: 301 and 302, one on each inbound lane in South-North direction.

**Fig. 7.** Urban avenue selected for this study in Cadiz city.

Fig. 8 shows the average values of intensity and speed in South-North direction and for both lanes (right and central), and it has the same layout used before in motorway and highway analysis. Intensity and speed values are slightly similar in both lanes.

**Fig. 8.** Average values of intensity and speed and intensity in the urban avenue.

The monthly average values of intensity have almost the same pattern during the whole year (except on July and August), with three peaks on weekdays (Fig. 8.a.1 and 8.c.1): A first maximum at 08:00, a second at 15:00; and a third at 20:00. These hours are

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where workers and students go to and from work and schools. Average value of this intensity is around 400 veh/h. On July and August, the maximum in the morning are less high. On weekends (Fig. 8.a.2 and 8.c.2) the pattern is different. First, the average values during the day are lower than weekdays, around 150 veh/h. Besides, the two maximum arise, one of them around 14:00 and the other around 21:00. In both cases (weekdays and weekends), the intensity is very low during the night. The monthly average values of speed on weekdays (Fig. 8.b.1 and 8.d.1) and weekends (Fig. 8.b.2 and 8.d.2) have similar shapes. During the day, the speed is around 35 km/h on weekdays and 40 km/h on weekends. During the night, the speed average is over limits.

## 5. Analysis methodology

The analysis has been performed assuming that the DWPT system provides energy to the EV motor during the stretch and also charges the battery, increasing the vehicle autonomy.

### *5.1. Energy transferred by the dynamic wireless power transfer system to the electric vehicle*

The energy received by the EV only depends on the power received by secondary coil and the time during which the DWPT system is transferring energy ($t_{tr}$). This effective transfer time is function of the numbers and length of the coils, and the EV speed.

$$t_{tr} = N_s \cdot N_c \cdot D_c / v_{ev} \tag{1}$$

where $N_s$ is the total number of segments, $N_c$ is the number of coils per segment, $D_c$ is the coil length and $v_{ev}$ is the average speed every hour, taken from the traffic measurement stations. The total number of segments ($N_s$) depends on the length of each road stretch considered in this work.

$$N_s = L_{sct} / D_s \tag{2}$$

where $L_{sct}$ is the length of the section in km, and $D_s$ is the total segment length, as seen in Fig. 3 and calculated as follows:

$$D_s = D_c \cdot N_c + (N_c - 1) \cdot D_g + D_i \quad (3)$$

where $D_g$ is the gap length, and $D_i$ is the distance between segments.

Thus, the energy received by one EV ($E_{tr}$) can be easily obtained as follows:

$$E_{tr} = P_{ev} \cdot t_{tr} \quad (4)$$

where $P_{ev}$ is the power transferred by the DWPT to the secondary coil in the EV (40 kW).

### *5.2. Energy stored by the electric vehicle battery*

As aforementioned, the energy transferred by the DWPT system is used to supply the EV motor, and the excess energy is stored in the battery.

Therefore, the energy stored in the battery ($E_{str}$) can be calculated as function of the energy received by the EV ($E_{tr}$) and the energy consumed by the EV per km ($E_{cons}$). This energy, for the EV under study, is shown in Fig. 2.

$$E_{str} = \eta_{ch} \cdot (E_{tr} - E_{cons} \cdot L_{sct}) \quad (4)$$

where $\eta_{ch}$ represents the efficiency of the battery charging and the pickup HF converter installed in the EV, which was assumed equal to 0.92 [36].

### *5.3. Power required by the entire dynamic wireless power transfer system*

The power required by the DWPT system depends on the traffic intensity of EVs on the road stretch, the energy transferred to the EV and the efficiency of the entire transfer system. The different elements involved in the power transfer are: the inductive coupling between two coils in movement, the HF inverter on primary coil and the level adapter converter. The ratio between the input energy to the primary and the output energy of the secondary coil provides an overall efficiency ($\eta_{tr}$) of 73% [36]. Therefore, the energy required by the DWPT system at an hour ($E_{DWPT}$), the power required by the DWPT ($P_{DWPT}$) and that provided by the grid (at 1.5 kV MVDC) can be obtained as follows:

$$P_{DWPT} = E_{DWPT} = \left( \frac{E_{tr}}{\eta_{tr}} \cdot N_{vh} \right) \cdot I_{lht} \cdot I_{ev} \quad (5)$$

where $N_{vh}$ is the traffic intensity, $I_{lht}$ and $I_{ev}$ are the per unity value of light EVs in the charging stretch and EVs penetration rate, respectively.

The real $I_{lth}$ values per hour were taken from traffic meters available in the stretches under study. Furthermore, an EVs penetration rate ($I_{ev}$) of 25% was considered for the three stretches. This value of EVs penetration was assumed according to the forecasts made by the International Energy Agency in its Global EV Outlook 2016 report [45], where a penetration rate of 25% for China, Europe and Japan is predicted by 2030, even with the drawbacks of recharging and long distance travel.

## 6. Results and discussion

In this section, the analysis methodology presented in Section 5 has been applied to the road stretches described in Section 4: a) highway, b) motorway and c) urban stretch. In all cases, the variables analysed were the energy transferred by the DWPT to the EV, the energy stored in the battery and the power required by the entire system from the grid. Due to the large amount of data, only the representative results and differences are shown.

### *6.1. Case study 1: Highway CA-33 stretch between Cádiz and San Fernando.*

The traffic data shown in Section 4.1.b allow a monthly and annual analysis for an average day in both driving directions**.** Thus, Fig. 9 shows the energy transferred to an EV in this road stretch. It can be seen in Fig. 9a the monthly values in the driving direction from Cádiz to San Fernando, and from San Fernando to Cádiz in Fig. 9b. The annual values are depicted in Fig. 9c (Fig. 9d) when the EVs travel from Cádiz (from San Fernando).

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**Fig. 9.** Energy transferred to the EV in the highway stretch. Monthly average: a) from Cádiz, b) from San Fernando; and Annual average: c) from Cádiz, d) from San Fernando.

The energy transferred along the stretch is stable, with average values over 3 kWh and fluctuations lower than 0.5 kWh, except in February with slightly higher values. The energy values are near the ones of the maximum speed limit because the vehicles are traveling near this limit. The annual average values are flattened, with less fluctuations along the day, highlighting the stability of the transferred energy.

As described in section 5, the increase of energy stored in the EV battery along the highway stretch can be calculated from the energy transferred to the EV. The representative values of the increase of energy stored are represented in Table 1. These values are calculated as a percent of the capacity, that is, the increase of the battery SOC (ΔSOC). As a result, Table 1 shows a SOC increase about 11% while the EV is running at lower speed limit (ΔSOC60) and over 1% at higher speed limit (ΔSOC100). That is, the EV moves through the stretch increasing its energy stored between those values. On the other hand, Table 1 also shows the decrease of energy stored in the EV battery when the EV moves without dynamic charging. In this case, the battery loses between 6.59% (weekends to Cádiz), and 9.78% (weekends to San Fernando). As a result, the global ΔSOC (with and without DWPT) is about 11%, or about 10% more autonomy in the stretch.

**Table 1.** Increase of the battery SOC (ΔSOC) along the highway stretch.

The power requirements for both sides of the highway are depicted in Fig. 10. In this case, the subplots located at the top represents monthly values while the ones located at the bottom depicts the annual average values. Note that it was considered a degree of EVs penetration of 25% in this study.

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**Fig. 10.** Power required by the entire DWPT system in the highway stretch. Monthly average: a) from Cádiz, b) from San Fernando; Annual average: c) from Cádiz, d) from San Fernando; and Days of maximum intensity: e) from Cádiz, f) from San Fernando.

It can be observed a great variability in the power requirements. In fact, there is a seasonal nature in the monthly average subplots, with higher values in spring and summer, but lower in winter. On weekends, the peaks are smaller than on weekdays. Moreover, in the annual average curves, the peaks change their position depending on the driving direction and the day of the week. On weekdays, the highest power is reached at 14:00 from Cádiz, and at 08:00 in the other direction. Furthermore, in the annual average subplots, there are two peaks on weekends, at 12:00 and 20:00, in both directions. These peaks reach 2.5 MW on weekdays, and under 1.7 MW on weekends. Additionally, the power falls to the lowest value at night. Finally, the power requirements of the day with the maximum traffic intensity in Summer and in Winter (see Appendix) are depicted in Figs. 10e and 10f. On weekdays, these values have a similar pattern to the ones of the annual average, but on weekends, they are different, although similar to weekdays.

As a summary of this case study (a 11 kilometres-long stretch of highway between two nearby localities, Cádiz and San Fernando, with vehicles running at speeds close to maximum speed limit of 100 km/h), it can be established:

- The energy transferred to a EV is low, about 3kWh, and remains stable.
- ΔSOC is stable and not high, about 3%. Although if the EV runs the stretch without dynamic charging, the energy stored in the battery will decrease over 10%.
- The power requirements are highly dependent on the hour of the day and the month of the year. Considering a degree of EVs penetration of 25%, the power reaches a peak of 2.5 MW at noon and falls to a bottom (a few hundred of kilowatts) at dawn.

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If the EV runs at minimum speed limit (60 km/h) the power peak will rise to 3.75 MW.

- The power requirement of the day with the maximum intensity (September, 25$^{th}$) is 2.7 MW, not very far from the one of the monthly average peak (see Appendix). This reflects a great stability in the power fluctuations.
- The power requirements also depend on the driving direction, not only the maximum value but the hour of the day and the month of the year.
- For the EV and the DWPT system considered in this study, the EV could run at 103.5 km/h without battery discharging. On the other hand, ΔSOC will be about 11% if the EV runs at 60 km/h.

### *6.2. Case study 2: Motorway E5-AP4 stretch between Cádiz and Seville.*

The first section of the motorway is almost half of the other two, and it affects the energy transferred and stored in the EV battery. Additionally, the average speed is slightly below that in the other sections and the traffic intensity is also significantly lower.

In this stretch, the average value of the energy transferred to the EV is around 3.6 kWh, with fluctuations less than 0.5 kWh, and it is very close to the value at maximum speed, 3.32 kWh. Besides, the daily fluctuations only happen at night and they are more pronounced on weekends.

