Impact of Wireless Power Transfer in Transportation:

Future Transportation Enabler, or Near Term Distraction

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***Abstract*—While the total liquid fuels consumed in the U.S. for transportation of goods and people is expected to hold steady, or decline slightly over the next few decades, the world wide consumption is projected to increase of over 30% according to the Annual Energy Outlook 2014 [1]. The balance of energy consumption for transportation between petroleum fuels and electric energy, and the related greenhouse gas (GHG) emissions produced consuming either, is of particular interest to government administrations, vehicle OEMs, and energy suppliers. The market adoption of plug-in electric vehicles (PEVs) appears to be inhibited by many factors relating to the energy storage system (ESS) and charging infrastructure. Wireless power transfer (WPT) technologies have been identified as a key enabling technology to increase the acceptance of EVs. Oak Ridge National Laboratory (ORNL) has been involved in many research areas related to understanding the impacts, opportunities, challenges and costs related to various deployments of WPT technology for transportation use. Though the initial outlook for WPT deployment looks promising, many other emerging technologies have met unfavorable market launches due to unforeseen technology limitations, sometimes due to the complex system in which the new technology was placed. This paper will summarize research and development (R&D) performed at ORNL in the area of Wireless Power Transfer (WPT). ORNL's advanced transportation technology R&D activities provide a unique set of experienced researchers to assist in the creation of a transportation system level view. These activities range from fundamental technology development at the component level to subsystem controls and interactions to applicable system level analysis of impending market and industry responses and beyond.**

Keywords*—*wireless power transfer, inductive charging, opportunity charging, dynamic wireless charging, electric vehicles.

I. INTRODUCTION

Oak Ridge National Laboratory's (ORNL) recent research and development (R&D) activities in the area of wireless power Transfer (WPT) include both stationary and dynamic wireless power transfer (DWPT) projects [2], [3] and numerous analysis studies. Valuable data has been collected to support the creation of standards for this emerging technology and to support component development as well as exploring the applications of new subsystems for WPT technology to be used in transportation. Infrastructure requirements and roadway electrification are also being studied at ORNL to provide initial cost estimations and provide data to support electric vehicle (EV) adoption impact projections, as well as infrastructure preparedness [4]. As ORNL works to develop and characterize the unique WPT characteristics and component requirements for power transfer levels above 6.6kW, test process and standards become critical areas of focus. ORNL R&D experiments as well as macroscopic transportation systems infrastructure studies and projections will be briefly covered in this paper.

II. FOCUSED R&D EFFORTS WITH ORNL DEVELOPED HARDWARE FOR WPT SYSTEMS

Through both internal and Department of Energy (DOE) sponsored funding, ORNL has been involved in WPT and DWPT research and applications development since 2009. These research efforts have produced power electronic enhancements and transportation system perspectives that will prove valuable as transportation systems involve more grid-connected electrified powertrains.

Publication of unbiased data regarding the characteristics of WPT systems and components is difficult to find since much of that data is restricted and considered sensitive by many businesses. At ORNL, the data produced is published shortly after the systems are built and tested and intellectual property protection is established, unless the R&D is co-funded by an industry partner.

A. Standards development and safety condisiderations

Safety considerations related to standards development and prototype deployment continues to be a primary R&D focus area of WPT development at ORNL. Society of Automotive Engineers (SAE) established the J2954 Standards Development Committee on the "Wireless Charging of Electric and Plug-in

Electric Vehicles [5].” The main goal of the standards development is to define and build consensus on vehicle/EVSE safety, limits, and performance targets, interoperability, charger control system, communications, design validation testing, field emission levels, positioning on primary and secondary units, and the minimum efficiency.

The development of standards for wireless power technologies in transportation has been long effort requiring substantial resources from various members, including ORNL. As a part of this effort ORNL studied impact of foreign objects between the coils, the efficiency and power transfer impact of misalignment and variations in airgap and also the center operating frequency. Most of these test results have been presented to the SAE J2954 standards development committee and published in several journal and conference publications. The testing various coil designs and associated stray field emissions and attenuation devices is required to support standards development. The testing of early coils is shown previously in Fig. 1.

