The Problem of Electric Vehicle Charging: State-of-the-Art and an Innovative Solution

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***Abstract*— This paper presents a comprehensive literature review with focus on the difficulties electric vehicles (EVs) face to charge the battery while on a trip, and proposes a solution without the need of an expensive change in infrastructure. The proposed method charges EVs while en route from another vehicle, which will be referred to as vehicle-to-vehicle recharging (VVR). The aim of this system is to bring an innovative way for EVs to charge their battery without getting off route on a highway. The electric vehicle can request such a service from a designated charger vehicle on demand and receive electric power wirelessly while en route. The vehicles that provide energy (charger vehicles) through wireless power transfer (WPT) only need to be semi-autonomous in order to engage/disengage during a trip. The state-of-the-art is divided into three subsections relevant to the proposed system and where most of the innovations to reduce the burden of charging EVs can be found: (1) infrastructure changes, (2) device level innovations, and (3) autonomous vehicles. The infrastructure changes highlight some of the proposed systems that aim to help EVs become a convenient solution to the public. Device level innovations covers some of the literature on technology that addresses EVs in terms of WPT. And finally, the autonomous vehicle subsection covers the importance of such technology in terms of safety and reliability, that could be implemented on the VVR system. Furthermore, modeling, analysis, and simulation is presented to validate the feasibility of the proposed system.**

***Index Terms*— Electric vehicles, charging electric vehicles, vehicle-to-vehicle recharging, wireless power transfer, battery state-of-the charge.**

I. Introduction

THE move towards a society where electric vehicles (EVs) and hybrid electric vehicles (HEVs) dominate the roads is within the near future [1], [2]. This push has been affected mainly by environmental concerns, primarily regarding the rate of fuel consumption around the world [3]. Of the biggest drawbacks preventing EVs from populating the roads is the time it takes to charge them. This becomes a greater hassle when going on trips requiring more than one pit-stop for recharging, which can represent a large portion of the trip time. While the introduction of fast charging stations represents a good step forward [4], [5], the pit-stop time lacks the convenience of conventional vehicles with internal combustion engines (ICE).

Fast charging in EVs has improved a lot since Tesla first introduced its Model S in 2012. The current technology for high speed charging systems is considered as "Level 3" or "DC fast charging", which is capable of delivering 50 kW of power in 0.5 hr [6]. In fact, not only has fast charging improved, but the general weight of the electrical components and cables in EVs have reduced. Interconnection of electric-vehicle power-train and power electronics along with new topologies have been used to achieve an increased volumetric and gravimetric power densities [7]–[11].

The amount of energy contained in a typical gasoline tank is considerably higher than other sources [12], [13]. Gasoline gallon equivalent (GGE) is the amount of electric energy needed to equal the energy content of one liquid gallon of gasoline, e.g., 1 GGE = 33.40 kWh. With most compact cars, tanks around 15 gallons of capacity and an electric compact car with a battery size of 75 kWh [14], a direct comparison indicates that such conventional vehicles carry almost seven times more energy than those electric vehicles. Moreover, with fast charging stations already in existence, and the demand for more to help push EVs on the roads, their effects on the utility grid will be of concern [15]–[25].

This struggle for EVs to be a convenient solution on longer trip has been addressed mainly in terms of infrastructure change, with several of those solutions to be discussed in detail in the next section. A common issue that those proposed infrastructures have is that they are expensive and/or would require a drastic change in terms of roads and highway re-construction. This paper proposes a new method for vehicles to charge their battery via another vehicle while en route. The idea would be denoted from here on as a vehicle-to-vehicle recharging (VVR) system, where a user driving on a trip can get extra energy on-demand throughout a trip to help give a boost of energy without needing to stop at a charging station. The vehicles requesting energy will be known as "user vehicles" in this paper, while the vehicles that charge the user vehicles will be known as "charger vehicles." These charger vehicles would be located throughout the highways either in designated depots or at current charging stations. Also, the number of charger vehicles throughout the highways would depend on the demand. Fig. 1 shows the current map for Tesla's fasting charging infrastructure in 2020 [26]. The proposed charging system is not expected

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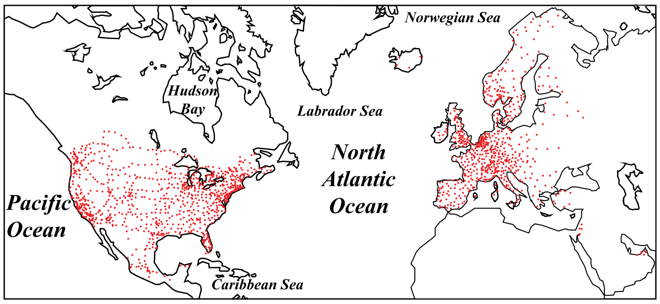

Fig. 1. Tesla's fast charging network map for 2020.

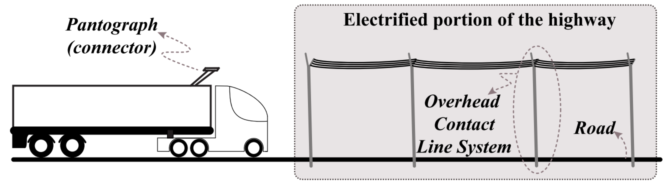

Fig. 2. Siemens catenary system for hybrid electric trucks.