The behavior of ΔSOC is similar to the one observed in the energy transferred. Nevertheless, the battery is discharged because the speed is above 103.5 km/h, the speed limit to the EV can run with no change in the battery SOC. The discharging levels are low, between 1.9% on weekdays and 2.5% on weekends. On the other hand, if the EV runs at minimum speed, the battery will increase its SOC up to 16%.

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The power required by the DWPT system is clearly affected by the traffic intensity and its length. As can be seen in Fig. 11, the peaks on weekends are about 1.1 MW, higher that the ones on weekdays (0.83 MW in the direction to Puerto Real and 0.72 MW in the direction to Jerez). The average levels are about 0.3 MW. The monthly values (Figs. 11a and 11b) are affected by the seasonality, mainly on weekends. Thereby, the summer levels double the winter and autumn levels. In the annual average requirements (Fig. 11c and 11d), the power levels on weekdays are stable along the day (about 0.31 MW) and drop to a bottom at night. But there are three remarkable peaks at 08:00, 14:00 and 18:00 in the lane to Jerez. Nevertheless, the weekends patterns are very different, concerning not only the weekdays, but also the traffic direction. In the lane to Jerez, there are two peaks at 12:00 and 19:00, while there is only one peak at 12:00 in the other lane. The maximum levels are in Summer in both ways (Fig. 11e and 11f) and they are higher than the average values.

**Fig. 11.** Power required by the entire DWPT system in the section 1 of the motorway stretch. Monthly average: a) from Puerto Real, b) from Jerez; and Annual average: c) from Puerto Real, d) from Jerez; and Days of maximum intensity: e) from Puerto Real, f) from Jerez.

The other sections have similar behaviors, but different of those observed in the previous section. In both, the energy transferred to an EV is quite close to that of the maximum speed limit (6.58 kWh) and with slightly fluctuations (less than 1 kWh), typical of a tollway stretch. Nevertheless, on the lane towards Puerto Real, the fluctuations are higher along the day, with a peak at 12:00 and a bottom at 15:00.

Similar patterns are obtained for the ΔSOC, with negative values because the traffic speeds are always above 103.5 km/h (where ΔSOC=0). In the section 2 of the stretch the battery decreases its SOC about 11.5%, and around 9.6% in section 3. Furthermore, the energy fluctuations are smaller in the lane towards Seville, with values on weekdays of

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2.6% and 3.4% on weekends. However, the maximum fluctuations are always above 7% in the lane towards Jerez.

In the second and third sections, the power requirements are dependent on the traffic intensity. Fig. 12 depicts the power consumed by the entire DWTP for the section 2 and Fig. 13 for the section 3.

The main difference between both of them is that the Section 3 has significantly higher power consumptions, which are dependent on the month of the year, and more differences between the consumptions of weekdays and weekends, without any seasonality.

Considering the annual average values, the patterns are similar to those seen in the section 1, with large fluctuations along the day. The power requirements are very low at night, rising early in the morning. On weekends, the pattern is quite similar, with remarkable peaks at 12:00 and 19:00, and a valley between both of them. Nevertheless, the power consumed on weekdays presents differences between both section. In the section 3, the fluctuations are low during daylight hours, less than 0.25 MW. But, in section 2, there are upturns above 0.5 MW, with the highest at 02:00 on the lane to Seville (1.4 MW) and at 08:00 (0.87 MW) on the opposite lane.

In section 2, the days of maximum traffic intensity from Jerez present quite higher power requirements than the monthly and annual average values, reaching 2.5 MW at 8:00, due to a remarkable increase of the traffic intensity as can be seen in Appendix. On the other lane, the power levels of the days of maximum intensity are slightly higher than the monthly average values. Finally, in section 3, Figs. 13e and 13f present remarkable differences because of traffic collapse in summer weekends.

**Fig. 12.** Power required by the entire DWPT system in the section 2 of the motorway stretch. Monthly average: a) from Jerez, b) from Las Cabezas de San Juan; and

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Annual average: c) from Jerez, d) from Las Cabezas de San Juan; and Days of maximum intensity: e) from Jerez, f) from Las Cabezas de San Juan.

**Fig. 13.** Power required by the entire DWPT system in the section 3 of the motorway stretch. Monthly average: a) from Las Cabezas de San Juan, b) from Dos Hermanas; and Annual average: c) from Las Cabezas de San Juan, d) from Dos Hermanas; and Days of maximum intensity: e) from Las Cabezas de San Juan, f) from Dos Hermanas.

The result analysis of this case study (DWPT of EVs in a 75.3 kilometres-long stretch of motorway that connects metropolitan areas of Cádiz and Seville) shows:

- As mentioned in Section 4.1 C), there are remarkable differences in the traffic intensity between the sections, and thus, in the power and energy requirements.
- The vehicles drive at speeds close to the limit (120 km/h), resulting less energy transferred and energy stored in the EV battery (about 16% in the stretch). In fact, the dynamic charging is only noticeable in case of sharp reduction of the driving speed ($\Delta$SOC increases about 75% driving at 60 km/h). Nevertheless, considering the current traffic data, the dynamic charging has a significant improvement in the consumption saving (about 63%) for the stretch or an increase of the EV autonomy. As in section 6.1, the EV could run at 103.5 km/h without battery discharging.
- There is a great stability in the energy transferred and stored in an EV. Only in the middle section the fluctuations are wider, with a maximum of 11.14%. Moreover, there are hardly any differences between weekdays and weekends, less than 1.66%.
- The power requirements are fully dependent on the time of the day and the day of the week. But, except in the section 2, they are dependent on seasonality. Influence of driving direction is less pronounced.
- The maximum power in monthly average data, for a penetration degree of 25%, is 1.09 MW (summer weekends) in the section 1, 1.56 MW (autumn weekdays) in the

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section 2 and 4.46 MW (summer weekends) in the section 3. On the other hand, the power of the day with the maximum intensity is 1346 MW (April, 5th), 2430 MW (June, 8th) and 10920 MW (June, 4th) respectively. Thus, the motorway stretch considered in this study presents a fully dependence on the time of the day as mentioned above.

### *6.3. Case study 3: Urban stretch, Avenue Juan Carlos I in Cádiz.*

In this case study, the length of the stretch is 2.4 km and the speed limit is 50 km/h. Traffic intensity is not enough to collapse the road and, thus, the speed is not very low. In night hours, the number of vehicles is small and some drivers exceed limits.

Fig. 14 shows the energy transferred to an EV in the urban stretch. As can be seen in Fig. 14a, most of the values are between 1 and 2 kWh, with an average about 1.6 kWh. The seasonality is low, with an increase in spring and a decrease in autumn. Moreover, the annual values are similar in both lanes, although the peaks are lower and the fluctuations rise slower in the central lane. The energy transferred is lower (around 1 kWh) at night hours than the rest of the day (above 1.5 kWh). Furthermore, the weekdays present higher values than the weekends, except at night.

**Fig. 14.** Energy transferred to the EV in the urban stretch: a) Monthly average, and b) Annual average.

Table 2 shows the representative values of the increase of the battery SOC (ΔSOC) of an EV while running the urban stretch. Due to the speed limit, the increase of energy is higher than those of the highway or motorway stretches. The average ΔSOC is about 4.5% and the maximum ΔSOC is 12.69%, in the central lane (weekends). If an EV runs on the

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stretch without dynamic charging, the decrease of SOC will be between 1.39% and 2.14%.

**Table 2**. Increase of the battery SOC (ΔSOC) of an EV along the urban stretch.

The power requirements are shown in Fig. 15. As can be seen, the monthly patterns are similar in both lanes, although the peaks are higher in the central lane. On weekends, the average values are half of the ones on weekdays. Additionally, there is a remarkable seasonality on weekdays (in summer half than in spring), but the response is flattened on weekends. The power requirements of the summer day with maximum intensity are over 20% higher than monthly average values. But, in winter, the maximum power requirements present a fully dependency on Cádiz Carnival, with levels over 4 times monthly average maximums.

**Fig. 15.** Power required by the entire DWPT system in the urban stretch: a) Monthly average; b) Annual average; and c) Days of maximum intensity

On the other hand, the annual values present more abrupt patterns than previous stretches, but lower due to the length of the lane and the intensity of traffic. The power required at night is negligible. As can be seen in Fig. 15b, on weekdays, there is a sharply increase at 07:00, until the absolute peak at 09:00. The power decreases slightly till 11:00, and then, it remains stable with a slightly increase at 03:00. A valley (05:00) and a peak (08:00) complete the pattern. On weekends, the power is lower and there are only two peaks at 01:00 and 08:00.

In this case study (DWPT of EVs in a 2.4 kilometres-long stretch of urban stretch in Cádiz), the result analysis shows:

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- The energy transferred to the EV presents small values, being almost twice during the day than at night.
- Due to the low speed, the energy stored in the EV battery is high, if they are compared with the ones of the other stretches. The average level is above 4.5% for only 2.4 kilometres.
- The power required by the DWPT depend on the hour of the day and always lower on weekends. This is the typical case of a city where the traffic is highly dependent on working hours.
- The maximum power is always below 0.5 MW, with a 25% degree of penetration.
- For the EV and the DWPT system considered in this study, the vehicle could run the stretch at 50 km/h (speed limit) without discharging the battery and increasing the energy stored up to 3%.

### *6.4. Analysis of the increase of the battery state-of-charge in terms of autonomy, length of stretch and speed.*

The increase of the battery SOC (ΔSOC) can be considered from the points of view of the increase of autonomy, the length of the stretch to achieve specific level of charge and the speed of the vehicles while charging. Table 3 shows the increase of EV autonomy and length of the stretch needed to achieve a ΔSOC of 100%, for the stretches under study. It resumes the analysis of the mean value of ΔSOC considering both directions, monthly and annual values and the type of day (as shown in Tables 1 and 2).