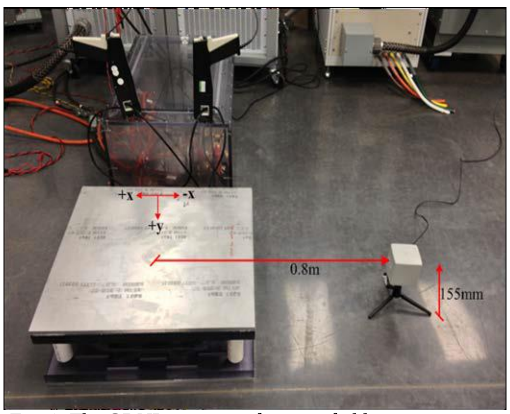


Fig. 1. The ORNL test setup for stray field measurements.

As a part of this effort, as another example, ORNL studied the efficiency impact of varying the airgap. The input and output power variations at different airgaps have been characterized over a band of switching frequency as shown in Fig. 2. In this test, the intention was to keep the vehicle side battery power constant at 5kW at different airgaps [6].

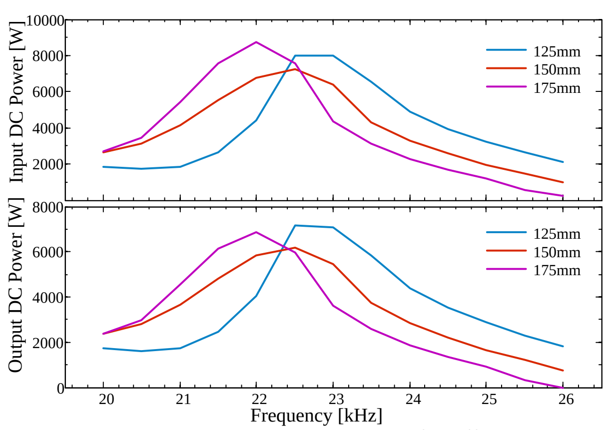
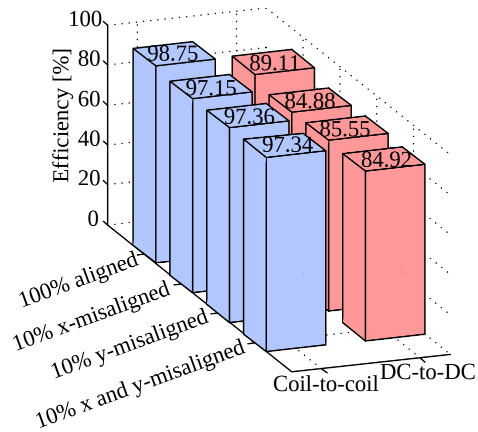


Fig. 2. Input and output power comparisons for different gaps.

As shown in Fig. 2, as the airgap increases from 125 to 150 and to the 175mm levels, the switching frequency should be reduced in order to operate at the resonant point which usually results in higher transfer efficiency. As the airgap increases, the coupling factor and the mutual inductance reduces. As a result, the system becomes more inductive. In order to balance the equivalent system inductive reactance with the capacitive reactance, switching frequency should be slightly reduced. Based on these results, ORNL team also developed an adaptive switching frequency operation algorithm to maximize the efficiency or the power transfer.

In a different set of tests, ORNL team investigated the impact of misalignment on the system efficiency. The secondary coil was misaligned 10% (of the side dimension) in x-axis, 10% in y-axis, and 10% in both axes [6]. The efficiency results for this case are shown in Fig. 3.



(d)

Fig. 3. Efficiency variation of misalignment tests.

B. Dynamic wireless controls and system impacts

As a part of the DWPT research ORNL built an isolated transportation system using a low speed neighborhood electric vehicle (NEV) as shown in Fig. 4.

Fig. 4. The ORNL NEV ready to receive WPT dynamically.

