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Research Article

The Effect of the Wireless Power Transfer for Electric Vehicles on State of Charge

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Abstract

Built-in batteries limit electric vehicles in terms of the vehicle's final destination and battery recharge time. This study investigated the battery charge status of electric vehicles charged with wireless power transfer (WPT) systems. The adequacy and impact of these systems will be seen according to the battery charge status because the battery charge status is directly related to the range of the vehicle. A simple battery model and a vehicle model based on power consumption were used in the simulation to measure the effect of wireless charging on battery status. These two models are vehicle and battery models in the Mathworks library. Two different situations are simulated namely urban and highway driving cycles. Different power levels have been observed to affect the battery charge status. It is possible to have an unlimited vehicle range at medium power levels in urban driving. The charge transferred to the batteries at the stopping points of the vehicles and the charge consumed during the cycle at power levels of 20 kilowatts are at the same level as the amount charged by this system. It has been found that wireless power transfer at medium power levels is sufficient to get rid of the charging problem. On highways, an approach can be created to achieve unlimited range by increasing the coverage area. As a result, wireless energy transfer will significantly reduce the dependency on high-capacity batteries and reduce the battery charging times to the shortest time, reducing electric vehicle costs and eliminating range anxiety.

Keywords: Electric Vehicles, Driving Range, Wireless Power Transfer.

Elektrikli Araçlarda Kablosuz Enerji Transferinin Batarya Şarj Durumuna Etkisi

Öz

Yerleşik piller, elektrikli araçları sürüş menzili ve şarj süresi açısından sınırlar. Bu çalışmada, kablosuz enerji transferi (KET) sistemleri ile şarj edilen elektrikli araçların batarya şarj durumları incelenmiştir. Batarya şarj durumlarına göre bu sistemlerin yeterliliği ve etkisi görülecektir, çünkü batarya şarj durumu aracın menzili ile doğrudan ilgilidir. Kablosuz şarjın pil durumuna etkisini ölçmek amacıyla yapılan simülasyonda güç tüketimini esas alan araç modeli ile basit bir pil modeli kullanıldı. Bu iki model de Mathworks kütüphanesinde bulunan araç ve batarya modelleridir. Şehir içi ve otoyol sürüş döngüleri olmak üzere iki farklı durumun benzetimi yapılmıştır. Farklı güç seviyelerinin batarya şarj durumuna etkisi gözlenmiştir. Şehir içi sürüşlerinde araç menzilinin sınırsız olması orta seviye güçlerde mümkündür. Araçların durma noktalarında bataryalara aktarılan şarj ile 20 kilowattlık güç seviyelerinde döngü boyunca tüketilen şarjın bu sistem tarafından şarj edilme miktarı ile aynı seviyelerdedir. Şarj etme sorunundan kurtulmak için orta güç seviyelerindeki kablosuz güç transferinin yeterli olduğu anlaşılmıştır. Otoyollarda ise kapsama alanı artırılarak sınırsız menzil elde etmek üzere bir yaklaşım oluşturulabilir. Sonuç olarak kablosuz enerji transferi yüksek kapasiteli bataryalara olan bağımlılığı önemli ölçüde azaltacak ve batarya şarj sürelerini en kısa süreye indirerek hem elektrikli araç maliyetlerini azaltacak hem de menzil kaygısını ortadan kaldıracaktır.

Anahtar Kelimeler: Elektrikli Araç, Sürüş Menzili, Kablosuz Enerji Transferi.

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1. Introduction

With the excessive use of fossil resources to generate energy, air pollution and global warming have increased. In addition, the possibility of the exhaustion of these resources has started to occur. Therefore, it is inevitable that the production costs of the energy obtained in this way will increase. For these reasons, studies have been initiated to reduce the use of these fossil fuels and the trend towards renewable energy sources in energy production. This orientation is experienced in transportation and transportation as in every field. Especially the number of vehicles increasing year by year increased the amount of harmful greenhouse gases emitted to the environment. This situation is one of the main factors leading to global warming. Therefore, the production of zero-emission vehicles in automobiles, buses, and heavy goods vehicles has become necessary to minimize this effect.

The production of Electric Vehicles (EV) and researches conducted for this purpose have gained momentum in recent years (Ehsani et al., 2007; Gysen et al., 2009; Honda, 2015; Koehn & Eckrich, 2004; Yong et al., 2015). The trend towards electric vehicles should increase and the use of vehicles using fossil fuels should decrease for a zero-emission and clean environment. It is important that electric vehicles can compete with vehicles that use oil in terms of cost. The biggest obstacle in this matter is the energy storage problem. It is undeniable that the more the storage problem is overcome, the more widespread it will become (Sellali et al., 2019). To this end, in recent years, a policy of developing EV technology and using EV use widely has been actively implemented in many countries to reduce the current fossil fuel consumption of vehicles and, therefore, harmful gas emissions from vehicles.

In addition to all these developments, the biggest obstacle to the widespread use of EVs is high-capacity batteries. Causes are low energy density, limited battery life, and costs. Lithium-ion (Li-ion) batteries are seen to be the most suitable type of battery to be used in electric vehicles (Gerssen-Gondelach & Faaij, 2012). The energy density of Li-ion batteries is 90-100 Wh/kg (Etacheri et al., 2011). Compared to gasoline, this energy density remains very low because the energy density of gasoline is 12000 Wh/kg. The energy cost of a Li-ion battery is $500/kWh. In addition, there is $1000/year more maintenance cost than gasoline vehicles (Gerssen-Gondelach and Faaij, 2012).

Besides the cost, the long charging time of EV batteries is one of the situations that most drivers cannot accept. There are charging times ranging from 1.5 hours to several hours for just one charge. This can be dozens of times the time it takes to refuel a gasoline or diesel vehicle. Therefore, EV users charge with cable by plugging their vehicles into the socket in every space they find to prevent this period. This solution also causes difficult situations for vehicle owners in some cases. For example, forgetting the vehicle on charge; reduces the battery life. Physical and electrical injuries may be exposed by connecting to high current cables. In addition, if these cables are left outside, there is a possibility that they may be affected by natural events such as wind, rain, and frost (Li & Mi, 2014).