The energy stored in the battery increases in the highway and urban stretches, where the speed is below 103.5 km/h (EV charging/discharging speed limit), while the battery discharges up to 21.47% in motorway stretch. In the urban stretch, when the vehicles move at lower speeds, the ΔSOC per kilometer is higher than in the other stretches. Thus, the minimum autonomy increase is 8.4 km for the central lane. As the length of the urban

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stretch is 2.4 km, the vehicle can run another 6 km at the same average speed until the battery reaches the initial SOC. In the motorway stretch, the DWPT system is not enough to cover the stretch without discharging the battery, so that the EV needs to use its battery between 14.44 and 20.24 km to cover the 75.3 kilometers-long. For this reason, when the driving speed is above the EV charging limit (103.5 km/h), the system can increase the vehicle autonomy, but never charge the battery, unless the driving speed is reduced. For example, with a small speed reduction to 100 km/h, the vehicle could raise the battery SOC about 6.4% or its autonomy over 7.5 km. Instead, in the highway stretch, the battery could increase its SOC up to 100% in a 331 kilometers-long stretch at current average speed, and only 64 kilometers-long in the city. In this case, the speed reduction may not be possible because they could lead to traffic jams.

**Table 3**. Increase of the EV autonomy and length of the stretch needed to achieve a ΔSOC of 100%.

The third point to be analyzed is the suitable speed while charging. Fig. 16a, shows the relation between ΔSOC and the average speed for the stretches under study. As noted above, the motorway sections have a great speed influence, because their average speeds are above the charge limit (103.5 km/h) and the stretches are longer. In these cases, it could be suitable a slow-speed additional lane, where the EVs run at lower speeds to increase the dynamic charging. To explore this possibility, Fig. 16b depicts the ΔSOC of the EV battery per kilometer at different speeds. Thus, if an EV runs at minimum speed limit (60 km/h), the ΔSOC will be 1%, but if it rises to 90 km/h the ΔSOC falls to 0.33%. So, Fig. 16b is a key for the selection of the EV speed during the dynamic charging. According to particular factors, the EV could drive faster or slower as a function of the

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road stretch with DWPT system and the desired SOC at the end of the stretch (increase of autonomy).

**Fig. 16.** ΔSOC as function of the EV speed: a) for the stretches under study, b) per kilometre of the road.

## 7. Conclusions

This paper had studied a DWPT system for three different stretches of traffic roads in order to evaluate power and energy requirements, and EV SOC, that must be considered in the design. The stretches of traffic roads are located in a surrounding area of the city of Cádiz (Spain): (1) highway; (2) motorway and (3) urban stretch. The sizing of the DWPT system depends on the EV and the road stretch, in other words, the traffic speed and intensity, directions, crossroads, seasonality, type of day and hour. This study was performed assuming a scenario with a 25% of EVs circulating and being charged by dynamic wireless charging.

The results analysis showed that in the urban stretch the energy transferred to an EV presents an average value about 0.6 kWh/km with large fluctuations (166%). In contrast, the energy fluctuations are much lower (16.5%) in the highway stretch and even more (around 10%) in the motorway stretch. In these stretches, due to the stability of the energy transferred to the EVs, the electrical installation that supplies the DWPT system could be mainly sized based on the energy requirements. Thus, the energy requirements are about 0.20 kWh/km in the motorway and 0.25 kWh/km in the highway, because of the high traffic speed.

The results also showed that the increase of the battery SOC is low. In the urban stretch, it is higher than in the others, about 1.9% per kilometre. For the EV and the DWPT system considered, the vehicle could run the urban stretch at 50 km/h (speed limit) without discharging the battery and increasing the energy stored up to 3%. Nevertheless,

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in the highway stretch, the increase is less than 0.26% per kilometre, and the SOC decreases around 0.2% in the motorway. Thus, it could be recommended a slow-speed additional lane to allow suitable charging along the route in highway and motorways, increasing the SOC and the autonomy of the EV at the end of the stretch. If a EV drives on this slow lane at 60 km/h, the SOC would increase about 1% per kilometre. On the other hand, at 103.5 km/h, the EV could run without battery discharging.

The power required by the DWPT system is dependent on traffic, the hour of the day, type of day and seasonality. In the urban stretch, the dependence is very large (between 0 and 1.7 MW) and the maximum power availability in the network should be used as the main parameter to size the DWPT system, instead of the maximum power requirements. On the contrary, the highway and motorway stretches are less dependent on seasonality and the DWPT system can be mainly sized by the power requirements. Thus, a rated power, based on the average values, is needed to ride through the daily fluctuations and an additional support to cover expected increases during daytime. This support could be provided by a renewable energy source (photovoltaic or wind) with energy storage system as backup power.

The methodology proposed in this paper is not affected by the layout chosen for the DWPT system. Obviously, the results obtained can be influenced by the selected configuration. It is noteworthy that more research is needed to study and evaluate how different configurations of the layout of the DWPT system affect the battery SOC, the autonomy of the vehicle and the power/energy required by the DWPT system. This methodology presented in this work could be used for analyzing other possible scenarios, configurations and stretches of roads, and help to evaluate and design DWPT for the dynamic charging of EVs in stretches of roads and the infrastructure needed for the electricity supply.

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## Appendix

**Table 4**. Maximum traffic intensity (vehicles/hour) in Summer and Winter days obtained from the sensors data ($N_{vhmax}$) and from the traffic intensity limits at 60 km/h ($N_{vh60}$) and 120 km/h ($N_{vh120}$) in the highway and motorway stretch, and 50 km/h ($N_{vh50}$) in the urban stretch.

**Table 5**. Maximum power required by the entire DWPT system ($P_{DWPTmax}$) obtained from the monthly average values and from the power limit on each stretch ($P_{DWPTlimit}$).

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**Highlights:**

- Dynamic wireless charging of electric vehicles in three road stretches was evaluated.
- Analysis of the electricity consumption of the dynamic wireless power transfer system.
- Analysis of the battery state-of-charge in terms of autonomy, stretch length and speed.
- Useful to evaluate dynamic wireless charging of vehicles and electricity infrastructure.