As part of the evaluation and development of this system, ORNL worked with industry partners - ElectroStandards Laboratory to utilize a lithium-ion capacitor bank that could be incorporated as the energy storage system (ESS) buffer on the grid side to smooth power pulsations leading to a more manageable power transfer. This smoother power profile at the grid side provides higher load factor and less stress to the power utility. On the vehicle side, a double-layer electrochemical carbon ultra-capacitor bank has been built and used for smoothing the vehicle side power pulsations. As shown in Fig. 5 the current spikes on the ESS on the vehicle side of the system are substantially reduced with the ultra-caps integrated into the system. The grid side power regulation technique employed by the ORNL system allows for direct connections to the vehicle ESS high voltage bus. The ability to bypass the typical onboard vehicle charger (OBC) increases system efficiency and reduces the cost on the vehicle component side if the vehicle does not have an OBC.

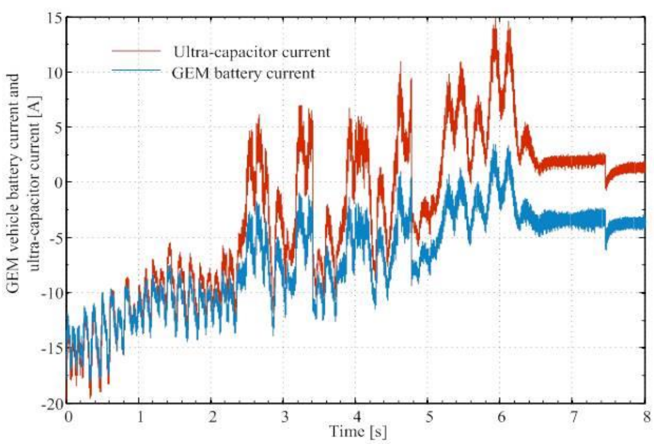


Fig. 5. DWPT test results confirm smoothing effect of ultra-capacitors integrated into vehicle side ESS on current spikes.

Important integration techniques as well as fundamental technology knowledge were gathered in this ORNL activity. At a subsystem/component level, specific experimental data has been generated which highlights the need for development of new component requirements and system considerations for a dynamic WPT system deployment. The complete findings of the initial study on DWPT at ORNL can be found in [2], [3].

Research activities at ORNL continue to discover characteristics of WPT systems in support of technology and standards development. In the spring of 2015, ORNL along with partners Evatran and Clemson University's – International Center for Automotive Research (ICAR) will be demonstrating ORNL design WPT systems into fully operational OEM vehicles in a variety of WPT applications.

C. Coupling coil learnings and efficient design challenges

Coil design is of essence in WPT systems since it determines the power transfer level, overall performance and efficiency, in addition to the shielding and magnetic emissions levels to be expected. The ORNL coil design relies on Litz cable coils over a soft ferrite structure and a non-magnetic case having very low profile. Fig. 4 illustrates an adjustable fixture fabricated for a primary and secondary coil pair wound with 7 turns of 6 AWG jacketed Litz cable for the transmit coil and 5 turns on the receive coil.

The coil design and parameter sensitivity have been covered in details in [7]. Basically, a magnetic vector potential due to an ideal primary coil at a field point that lies at the location of the secondary coil can be developed. For a coil pair having a radius *a*, assuming infinitesimal conductor radius, and a coil to coil spacing, *z*. Then the radius from the primary coil origin to the field point is $r = \sqrt{(a^2 + z^2)}$ and vector potential, A_ϕ, for a case of N_1 primary turns and I_1 Amps yield a primary excitation of N_1I_1 amp-turns. This primary excitation is depicted as I_{dl} in Fig. 6 where $a_1=a_2=a$.