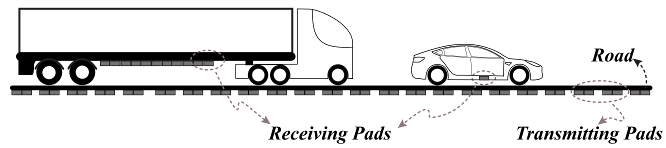

Fig. 3. Charge-on-the-Move infrastructure illustration.

to replace charging stations, but to work as a premium service available for those customers who value the time spent in a trip more than extra payment for the service. The proposed system could also be used for emergencies for police cars or ambulances that are EVs and running low on battery, since time is of the essence for such vehicles that are on duty. In-fact, some argue that police stations would have a difficult time transitioning to fully EVs due to limitations of the current battery technology [27], which the VVR system could help overcome in some situations.

In addition to the comprehensive modeling, analysis, and simulation of the proposed system, this paper addresses the current state-of-the-art of the solutions for electric vehicle charging. This paper is organized as follows: the literature review will be presented in Section II, and is divided into II.*A Infrastructure Changes*, II.*B Device Level Innovations*, and II.*C Autonomous Vehicles*. Section III is the proposed system and is subdivided into III.*A Modeling and analysis* and III.*B Results*. Finally, section IV will present the conclusion.

II. State-of-the-Art

A. Infrastructure Changes

This section includes the proposal of infrastructures that would ease the way for EVs on the road. Although such infrastructure would be expensive to implement, it would have advantages such as: (1) increasing driving range, (2) decreasing battery size, and (3) improving convenience [28]–[32]. In [33], a metering and wireless charging system was proposed that can account for the exact amount of electric power received by each vehicle, with a billing strategy. It is presented for infrastructures where wireless pads are placed under designated regions of the roads and vehicles can charge wirelessly while passing by. As multiple vehicles (that are close to each other) pass by a specific transmitter, it would be difficult to account for the energy consumed by each vehicle. The authors propose identification and metering equipment, charge control unit, and a dedicated software installed on the EV's to help alleviate this issue.

Other types of infrastructures have been proposed to help vehicles to charge-on-the-move (CoM). The idea of CoM for EVs is not a new concept, in fact it has been implemented for years as an overhead catenary system. Such system was used on busses, trams, and trains as well as road freight vehicles. In 2011, Siemens developed a refined catenary system that was tested on hybrid electric trucks [34]. In this system, using a pantograph type conductors, the vehicles can autonomously connect and charge from electrified parts of the highway as seen in Fig. 2. The amount of power these vehicles can receives from the two wire overhead system is about 260 kW.

A change in the current infrastructure was proposed in [35] where cars could CoM as illustrated in Fig. 3. The authors discuss the two major parts for such system which are the inductive power transfer (IPT) devices for both vehicles and roads. The IPTs on the road would be 1.5 m in length and spaced out on highways and rural roads. The authors also present a comprehensive consideration of the infrastructure updates, with an estimated cost of 76 billion euros for about 86% of the car-miles in Great Britain. The majority of this cost is due to the integration of IPT devices on the roads on a national scale. A study on the feasibility of such infrastructure was conducted in [36], where true decarbonization of the national road freight system was presented. The authors also highlight a logistic concept for road freight operations that is divided into four categories along with the proposal of different vehicles and charging methods for each.

In [37], an On-Line Electric Vehicle system is presented that incorporates high efficient and low electromagnetic field (EMF) wireless power transfer. This system (presented in Fig. 4(a)) is comprised of power lines connected to an inverter that extends under ground to generate resonant magnetic field, while the EVs have a pickup modules, batteries, capacitors and electric motors. The authors use vertical magnetic flux type pickup coil along with a proper design of power lines to achieve 80% efficiency as highlighted in Fig. 4(b). The authors also propose two methods for EMF shielding for the design.

Another proposal of infrastructure change for EVs was presented in [38] (Fig. 5) that consists of WPT, supercapacitors and electric motors. The author highlights the importance of using WPT based on magnetic resonance for high efficiency along with supercapacitors as buffer devices instead of Li-ion batteries. The claim is that the incorporation of such devices will allow the feasibility of a convenient EV infrastructure. The author also showcases experimental results for WPT with 90% efficiency at an operating frequency of 10 MHz. It is

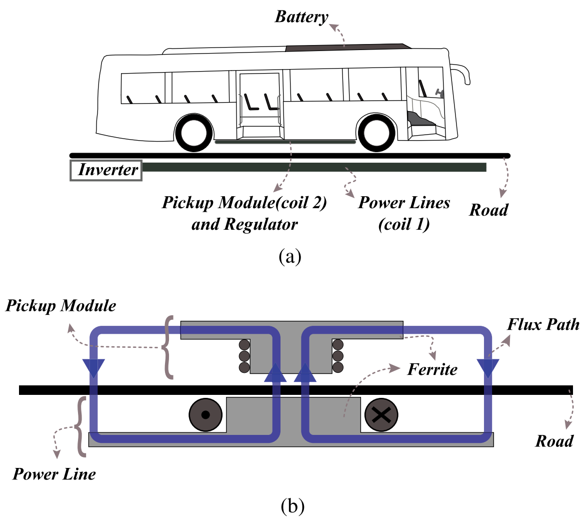

Fig. 4. (a) On-line EV system. (b) Vertical magnetic flux pickup coil and design of power line.