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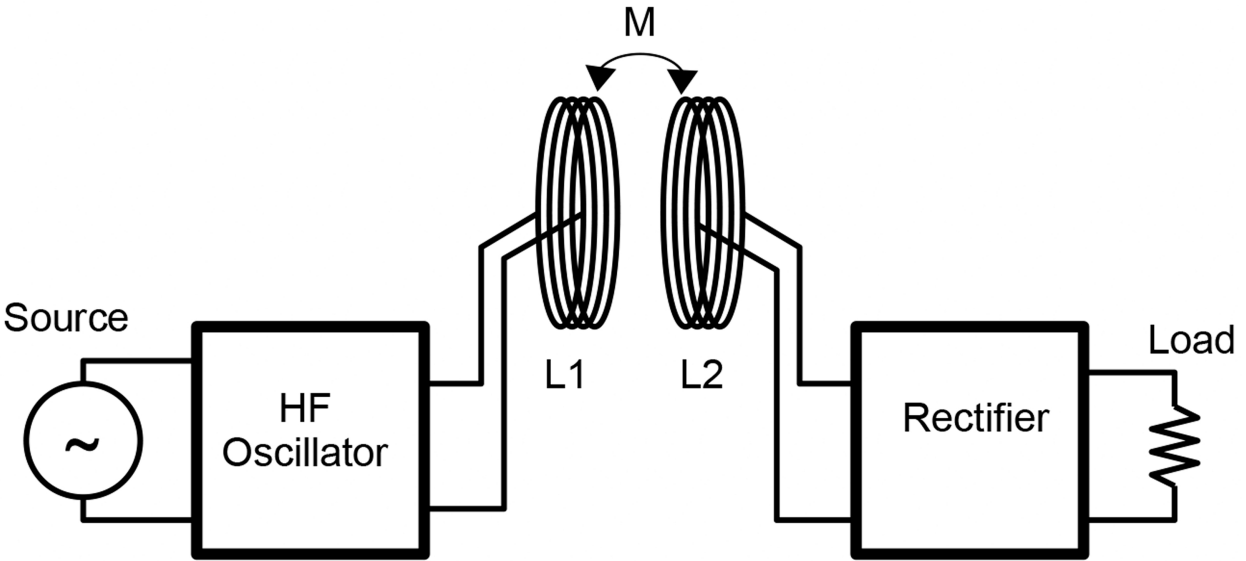
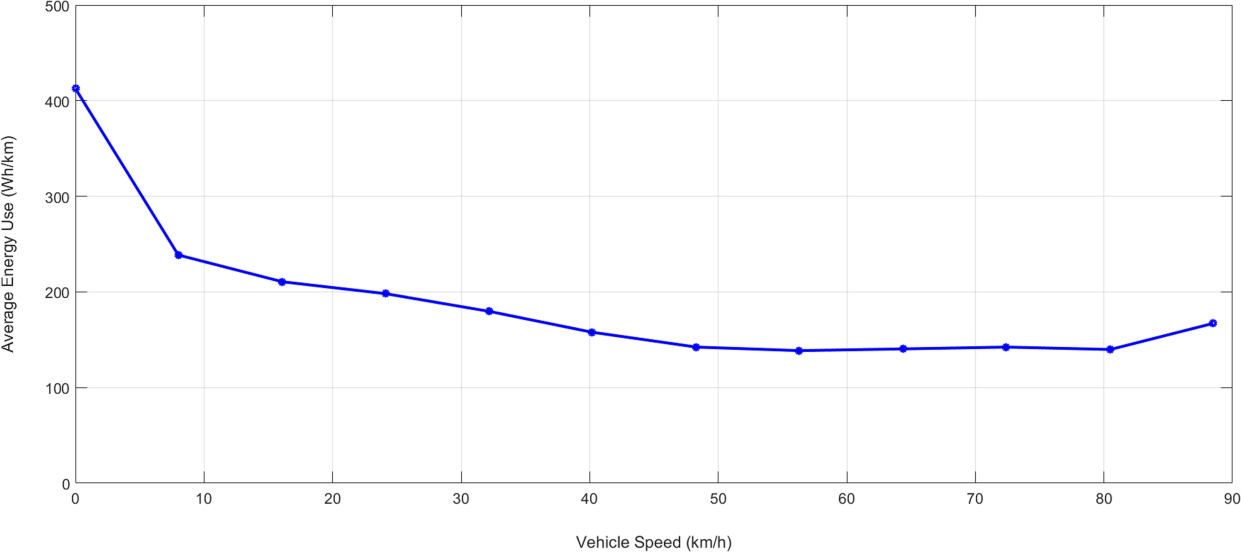
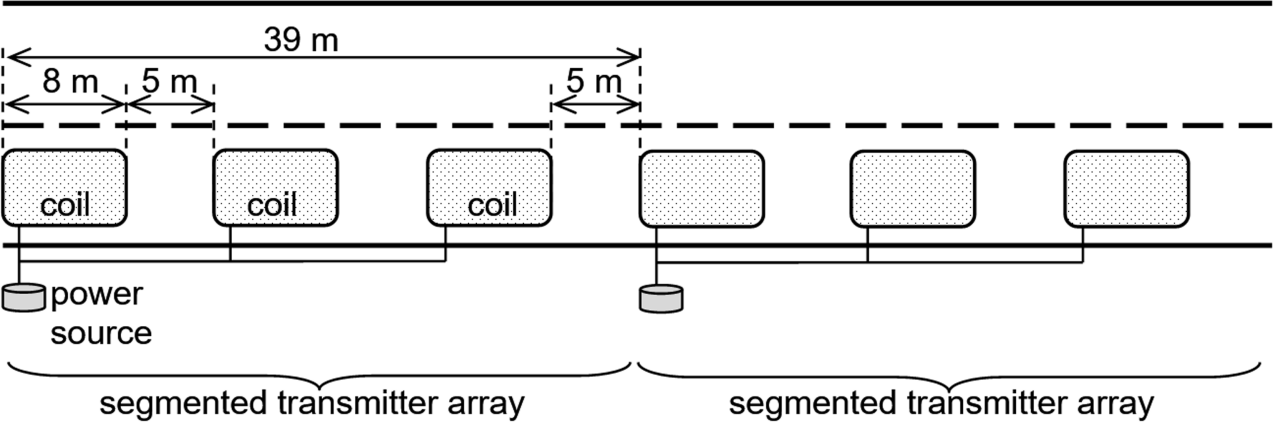
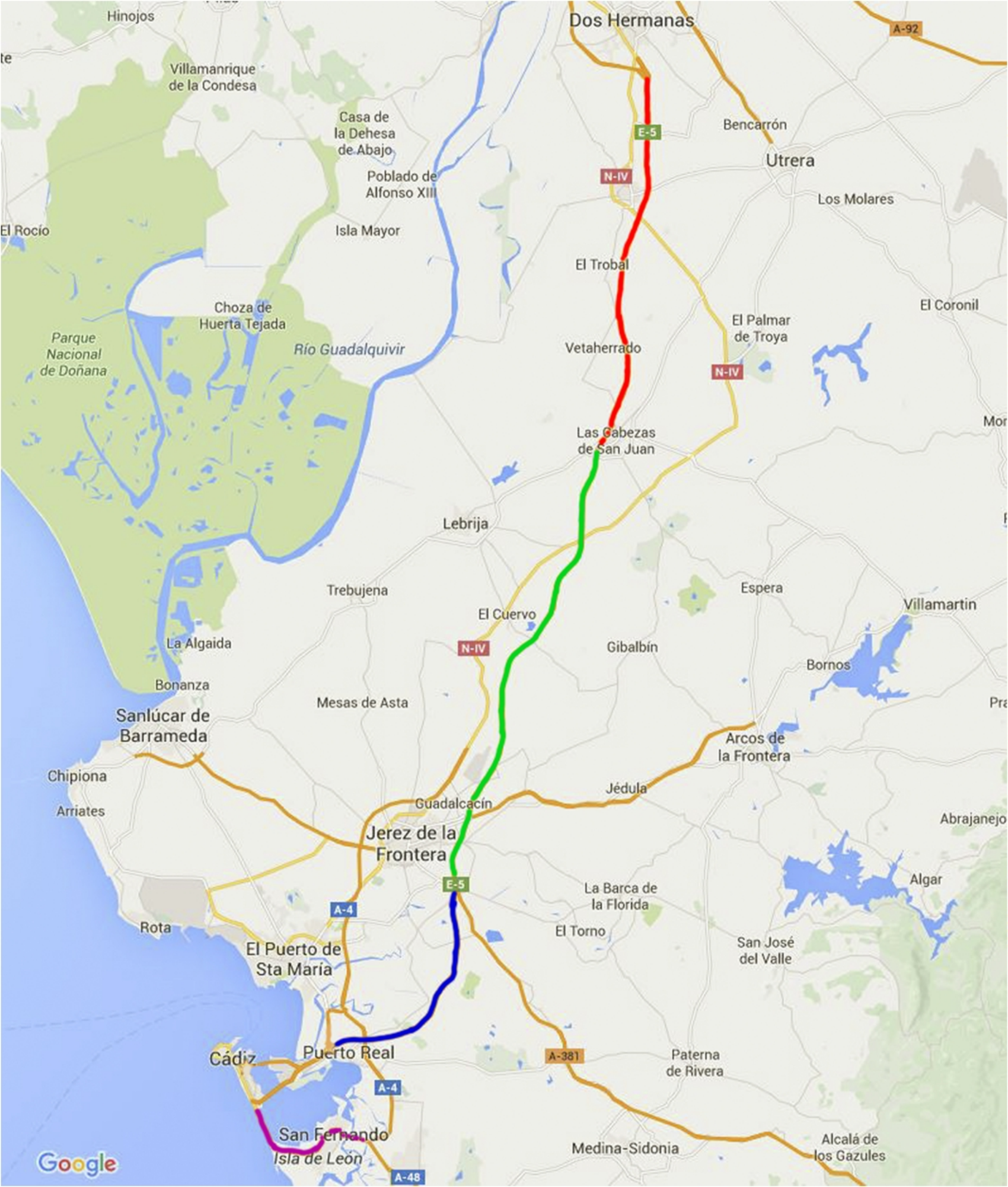
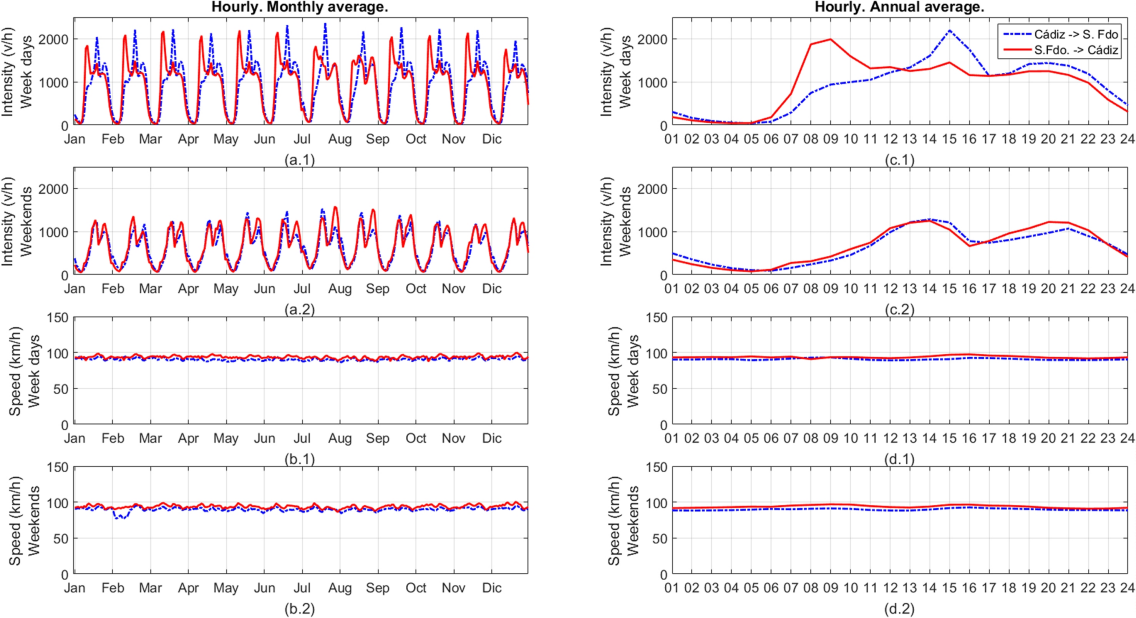
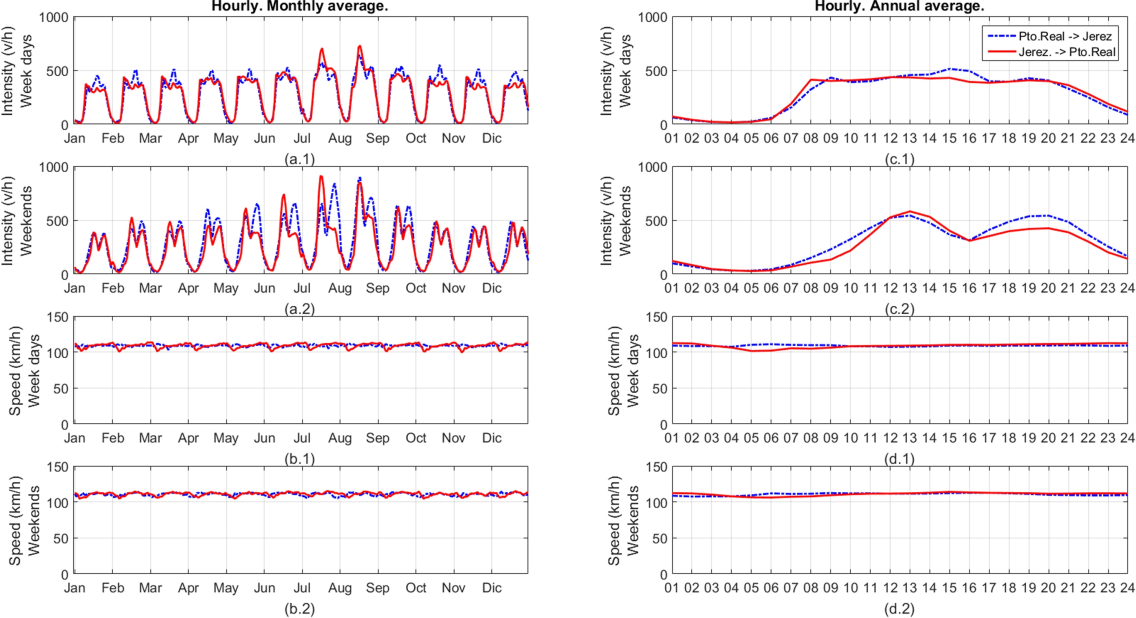