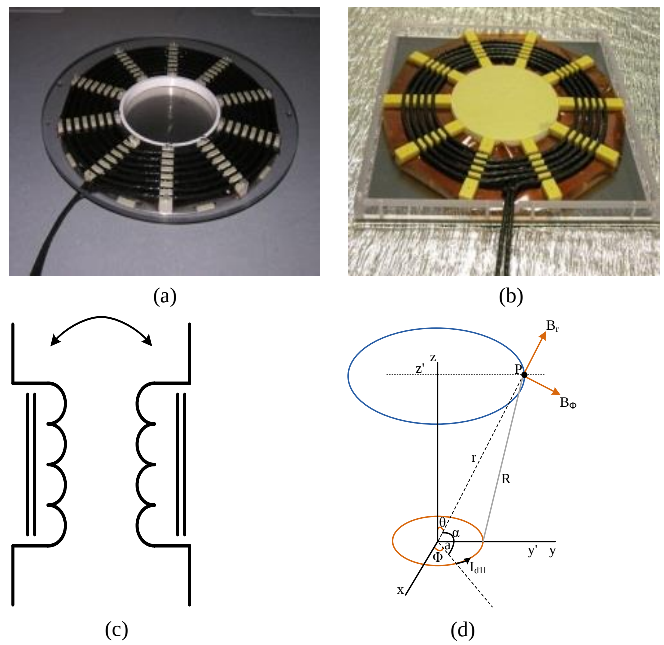


Fig. 6. Experimental fixture with distributed Litz winding: (a) 7 turns for transmit coil, (b) 5 turns for receive coil, (c) coupling coil symbol with loosely coupled transformer ferrite core back iron, and (d) vector field analysis diagram.

D. High Frequency (HF) Power Inverter Regulation

Load conditions; i.e., state-of-charge of the battery and coupling coefficient; i.e., vehicle coil to primary pad gap and any misalignment between transmit and receive coils determine the frequency response of the WPT system. The amount of power transferred to the secondary coil is governed by the switching frequency, duty cycle, and the input voltage of the inverter [8]. This relationship can be expressed as (1) where the HF power inverter rail voltage is U_{d0}, pulse duty ratio *d*, and angular frequency ω.

$$U_1(t) = \frac{4U_{d0}}{\pi}\sin\left(d\frac{\pi}{2}\right)\cos(\omega t) \qquad (1)$$

Although the primary coil voltage can be controlled by the active front end converter to vary the dc rail voltage U_{d0}, the ultimate objective is to dynamically change the switching frequency and the duty cycle in order to achieve the best operating conditions in terms of efficiency and power transfer. In the ORNL laboratory setting the HF power inverter voltage was adjusted using a power supply. In a commercialized version of this WPT technology a radio communication link would be needed. The vehicle side radio passes the measured data, such as battery voltage, battery current, and battery management system (BMS) messages needed for regulation to the grid-side unit (GSU). The grid-side radio receiver receives this information and passes the information onto the control module where it is combined with supporting primary side measurements for power regulation. The control system has an embedded digital signal processing (DSP) which determines the switching frequency and the appropriate duty cycle according to the control law being used. The switching signals for the inverter IGBTs are generated by the DSP control algorithm and applied to the HF power inverter gate drives. The control system can also regulate the inverter power based on the reference power commands that can be received through the V2I communications from a smart grid compliant utility. This is a fundamental requirement for grid-side regulation as the unique vehicle charging profiles can be accessed from the vehicle continuously. These fundamental research activities performed on ORNL developed WPT hardware provided a knowledge base for other analysis at ORNL to investigate transportation impacts at the macro-scale of WPT deployment.

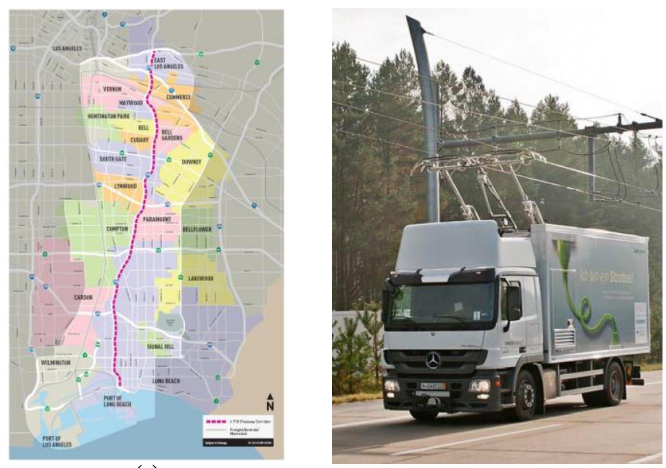
III. TRANSPORTATION ANALYSIS STUDIES

On the transportation system level, WPT application analysis studies at ORNL have provided an initial assessment into the infrastructure (both roadway and electrical grid) required to deploy this technology. Further, the impact on future city development or re-building of cities damaged by large natural disasters should be influenced by these initial results which provide insight into both cost and consumer acceptance of this technology.

