Sizing Dynamic Wireless Charging for Light-Duty Electric Vehicles in Roadway Applications

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***Abstract*—Dynamic wireless charging is a possible cure for the range limitations seen in electric vehicles (EVs) once implemented in highways or city streets. The contribution of this paper is the use of experimental data to show that the expected energy gain from a dynamic wireless power transfer (WPT) system is largely a function of average speed, which allows the power level and number of coils per mile of a dynamic WPT system to be sized for the sustained operation of an EV. First, data from dynamometer testing is used to determine the instantaneous energy requirements of a light-duty EV. Then, experimental data is applied to determine the theoretical energy gained by passing over a coil as a function of velocity and power level. Related simulations are performed to explore possible methods of placing WPT coils within roadways with comparisons to the constant velocity case. Analyses with these cases demonstrate what system ratings are needed to meet the energy requirements of the EV and what effect longitudinal alignment has on WPT. The simulations are also used to determine onboard energy storage requirements for each driving cycle.**

***Index Terms*—Road transportation, electric vehicles, dynamic wireless charging, driving cycles, transportation electrification, wireless power transfer**

I. Introduction

Near-field, magnetically coupled wireless power transfer (WPT) uses a loosely coupled transformer, which is usually comprised of a primary and secondary unit, in order to transfer energy over an airgap. The technology has several advantages over conductive charging, and has become more accepted over time. It has already been widely commercialized for use in low power applications such as cell phone and toothbrush charging, but recently has also become a trend of conversation within the electric vehicle (EV) industry. The Society of Automotive Engineers (SAE) has taken notice of this and implemented standard J2954 for static wireless charging that establishes charger power levels and seeks to make WPT devices interoperable [1]. A few manufacturers already produce WPT coils for consumer use with EVs. Also, several projects involving electric buses and rail transit systems have already been successfully demonstrated [2].

Researchers have made significant progress with WPT systems in recent years. Many different topologies have been developed, many that use power electronics that push the limits of available components [3] [4]. Oak Ridge National Laboratory (ORNL) has been a leader in this research area. Work at ORNL has progressed from a smaller Global Electric Motorcars vehicle with a 1.5kW system [5] [6] [7] to a Toyota Rav4 EV with a 10kW+ system [8]. Both of these systems have successfully demonstrated both static and dynamic WPT. Static WPT has a solid research foundation whereas dynamic charging is still relatively undeveloped. Many papers refer to a concept known as “quasi-dynamic charging” in an attempt to reconcile static and dynamic charging. In quasi-dynamic charging, the EV moves and then stops over a conveniently placed WPT device. This is commonly set in the context of traffic lights, delivery vehicles, and public buses. This approach simplifies dynamic wireless charging to timed static charging. However, truly dynamic WPT, especially in the cases of highway implementation, is not so idealized. There are several issues persist as significant challenges as listed in [9]. This paper provides insight into two of these, the power rating of WPT coils and vehicle alignment, by using experimental data from recent WPT tests [10] as well as data from dynamometer tests of a widely available EV.

II. Electric Vehicle Energy Use

The transportation sector is responsible for about 28% of the total energy use of the United States yearly [11]. Significant media and regulatory attention on the energy efficiency of vehicles has brought about driving cycles that provide standardized cases for different driving situations. The cycles considered in this paper are given in Table 1 for reference [12] [13]. It is mandated that all automobile manufacturers use the driving cycles to benchmark any vehicle they sell. This data is publicly available [14], but unfortunately does not show instantaneous energy use, which is useful for dynamic WPT analysis. Although many accurate models are available to remedy this problem, Argonne National Laboratory (ANL) has made instantaneous test data publicly available [13]. The

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TABLE I
DRIVING CYCLES

	UDDS	Cold UDDS	US06	HWFET
Trip Type	Low Speeds, Stop-and-Go Urban Traffic	Urban with Colder Ambient Temperatures	High Speeds, Harder Braking/ Acceleration	Highway Speeds, Free Flowing Traffic
Top Speed	56mph	56mph	80mph	60mph
Average Speed	19.6mph	19.6mph	48.4mph	48.3mph
Simulated Distance (miles)	7.44	7.44	8	10.25
Time (secs)	1369	1369	600	765
Temperature	72°F	20°F	75°F	75°F
Energy Use Nissan LEAF (kWh)	1.446	2.756	2.368	2.678