Overcoming these problems is only possible with wireless power transfer (WPT) technology. Research has shown that WPT is possible through the transmission of electromagnetic energy. This solution can be provided in the desired power range and high efficiency to charge EVs when high-quality WPT designs are developed (Bosshard et al., 2016; Klontz et al., 1993; Mecke & Rathge, 2004; Mohamed et al., 2019).

WPT systems for EV are categorized as static (SWPT), semi-dynamic (SDWPT) or dynamic charging systems (DWPT). SWPT systems require a go-to station, like plug-in chargers available. But it provides the advantages of WPT systems. A built-in receiver pad and an external charging pad on the pavement replace the conductive charging system. SDWPT systems can be installed at traffic lights as well as bus and taxi stands to provide short-term charging while accelerating and slowing down in a dynamic environment. DWPT systems allow battery charging while vehicles are in motion, thus increasing driving distance. Depending on the level of power, it becomes a solution to “range anxiety” (Chopra & Bauer, 2011). WPT reduces the initial investment in a new EV. Because, thanks to WPT systems, it has been reported that the battery capacity can be reduced by up to 20% as the energy requirement is reduced (Li & Mi, 2014). Therefore, WPT is very attractive to EVs and can help increase EV purchasing.

Even though the market demand was huge, people were just wondering if WPT could be realized efficiently at a reasonable cost. An article was published by the MIT research team in which 60 W power was transferred from a distance of 2m with the magnetic resonance theory strongly coupled with 40% efficiency (Course et al., 2007). If the radiation is omnidirectional, the power transmission efficiency is very low, and unidirectional radiation requires an uninterrupted line of sight and advanced tracking mechanisms. The resonant frequency is usually selected at the MHz level and assumed to be air-core coils to transfer power more efficiently and more efficiently.

Recently, as electric vehicle charging is needed and also as technology advances, the power transmission distance has increased from a few millimeters to several hundred millimeters at the kilowatt power level (Covic and Boys, 2013; Eghtesadi, 1990; Lukic and Pantic, 2013; Moradewicz and Kazmierkowski, 2010; Musavi et al., 2012; Nagatsuka et al., 2010; Sallán et al., 2009; Villa et al., 2009). Partners for Advance Transit and Highways (PATH) program was launched in the 1970s. A bus with 35 passengers was tested along a 213 m track. The track has two power sections. In addition, the system is designed for 60 kW power transfer. The bipolar primary line was supplied with 1200 A, 400 Hz AC. The receiver was 7.6 cm from the primary piece. The efficiency achieved was around 60%.

Over the past fifteen years, researchers at the University of Auckland have focused on the inductive power supply of moving objects. Their recent success in designing pads for stable charging of EV is striking. A 766mm × 578mm pad that provides 5 kW of power with an efficiency of over 90% for distances of about 200mm has been reported (Budhia et al., 2011; Wu et al., 2012). The resulting lateral and longitudinal misalignment tolerance is 250 and 150 mm, respectively. Information from the online electric vehicle (OLEV) project at the Korea Institute of Advanced Science and Technology (KAIST) also contributes to the WPT design. Three generations of OLEV systems have been built: a light golf cart for the first generation, a bus for the second, and an SUV for the third. The success of the second and the third is remarkable: 70% efficiency at 60 kW power for buses, 83% efficiency at 20 kW for SUVs. This performance has been achieved with a misalignment tolerance of up to 160 mm in the vertical distance and up to 200 mm in the lateral distance (Huh et al., 2011; Lee et al., 2010). In the United States, more and more attention has been drawn to WPT since the publication of the 2007 Science document (Kurs et al., 2007). WiTricity Corporation with MIT technology launched the WiT-3300 development kit, which provides 90% efficiency in a 180 mm range at 3.3 kW output.

Recently, a wireless charging system prototype for EV was developed at Oak Ridge National Laboratory (ORNL) in the USA. Tested efficiency is about 90% for 3 kW power distribution (Ning et al., 2013). Research conducted in Michigan University-Dearborn obtained a 200 mm distance, 8 kW WPT system with a dc-dc efficiency of up to 95.7% (Nguyen et al., 2014). From a functional point of view, it can be seen that WPT for EV is readily available in both fixed and dynamic applications. However, many issues need to be developed and spent on performance optimization, establishing industrial standards and making it more cost-effective to become commercially widespread.

This paper starts with the basic WPT theory, and then gives a brief overview of the main parts in a WPT system. The electric vehicle model and battery model are introduced in section 2. Different scenarios such as semi-dynamic wireless energy Transfer and dynamic wireless power transfer for an electric vehicle are shown in section 3. Lastly, the final section presents the conclusions and plans for future work

2. Material and Method

2.1. Wireless Power Transfer System for Electric Vehicles

WPT for electric vehicles consists of two systems, transmitter and receiver. The assembly in the vehicle is the transmitter and receiver assembly and is placed on the vehicle chassis. The transmitter assembly is placed on the pavement of the road or in the parking space. A large air gap separates both subsystems. The general diagram of the wireless power transfer system is given in Figure 1. Thanks to the energy distribution system, low-frequency AC power is supplied to the system. DC power is obtained with the help of rectifiers. A high-frequency current to the coils is required for magnetic power transfer. Therefore, DC power is applied as an input to high-frequency converters, resulting in high-frequency current. The operating frequency is determined in the resonant circuit. This circuit has a primary compensation network and a primary conduction coil. With the receiving coil, power is taken from the high-frequency magnetic field. After the induced current passes through the secondary compensation network, it is converted to dc power by rectifiers. In the last step, the battery is charged with DC current (Machura et al., 2020).