M
Source
~
HF
Oscillator
L1
L2
Rectifier
Load

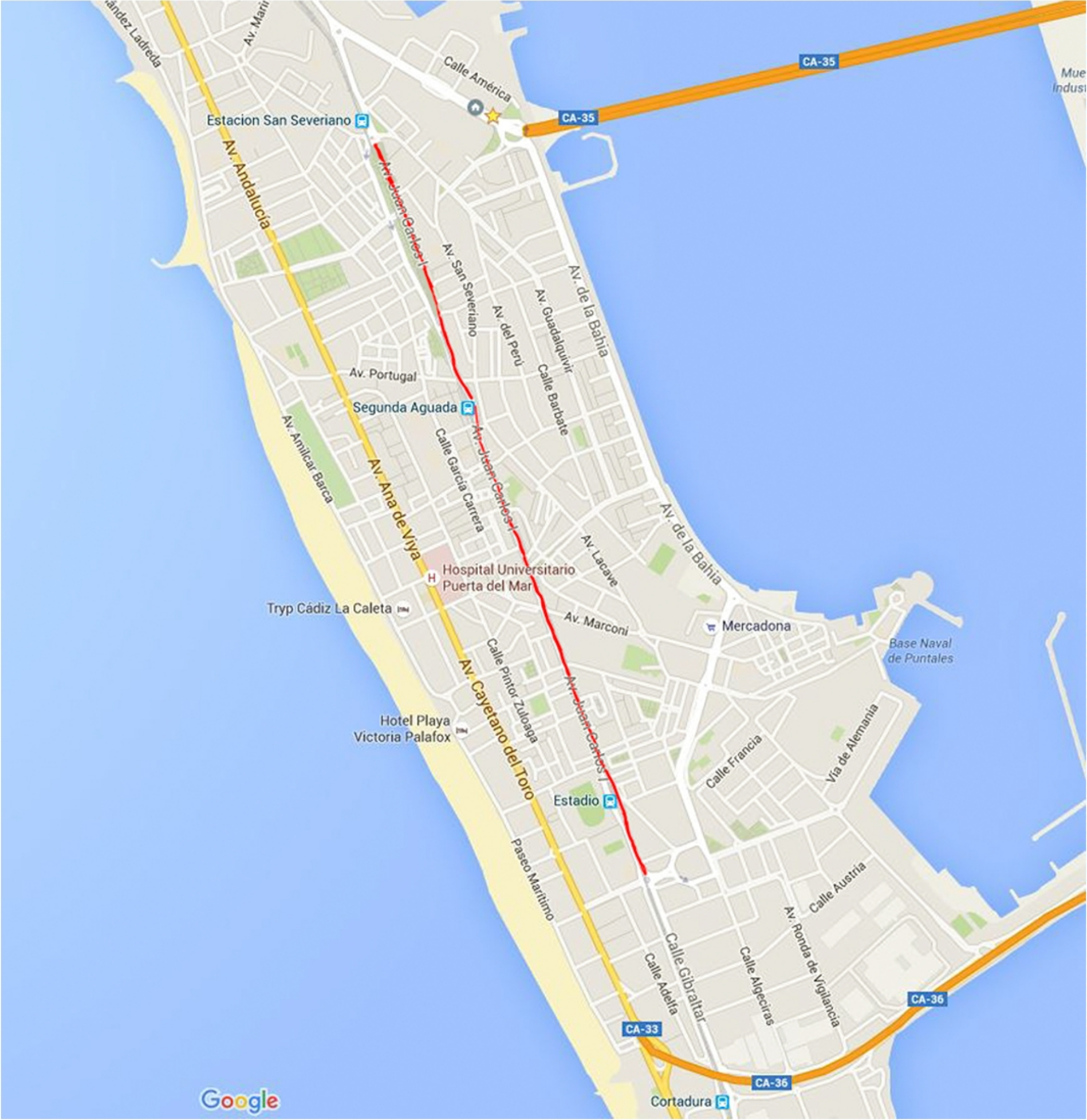

Average Energy Use (Wh/km)
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
Vehicle Speed (km/h)

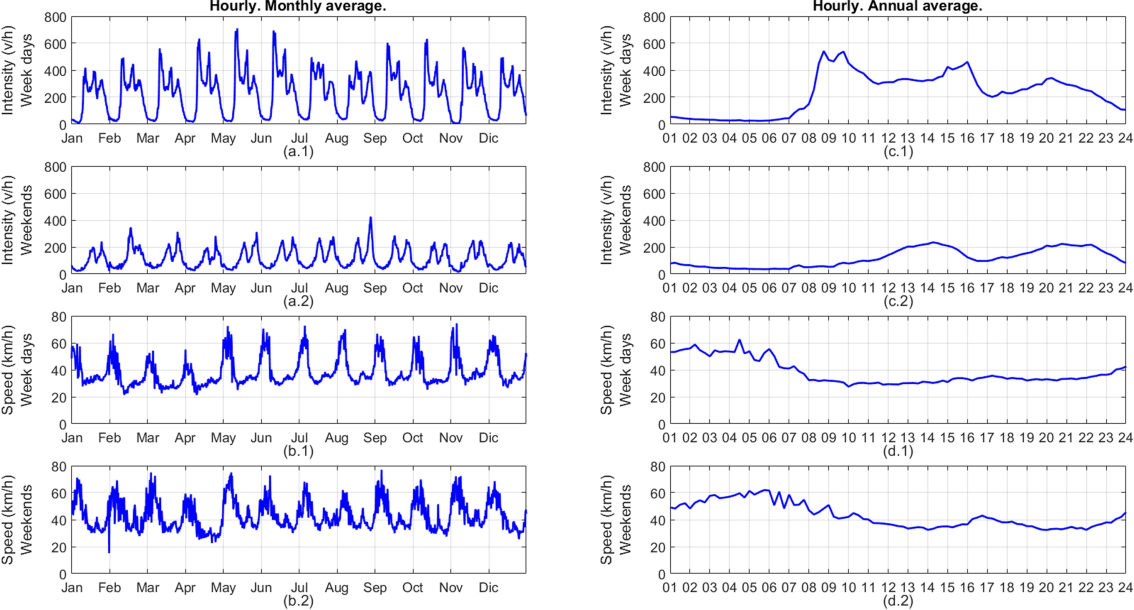

39 m
8 m
5 m
5 m
coil
coil
coil
power
source
segmented transmitter array
segmented transmitter array

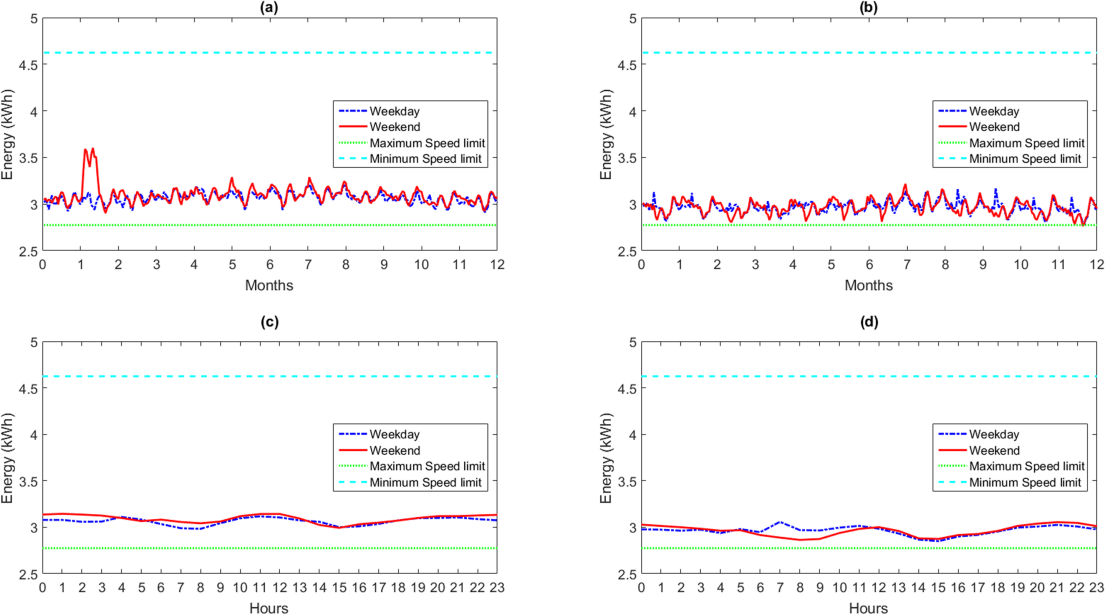

Hinojos
Dos Hermanas
A-92
Villamanrique de la Condesa
Casa de la Dehesa de Abajo
Bencarrón
E-5
Utrera
N-IV
Poblado de Alfonso XIII
Los Molares
El Rocío
Isla Mayor
El Trobal
El Coronil
Choza de Huerta Tejada
El Palmar de Troya
Parque Nacional de Doñana
Río Guadalquivir
Vetaherrado
N-IV
Las Gabezas de San Juan
Lebrija
Trebujena
Espera
El Cuervo
Villamartin
La Algaida
N-IV
Gibalbín
Bornos
Bonanza
Mesas de Asta
Sanlúcar de Barrameda
Arcos de la Frontera
Chipiona
Jédula
Arriates
Guadalcacín
Abrajanejo
Jerez de la Frontera
E-5
Algar
La Barca de la Florida
A-4
Rota
El Torno
El Puerto de Sta María
San José del Valle
Cádiz
Puerto Real
A-381
Paterna de Rivera
A-4
San Fernando
Isla de León
Medina-Sidonia
Alcalá de los Gazules
A-48
Google