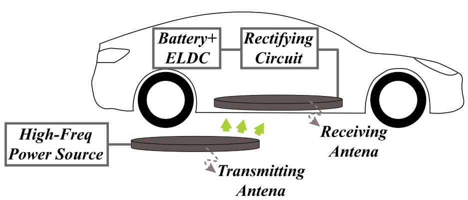

Fig. 5. Infrastructure with EV's that consists of supercapacitors (ELDC) and batteries on-board.

worth mentioning that in this setup the vehicles would charge while stationary to get a boost of energy. A similar setup which requires adding transmitting coils under the roads was discussed in [39]. Herein, the authors propose an innovative way of WPT using multiple transmitting coils that are connected together and can turn off/on selectively. They derive an expression for the efficiency of the proposed system, and also provide simulation and experimental results.

In [40], another system which involves charging vehicles while on the move via dielectric coupling is presented. Here, the vehicle's tires have a steel belt around them that interacts with electrified roadways while on the move to allow for WPT (as illustrated in Fig. 6). The Authors show experimental results with a 1/32 scale models of EVs, and assert that this approach is promising since it can achieve high efficiency with impedance matching circuits. Another take on EV infrastructure (similar to that discussed in this paper) was introduced in [41], [42]. The authors use large vehicles (like a truck or bus) on highways to transfer energy to other vehicles on the road, therefore overcoming the need for EVs to stop for a charge. The system presented in this paper, however, proposes a better solution with an optimized charger vehicle.

B. Device Level Innovations

The topic itself of WPT in electric vehicles has become more popular, and many methods and different approaches of WPT have been introduced and discussed in

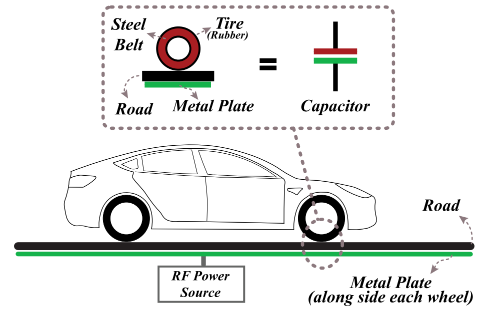

Fig. 6. CoM infrastructure via dielectric coupling.

detail [43]–[49]. A study for evaluating different power pads used for electric vehicles based on their power transfer efficiency was conducted in [50]. It's a bigger challenge to charge vehicle on the move (dynamic wireless energy transfer), and most of the studies conducted are for static wireless charging as presented in a detailed review in [51]. They also present a unique issue to dynamic wireless energy transfer, that is the need for alignment between the two coils which greatly affects the transmission power.

The main technologies for WPT are through radio waves [52], resonances coupling and inductive power transfer. In recent years though, the WPT based on resonance coupling has been explored and became more popular due to its high efficiency [53]–[59], and was first discussed in [60].

Even with such technologies, one of the challenges that wireless charging faces is when the energy transfer is done with coils that are not aligned and with a dynamic changing distance between them (dynamic WPT) [61]. In [62], the authors show that the worry of the change in distance between the two coils can be overcome by choosing an optimal transmission frequency for the WPT with coupled-mode and resonance theory. The analysis there is based on a circuit model of a strongly magnetic resonance WPT. Another study in [63] highlights the WPT systems' dependency on the complex impedance of the receiver. The authors propose a complex impedance tuning method that comprises of a DC/DC converter and LC filters. They show that it is possible to tune the receiver load resistance in a wide range of values from the circuits low-frequency region.

One important aspect of control in WPT systems is certainly maximizing the power efficiency, and plenty of research on that topic has been conducted [64]–[71]. Another aspect of dynamic WPT is the consideration and estimation of the coupling coefficient as presented in [64]. Herein, the authors present a method for real time coupling coefficient estimation, along with a controller to maximize the WPT efficiency using the DC/DC converter on the receiver side. In [72], a state feedback controller was designed to watch out for the changes of mutual inductance that helps improve the general stability of the system. The authors mention that such controller could be usable in applications of dynamic WPT on EVs.