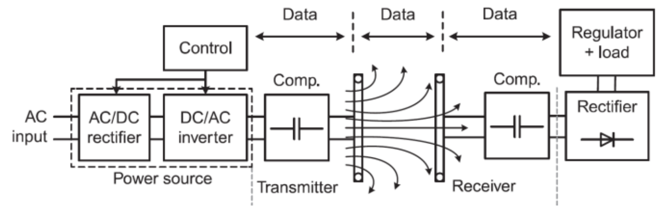

Figure 1. Wireless Power Transfer System

As is known, the value of the leakage inductance must be minimized to have high efficiency in transformers. Minimizing the leakage inductance means that the magnetic flux reaches the secondary side from the primary side to the highest value. The most increased magnetic flux is possible with the highest coupling factor of the windings on the primary and secondary sides. Today, the coupling factor of high-efficiency transformers can reach 99% values. However, the coupling factor of the windings used in the WPT system is very low. The issue of increasing the coupling factor that directly affects the efficiency of WPT is still being studied. In these studies, the design of the windings is especially emphasized. Resonance is what makes it possible to apply WPT at high efficiency despite the very small coupling factor. In addition to the windings, capacitors that will resonate with the windings at the operating frequency are added to the circuit. Thanks to these resonance capacitors, the reactive power in the circuit is eliminated, and WPT with high efficiency and power can be achieved.

In SWPT and SDWPT systems, power supplies can energize one or more transmit coils. The coils in the transmitter system can be of different structure. These are generally circular, rectangular and double D-shaped (Bosshard et al., 2016). Coppers are mostly used conductors in coils. However, new materials with high conductivity have been investigated for their positive properties (Do Chung et al., 2014; Sedwick, 2010). Each vehicle uses only one transmit coil.

Different options are available in DWPT systems. Many separate transmitters can be used, similar to the transmit pads in the SWPT system. In addition, a single long transmitter system can also be used (Kissin et al., 2009). Both systems have pros and cons relative to each other. Using a long transmitter provides ease of control. Because the number of system components is small. In this system, the transmitter produces a constant power output and current when the receiving system approaches the ground system. Also, because the coil is powered from a single power source, the component ratios must be high. Therefore, the costs increase. In the event of a malfunction, the entire system must be shut down. During partial load transfer on a single transmitter rail, the entire rail is always energized. The connection between the transmitter and receiver is low because the size difference is high. As a result, productivity also decreases. The coupling between coils in a WPT system can change as the size difference of the coils changes. Because the magnetic flux connection changes as the size difference changes (Deng et al., 2015; Lin et al., 2015; Miller & Daga, 2015).

Electromagnetic field radiation can be a problem for WPTs. This radiation can occur due to unused parts. It must be suppressed or protected to prevent contact with living materials and limit human exposure (Lin, 2006; Protection, 2009).

The use of multi-emitter chargers increases the number of required components. These are power supplies, high frequency inverters and necessary connections (Fujita et al., 2017). Thanks to the large number of transmitters, a problem in one section will not affect the operation of other sections. In addition, it is clear that the system reliability is high since this fault can also be eliminated through redundancy. By connecting more than one transmitter to a charging coil unit, the number of components can be reduced (Chen et al., 2014). Since the vehicle will emit a magnetic field only when it passes over it, electromagnetic radiation leaking from other parts is prevented and leakage is minimized. Disadvantages of multi-transmitter are high cost and control complexity to improve transfer efficiency and reduce power fluctuations.

The distance between the charging coils significantly affects the system performance. Therefore, the distance between the charging coil units should be optimized (Buja et al., 2016). Too small of a gap can create a connection between the transmitter pads. This creates a negative current voltage which causes the number of charge coil units to increase. Increasing the distance between the coils is also not a solution because interruptions in power transmission can cause adverse effects on the grid network.

2.2. Simulation Model

While simulating, State of Charge was observed using a vehicle model, battery model of this vehicle, and scenarios where WPT can be applied. With particular emphasis on SDWPT and DWPT systems, although a moving vehicle consumes the battery, the range change depending on the state of charge of the battery with WPT has been interpreted. "The electric vehicle reference application" in the Mathworks library was used for simulation. This model represents a completely electric vehicle model with a motor-generator, battery, direct transmission, and associated powertrain control algorithms. This design is often used for powertrain matching analysis and component selection, control and diagnostic algorithm design, and in-loop hardware testing. In this study, the effect of wireless charging situations of the battery in different scenarios on the overall charge of the battery was examined.

2.2.1. Electric Vehicle Model

The amount of range of an EV depends on internal and external factors. The capacity of the battery system, the drive factor and other ancillary components constitute internal factors, while external conditions include temperature, terrain and weather. The vehicle model used to determine the power drawn from the battery is force-based (Mi and Masrur, 2017). Thanks to this model, the effect of general external forces resisting the vehicle's movement on the behavior of the system can be easily observed. The forces acting on the vehicle are solved in two dimensions.

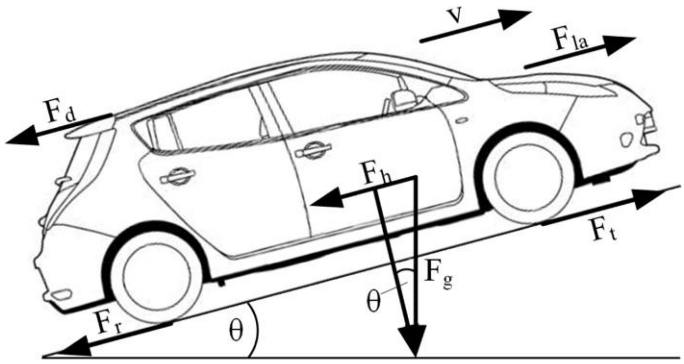

Figure 2. Forces Acting on the Vehicle (Machura et al., 2020)

The effect of forces on the vehicle is shown in Figure 2. When calculating the load, all forces are multiplied by the velocity. P_r, which is the interaction between the tires and the road surface, is the rolling resistance of the tire and is calculated using Equation (1). The type of tire used in the vehicle affects the load as it will change the rolling resistance. The load due to the interaction between the air volume and the vehicle chassis is called aerodynamic drag and is denoted P_d. It depends on the shape of the vehicle and the amount of frontal space. It can be calculated using Equation (2). The load originating from the weight of the vehicle and affected by the slope of the road is P_h and is determined by Equation (3). The load resulting from the linear acceleration of the vehicle is denoted by P_{la} and calculated using Equation (4). The use of electronic and mechanical power, such as interior heating, cooling and ventilation, also affects the vehicle as a load. This total load is denoted by P_{aux}. The sum of all loads calculated by Equation (5), P_t, gives the Equation of the required load for the movement of the vehicle.