Government incentives still drive EV purchases in the U.S. as is evident from the fact that areas with leading EV sales penetrations are also areas that have substantial incentives in addition to the federal incentives. This tendency to influence electric mobility through subsidies will need to continue through the near term gasoline price decreases in the United States, and highlights the long term strategy required for proper development, application and deployment of WPT technologies over limited near term use of the technology.

The light duty vehicle (LDV) market has intrinsic interest in WPT technologies as a way to increase adoption rates of EVs enabling new developments in electrified propulsion as well as key enablers benefitting various OEM corporate average fuel economy (CAFÉ) figures. As listed in the 2025 CAFÉ regulations, there are technology multipliers in place for electric vehicle sales between 2017 and 2021, which motivate OEMs to sell more EVs as this multiplier will credit their overall fleet fuel economy numbers in the 2025 calculations.

In addition to LDV transportation solutions, there are a few critical transportation industries that hold key opportunities in the development and maturing of WPT technologies. One particular industry relates to moving goods from shipping ports to distribution areas, this function is often referred to as drayage operations. Some of the very unique operating modes of drayage vehicle operations hold promise for PEVs and WPT power supply may significantly assist in the ability for those vehicles to provide continuous operation. Also, the intense focus on reducing the impact of these operations by major municipalities builds a strong business case to deploy WPT in this unique market. Figures 7(a) and (b) indicate a region of focus and scope of considered technologies to combat the pollution and energy consumption related to this significant regional activity [9]. The referenced report produced on behalf of the South Coast Air Quality Management District establishes cost of drayage operation in this area in terms of resources and energy consumption as well as the local impact to health and quality of living. Zero emission drayage operations are the long term goal of many large port cities, and WPT technologies applied to this pre-existing market would allow the technology to mature under a sustainable market, which would lead to WPT deployments in other related transportation areas, particularly in dense urban populations.



(a) (b)

Fig. 7. Map highlighting key market areas greatly impacted by air quality (a) and considered technologies that would enable cleaner and more efficient port drayage operations in the same region (b) [9].

Infrastructure improvements required to support a variety of electrically enabled drayage operations will have similar considerations, but the use of a technology that may also support electric LDV transportation would have a significant advantage in the long term goal of electrifying transportation, especially throughout densely populated areas.

A. Dynamic Wireless Power Transfer Considerations

The deployment of a DWPT system for personal or commercial transportation in the U.S. would be a massive undertaking that would require a focused long term transportation plan for the deployment area. The road infrastructure improvements and dedicated vehicle sales penetration requirements would require a level of coordination and unified motivation that has not existed in this country since the Eisenhower Interstate Highway System project conceived in the 1950s which is still expanding today.

In an effort to establish an understanding of the ancillary infrastructure and systems that would be required for deployment of a DWPT application to be effective, ORNL performed a study to estimate power requirements and project various subsystem costs. Atlanta, GA was selected for this test case as significant vehicle travel data has been gathered which could be re-analyzed for this study. Three additional DOE national laboratories partnered in this study, each bringing valuable data and/or analysis capabilities.

Data from Argonne National Laboratory's (ANL) chassis dynamometer testing facility and Idaho National Laboratory's (INL) field testing on advanced vehicles was used to help build assumptions for vehicle power requirements to maintain real world minimum highway speeds. Figure 8 shows compilation power versus speed data from various data sources and standardized test procedures.

