ADVANCES IN TRANSPORTATION STUDIES
An International Journal

Editor in Chief: Alessandro Calvi

Section A & B

Volume LIII April 2021

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ADVANCES IN TRANSPORTATION STUDIES

An International Journal

Section A

Advances in Transportation Studies: an international Journal Section A 53 (2021)

ISBN 979-12-80414-34-2 – ISSN 1824-5463 – DOI 10.53136/97912804143421 – pag. 5-22

A multi-criteria decision-making approach for a statewide deployment of dynamic wireless charging for electric vehicles

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subm. 1st May 2020 *approv. after rev. 2nd August 2020*

Abstract

Dynamic Wireless Charging (DWC) technology can provide an innovative charging solution that can overcome the barriers to electric vehicle (EV) adoption, namely range anxiety and charging time. To effectively implement this technology, dynamic charging lanes should be strategically located along the road network. This paper proposes a multi-criteria decision-making approach for the deployment of DWC on a road freight transportation network, since trucks are likely to be the first adopters of DWC technology. The proposed methodology involves calculating a suitability index for each candidate link based on four categories of location criteria: demand-related, cost-related, EV-related, and other criteria. Equal weights are assumed for each criterion in the base case, and a sensitivity analysis is conducted to assess the effect of changing the weights of the criteria. It was found that the most suitable locations for DWC lanes are on interstates that are characterized by high truck traffic. Furthermore, the most suitable locations are near airports and ports and away from EV charging stations. Meanwhile, the most suitable locations are not strongly affected by distance from intermodal facilities, military bases, planned construction/preservation projects, and floodplains. This is the first study that provides a comprehensive list of all the location criteria and corresponding values as reported in the literature. The proposed approach is transferable to other locations and can assist transportation agencies to identify the most suitable locations for DWC lanes.

Keywords – dynamic wireless charging, suitability analysis, GIS, multi-criteria decision-making, electric vehicles

1. Introduction

While improving fuel technology and promoting alternative, sustainable modes of transportation, such as electric vehicles (EVs), can be solutions to looming environmental concerns, EV adoption has been slow, particularly for larger light-duty and heavy-duty vehicles. This slow growth is mainly due to concerns regarding the range of EVs, lack of infrastructure, and long charging times at charging stations (e.g., [12, 31, 59]).

Dynamic Wireless Charging (DWC) offers an alternative charging method that has the potential to give an EV limitless range by wirelessly transferring power to the vehicle while it travels along the roadway. This charging solution can reduce the vehicle's battery size, which in turn can lower the vehicle's weight and cost. In addition, DWC can increase battery life by reducing the number of discharge cycles and eliminating the need for rapid charging, and can improve the productivity of vehicles by eliminating long charging times. DWC can be compatible with all types of vehicles and can enable the charging of heavy-duty vehicles which has not been feasible with stationary charging so far [6].

The dynamic charging technology considered herein refers to inductive wireless charging, where transmitter coils or charging pads are embedded within a road section and a receiver coil or pick-up unit is planted under the vehicle. Power is wirelessly transferred through the air gap between the transmitter and receiver for charging the vehicle's battery. The transmitter coils can have individual power supplies and can be energized only when an equipped EV passes on top of each coil [17]. Roadside equipment (grid connections, power inverters, transformers, cooling units and communication systems) is also used to transfer power from the utility to the transmitter coils within the pavement [6]. Pilot tests and case studies have demonstrated capabilities to charge a light-duty EV dynamically at up to 20-40 kW at highway speeds with around 80% charging efficiency [23] and a heavy-duty EV at around 180 kW, with 90% energy power transfer efficiency [6, 57, 69]. More information on the existing worldwide case studies can be found in Jang [37] and Konstantinou [44]. Figure 1 shows the main components of the DWC technology that includes the charging coils embedded in the road, the pick-up unit under the vehicle and the roadside equipment which is connected to the road through cables. This illustration is a concept level drawing of a "smart powered" roadway [63].

As with any refueling infrastructure, the provision of sufficient DWC infrastructure depends on a relatively high level of adoption of the technology. However, the adoption of DWC technology also depends on the availability of related infrastructure, leading to a "chicken and egg" problem. Hence, to effectively implement DWC technology and attract first adopters to the system, charging lanes need to be strategically deployed along the road network. As argued in Chen et al. [15], commercial fleets, such as buses and trucks, are likely to be early adopters of dynamic charging infrastructure due to the higher benefits offered to vehicles that travel on fixed routes. While past work has examined the deployment of this technology on bus transit routes (e.g., [42, 47]), the deployment of the DWC technology on a road freight transportation network has not been examined to date. This is a complex problem involving several stakeholders and different categories of criteria (economic, engineering, market etc.) [44].