$$P_r = F_r r * |v| = \mu_{rr} mg \cos\theta * |v| \quad (1)$$

$$P_d = F_d * |v| = C_d \rho A |v|^3 \quad (2)$$

$$P_h = F_h * |v| = mg \sin\theta * |v| \quad (3)$$

$$P_{la} = F_{la} * |v| = ma * |v| \quad (4)$$

$$P_t = F_t * v = (F_r + F_d + F_h + F_{la}) * |v| + P_{aux} \quad (5)$$

In this study, a rigid car body model with three degrees of freedom (3DOF) was used. The fixed tool body was designed by Mathworks. This model is a model with configurable axle stiffness to calculate the longitudinal, vertical and pitch motion of the vehicle. Inputs such as the mass of the vehicle, aerodynamic drag, road slope, weight distribution between the axles depending on the acceleration and road profile are available in the vehicle model block. The parameters of the model are given in Table 1.

Table 1. Vehicle model parameters

Parameters	Values
Mass (m) [kg]	1200
Front area (A) [m^2]	2
Coefficient of drag (C_d)	0.3
Coefficient of rolling (C_r)	0.1
Air density (ρ) [kg/m^3]	1.293

According to the standards specified in SAE J2954, WPT efficiency for power levels up to 11 kW should be at least 85%

without any displacement and 80% with lateral alignment (Schneider, 2016). Therefore, for SDWPT systems, the efficiency is set to 85% because the misalignment between the transmit and receive coils is close to zero. Also, maximum power is transferred as soon as the WPT coils overlap. Different amounts of power can be used for power transmissions. However, designs up to 50 kW are being studied for light-duty vehicles (Bosshard et al., 2016).

2.2.2. Battery Model

The vehicle model allows to measure the loads on the vehicle and the powertrain. The electrical power that moves the vehicle is provided by the battery connected to the driveline. The power transmission scheme of this vehicle model is also given in Figure 3.

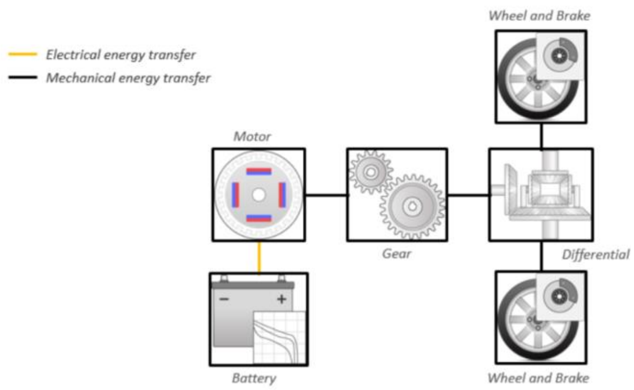

Figure 3. Power Transmission Diagram of Vehicle Model

Various parameters such as capacity, state of charge, temperature, health status, and age can affect a battery's performance. Therefore, there are various models that are used for different purposes. Electrochemical models and electrical models are a few of these models. (Gu et al., 2016; Hariharan et al., 2017; Lotfi et al., 2016; Zheng et al., 2018).

Mathematical models (Rong & Pedram, 2006; Wang et al., 2016) show system behavior, but they do not seem practical. Instead, electric models are used to model batteries with alternative systems. Equivalent electrical circuits in these models include resistors and capacitors. (Chen and Rincon-Mora, 2006; Tremblay and Dessaint, 2009). Electric models are extremely low complexity and easy to implement in circuit simulators. They are often used to estimate battery state of charge (SoC).

While evaluating the effectiveness of the WPT system, the SoC level is examined. Therefore, the electrical model of the battery is required. The SoC of the battery depends on the open circuit voltage and internal resistance, and this feature is provided by the battery model. Figure 4 shows the electrical equivalent battery model used. The model is a combination of a Thevenin-based model and a runtime-based model. Compared to the simplest equivalent battery model containing a single resistor and capacitor, the Model uses two resistor-capacitor pairs. Although it is more complex than a single resistor and capacitor, its accuracy is higher (Chen & Rincon-Mora, 2006). It also becomes possible to examine the transient response. With Equation (5), the power that moves the vehicle is calculated and the power drawn from the charging coil is determined.

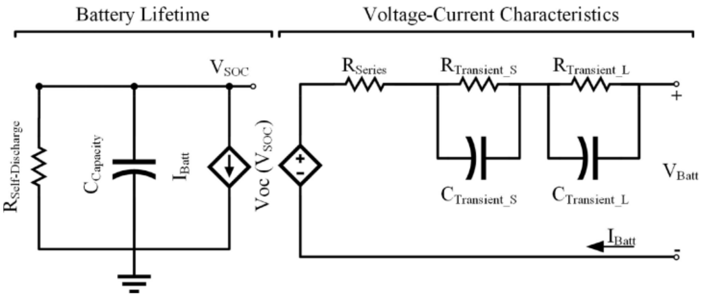

Figure 4. Model of the Electrical Battery (Rong & Pedram, 2006)

The charge cycle is the most important factor affecting battery life. A cycle is defined as the initial discharge of the battery from 100% to 0% and then recharge to 100%. In order to extend the battery life, the available battery types are limited. The cycle ranges from 80% to 20%, with a 20% margin of safety at both ends of the discharge-charge cycle. Generally, as the number of cycles increases, the usable capacity decreases linearly (Beard, 2019).