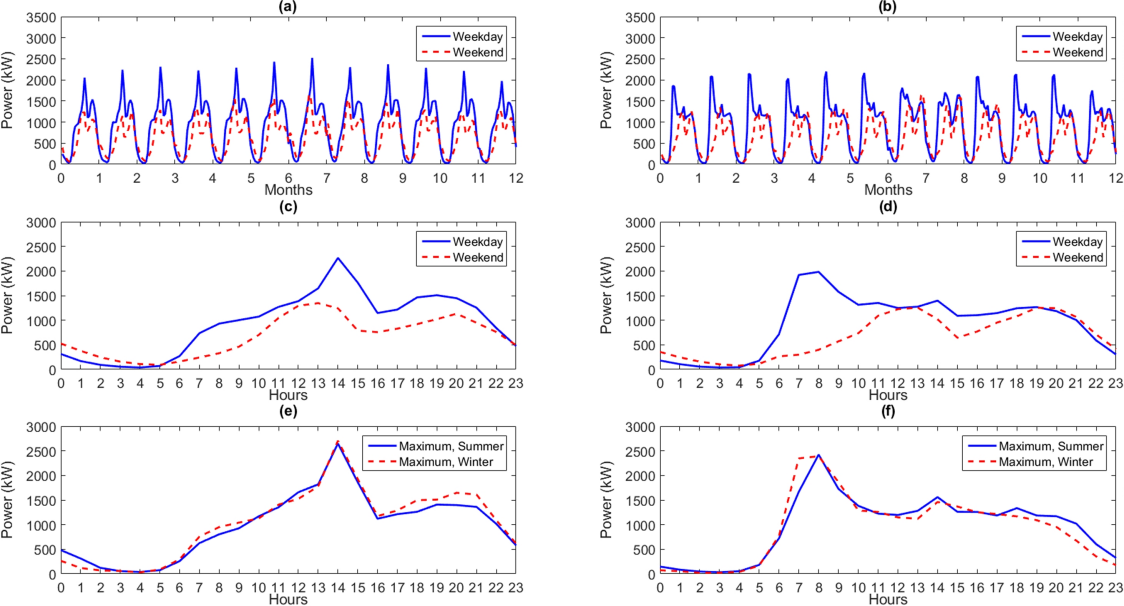

Hourly. Monthly average.
Hourly. Annual average.
Cádiz -> S. Fdo
S.Fdo. -> Cádiz
Intensity (v/h)
Week days
Weekends
Speed (km/h)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dic
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(a.1)
(a.2)
(b.1)
(b.2)
(c.1)
(c.2)
(d.1)
(d.2)

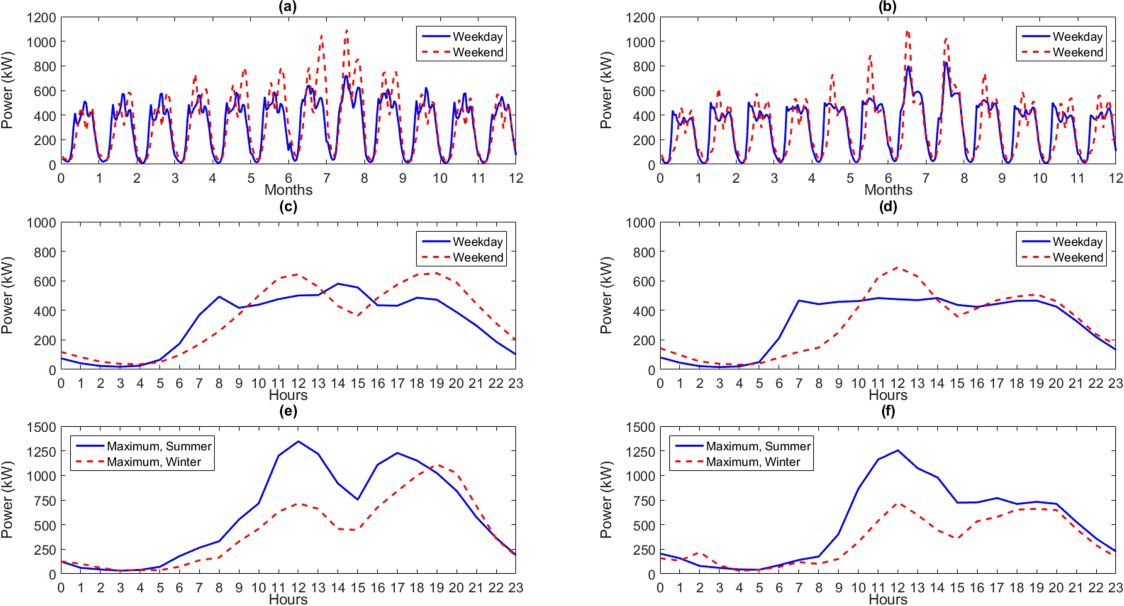

Hourly. Monthly average.
Intensity (v/h)
Week days
1000
500
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dic
(a.1)
Intensity (v/h)
Weekends
1000
500
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dic
(a.2)
Speed (km/h)
Week days
150
100
50
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dic
(b.1)
Speed (km/h)
Weekends
150
100
50
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dic
(b.2)
Hourly. Annual average.
Pto.Real -> Jerez
Jerez. -> Pto.Real
Intensity (v/h)
Week days
1000
500
0
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(c.1)
Intensity (v/h)
Weekends
1000
500
0
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(c.2)
Speed (km/h)
Week days
150
100
50
0
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(d.1)
Speed (km/h)
Weekends
150
100
50
0
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(d.2)

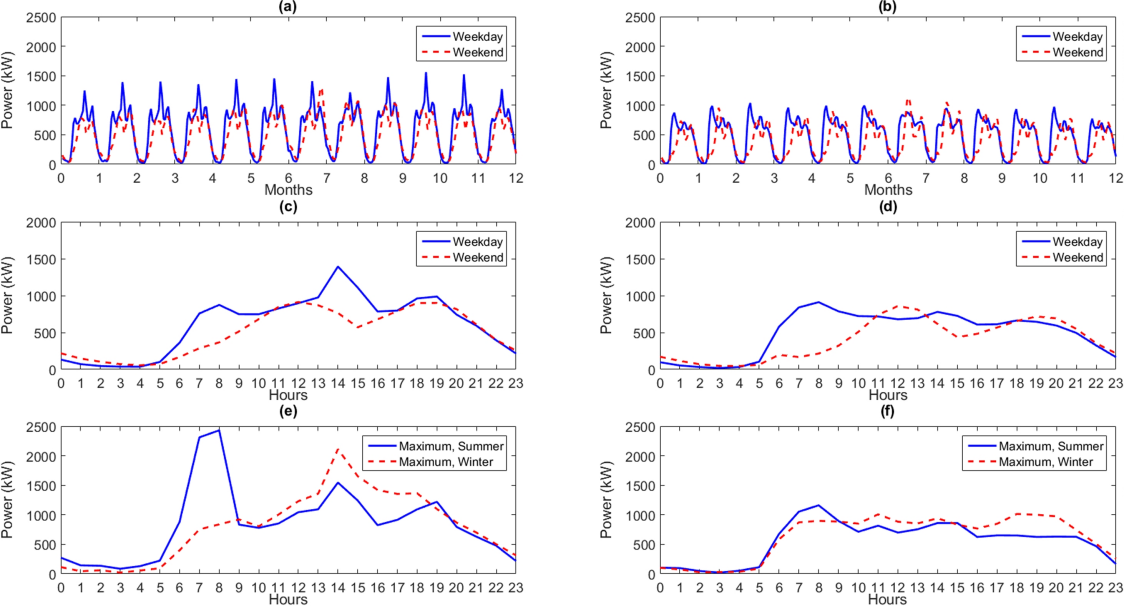

Calle América
CA-35
CA-35
Estacion San Severiano
Av. Andalucía
Av. Juan Carlos I
Av. San Severiano
Av. del Perú
Av. Guadalquivir
Av. de la Bahía
Av. Portugal
Segunda Aguada
Calle Barbate
Av. Amilcar Barca
Calle García Carrera
Av. Ana de Viya
Av. Juan Carlos I
Av. Lacave
Av. de la Bahía
Hospital Universitario
Puerta del Mar
Tryp Cádiz La Caleta
Av. Marconi
Mercadona
Base Naval
de Puntales
Calle Pintor Zuloaga
Av. Juan Carlos I
Av. Cayetano del Toro
Hotel Playa
Victoria Palafox
Calle Francia
Vía de Alemania
Estadio
Paseo Marítimo
Calle Austria
Calle Gibraltar
Calle Adelfa
Calle Algeciras
Av. Ronda de Vigilancia
CA-36
CA-33
CA-36
Cortadura
Google

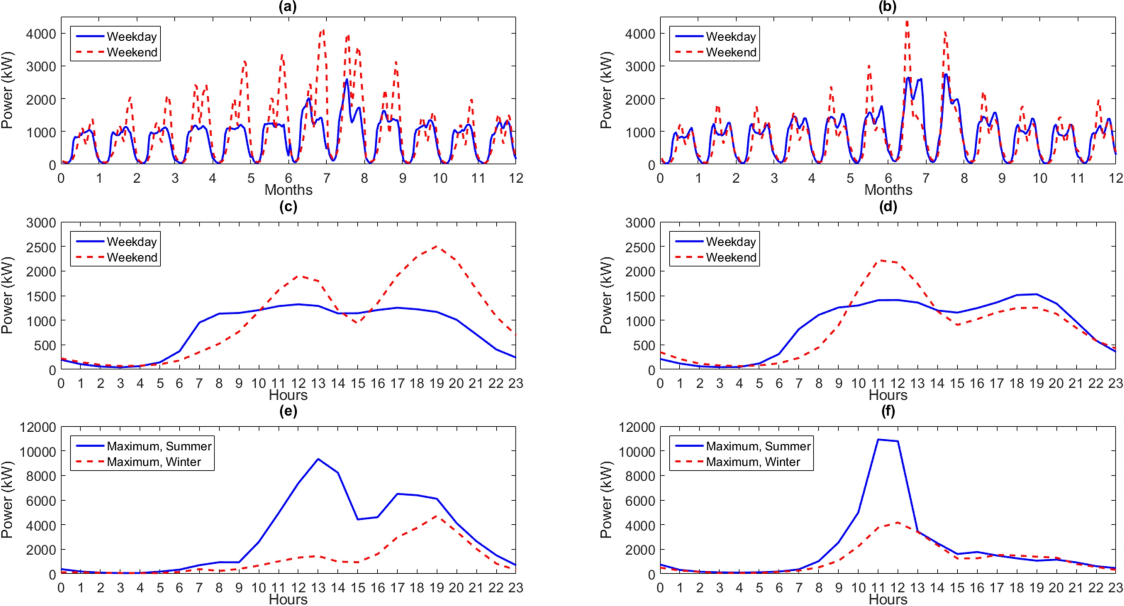

Hourly. Monthly average.
Hourly. Annual average.
Intensity (v/h)
Week days
Weekends
Speed (km/h)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dic
01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
(a.1)
(a.2)
(b.1)
(b.2)
(c.1)
(c.2)
(d.1)
(d.2)