2012 Nissan LEAF, one EV out of several EVs tested by ANL, will be used in this paper. The Nissan LEAF was tested using a dynamometer set to realistic coast down coefficients in a controllable test chamber. These coefficients were calculated from the actual on-road vehicle dynamics of the vehicle using standardized tests. They represent physical forces such as aerodynamic drag, tire rolling resistance, and powertrain losses [15]. These coefficients, as well as the other physical parameters of the Nissan LEAF as within are given in Table 2 [13]. In Fig. 1, the energy use of the Nissan LEAF is shown over the course of the UDDS drive cycle and is 1.457kWh in total. In Fig. 2 the energy use over the US06 drive cycle is displayed and is 2.678kWh in total. Although the US06 cycle is only 0.56 miles longer than the UDDS cycle, it uses over 1kWh more due to the aggressiveness of the cycle. This statement can generally be extended to driving as a whole: higher speeds and rapid accelerations use more energy [15].

The energy used by the Nissan LEAF was derived from the test data as the integration of power, which is the product of the high-voltage battery current and voltage using the 500A max clamp series [16]. Although the analysis here considers a currently known vehicle, modeling approaches can be used to generalize the methodology within this paper for use with models of future EVs or those that do not have readily available instantaneous dynamometer test data. The reader is encouraged to read about tractive power within [15] and refer to models such as the U.S. Department of Energy's Autonomie and FASTSim [17] [18].

TABLE II
ANL NISSAN LEAF DYNAMOMETER SETUP

Test Weight (lbs)	3746
Target A (lbs)	41.06
Target B (lbs/mph)	-0.3082
Target C (lbs/mph^2)	0.02525