In this study, the battery block in the Mathworks library was used. This block is shown in Figure 5. Here, according to the drawn or incoming current and temperature condition, the model SoC and the voltage state of the battery are learned. The battery state of charge (SoC) is calculated by Equation (6).

$$SoC = SoC(0) - \frac{1}{C_n \int_{t_0}^{t} I dt} \tag{6}$$

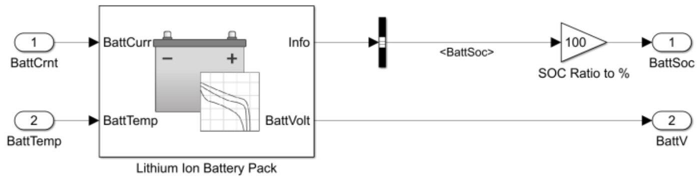

Figure 5. Battery Block

3. Results and Discussion

The way to measure the effect of WPT on the electric vehicle battery is to observe the conditions of the vehicle during motion. The charge level of the battery and its ability to be charged with WPT can be easily affected by factors such as the instant speed of the vehicle, weather, and road conditions. Therefore, simulation can only be possible by accessing the speed graph, environmental information, weather, and road information of the vehicle along a route. With the help of the simulation carried out by having this information, it was investigated at what power wireless charging WPT would enable unlimited range. In this study, wireless charging on the road was applied in two different environments. The first scenario is when the state of charge is monitored to be charged at traffic lights where vehicles usually stop. This scenario will show the advantages of a system called SDWPT, essentially similar in structure to SWPT. In the second scenario, only dynamic wireless charging is used to transfer power to the battery system. In this scenario, the effect of WPTs of different powers on the charge status will be monitored in proportionally certain parts of the road.

Certain driving cycles were used to see the effect of wireless charging on the battery state of charge. These cycles are used by automobile manufacturers to demonstrate product compliance with emission restrictions. In addition, such cycles are used to determine vehicle performance. Two different driving cycles were used in the study. These are the Urban Dynamometer Driving Program (UDDS) and the Highway Fuel Economy Test (HWFET). Information on driving cycles is shown in Table 2.

Table 2. Information on Driving Cycles

Parameters	UDDS	HWFET
Total time [s]	1369	765
Total distance [m]	11 997	16 503
Average speed [km/h]	31.6	77.7
Maximum speed [km/h]	91.2	96.3
Standing time [s]	189	0
Number of stops	14	0
Average stop time	13.5	0

Driving cycles are applied to the vehicle model. Depending on the vehicle parameters, the power drawn from the battery and the auxiliary power consumption are determined. Both outputs are transferred to the battery model to determine the charge used and calculate the SoC. Figure 6 shows the general layout of the model.

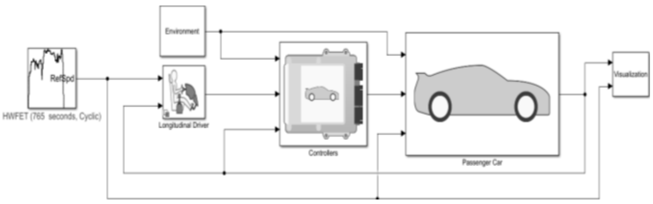

Figure 6. The general layout of the model

3.1. Semi-Dynamic Wireless Energy Transfer

In the first scenario, EV, a semi-dynamic wireless charging system is suitable because the number of stops of the vehicles in general use in the city is high. In addition, their average speed is low. This requires fixed wireless charging systems that can only be placed at traffic lights or intersections.

The UDDS, depicted in Figure 7, represents urban driving. It has an average speed of 31.6 km/hour. As shown in the graph, there are many moments when the speed drops to 0 km/h. These speeds indicate the points where it stopped, which was determined to stop 14 times in total.

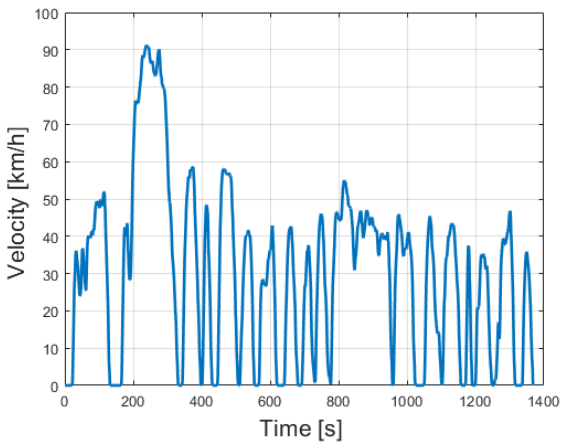

Figure 7. Urban (UDDS) cycle Velocity / Time graph

If the vehicle whose battery status starts with a full charge, i.e. 80%, is not charged at all, a decrease of 5.59% is observed in this cycle, decreasing to 74.41%. As stated in the introduction, the amount of power transferred in wireless energy transfer has increased to around 50 kW. Therefore, when applying the scenarios, the highest power was determined as 50 kW. Wireless charging powers were applied at 10 kW intervals. The currents and voltages required for this are given in Table 3. Taking into account that the battery voltage is 380 Volts, the current values have been calculated. According to SAE J2954 standards, the efficiency should be 85% in the absence of any misalignment. Efficiency has been chosen as 85% for this charge to be made when the vehicles are stopped.

Table 3. Power and applied currents for UDDS cycle

Power [kW]	Current [A]	Current [A] with 85% efficiency
10	26.31	22.36
20	52.63	44.73
30	78.95	67.11
40	105.26	89.47
50	131.57	111.84

The determined currents were provided to charge the battery model by giving negative current in the vehicle stopping times (V=0 m/s). 0 kW is the state of charge when the vehicle does not have wireless power transfer. A regenerative braking system is used in this vehicle model, which recharges the battery when braking. Therefore, despite the absence of WPT, the battery has been charged slightly when the vehicle slows down. However, the effect of this system on the general condition of the battery is limited as can be seen in the graphic in Figure 8. Again, as seen from the graph, WPTs with 10 kW and 20 kW power have brought the battery charge to 76.69% and 78.97% at the end of the cycle. Although it is higher than the initial state and not equal to the initial state, it has been achieved by 2.28% and 4.56%, respectively, compared to the case without WPT. With 30 kW wireless charging, the amount of charge used by the vehicles during the journey can be added to the battery as a recharge. With 40 kW and 50 kW charging, much higher levels than the initial state can be increased and much more charge can be loaded into the battery than used.