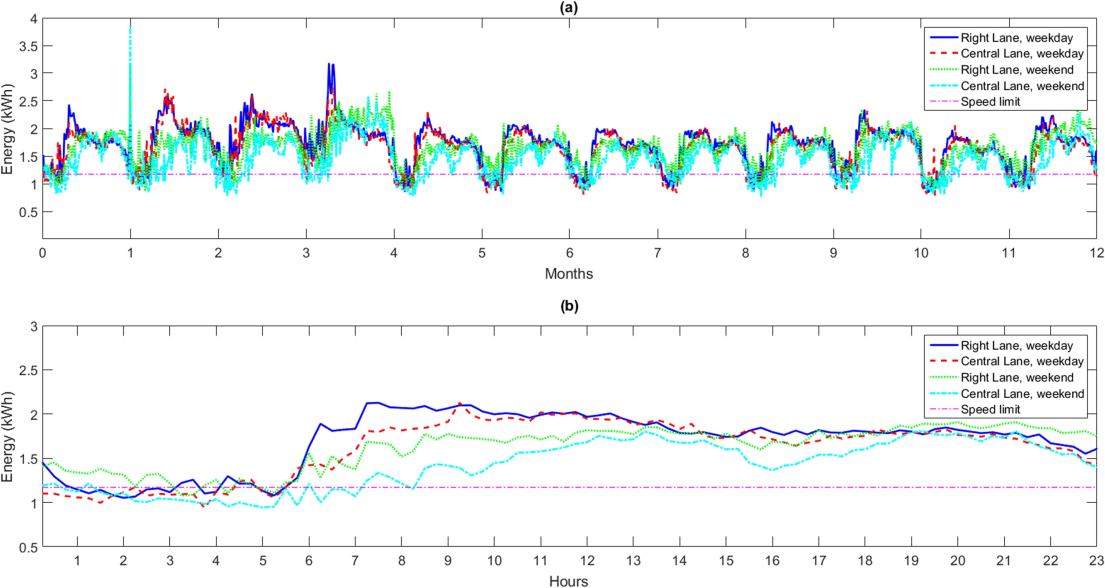

(a)
Energy (kWh)
Months
Weekday
Weekend
Maximum Speed limit
Minimum Speed limit
(b)
Energy (kWh)
Months
Weekday
Weekend
Maximum Speed limit
Minimum Speed limit
(c)
Energy (kWh)
Hours
Weekday
Weekend
Maximum Speed limit
Minimum Speed limit
(d)
Energy (kWh)
Hours
Weekday
Weekend
Maximum Speed limit
Minimum Speed limit

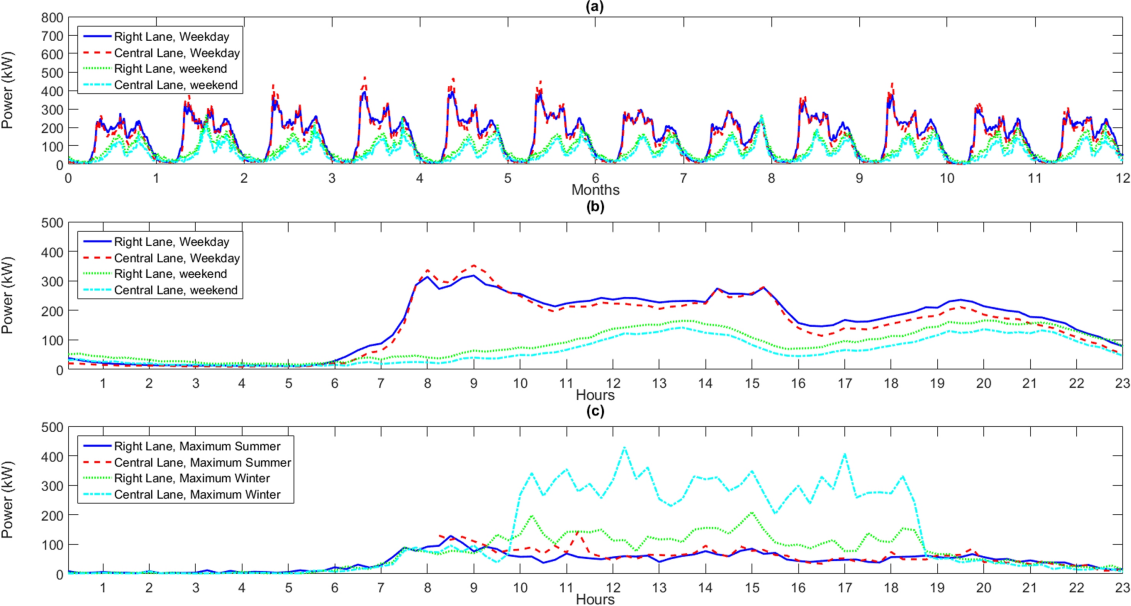

(a)
Power (kW)
Months
Weekday
Weekend
(b)
Power (kW)
Months
Weekday
Weekend
(c)
Power (kW)
Hours
Weekday
Weekend
(d)
Power (kW)
Hours
Weekday
Weekend
(e)
Power (kW)
Hours
Maximum, Summer
Maximum, Winter
(f)
Power (kW)
Hours
Maximum, Summer
Maximum, Winter

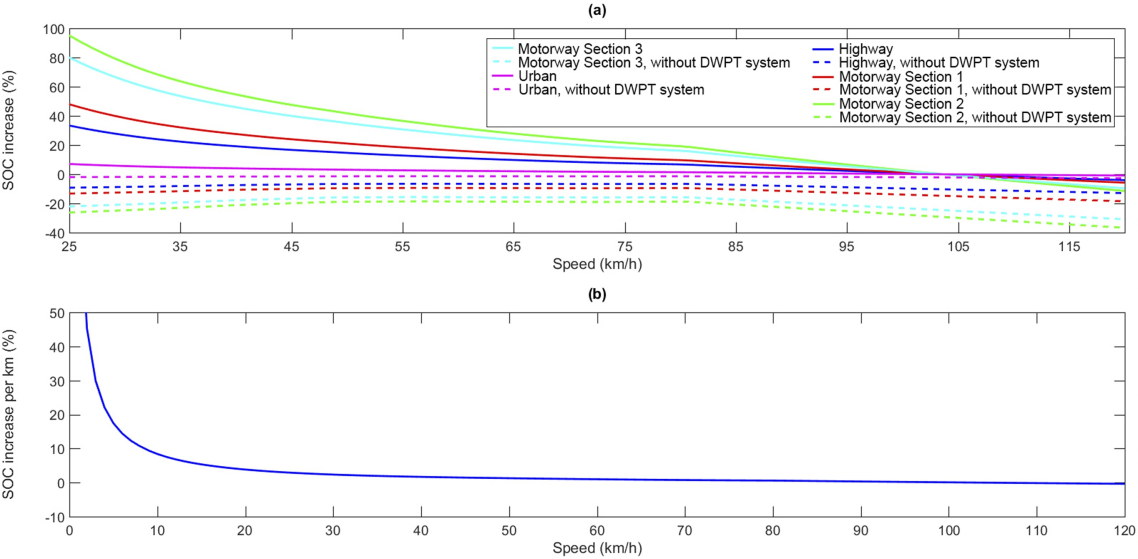

(a)
Power (kW)
Months
Weekday
Weekend
(b)
Power (kW)
Months
Weekday
Weekend
(c)
Power (kW)
Hours
Weekday
Weekend
(d)
Power (kW)
Hours
Weekday
Weekend
(e)
Power (kW)
Hours
Maximum, Summer
Maximum, Winter
(f)
Power (kW)
Hours
Maximum, Summer
Maximum, Winter


(a)
Power (kW)
Months
Weekday
Weekend
(b)
Power (kW)
Months
Weekday
Weekend
(c)
Power (kW)
Hours
Weekday
Weekend
(d)
Power (kW)
Hours
Weekday
Weekend
(e)
Power (kW)
Hours
Maximum, Summer
Maximum, Winter
(f)
Power (kW)
Hours
Maximum, Summer
Maximum, Winter


(a)
Weekday
Weekend
Power (kW)
Months
(b)
Weekday
Weekend
Power (kW)
Months
(c)
Weekday
Weekend
Power (kW)
Hours
(d)
Weekday
Weekend
Power (kW)
Hours
(e)
Maximum, Summer
Maximum, Winter
Power (kW)
Hours
(f)
Maximum, Summer
Maximum, Winter
Power (kW)
Hours


(a)
Energy (kWh)
Months
Right Lane, weekday
Central Lane, weekday
Right Lane, weekend
Central Lane, weekend
Speed limit
(b)
Energy (kWh)
Hours
Right Lane, weekday
Central Lane, weekday
Right Lane, weekend
Central Lane, weekend
Speed limit


(a)
Right Lane, Weekday
Central Lane, Weekday
Right Lane, weekend
Central Lane, weekend
Power (kW)
Months
(b)
Right Lane, Weekday
Central Lane, Weekday
Right Lane, weekend
Central Lane, weekend
Power (kW)
Hours
(c)
Right Lane, Maximum Summer
Central Lane, Maximum Summer
Right Lane, Maximum Winter
Central Lane, Maximum Winter
Power (kW)
Hours