Dynamic WPT technologies also face an issue when there is a tilt between the two coils. In fact, a study conducted in [73] shows the effects of the tilt angle between the transmitting and receiving coils. The authors showcase three different scenarios

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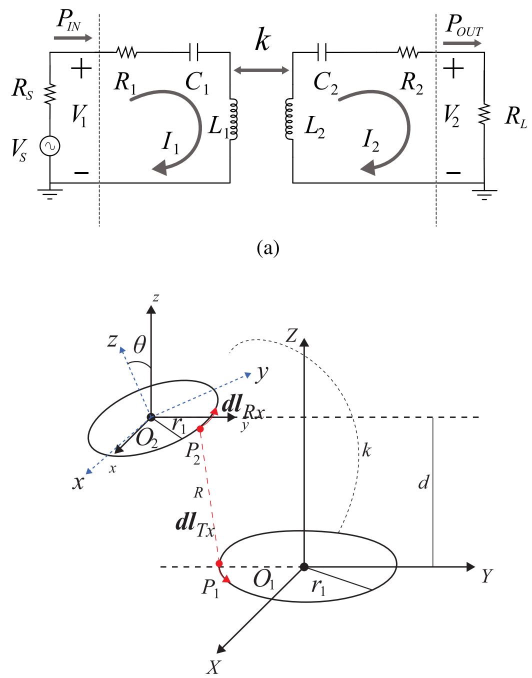

(b)

Fig. 7. (a) Circuit model of WPT system with a single TX and RX. (b) WPT system with angle and horizontal misalignment.

and propose a method to obtain the optimal tilt angle for high WPT efficiency, with respect to their relative position. The analysis for power efficiency was based on a circuit model (illustrated in Fig. 7(a)) with a single transmitter (TX) and receiver (RX). The coupling coefficient (k) was calculated considering a misalignment both in angle and horizontal position as shown in Fig. 7(b). Moreover, research on the effects of the vehicle's speed at which it passes the WPT area was conducted in [74]. The authors show that different speeds affect the efficiency of the WPT and propose a control method to optimize the energy transfer with respect to the driving speed. With the topic of dynamic WPT becoming more popular, recent research control methods for dynamic WPT have been proposed in the literature such as [75]. Herein, a power control method that changes the amount of power being transferred based on the state of charge (SOC) of the battery is presented. The authors argue that with such method, dual-sided communication is avoided. They also provide some experimental results from a built prototype that can transmit about 1.5 kW of power.

C. Autonomous Vehicles

As mentioned in the last section, the concept of this paper focuses on a vehicle-to-vehicle recharging (VVR) system where a user vehicle can get extra energy on-demand to prolong the duration of the trip without having to pit-stop. This is similar to the concept of vehicular platooning, where one vehicle follows another safely with a small distance between each other at high speeds. In the VVR system, the charger vehicle only needs to be semi-autonomous in order for it to guarantee a constant distance while charging, and this level of "semi-autonomous" is currently available in the market. Although, research on vehicular platooning has attracted attention as vehicles get higher level of autonomy, specifically with connected autonomous vehicles [76]–[78]. Also, plenty of research has been conducted on vehicular platooning in terms of safety [79]–[83]. It is worth mentioning that it is possible to achieve vehicular platooning safely at small distances between vehicles, with no information or communication from the lead vehicle [84]–[90].

Fully autonomous vehicles (self driving cars) are vehicles that are equipped with sensors to identify and navigate through the environment nearby with no human input at all. If both the user vehicle and the charger vehicle have full autonomous capability, it would make for a stronger case in terms reliability and safety. Recently, the concept of autonomous vehicles have become more popular [91]–[95]. The automotive industry, along with research institutions, are also playing a role in advocating some of the highlights of autonomous (or semi-autonomous) vehicles in terms of safety. At the present time, multiple studies have been conducted on the improvement of the self driving cars in terms of safety [96]–[98] and control [99]–[102].

Autonomous vehicles always need to answer the question of "what to do next?". These vehicles need to use information gathered by their localization center to answer that question. The localization techniques used in autonomous vehicles can be summed up in two categories [103]: sensor based, and cooperative localization techniques. The first technique is comprised of vehicles that only rely on on-board sensors to make decisions. Although the sensors used in such a technique are typically more accurate and reliable, they come with an increase of cost. The second technique makes decisions based on communications of vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and on-board sensors. The authors in [104] show that such a cooperative localization technique can indeed increase the system performance, robustness, and a general better awareness of the surrounding environment. In recent years, the exploration of autonomous vehicles have also expanded to the airspace [105]–[111], and also underwater [68], [112]–[115].

One of the most important features that autonomous vehicles must comprise of is the steering control for path tracking capability. In [116], a model predictive controller (MPC) was introduced for path tracking that reduces that lateral tracking deviation and keeps the vehicle stable for high and low speeds. Due to the computational complexity in which an MPC controller can impose when considering path tracking as an optimization problem, [117]–[119] have suggested combining the MPC with a Laguerre function and/or an exponential weight to reduce such complexity. Another adaptation of an MPC was presented in [120], where a linear MPC is capable of path tracking with minimum side to side deviation at high speeds. In [99], a detailed comparison between a path tracking and a torque-vectoring controller is presented. Although torque-vectoring controllers require vehicles that have motors on each wheel, they still provide a great solution for vehicle stability and performance when compared to path tracking controllers based on steering system actuation.