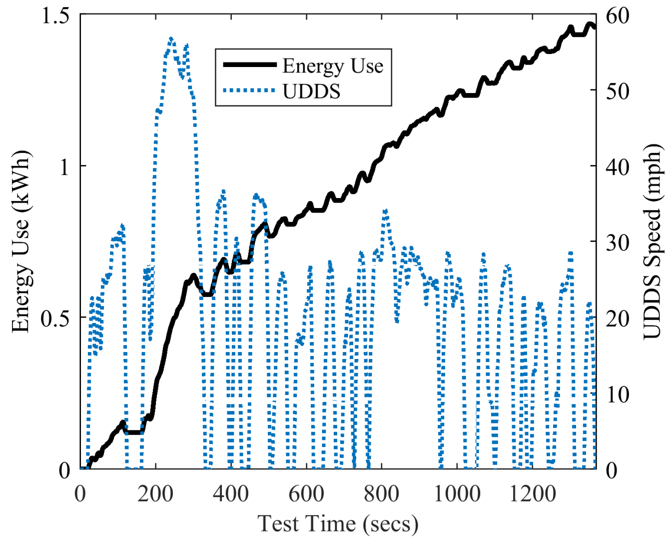

Fig. 1. Nissan LEAF Energy Use, UDDS Drive Cycle

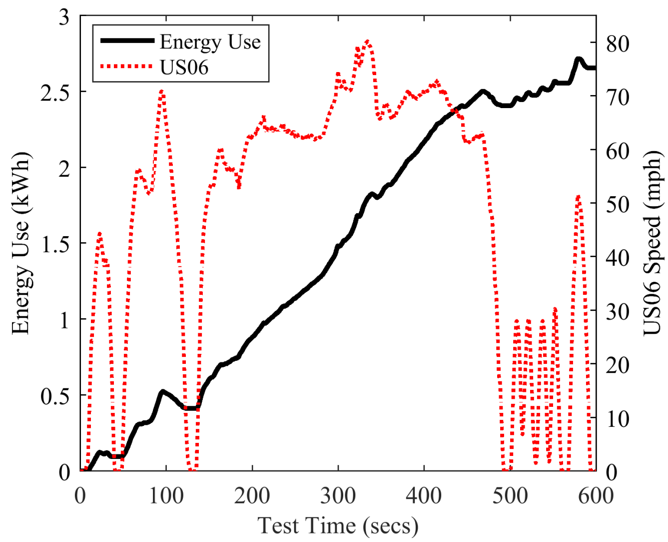

Fig. 2. Nissan LEAF Energy Use, US06 Drive Cycle

III. Current ORNL Coil Design and the Effect of Speed on Dynamic WPT

At ORNL, experiences with wide bandgap power electronics has led to continued progress in the WPT research area [8]. The most recent contribution was the demonstration of dynamic WPT at 10kW. The experimental setup is shown in Fig. 3. In the experiment, two 79cm primary coils were used to power a Toyota Rav4 EV through dynamic wireless charging [10]. The primary and secondary coils were matched coils as seen in the ORNL paper on static WPT, where many details can be found on the coil and electronic design [8]. The power transfer over different longitudinal positions was taken as part of the dynamic tests. Using this data, MATLAB was used to produce an accurate curve fit of the data as seen in

Fig. 3. Experimental Setup: A Two-Coil Track with Matched Coils

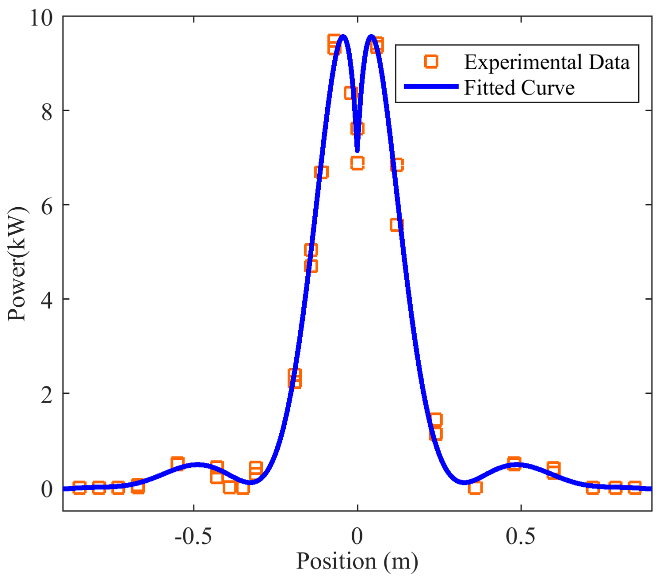

Fig. 4. Lateral Displacement vs. Power, Defined as $P_{coil}(x)$.

Fig. 4. This curve was used for the analyses in this paper with following assumptions:

1) The EV passes over the coil perfectly centered laterally. Lateral misalignment is not considered.
2) The coil power curve is valid for a 1.6 meter longitudinal range parallel to the direction of motion (-0.8m – 0.8m)
3) No overlap between adjacent coil curves exists (minimum spacing requirement of about 81cm between coils).
4) Roadway features such as grade, prevailing wind, and curves are not included.
5) Higher powers are equivalent to scaled versions of the original power curve. Speed has no effect on the coil power in Fig. 4.

Many variables affect the performance and sizing of a dynamic WPT system and make such assumptions necessary. Among these, the human element of driving notably complicates any discussion of vehicle positioning in WPT due to the great variance in alignment that drivers exhibit. There has been research done in this area. For example, in a parking situation where drivers knew that they must park accurately over a WPT device for static WPT charging, they varied on average 9.57cm laterally and 73.48cm longitudinally [19]. Roadways are designed with this inevitable error in mind. In the United States, the standard width of a traffic lane for most applications is 3.6m (12ft) compared to the average vehicle width of 2.1m (6.9ft) to 2.6m (8.5ft) [20]. In terms of lateral alignment, this means that there can be up to one meter for a driver to vary side to side even without considering the accidental lane departures that occur during normal driving [21]. This scale of misalignment would affect the energy transfer in many WPT designs. Other energy considerations could include accessory loads such as air conditioning and heaters that can dramatically increase the energy consumption of an EV and thus decrease range [22]. Drivers have been shown to predictably turn on these loads due to ambient conditions [23].