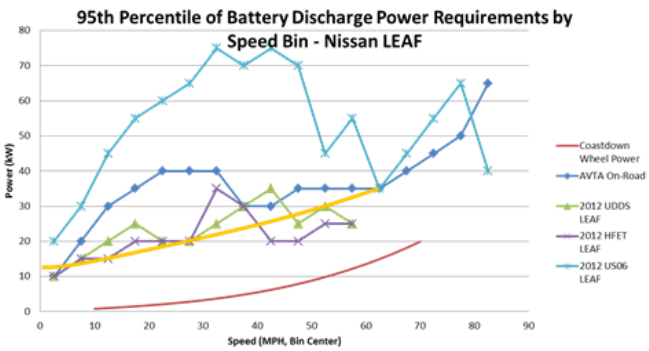
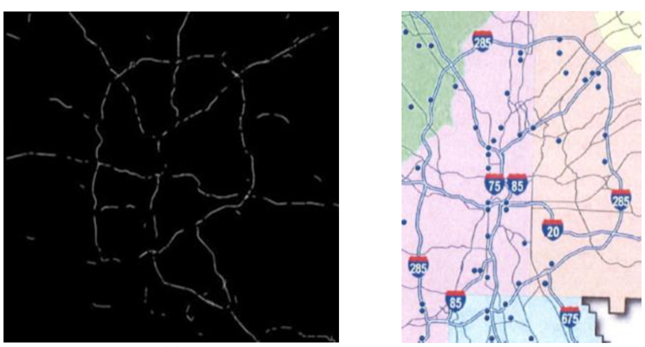


Fig. 8. Data from partnering national labs provided foundation for the power versus speed curve assumption requirements for DWPT.

The local municipality must develop the business case for substantial investment in infrastructure with a justification in many parameters regarding transportation benefits. Obtaining the most frequently traveled roadways based on vehicle miles traveled (VMT) and representative traffic volumes versus time of day are key characterizations which will assist in providing maximum system use per infrastructure investment. Figures 9 (a) and (b) show arterial road selections based on information from the National Renewables Energy Laboratory (NREL) which helped to identify routes that would optimize roadway electrification return on investment.



(a) (b)

Fig. 9. Indication of the 1% of roads where 17% of VMT take place (a), complex data collection points in Atlanta area (b).

The 25 kW power requirement for sustained vehicle travel includes all onboard vehicle systems and typical commuter grades, but is still conservative and builds in a measure of confidence that the system losses in transferring power dynamically (which are yet to be fully understood) will not invalidate the infrastructure requirement projections. It is also worthwhile to note here that the intent of this low power transfer rate DWPT system is to maintain the state of charge (SOC) level of the ESS during the drivers commute, and not to significantly raise the SOC. Based on volume pricing for ORNL representative hardware designs, estimates were made for a deployment of circular primary WPT pads to be embedded into a roadway, along with appropriate power electronic devices, which would provide power at traffic volume requirements at various times of the day. Figure 10 provides a rough system overview of the subsystems needed for a DWPT deployment.

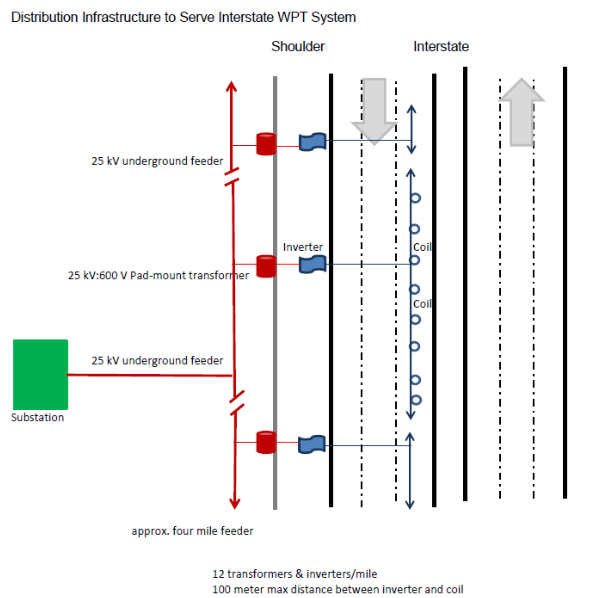


Fig. 10. Shows the scope of the DWPT systems involved in a deployment and highlights the areas where the system crosses traditional transportation boundaries.