To address this gap, this study proposes a multi-criteria approach for determining the optimal statewide deployment of DWC on road freight transportation networks. The proposed methodology involves the following steps: (1) perform a literature review to determine the appropriate assessment criteria for locating DWC lanes, (2) propose and test a GIS- and link-based screening methodology (spatial model) to identify suitable locations for DWC lanes based on multiple objectives, (3) conduct a sensitivity analysis to determine the relative importance of the criteria considered in identifying the most suitable locations for DWC lanes, and (4) evaluate the resulting DWC deployment strategy to ensure its feasibility. This is the first study that provides a comprehensive

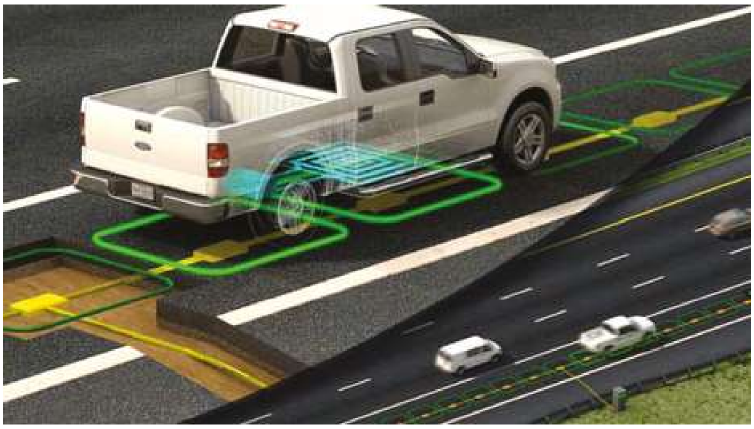

Fig. 1 - Main components of dynamic wireless charging (DWC) technology [70]

list of all the location criteria and corresponding values as reported in the literature. The proposed approach is transferable to other locations and can assist transportation agencies to identify the most suitable locations for DWC lanes.

2. Literature review

2.1. Related studies on identifying candidate locations for DWC

Because the DWC technology is relatively new, there is limited scientific research on the topic, and what exists is mainly focused on technical aspects. Only a few studies have examined optimal locations for DWC infrastructure. Those studies proposed mathematical programming approaches and optimization methods [e.g., 32, 38, 42, 43, 47] or examined the optimal number and locations of wireless charging facilities for EVs using macroscopic allocation [e.g., 24, 60, 72] and user equilibrium models [e.g., 15, 16, 46]. A more detailed analysis of those studies can be found in Jang [37]. The aforementioned studies focused on mathematical programming techniques to achieve the optimal deployment of DWC lanes for general vehicles or buses at either a micro- (e.g., [38]) or a macro-level (e.g., [60]). A number of assumptions were made in these studies, such as the type of network or route, the characteristics of EVs (state of charge of the battery, range, etc.), or the finite number of locations available for DWC deployment. In addition, the models used in these studies differ in terms of their objective functions and/or the types of routes, which were nevertheless mainly located in cities (even at the macro-level).

However, a state-level GIS approach for the problem of locating DWC lanes has not yet been implemented. GIS-based multi-criteria evaluation techniques are commonly used in the literature for different spatial decision problems, such as land use assessment (e.g., [50]); site selection for health care services (e.g., [51]), wind power plant sites (e.g., [5]), landfill sites (e.g., [1]), freight village sites (e.g., [55]); and traffic safety and vehicle routing (e.g., [29, 71]). Several studies related to the management and operation of truck lanes using GIS methods (e.g., [48, 58]) are also relevant to the concept of DWC deployment.

Although a variety of studies have applied a complete GIS-based approach to spatial decision problems, only a few studies have addressed the optimal deployment of alternative fuel charging stations. Erbaş et al. [21] evaluated the problem of locating EV charging stations in Ankara, Turkey, in terms of environmental/geographic, economic, and urbanity criteria using a GIS-based fuzzy analytical hierarchy process and the TOPSIS method to rank the alternative locations. Nicholas et al. [54] proposed a GIS-based model as a first step in identifying candidate locations for hydrogen stations in Sacramento County, California. Namdeo et al. [53] used a multidimensional spatial analysis considering socio-economic factors and commuting, vehicle, and household numbers to locate public charging stations in the Tyne and Wear regions in the United Kingdom. Other studies adopted similar approaches that used statistical data transferred into GIS to identify areas of high charging demand [20, 28, 74]. Andrenacci et al. [4] used a distance-based approach and a clustering approach to optimally allocate EV charging infrastructure.