Speed is the primary variable considered in this paper. Using $P_{coil}(x)$ as shown in Fig. 4, (1) defines location x in meters as a function of time and (2) describes the energy gained from a coil as a function of speed v in meters per second. Recall that $P_{coil}(x)$ is a valid for the range -0.8 to 0.8 meters, a total longitudinal range of 1.6 meters.

$$x(t) = v \cdot t - 0.8 \tag{1}$$

$$E_{coil} = \int_0^{1.6/v} P_{coil}(x(t))dt \tag{2}$$

$$C_{pwlvl} = \frac{P_{scaled}}{9.573kW} \tag{3}$$

The integration in (2) was done for speeds ranging from 1 to 90 miles per hour and is shown in Fig. 5. The power levels were chosen in this case to be the levels in SAE standard J2954. Again, higher or lower powers than 10kW were assumed to be scaled versions of $P_{coil}(x)$ and were equal to $P_{coil}(x) \cdot C$ where C_{pwlvl} is a scaling constant. C_{pwlvl} was calculated using (3) where P_{scaled} is the maximum value of the scaled version of $P_{coil}(x)$.

IV. Simulation of Dynamic WPT on Roadways

The 2012 Nissan LEAF as tested by ANL, an example of a typical light-duty EV, uses approximately 0.23kWh/mile to 0.42kWh/mile [13]. The comparison of this with Fig. 5 demonstrates that many coils per mile are required to power an EV. For example, at a power level of 22kW and a constant speed of 20mph, each coil provides 0.22Wh of energy as shown in Fig. 5. For the LEAF using 0.23kWh per mile, this would mean that over a thousand coils per mile would be required to offset energy use. The conclusion from Fig. 5

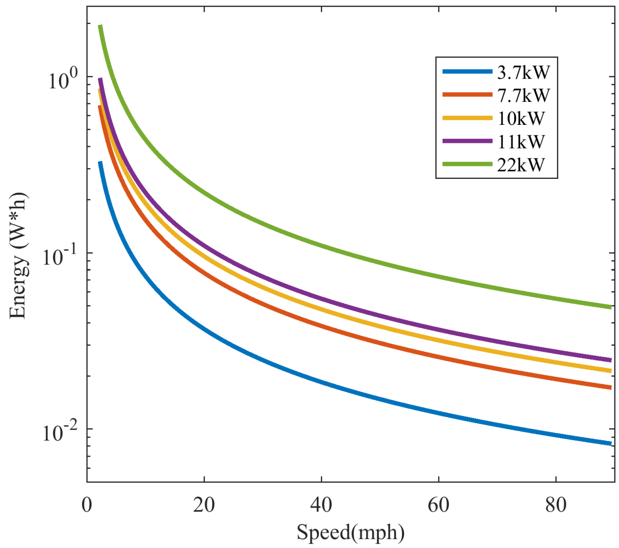

Fig. 5. Energy Transferred per Coil vs. Speed

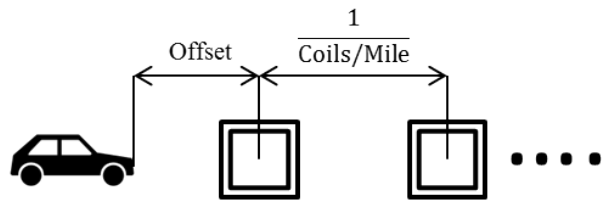

Fig. 6. Scenario Layout Using Equidistant Coil Spacing

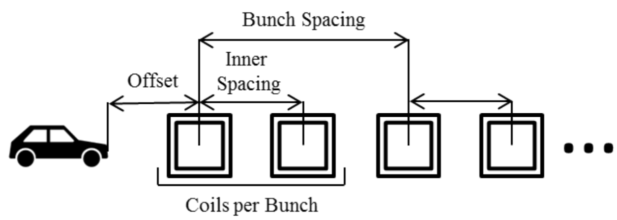

Fig. 7. Scenario Layout Using Bunched Coil Spacing

is then that speed greatly limits the energy transfer of WPT systems.