To build a representative cost projection for DWPT system deployment, many areas outside of the actual WPT components were considered. Information from established interstate/highway construction firms was combined with data from the power distribution sector to ensure that bringing the point of connection to the grid supply was considered along with construction costs for a more comprehensive projection. As peak traffic volumes (and corresponding peak levels of power required for transportation) may align with current high power demand from the business sector, the assumption must be made that additional infrastructure and grid power capacity will be required to meet these new customer requirements.

Summary of system assumptions for DWPT feasibility study deployment scenario are given as:

- Though many coupling technologies are currently competing for DWPT optimization, relevant data from stationary circular coil R&D work at ORNL was readily available; therefore, component cost and power transfer efficiencies are based on this hardware.
- Greater vehicle speed requires higher power transfer levels and relatively higher power from the vehicle propulsion system. Various categories of roadways and defined speeds identify traffic congestion.
  - 40 mph was selected to meet speed minimums for operational status of typical commuter roadways.

- The assumed speed implies a power transfer level of 25kW from Fig. 8.

- An attempt to incorporate a level of system integrity was built into the DWPT deployment architecture in Fig. 10.

- Traffic volumes were estimated using data from the Georgia Department of Transportation (GDOT), State Traffic and Report System (STARS), and supporting traffic polling systems.

- For Atlanta area projections, the traffic mix contained 35% of vehicles that were capable of using the DWPT system, and all vehicles used the dedicated lane.

- Feeder lines, transformers and associated materials and labor cost associated with projections are based on current rates, though the DWPT system and associated capable vehicles are based roughly on a 2040 timeframe.

Brief summary of cost projections from the DWPT feasibility study are given below:

- DWPT system hardware and deployment cost including labor: $2.8 million per lane per mile.

- Infrastructure cost to bring power to DWPT system points of connection: $350,000 per lane per mile

- Other costs for consideration are the road modification traffic interruptions and the maintenance schedule and procedure changes – which have not yet received full consideration.

B. Impact to adoption of electric drive vehicles based on the presence of electrified roadways

There is no question that the presence of an electrified roadway (or a DWPT system) made available for either commercial or private transportation tractive power will change the perspective on electric drive vehicles. The accurate prediction of the impact on consumer buying decisions is a critical piece of information that could get a DWPT system project approved, or cancelled. In an effort to understand the impact of advanced technologies on consumer behavior, ORNL has developed the Market Acceptance of Advanced Automotive Technologies (MA^3T) Model for the DOE's Vehicle Technologies Office. The MA^3T model has over 40 vehicle architecture choices and allows for variations in infrastructure, behavior and even policy to predict market share response. This model was recently modified to include characteristic impact of WPT in dynamic deployments [10]. The work performed in the referenced study highlights the significant impact that roadway electrification would have on the consumer choices made with regard to electrified roadway capable vehicles. This model was exercised to show the impact of the deployment scenario represented by the Atlanta DWPT deployment study. Figure 11 shows the resulting impact on consumer PEV adoption with various levels of infrastructure and power transfer levels. It should be noted that for this scenario projection, there was no implied cost to the vehicle operator for using the DWPT other than the purchase of the vehicle capable of utilizing the electrified roadway.

This type of response to a new transportation technology deployment would represent a paradigm shift in energy consumed for transportation in urban areas. At the base level shown in Fig. 11, there is no DWPT system deployment throughout the timeline. In each of the other deployment scenarios the DWPT systems begin deployment in 2020 and complete the represented percentage of roadway electrification by 2027. The similar trend line for the 0.5% deployment at 100kW transfer and the 1.0% deployment at 30kW provides another interesting relationship for cost predictions and the importance of R&D in the high power transfer areas.