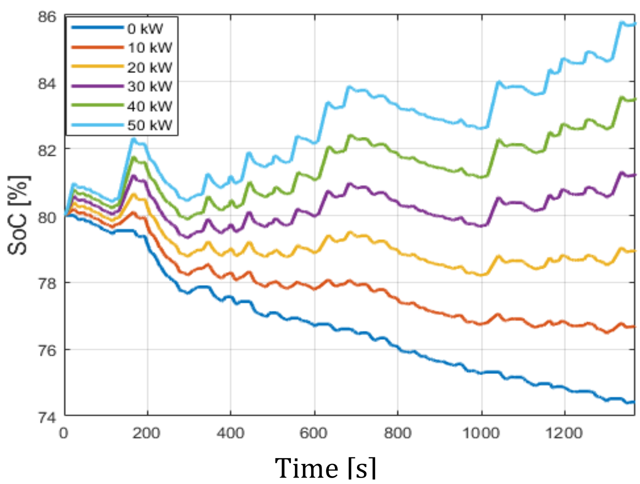

Figure 8. SoC graph for SDWPT in different Powers

3.2. Dynamic Wireless Power Transfer

During a traditional highway ride, EV never gets idle and stops. Therefore, static charging or semi-dynamic charging cannot be applied. The second scenario is applied for highways that never stop during the cycle. DWPT needs to be implemented here. The total driving amount on highways in our country is approximately 128 billion km as of 2017 (T.C. Ministry of Transport and Infrastructure, 2018). By 2020, the total length of highways in our country is 3060 km, and the length of intercity roads, which are referred to as divided state roads, is 20,723 km. Yet, the ratio of highway length to total road length in our country is 4.4% (TR General Directorate of Highways, 2020). However, since we are a developing country, the development of the industry and the population growth of the cities are inevitable. Therefore, this rate will increase in the coming years. In addition, although there are no highways in intercity roads, it is possible to install these systems in some parts.

All these data show that most of the daily kilometers traveled are spent on these roads. This means that by integrating the DWPT system into important roads, EVs' battery charging needs can be met. The HWFET shown in Figure 9 represents a trip on the highway. It is seen in Table 2; the average speed is high and there is no stopping point. Also, the average speed is close to the maximum speed.

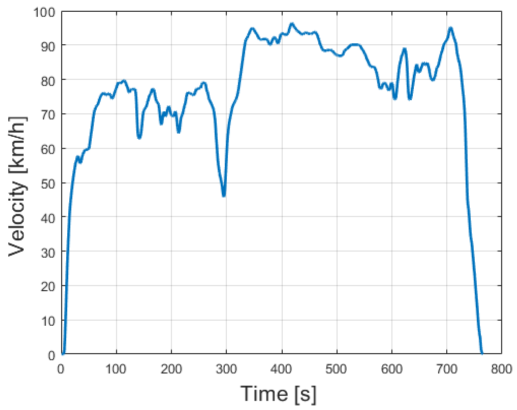

Figure 9. Highway (HWFET) cycle Velocity / Time graph

To implement DWPT on highways, a transmitter system is required on a proportionally significant part of the road. The ratio of the path length covered by this system to the total path length is called the coverage area. Coverage is an important parameter when determining cost. The coverage area was determined as 10% in this study. Since the vehicles are mobile, the efficiency was determined as 80% and the system was tested for power levels up to 50 kW. Table 4 contains these power values and current amounts.

Table 4. Power and applied currents for HWFET cycle

Power [kW]	Current [A]	Current [A] with 80% efficiency
10	26.31	21.05
20	52.63	42.10
30	78.95	63.16
40	105.26	84.21
50	131.57	105.25

The results of the simulation made for 10% coverage are given in the graphic in Figure 10. Again, the 0 kW is the situation where there is no WPT system along the way. Here, the charge decreases from 80% to 71.2% and there is a charge loss of 8.8%. It does not seem possible to compensate for the lost charge for this coverage area in all charging situations. However, there is a proportional effect for each state of charge.

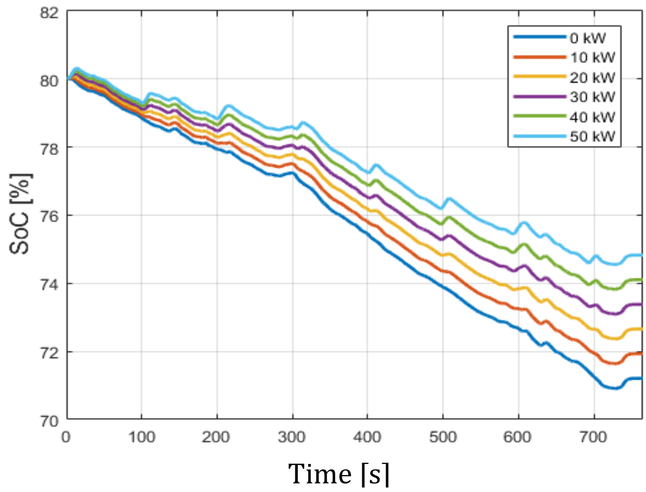

Figure 10. SoC graph for DWPT in different powers

4. Conclusions and Recommendations

In this study, the effects of semi-dynamic and dynamic WPT systems on vehicle battery charge state were investigated. Simulations were made in different scenarios using "The electric vehicle reference application" in the Mathworks library. Urban (UDDS) and highway (HWFET) loops were used to simulate wireless charging in these scenarios.