Vehicle speeds on roadways can vary greatly within a dynamic WPT system, with many possible stops, acceleration differences, preferential cruising speeds, and driving styles. In addition, ambient conditions, differences in traffic light cycles, surrounding vehicle lengths, emotion, and many other factors will affect speed. Thus for every position in a dynamic WPT enabled lane, there will be an element of randomness to how fast an EV is going over a coil and how much energy is transferred. Thus including "offset", the distance of the first coil relative to the EV starting position, is paramount when simulating with the driving cycles in Table 1. This is illustrated for the two spacing methodologies in Fig. 6 and Fig. 7. Two coil placement schemes were considered to determine if there was any difference between "bunching" coils close together or keeping them "equidistant". The "bunched" method has been especially considered in literature as high powered WPT coils could possibly require additional substations to be specially built nearby. This is already the case in the ORNL test setup in Fig 3. These two cases were compared on the same coils per mile basis in this analysis. Due to the spacing requirement made in assumption 3, the number of coils per mile was limited to 1005. This yields a spacing of 81.1cm, barely greater than the spacing minimum given in assumption 3.

Offset can significantly vary the energy gains over the course of the driving cycle, especially in the UDDS and US06 cycles where the EV has the potential to stop directly over a coil. However, truly dynamic charging does not permit these more optimal situations to be any more likely than the cases where the EV does not stop over a coil. Thus, all offsets were assumed equally as likely to occur. The maximum offsets are given in (4) and (5) for the equidistant case, $M_{equidistant}$, and the bunched spacing case, $M_{bunched}$, where $N_{coils/mile}$ represents the number of coils per mile, D_{cycle} represents the cycle distance, and N_{bunch} represents the desired number of coils per bunch. Notice that the "round" function was used to determine the closest number of bunches to yield the $N_{coils/mile}$ requirement for a given N_{bunch}.

$$M_{equidistant} = \frac{1}{N_{coils/mile}} \tag{4}$$

$$M_{bunched} = \frac{D_{cycle}}{round(N_{coils/mile} \cdot D_{cycle}/N_{bunch})} \tag{5}$$

The goal in any dynamic WPT system is ultimately to be "energy sustaining." An energy sustaining charging system is one that replaces energy as it is used in order to keep the net energy balance of the system near zero. In the case of EVs, this could mean a greatly increased range and a less varying state of charge. For every driving cycle and coil placement scheme, there exists a maximum, minimum, and average energy that is gained from the roadway coils over the span of a driving cycle. The most important of these for sizing a dynamic WPT system is the average value. Over a long range, the ability of the dynamic WPT system to sustain the EV will be dependent on this number. In Table 3, the simulation parameters are shown. The simulations were done for the UDDS, Cold UDDS, HWFET, and US06 cycles as shown in Table 1 and for the equidistant and bunch cases as outlined in (4), (5), and Table 3.

The simulations also determined the maximum energy storage the 2012 Nissan LEAF needs to undergo each driving cycle. The instantaneous energy as in Fig. 1 and Fig. 2 was compared to the amount of energy seen from the roadway over a cycle. This "roadway energy" varies due to offset, and the maximum difference can be found by iterating over all possible offsets. This difference of energy represents the amount of on-board energy storage that the 2012 Nissan LEAF would need in order to undergo a cycle with the given WPT system present. Again, this amount is valid for only one cycle, and more storage would certainly be required for continuous operation due to the variance in roadway energy due to offset.

V. Results

The simulations were first ran using the equidistant spacing method. The results for the average energy seen from the roadway coils or the "average roadway energy" are shown in Fig. 10-12. Note that the Cold UDDS and UDDS cycle yield the same average roadway energy since they are the same in terms of speed and only vary in energy use. The same simulations were done for bunched spacing. The results for the bunch spacing defined in Table 3 were found to be identical to Fig. 10-12.