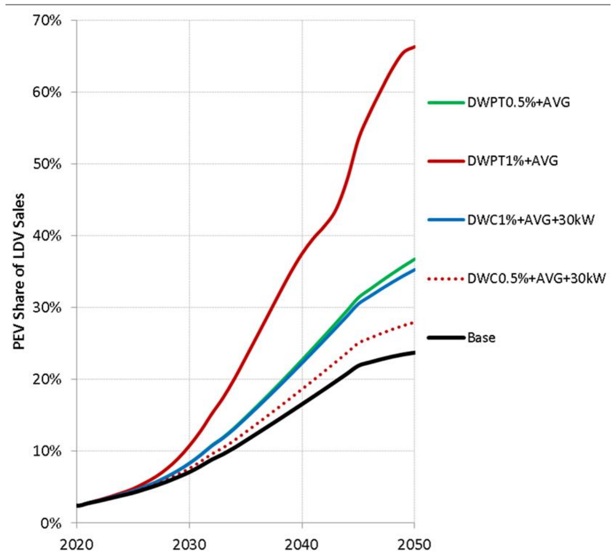


Fig. 11. Shows the regional impact for PEV sales assuming a DWPT deployment for 30kW and 100kW transfer levels.

C. Building the business case

The high cost of deployment of a DWPT is a significant hurdle for entry to all transportation entities. The fact that there are currently very few vehicles (most of them research prototypes or fixed route vehicles) capable of utilizing an electrified roadway indicates that DWPT and its potential deployment benefits may still be decades in the future. However, with the expected rise in shipment of goods through the next three decades, DWPT would seem have an opportunity, with proper planning, which would positively impact a future market rather than attempting to be reactionary. As discussed in [9] the rationale for a significant change from current goods movement technologies make long term investment sense. When health care costs are taken into account, the DWPT case grows stronger for the intervention of the federal government. The declining revenue streams for the Department of Transportation (DOT) in the U.S. point to a maintenance budget based on fuel taxes that simply will not be able to keep up with mounting repairs to the current highway system. The next round of CAFÉ 2025 efficient vehicles will not help improve the current maintenance budget shortfalls, a change in the model for funding roadway infrastructure repair and expansion will be required.

D. Corresponding transportation technology development

For DWPT systems to become a reality, additional transportation technologies will need to be commercially available, and their integration should be standardized by a regional transportation stakeholders. A few of the systems that will have a significant impact on DWPT deployment are related to autonomous driving technologies. Lane following technologies will be important to keep proper alignment between the vehicle and the grid-side power supply. Vehicle connectivity, both to other vehicles and with the grid as well as vehicle speed control will also be required for proper system effectiveness. These topics are not covered in this paper, but recognized here as their inclusion into a DWPT system will have a cost impact that was not accounted for in these studies.

IV. SUMMARY OF WPT IMPACT ON TRANSPORTATION

It is difficult to project the total impact that WPT, in its many applications, may have in the future of transportation. It is far easier to recognize that the proper application of the technology will play a significant role in expanding the use of electrified powertrains and a complimentary role in reducing the vehicle ESS capacity requirements, given the appropriate infrastructure planning. In the role of technology investigator, one is often saddled with the responsibility to project a final outcome based on insufficient data in an attempt to either promote or invalidate a technology or its application. In the case of WPT, the correct choice is to promote the continued development and the understanding of the WPT system, applications and barriers before rushing into deployment. While the global standards community continues to accumulate the data and information required to provide appropriate safety and interoperability guidelines and requirements, the research community is directed to investigate to system variations which may not offer the best overall transportation efficiency. First adopters of this technology may ultimately invest in a deployment that will be outdated as the standards develop.

As workplace charging continues to grow and is often provided at little to no cost to the vehicle owner, the impact of various levels of infrastructure improvements and the related increase in the adoption of electric vehicles will become move evident. WPT technology will have to reach a similar level of deployment as current conductive charging technology before significant impacts are made to personal EV purchases. As the power transfer levels rise, the applications for medium duty (i.e. port drayage operations) stationary in-route recharging, will drive down ESS size requirements for these vehicles and truly begin to highlight the level of impact that WPT can attain in converting fleets to EV operation.

This paper summarizes a portion of the research of WPT systems and their potential impact in the transportation community. It was intended to quantify project DWPT system cost barriers and introduce the reader to a wide variety of considerations regarding this technology. Further investigation of the referenced sources in strongly encouraged.

ACKNOWLEDGMENT

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