Modeling of autonomous vehicles is desired to ensure that proposed control systems work as expected. In [101], the authors propose a game theoretic traffic model that can be used to test multiple vehicles' decisions based on safety and correct performance. The authors also state that their developed simulator can be used to tune and calibrate parameters of control policies in autonomous vehicles. Other game theoretic modeling techniques for autonomous vehicles were presented in [121]. Herein, the models were used as a solution to paradigms that are important when considering a driver's interaction with the vehicles active front steering collision avoidance controller. A similar study was also conducted in [122], where the focus of the game theoretic model was to analyze the interaction between the driver and an automated steering system that is based on a cooperative pareto steering strategy. As the topic is still passing its early stages, modeling of autonomous vehicles will continue to be a discussed subject in the literature in the foreseeable future. All the current and new autonomous vehicle developments can be used to make the proposed VVR system more efficient.

III. Proposed System

As the literature review suggests, the problem of electric vehicle charging remains open ended. Although there are many technical solutions presented in the technical literature, most of them carry inherent economic and/or implementation challenges. This section presents an alternative solution that allows EV batteries to be charged with minimum infrastructure changes and with the ability to reduce the pit-stop time to zero.

The proposed system in constituted by a charger vehicle that is capable of charging another vehicle wirelessly on a highway. The user vehicle would be en route on a trip that would typically require at least one pit-stop. During the trip, the user vehicle can request for the VVR as the SOC of the battery goes low. Fig. 8 shows a general overview of how the charger vehicle engages and disengages from the user vehicle. It is assumed that the user vehicle starts its trip with a full SOC (see Fig. 8(a)). As the vehicle goes about the route and starts to an uncomfortable low level, it requests for VVR and the charger vehicle joins the route as highlighted in Fig. 8(b). Fig. 8(c) shows both vehicles during VVR process with both vehicles traveling at close distance. Finally, in Fig. 8(d), the user vehicle is either fully charged or requests a disengage from the VVR, which will find an exit to either recharge its own battery or park and wait for the next user vehicle. The concept is that these charger vehicles would have either large batteries or an on-board electric generator that is capable of delivering power to multiple vehicles as shown in Fig. 9. Fig. 9 (left) shows the charger vehicle 100% electric, implemented with a large battery package, while Fig. 9 (right) introduces the hybrid charger vehicle with an embedded generator set. The proposed system could be implemented with either option. The hybrid charger vehicle could be implemented first to lower the cost of the entire system, and as batteries costs reduce, then electric charger vehicles would be a substitute to the hybrid counterparts. Note that the WPT charging mechanism can be placed at either the front or back of either of those vehicles.

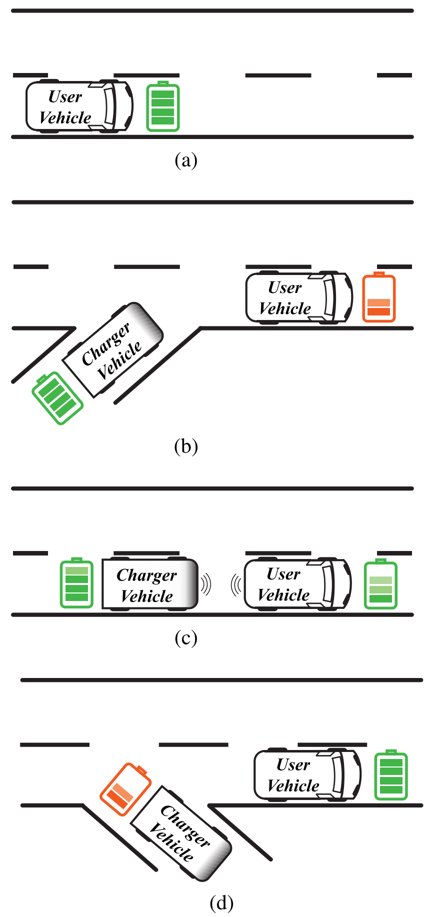

Fig. 8. (a) User vehicle en route. (b) User vehicle requesting VVR. (c) VVR application. (d) Charger vehicle disengaging/leaving route.

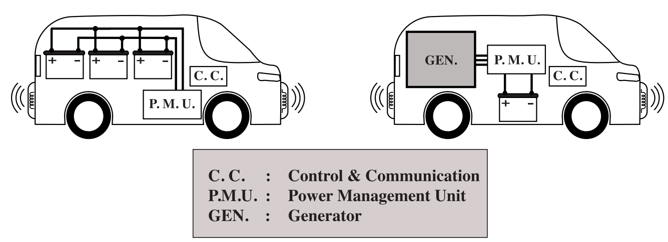

Fig. 9. Charger vehicle that is either fully EV (left) or HEV (right).

A. Modeling and Analysis

In the VVR system presented in this study, the user and charger vehicles are electric vehicles. Fig. 10 shows the block diagram of the proposed system. Both the user and charger vehicle models are equation-based approach similar to that presented in [123].