Notice the linearity seen in Fig. 10-12. This was found to be directly related to the *average speed of each cycle*. The line defined in (6) accurately represents the average roadway energy E_{cycle} in all cases simulated. In (6), $N_{coils/mile}$ represents the number of coils per mile, D_{cycle} is the cycle distance in miles, C_{pwlvl} represents the power level factor as in (3), and $E_{coil}(v_{avg})$ represents the energy gained by passing over a coil at the average speed of a cycle in Table 1.

$$E_{cycle} = N_{coils/mile} \cdot D_{cycle} \cdot C_{pwlvl} \cdot E_{coil}(v_{avg}) \qquad (6)$$

This simplification allows for the accurate sizing of a dynamic WPT system for any given energy requirement as a function of average speed. For the 2012 Nissan LEAF, Fig. 8 describes the coils per mile and power levels required to make the average roadway energy equal the energy use. These curves were generated for up to 1005 coils per mile, and are valid for equidistant and bunch spacing cases. Fig. 8 is extremely important as it gives sizing standards for a dynamic WPT system using the ORNL coil topology. Fig. 9 shows an example of a properly sized system for the UDDS cycle. In this scenario, the net energy of the LEAF goes to zero as the roadway energy replaces the energy used by the LEAF.

In Fig. 13-16, the instantaneous energy use for the 2012 Nissan LEAF was used to determine the theoretical energy storage need for each cycle for the equidistant case. The energy storage requirements generally approximate the difference in the energy use and average roadway energy. With properly sized WPT systems on roadways, EVs can see a significant reduction in onboard energy requirements.

TABLE III
Equidistant and Bunched Simulation Parameters

Parameter	Value
Timestep (secs)	0.1 secs
Coils per Mile Range	[1, 1005]
Offset Step (miles)	0.0001
Minimum Offset, Bunched and Equidistant (miles)	0
Inner Bunch Spacing (miles)	0.001
Coils per Bunch	3

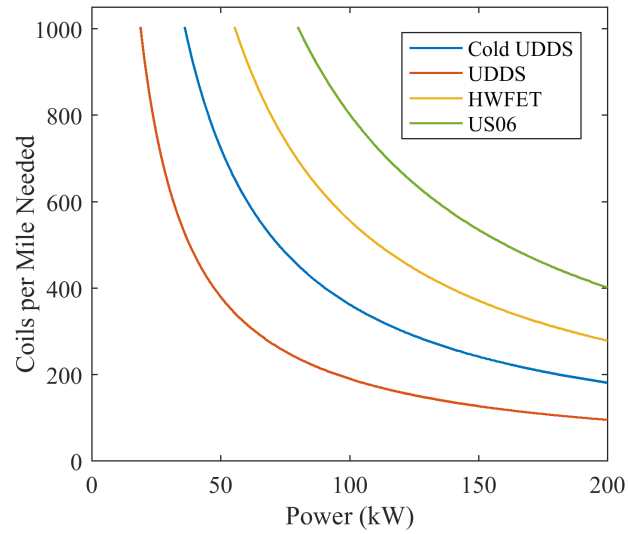

Fig. 8. Sizing the Dynamic WPT System by Drive Cycle

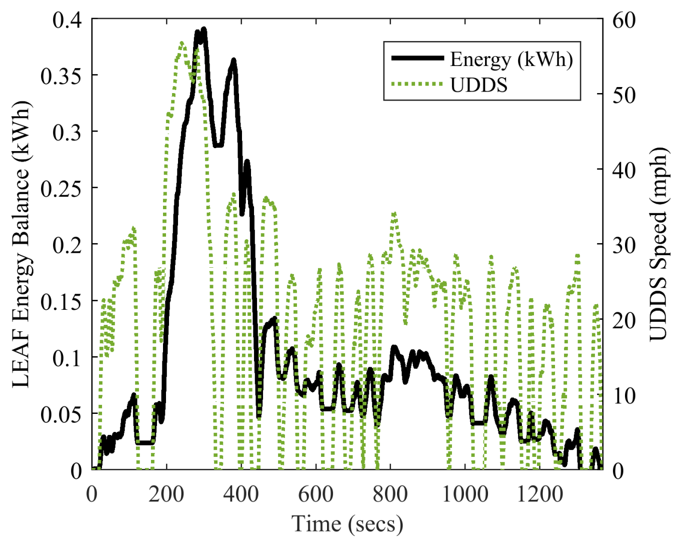

Fig. 9. Energy Balance of LEAF in UDDS Cycle, 380 coils per mile equidistant, 50kW rating