The following conclusions can be drawn with the two driving cycles and the scenarios applied. When WPT technology is designed according to standards, it can increase the reach range with high impact. Considering that it is possible to reach an unlimited range, it will relieve users and manufacturers significantly, as there is no charging concern. While SDWPT is used in the city on the busiest roads, DWPT should be used on highways. High power level creates electromagnetic field pollution. Therefore, it is desirable to produce longer range at less power level. It is one of the issues that need to be designed and focused on. With the results achieved, the range problem can be eliminated with the SDWPT system at medium power levels. Therefore, with this system, electromagnetic field emission will be relatively less and health and safety concerns will be minimized proportionally. In addition, by increasing the coverage area for DWPT, such limitations can be avoided. This result is extremely important because the deployment of WPT systems poses a health and safety concern. The study focused on a single vehicle model and two different scenarios. This study can be adapted by applying different driving cycles to various vehicle models. In this way, parameters to obtain the longest range with the least cost can be obtained for different systems.

References

Beard, K. W. 2019. *Linden's handbook of batteries*. McGraw-Hill Education,

Bosshard, R., Iruretagoyena, U. ve Kolar, J. W. 2016. Comprehensive evaluation of rectangular and double-D coil geometry for 50 kW/85 kHz IPT system. *IEEE journal of emerging and selected topics in power electronics,* 4:4, 1406-1415.

Budhia, M., Boys, J. T., Covic, G. A. ve Huang, C.-Y. 2011. Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems. *IEEE transactions on industrial electronics,* 60:1, 318-328.

Buja, G., Bertoluzzo, M. ve Dashora, H. K. 2016. Lumped track layout design for dynamic wireless charging of electric vehicles. *IEEE Transactions on Industrial Electronics,* 63:10, 6631-6640.

Chen, L., Nagendra, G. R., Boys, J. T. ve Covic, G. A. 2014. Double-coupled systems for IPT roadway applications. *IEEE Journal of Emerging and Selected Topics in Power Electronics,* 3:1, 37-49.

Chen, M. ve Rincon-Mora, G. A. 2006. Accurate electrical battery model capable of predicting runtime and IV performance. *IEEE transactions on energy conversion,* 21:2, 504-511.

Chopra, S. ve Bauer, P. 2011. Driving range extension of EV with on-road contactless power transfer—A case study. *IEEE transactions on industrial electronics,* 60:1, 329-338.

Covic, G. A. ve Boys, J. T. 2013. Modern trends in inductive power transfer for transportation applications. *IEEE journal of emerging and selected topics in power electronics,* 1:1, 28-41.

Deng, J., Li, W., Nguyen, T. D., Li, S. ve Mi, C. C. 2015. Compact and efficient bipolar coupler for wireless power chargers: Design and analysis. *IEEE Transactions on Power Electronics,* 30:11, 6130-6140.

Department for Transport. (2018). *Road traffic estimates great britain 2017*. Great Britain: Dept. Transport.

Do Chung, Y., Lee, C. Y., Kang, H. K. ve Park, Y. G. 2014. Design consideration and efficiency comparison of wireless power transfer with HTS and cooled copper antennas for electric vehicle. *IEEE Transactions on applied superconductivity,* 25:3, 1-5.

Eghtesadi, M. (1990). Inductive power transfer to an electric vehicle-analytical model. 40th IEEE Conference on Vehicular Technology, IEEE, 100-104.

Ehsani, M., Gao, Y. ve Miller, J. M. 2007. Hybrid electric vehicles: Architecture and motor drives. *Proceedings of the IEEE,* 95:4, 719-728.

Etacheri, V., Marom, R., Elazari, R., Salitra, G. ve Aurbach, D. 2011. Challenges in the development of advanced Li-ion batteries: a review. *Energy & Environmental Science,* 4:9, 3243-3262.

Fujita, T., Yasuda, T. ve Akagi, H. 2017. A dynamic wireless power transfer system applicable to a stationary system. *IEEE Transactions on Industry Applications,* 53:4, 3748-3757.

Gerssen-Gondelach, S. J. ve Faaij, A. P. 2012. Performance of batteries for electric vehicles on short and longer term. *Journal of power sources,* 212, 111-129.

Gu, R., Malysz, P., Yang, H. ve Emadi, A. 2016. On the suitability of electrochemical-based modeling for lithium-ion batteries. *IEEE Transactions on Transportation Electrification,* 2:4, 417-431.

Gysen, B. L., Paulides, J. J., Janssen, J. L. ve Lomonova, E. A. 2009. Active electromagnetic suspension system for improved vehicle dynamics. *IEEE transactions on vehicular technology,* 59:3, 1156-1163.

Hariharan, K. S., Tagade, P. ve Ramachandran, S. 2017. *Mathematical Modeling of Lithium Batteries: From Electrochemical Models to State Estimator Algorithms*. Springer,

Honda, T. (2015). *Development of handling performance control for SPORT HYBRID SH-AWD* (0148-7191). Retrieved from

Huh, J., Lee, W., Cho, G.-H., Lee, B. ve Rim, C.-T. (2011). Characterization of novel inductive power transfer systems for online electric vehicles. 2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), IEEE, 1975-1979.

Kissin, M. L., Boys, J. T. ve Covic, G. A. 2009. Interphase mutual inductance in polyphase inductive power transfer systems. *IEEE Transactions on Industrial Electronics,* 56:7, 2393-2400.

Klontz, K., Esser, A., Bacon, R., Divan, D., Novotny, D. ve Lorenz, R. (1993). An electric vehicle charging system with'universal'inductive interface. Conference Record of the Power Conversion Conference-Yokohama 1993, IEEE, 227-232.

Koehn, P. ve Eckrich, M. (2004). *Active steering-the BMW approach towards modern steering technology* (0148-7191). Retrieved from

Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P. ve Soljačić, M. 2007. Wireless power transfer via strongly coupled magnetic resonances. *science,* 317:5834, 83-86.

Lee, S., Huh, J., Park, C., Choi, N.-S., Cho, G.-H. ve Rim, C.-T. (2010). Online electric vehicle using inductive power transfer system. 2010 IEEE Energy Conversion Congress and Exposition, IEEE, 1598-1601.

Li, S. ve Mi, C. C. 2014. Wireless power transfer for electric vehicle applications. *IEEE journal of emerging and selected topics in power electronics,* 3:1, 4-17.