There are two globally accepted methods for modeling an EV, a forward-facing powertrain model and a backward-facing powertrain model [124]. This paper employs a forward-facing powertrain model and was implemented in MATLAB®/Simulink®. The driver model block can be seen in detail in Fig. 11, where the objective here is to ensure that the vehicle speed obtained from the glider model is following the drive cycle data (reference vehicle speed). It does that by getting the difference (error), which is then applied to a

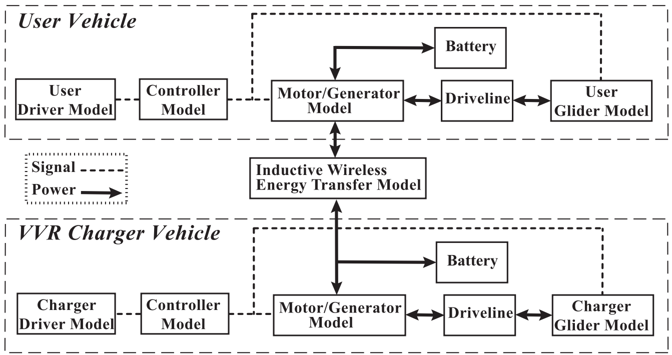

Fig. 10. Block diagram of the VVR system.

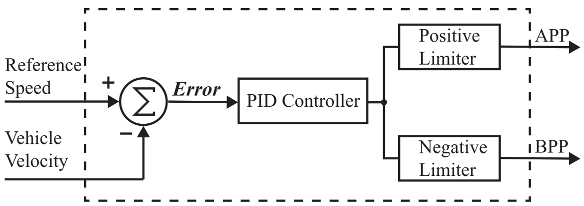

Fig. 11. Driver model block diagram.

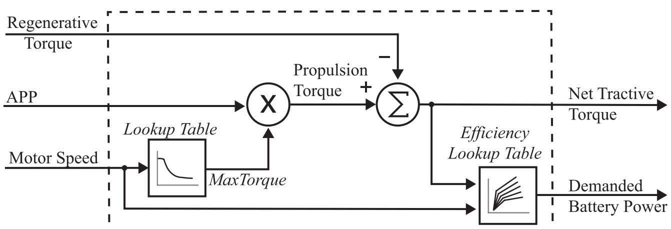

Fig. 12. Motor model block diagram.

PID controller to define the accelerator pedal position (APP) along with the brake pedal position (BPP). The APP then goes to the motor block shown with more details in Fig. 12. Herein, the APP requests the amount of torque to reduce the speed difference error, but is limited by a one-dimensional lookup table that defines how much maximum torque is allowed at the current motor speed. The output of the limiter is the positive torque needed for propulsion, subtracted by the regenerative torque (obtained from a brake model) to get the total net tractive torque going to the driveline. This net torque at the current speed defines the power needed from the battery based off the motors efficiency map (a 3D lookup table also highlighted in Fig. 12). For this simulation, the motor efficiency map that was used was similar to that of an induction motor used in the Tesla model S shown in Fig. 13.

The Battery's SOC is calculated using the coulomb counting method as shown in [126], which can be re-written as:

$$SOC = SOC(t_0) - \frac{1}{C_{rated}} \int_{t_0}^{t_{final}} I_{Bat} dt \tag{1}$$

where C_{rated} is the rated energy capacity of the battery, t_0 is the initial time, t_{final} is the final time, and I_{Bat} is the battery current. The convention here is that positive current I_{Bat} is coming from the battery. For a simplified battery model

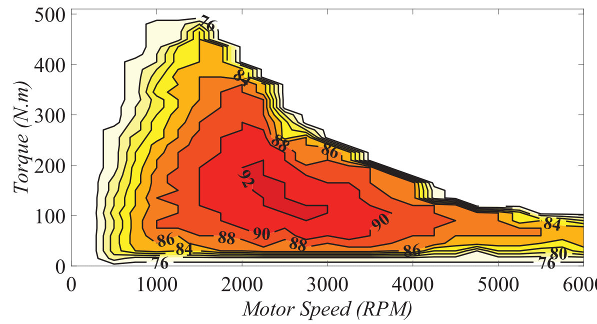

Fig. 13. Tesla Model S induction motor efficiency map [125].

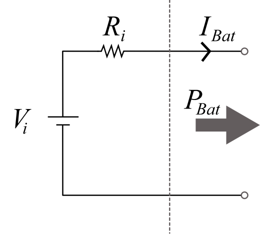

Fig. 14. Battery model.

(shown in Fig. 14) consisting of an internal resistance (R_i) and voltage (V_i) connected in series only, the current I_{Bat} is a function of the power output of the battery (P_{Bat}), and can be defined as:

$$I_{Bat} = \frac{V_i - \sqrt{V_i^2 - 4R_i P_{Bat}}}{2R_i} \tag{2}$$

where $P_{Bat} = \frac{1}{\eta} P_{motor} + P_{accessory}$, η is the efficiency of the motor, P_{motor} is the output power of the motor, and $P_{accessory}$ is the power consumed by the accessory load. In this simulation, the battery current is positive when delivering power to the driveline, and negative when there is regenerative energy coming back to it. Research on battery management techniques have been discussed in the literature such as in [127], where the authors propose a hierarchical energy management strategy for HEVs that can be used for EVs.