VI. Conclusion

In this paper, dynamic WPT was analyzed using ORNL coil design. Sizing guidelines were developed using standardized driving cycles and ANL test data by introducing a novel simplification based on average speed. This result is shown in Fig. 8. Though this analysis is performed using the ORNL coil topology, the methodology can be used with other WPT topologies in roadway applications and large-scale traffic analysis if the average speed and the energy use is known. The results also highlight the necessity of high powered WPT systems to be further developed for dynamic applications where SAE standard J2954 does not apply. The concept of variability due to offset is also highly applicable to "traffic

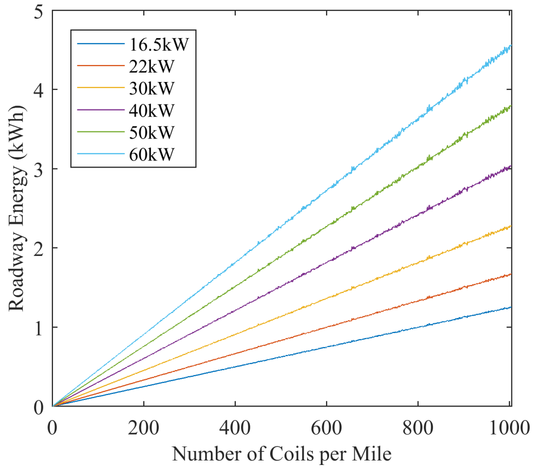

Fig. 10. Average Roadway Energy UDDS and Cold UDDS Cycles

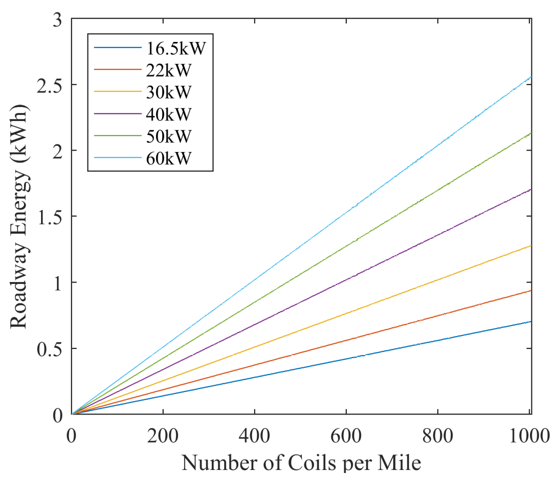

Fig. 11. Average Roadway Energy HWFET Cycle

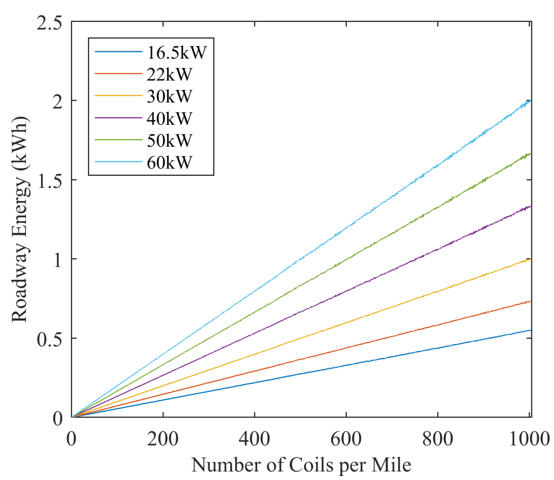

Fig. 12. Average Roadway Energy US06 Cycle

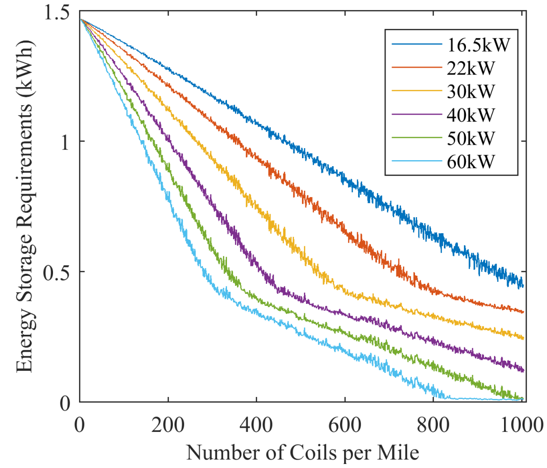

Fig. 13. Sizing Energy Storage for the UDDS

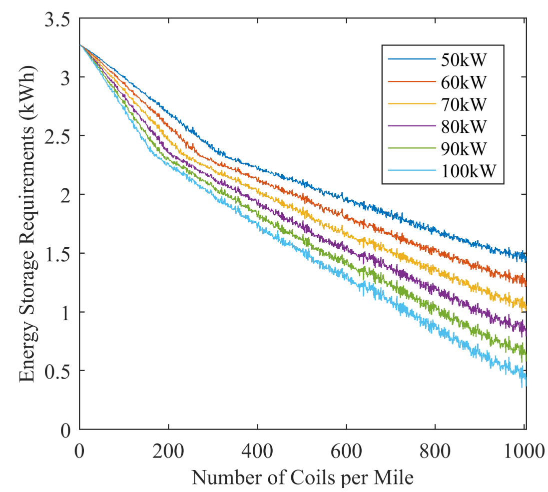

Fig. 14. Sizing Energy Storage for the Cold UDDS

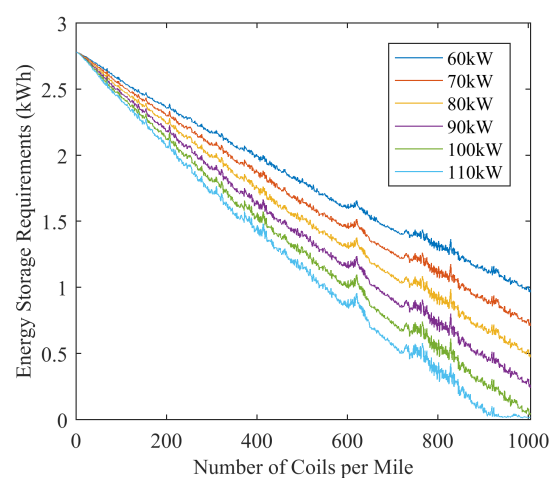