Lin, F. Y., Covic, G. A. ve Boys, J. T. 2015. Evaluation of magnetic pad sizes and topologies for electric vehicle charging. *IEEE Transactions on Power Electronics,* 30:11, 6391-6407.

Lin, J. C. 2006. A new IEEE standard for safety levels with respect to human exposure to radio-frequency radiation. *IEEE Antennas and Propagation Magazine,* 48:1, 157-159.

Lotfi, N., Landers, R. G., Li, J. ve Park, J. 2016. Reduced-order electrochemical model-based SOC observer with output model uncertainty estimation. *IEEE Transactions on Control Systems Technology,* 25:4, 1217-1230.

Lukic, S. ve Pantic, Z. 2013. Cutting the cord: Static and dynamic inductive wireless charging of electric vehicles. *IEEE Electrification Magazine,* 1:1, 57-64.

Machura, P., De Santis, V. ve Li, Q. 2020. Driving Range of Electric Vehicles Charged by Wireless Power Transfer. *IEEE Transactions on Vehicular Technology*.

Machura, P. ve Li, Q. 2019. A critical review on wireless charging for electric vehicles. *Renewable and Sustainable Energy Reviews,* 104, 209-234.

Mecke, R. ve Rathge, C. (2004). High frequency resonant inverter for contactless energy transmission over large air gap. 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No. 04CH37551), IEEE, 1737-1743.

Mi, C. ve Masrur, M. A. 2017. *Hybrid electric vehicles: principles and applications with practical perspectives*. John Wiley & Sons,

Miller, J. M. ve Daga, A. 2015. Elements of wireless power transfer essential to high power charging of heavy duty vehicles. *IEEE Transactions on Transportation Electrification,* 1:1, 26-39.

Mohamed, A. A., Meintz, A., Schrafel, P. ve Calabro, A. 2019. Testing and assessment of emfs and touch currents from 25-kW IPT system for medium-duty EVs. *IEEE transactions on vehicular technology,* 68:8, 7477-7487.

Moradewicz, A. J. ve Kazmierkowski, M. P. 2010. Contactless energy transfer system with FPGA-controlled resonant converter. *IEEE transactions on industrial electronics,* 57:9, 3181-3190.

Musavi, F., Edington, M. ve Eberle, W. (2012). Wireless power transfer: A survey of EV battery charging technologies. 2012 IEEE Energy Conversion Congress and Exposition (ECCE), IEEE, 1804-1810.

Nagatsuka, Y., Ehara, N., Kaneko, Y., Abe, S. ve Yasuda, T. (2010). Compact contactless power transfer system for electric vehicles. The 2010 International Power Electronics Conference-ECCE ASIA-, IEEE, 807-813.

Nguyen, T.-D., Li, S., Li, W. ve Mi, C. C. (2014). Feasibility study on bipolar pads for efficient wireless power chargers. 2014 IEEE Applied Power Electronics Conference and Exposition-APEC 2014, IEEE, 1676-1682.

Ning, P., Miller, J. M., Onar, O. C., White, C. P. ve Marlino, L. D. (2013). A compact wireless charging system development. 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), IEEE, 3045-3050.

Protection, I. C. o. N.-I. R. 2009. ICNIRP statement on the “Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)”. *Health physics,* 97:3, 257-258.

Rong, P. ve Pedram, M. 2006. An analytical model for predicting the remaining battery capacity of lithium-ion batteries. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems,* 14:5, 441-451.

Sallán, J., Villa, J. L., Llombart, A. ve Sanz, J. F. 2009. Optimal design of ICPT systems applied to electric vehicle battery charge. *IEEE transactions on industrial electronics,* 56:6, 2140-2149.

Schneider, J. 2016. Wireless power transfer for light-duty plug-in/electric vehicles and alignment methodology. *SAE International J2954 Taskforce*.

Sedwick, R. J. 2010. Long range inductive power transfer with superconducting oscillators. *Annals of Physics,* 325:2, 287-299.

Sellali, M., Abdeddaim, S., Betka, A., Djerdir, A., Drid, S. ve Tiar, M. 2019. Fuzzy-Super twisting control implementation of battery/super capacitor for electric vehicles. *ISA transactions,* 95, 243-253.

T.C. Karayolları Genel Müdürlüğü (2020). Yol Ağı Bilgileri. Retrieved from https://www.kgm.gov.tr/Sayfalar/KGM/SiteTr/Kurumsal/YolAgi.aspx

T.C. Ulaştırma ve Altyapı Bakanlığı, S. G. D. B. 2018. Karayolları Genel Müdürlüğü 2019-2023 Stratejik Planı.

Tremblay, O. ve Dessaint, L.-A. 2009. Experimental validation of a battery dynamic model for EV applications. *World electric vehicle journal,* 3:2, 289-298.

Villa, J. L., Sallán, J., Llombart, A. ve Sanz, J. F. 2009. Design of a high frequency inductively coupled power transfer system for electric vehicle battery charge. *Applied Energy,* 86:3, 355-363.

Wang, D., Yang, F., Tsui, K.-L., Zhou, Q. ve Bae, S. J. 2016. Remaining useful life prediction of lithium-ion batteries based on spherical cubature particle filter. *IEEE Transactions on Instrumentation and Measurement,* 65:6, 1282-1291.

Wu, H. H., Gilchrist, A., Sealy, K. D. ve Bronson, D. 2012. A high efficiency 5 kW inductive charger for EVs using dual side control. *IEEE Transactions on Industrial Informatics,* 8:3, 585-595.

Yong, J. Y., Ramachandaramurthy, V. K., Tan, K. M. ve Mithulananthan, N. 2015. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. *Renewable and Sustainable Energy Reviews,* 49, 365-385.

Zheng, L., Zhu, J., Wang, G., Lu, D. D.-C. ve He, T. 2018. Lithium-ion battery instantaneous available power prediction using surface lithium concentration of solid particles in a simplified electrochemical model. *IEEE Transactions on Power Electronics,* 33:11, 9551-9560.