The driveline block converts that total tractive torque to tractive force, which is then the input of the glider model. The glider model (or vehicle model) is a physics-based model inspired from [128]–[130] where the tractive force overcomes all other forces acting on the vehicle. Fig. 15(a) shows the a free body diagram of the vehicle highlighting the forces acting on it. The block diagram of that can be seen in Fig. 15(b) where the inertial force is used here to obtain the acceleration, then integrating it to obtain the vehicle velocity.

The controller must guarantee that the charger vehicles' battery has a state of charge (SOC) that does not go below 10%, and it must also ensure that only when the system is engaged that it charges the user vehicle. When the vehicle is engaged, the battery of the charger vehicle sends energy through the inductive WPT model simplified here as a constant representing an efficiency of 90%, similar to the efficiency in

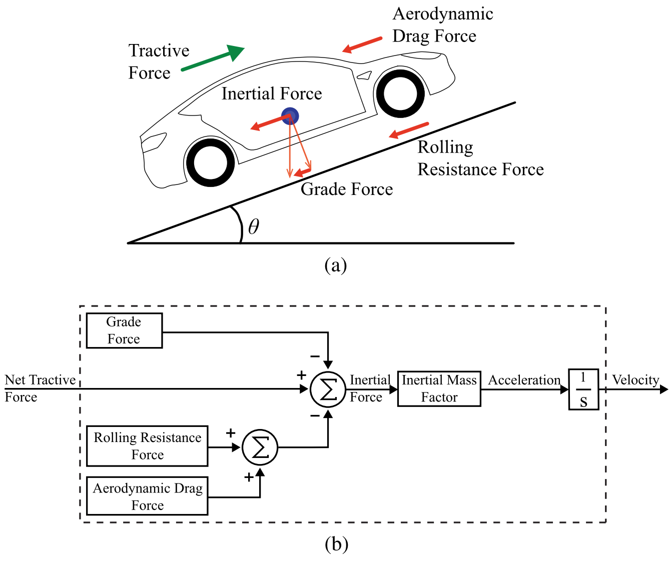

Fig. 15. (a) Free body diagram of vehicle. (b) Block diagram of vehicle model.

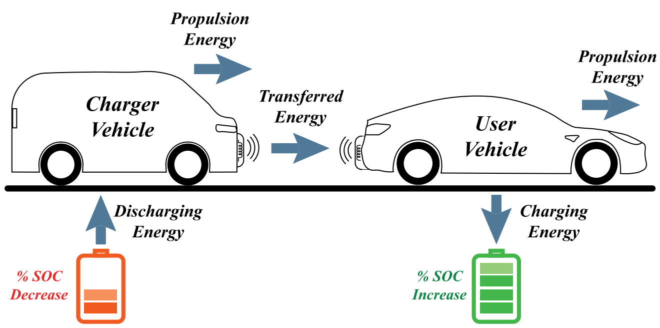

Fig. 16. Energy distribution throughout the VVR system.

the literature [53]. Note that in this model, the user and charger vehicle powertrain model work in a similar fashion.

B. Results

1) Energy Analysis: One important aspect to consider for the VVR system is how much energy the charger vehicle will use. This incorporates the power that will be consumed by the charger vehicle and the power being transferred to user vehicle during the VVR application. Fig. 16 provides an illustration of energy consumption of the system. Note that in Fig. 16 the energy transferred should overcome the energy to propel the user vehicle in order to charge its battery.

This type of analysis helps understand the cost of using the VVR, since the user vehicle will be responsible for the total energy being consumed by the charger vehicle during the VVR. Although the VVR system would be more costly than using a typical charging station along the route, the argument here is for a convenient solution since there is no need to pull over and waste time on just charging. An argument can also be made in terms of stress on the grid, since the VVR vehicles can be charged during non-peak times and provide the energy to the user vehicles during peak times. Peak times here is defined as the period of time throughout the day in which the electric utility company is observing the most demand from the consumers. Another point is the charger vehicles don't have to be fully electric vehicles, they can be hybrid with an on-board generator.

TABLE I
GLIDER MODEL PARAMETERS

Parameters	User Vehicle	Charger Vehicle
Aerodynamic Drag Coeff.	0.38	0.38
Air Density	$1.23\ kg/m^3$	$1.23\ kg/m^3$
Frontal Area	$1.8\ m^2$	$2.1\ m^2$
Gravity	$9.81\ m/s^2$	$9.81\ m/s^2$
Mass of Vehicle	$1800\ kg$	$3114\ kg$
Rolling Resistance Coeff.	0.01	0.012
Incline Angle	$0\ Degrees$	$0\ Degrees$
Vehicle Inertial Mass	$2000\ kg$	$4784\ kg$

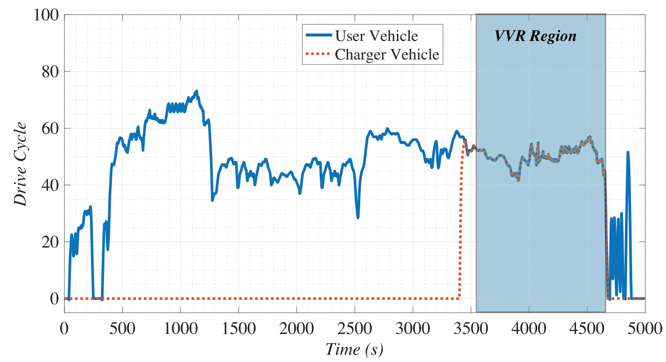

Fig. 17. Drive cycle of the user and charger vehicles.