(a)
SOC increase (%)
Speed (km/h)
Motorway Section 3
Motorway Section 3, without DWPT system
Urban
Urban, without DWPT system
Highway
Highway, without DWPT system
Motorway Section 1
Motorway Section 1, without DWPT system
Motorway Section 2
Motorway Section 2, without DWPT system
(b)
SOC increase per km (%)
Speed (km/h)

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| | | Weekday | | Weekend | |
|---|---|---|---|---|---|
| **Monthly** | **Sensor** | **33.1c** | **33.1d** | **33.1c** | **33.1d** |
| | **ΔSOCmax** | 4.49 | 4.81 | 4.84 | 7.20 |
| | **ΔSOCmed** | 2.71 | 3.58 | 2.68 | 3.81 |
| | **ΔSOCmin** | 1.26 | 2.21 | 0.83 | 2.14 |
| | **ΔSOC60** | 11.19 | | | |
| | **ΔSOC100** | 0.94 | | | |
| | **Without Dynamic Charging** | | | | |
| | **ΔSOCmax** | -7.69 | -7.52 | -7.50 | -6.59 |
| | **ΔSOCmed** | -8.68 | -8.19 | -8.70 | -8.07 |
| | **ΔSOCmin** | -9.66 | -8.96 | -9.78 | -9.01 |

| | | Weekday | | Weekend | |
|---|---|---|---|---|---|
| **Annual** | **Sensor** | **33.1c** | **33.1d** | **33.1c** | **33.1d** |
| | **ΔSOCmax** | 3.51 | 4.02 | 3.49 | 4.25 |
| | **ΔSOCmed** | 2.70 | 3.57 | 2.67 | 3.81 |
| | **ΔSOCmin** | 1.65 | 2.86 | 1.78 | 2.95 |
| | **ΔSOC60** | 11.19 | | | |
| | **ΔSOC100** | 0.94 | | | |
| | **Without Dynamic Charging** | | | | |
| | **ΔSOCmax** | -8.22 | -7.94 | -8.24 | -7.82 |
| | **ΔSOCmed** | -8.68 | -8.19 | -8.70 | -8.06 |
| | **ΔSOCmin** | -9.23 | -8.59 | -9.21 | -8.53 |

**Table 1.** Increase of the battery SOC (ΔSOC) along the highway stretch

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| | | Weekday | | Weekend | |
|---|---|---|---|---|---|
| **Monthly** | **Sensor** | **301** | **302** | **301** | **302** |
| | **ΔSOCmax** | 10.14 | 8.48 | 10.14 | 12.69 |
| | **ΔSOCmed** | 4.85 | 4.57 | 4.67 | 3.96 |
| | **ΔSOCmin** | 1.81 | 1.60 | 1.88 | 1.51 |
| | **ΔSOC50** | 3.08 | | | |
| | **Without Dynamic Charging** | | | | |
| | **ΔSOCmax** | -1.39 | -1.39 | -1.39 | -1.39 |
| | **ΔSOCmed** | -1.72 | -1.68 | -1.69 | -1.59 |
| | **ΔSOCmin** | -2.07 | -2.02 | -2.07 | -2.14 |

| | | Weekday | | Weekend | |
|---|---|---|---|---|---|
| **Annual** | **Sensor** | **301** | **302** | **301** | **302** |
| | **ΔSOCmax** | 6.26 | 6.26 | 5.50 | 5.15 |
| | **ΔSOCmed** | 4.76 | 4.48 | 4.55 | 3.85 |
| | **ΔSOCmin** | 2.65 | 2.19 | 2.75 | 2.23 |
| | **ΔSOC50** | 3.08 | | | |
| | **Without Dynamic Charging** | | | | |
| | **ΔSOCmax** | -1.39 | -1.39 | -1.39 | -1.39 |
| | **ΔSOCmed** | -1.71 | -1.67 | -1.68 | -1.57 |
| | **ΔSOCmin** | -1.9 | -1.9 | -1.83 | -1.79 |

**Table 2**. Increase of the battery SOC (ΔSOC) of an EV along the urban stretch.

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| Stretch | | Sensor | ΔSOC (%) | Average speed (km/h) | Length (km) | Autonomy increases (km) | Length for 100% ΔSOC (km) |
|---|---|---|---|---|---|---|---|
| **Highway** | | | | | | | |
| | **Min** | 33.1d | 2.68 | 93.6 | 11.3 | 14.77 | 418.86 |
| | **Max** | 33.1c | 3.81 | 90.3 | 11.3 | 16.58 | 331.04 |
| **Motorway** | | | | | | | |
| **Section 1** | **Min** | 87.5c | -2.62 | 109.4 | 16.2 | 13.56 | - |
| | **Max** | 87.5d | -1.87 | 109.3 | 16.2 | 14.31 | - |
| **Section 2** | **Min** | 76.82c | -11.09 | 117.7 | 32.1 | 22.11 | - |
| | **Max** | 76.82d | -6.56 | 113.1 | 32.1 | 25.81 | - |
| **Section 3** | **Min** | 40.5d | -7.76 | 115.6 | 27.0 | 19.81 | - |
| | **Max** | 40.5c | -6.53 | 115.1 | 27.0 | 20.91 | - |
| **All Sections** | **Min** | | -21.47 | 114.2 | 75.3 | 55.06 | - |
| | **Max** | | -14.96 | 112.4 | 75.3 | 60.86 | - |
| **Urban** | | | | | | | |
| | **Min** | 302 | 3.96 | 40.0 | 2.4 | 8.40 | 71.95 |
| | **Max** | 301 | 4.85 | 36.0 | 2.4 | 9.28 | 63.90 |

**Table 3**. Increase of the EV autonomy and length of the stretch needed to achieve a ΔSOC of 100%.

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| Stretch (Sensor) | Season | Date | Day | $N_{vhmax}$ | $N_{vhmax60}$ | $N_{vhmax120}$ | $N_{vhmax50}$ |
|---|---|---|---|---|---|---|---|
| | | | | v/h | v/h | v/h | v/h |
| **Highway Stretch** | | | | | | | |
| **33.1C** | Summer | July, 07th | Weekday | 2531 | 1396 | 2708 | - |
| | Winter | September, 25th | Weekday | 2579 | 1396 | 2708 | - |
| **33.1D** | Summer | May, 14th | Weekday | 2405 | 1396 | 2708 | - |
| | Winter | November, 3rd | Weekday | 2316 | 1396 | 2708 | - |
| **Motorway Stretch** | | | | | | | |
| **85.7C** | Summer | April, 5th | Weekday | 1118 | 1410 | 2774 | - |
| | Winter | November, 3rd | Weekday | 899 | 1410 | 2774 | - |
| **85.7D** | Summer | August, 16th | Weekend | 1040 | 1410 | 2774 | - |
| | Winter | October, 10th | Weekend | 798 | 1410 | 2774 | - |
| **76.82C** | Summer | June, 8th | Weekday | 757 | 1442 | 2806 | - |
| | Winter | October, 9th | Weekday | 807 | 1442 | 2806 | - |
| **76.82D** | Summer | June, 27th | Weekend | 635 | 1442 | 2806 | - |
| | Winter | February, 15th | Weekend | 685 | 1442 | 2806 | - |
| **40.5C** | Summer | April, 5th | Weekend | 3481 | 1457 | 2821 | - |
| | Winter | February, 22th | Weekend | 2309 | 1457 | 2821 | - |
| **40.5D** | Summer | July, 4th | Weekend | 2972 | 1457 | 2821 | - |
| | Winter | December, 5th | Weekend | 2269 | 1457 | 2821 | - |
| **Urban Stretch** | | | | | | | |
| **301** | Summer | April, 27th | Weekday | 695 | - | - | 1143 |
| | Winter | February, 2nd | Weekday | 952 | - | - | 1143 |
| **302** | Summer | April, 12th | Weekday | 872 | - | - | 1143 |
| | Winter | February, 2nd | Weekday | 1080 | - | - | 1143 |

**Table 4**. Maximum traffic intensity (vehicles/hour) in Summer and Winter days obtained from the sensors data ($N_{vhmax}$) and from the traffic intensity limits at 60 km/h ($N_{vh60}$) and 120 km/h ($N_{vh120}$) in the highway and motorway stretch, and 50 km/h ($N_{vh50}$) in the urban stretch.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

| Stretch (Sensor) | Hour | Month | Day | $P_{DWPTmax}$ kW | Intensity v/h | Speed Km/h | Segments | $P_{DWPTlimit}$ kW |
|---|---|---|---|---|---|---|---|---|
| **Highway Stretch** | | | | | | | | |
| **85.7C** | 14:00 | July | Weekday | 2521 | 2382 | 88.4 | 289 | 11560 |
| **85.7D** | 08:00 | May | Weekday | 2197 | 2193 | 92.9 | 289 | 11560 |
| **Motorway Stretch** | | | | | | | | |
| **85.7C** | 12:00 | August | Weekend | 1091 | 898 | 109.4 | 415 | 16600 |
| **85.7D** | 11:00 | July | Weekend | 1096 | 909 | 110.9 | 415 | 16600 |
| **76.82C** | 14:00 | October | Weekday | 1560 | 676 | 111.4 | 823 | 32920 |
| **76.82D** | 12:00 | July | Weekend | 1134 | 529 | 123.8 | 823 | 32920 |
| **40.5C** | 20:00 | July | Weekend | 4126 | 2075 | 110.4 | 692 | 27680 |
| **40.5D** | 11:00 | July | Weekend | 4466 | 2140 | 106 | 692 | 27680 |
| **Urban Stretch** | | | | | | | | |
| **301** | 15:15 | April | Weekday | 394.4 | 515 | 31.3 | 61 | 2440 |
| **302** | 15:15 | April | Weekday | 474 | 536 | 32.4 | 61 | 2440 |

**Table 5**. Maximum power required by the entire DWPT system ($P_{DWPTmax}$) obtained from the monthly average values and from the power limit on each stretch ($P_{DWPTlimit}$).

ACCEPTED MANUSCRIPT