Fig. 15. Sizing Energy Storage for the HWFET

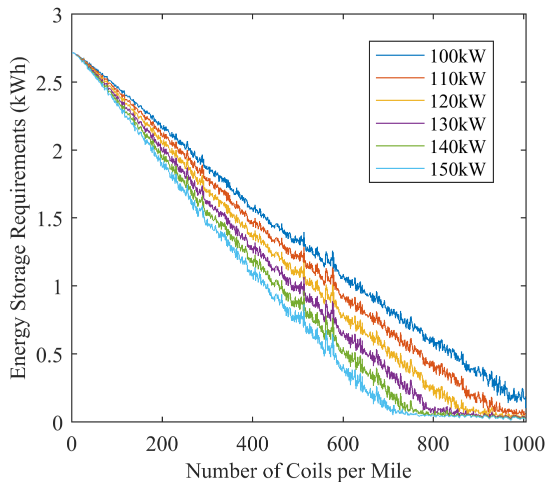

Fig. 16. Sizing Energy Storage for the US06

light" quasi-dynamic WPT where alignment in both the lateral and longitudinal directions is especially important.

The results also show that for applications on highways and interstates, very high power ratings and coil density numbers are needed in order to sufficiently power EVs using ORNL coil design. If such a small EV such as the Nissan LEAF requires power levels as large as 80kW with nearly 50% roadway coverage for the US06 drive cycle, much higher power levels would be required for larger EVs, such as electric commercial buses or semi-trailer trucks. At high speeds, time is a significant limiting factor on energy transfer, as Fig. 5 illustrates. In the future, dynamic WPT device design must take this into consideration and try to maximize both power and transfer time at high speeds. Lateral alignment issues also must be considered and demonstrations of WPT at high speeds must be performed.

Acknowledgments

The authors would like to thank Omer Onar and the rest of the team for their input on the testing mentioned in this paper.

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