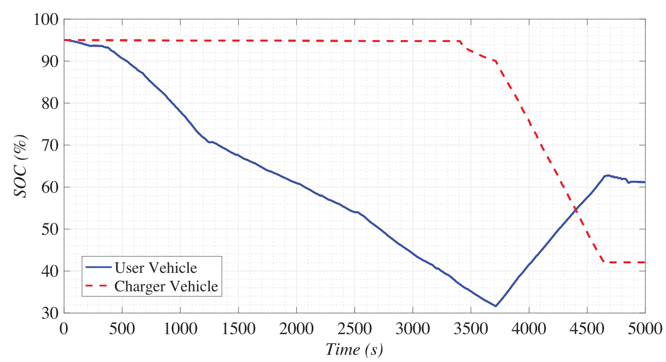

Fig. 18. SOC of user and charger vehicles.

2) Drive-Cycle Analysis: MATLAB® and Simulink® was used to simulate the proposed system. The block diagram presented in Fig. 10 was implemented where both the user and driver vehicle are EVs. As mentioned before, the glider model presented here is a physics based model, and the parameters used are presented in Table I.

The VVR system presented in this paper was simulated with the following scenario for the drive cycles: A lower scale user vehicle is on a trip that requires at least one pit-stop or a VVR request (about 100 miles). Fig. 17 shows the drive cycle used in the simulation, which was made up from a combination of well known highway drive cycles also used in [123]. It is evident from Fig. 17 that the charger vehicle

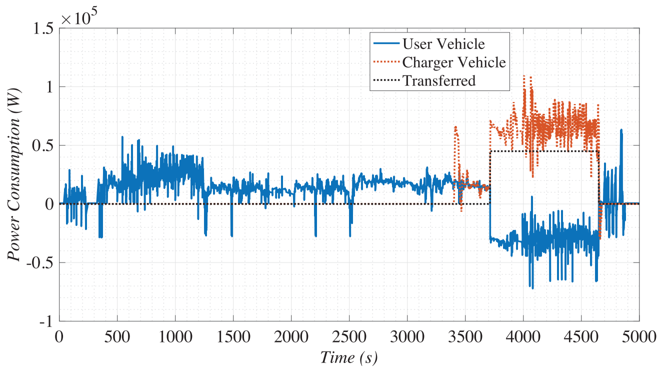

Fig. 19. Total power consumption of user and charger vehicles (including WPT).

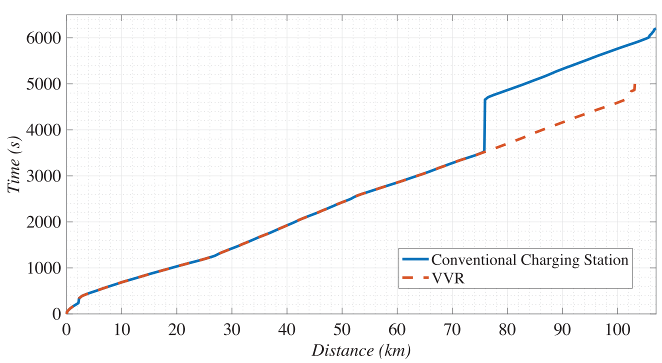

Fig. 20. Elapsed time versus distance: Comparison between EV using conventional charging station versus the VVR system during the same trip.

was requested at about 3,450 seconds and joined the user vehicle a little after. Then as both vehicles get off the highway (at about 4,700 seconds), the charger disengages and the user continues the trip. The user vehicle here has a battery size of about 23.7 kWh, while the charger vehicle's battery capacity is 35.91 kWh. The state of charge (SOC) of both the user and charger vehicle is presented in Fig. 18, highlighting the region in which the user vehicle battery is no longer used for its own propulsion. Fig. 19 shows the power consumed by the user vehicle, charger vehicle, and the power transferred during the application of VVR. A comparison between an EV using VVR versus stopping by a conventional charging station to charge its battery is presented in Fig. 20. It is clear that the EV charging with VVR would reach the destination 20 minutes earlier than if it would have stopped at a conventional charging station. It is then a matter of preference on whether customers are willing to pay a premium to reduce such a trip presented in this analysis by 20%.

IV. Conclusion

It is inevitable that EVs will be the norm of transportation in the near future. The struggle that EVs face right now is the inconvenience in terms of how long it takes to charge while on a trip. This paper proposed an electric vehicle charging system that allows an EV to charge its battery while en route. The process of transferring electric power from one specialized vehicle (charger vehicle) to another (user vehicle) during a trip is implemented wirelessly. This VVR system will allow EVs to drive further distances without the need for a pit-stop. In addition to modeling, analysis, and simulation of the proposed system, this paper also presented an extensive state-of-the-art study highlighting the prospective solutions to mitigate the EVs charging problem, i.e., (1) infrastructure changes, (2) device level innovations, and (3) autonomous vehicles.

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