2.2. Location criteria for DWC deployment

To provide a realistic DWC infrastructure deployment scenario, important factors need to be considered regarding the most suitable locations for the technology. A number of location criteria or objectives can be derived directly or indirectly from the literature and can be categorized into the five groups of factors summarized below.

a. Demand-related criteria: A primary factor for locating DWC lanes is the daily traffic of the candidate roads [68]. According to Limb et al. [45], the technology should be deployed in areas with high traffic. Since trucks are expected to be among the first adopters of the technology [15], it would be reasonable to examine roadway segments that are key trucking corridors. This criterion is generally important for emerging technologies and has been extensively used in different suitability analyses for truck-only lanes, freeway corridors for managed lane strategies, and other (e.g., [58]). Proximity to land designated for specific uses, such as airports, ports, intermodal facilities, and military bases, also plays a major role in determining the optimal locations for DWC lanes, according to the patterns found in DWC-related case studies. Such locations are the origins and/or destinations of a high percentage of heavy-/medium-duty vehicles and can simultaneously contribute to the recognition of the technology by the general public [64]. As far as the military bases are concerned, military bases are usually the places where cutting-edge technologies are tested. In particular, the US army is the federal government's largest user of oil and historical early adopter of innovative technologies and has invested in the electrification of vehicles. The US Department of Defense has plans for pilot programs testing fleets of electric trucks, buses and related infrastructure [61, 67]. Additionally, the option of DWC could reduce the weight of the military trucks, which is critical for their efficient mobility [30].

b. Cost-related criteria: It has been reported that the largest part of the cost of electrified roads comes from the construction and installation work itself, being around one-third of the total costs of the technology (e.g., [39]). This cost is related to the civil and the electrical infrastructure. In terms of the civil infrastructure-related cost, it may be important to link the installation of DWC technology with the implementation of any planned maintenance/resurfacing/reconstruction activities to reduce the cost of deployment and minimize the disruption to the road networks during construction [6]. According to experts' opinions from state transportation agencies, "heavier" work types, such as a total pavement replacement or new road construction, may be more appropriate than "lighter" work types, such as overlays, to be combined with DWC deployment.

Once implemented, DWC technology will draw a significant amount of electric power, and the goal of a DWC deployment strategy would be to distribute the technology in such a way that sufficient power provision is available and cost-effective (electrical infrastructure-related cost). As a result, access to the power network is an important factor in identifying the optimal locations of the technology. A feasibility study of DWC in Los Angeles, California found that the distance of DWC lanes from substations (which can be analogous to the cable cost) should be less than 1 mile to ensure sufficient energy distribution [64]. However, this distance may differ depending on the density of substations in each candidate area. The expected loading/capacity from the substations should also be estimated, since it will determine the power capability of the system and the suitability of each substation for connection to a DWC lane.

c. EV-related criteria: The locations of existing EV charging stations can influence decisions regarding the placement of DWC lanes. While a common approach to locating DWC lanes might be to consider existing charging stations as candidate locations because the infrastructure is in place and the demand patterns are known (e.g., [25]), the opposite may apply in the case of DWC lane deployment. In particular, it is reasonable to assume that locating DWC lanes away from existing charging stations can allow for longer trips and help avoid multiple "re-energizing" stops. This way, DWC can also cover any service gaps between existing EV charging stations. Market penetration of EVs is also an essential aspect to locating a DWC system. More specifically, it is recommended that DWC lanes be built in areas with the highest penetration of EVs [45, 68].

d. Supply-related criteria: The identification of suitable locations for DWC lanes also depends on the road characteristics and road environment of candidate locations. It is recommended that DWC lanes be positioned in a way that limits the physical constraints that the road environment imposes on the system. As a result, the availability of space on and within the road (for the wireless inductive system) and the terrain features are critical factors in DWC placement. Another aspect of road characteristics is related to the proposed length of the DWC components [68]. While it seems technically feasible to make longer charging pads or coils and thereby, design an ultimately cheaper system, longer coils can reduce the practical availability of power transferred to vehicles. In specific, with longer coils, multiple vehicles driving on the top of it share equally the total power provided. The coil is energized full time regardless of the presence of an EV. This set-up requires a simple power supply structure and control but may result in a continuous loss of energy [56, 68]. Shorter charging pads might instead be chosen because they have the advantage of enabling the transfer of power to slow moving or stopped vehicles [73]. In this case, the coils can deliver individual power supplies so that only one vehicle is travelling on the top of the coil at every moment of time. This set-up has the advantage of providing a compact structure which is beneficial to the implementation process, but the disadvantages of the complexity of the power supply architecture and control and the high maintenance cost are important [56, 68]. Thus, there is a great flexibility in the installation of a DWC system. In order to reduce the waste of energy and leakage flux, the segmented tracks consisting of a string of short coils is usually proposed [17]. In general, three main parameters of a DWC system that determine the optimal placing are the transferred power, the length of each coil, and the operating frequency. In either case, based on the initial goals and assumptions for the length of the DWC infrastructure, it should be ensured that the existing candidate road is long enough to implement the technology. The length of the proposed DWC lane is also associated with the set-up of the coils, accessibility to and capabilities of the local power network; there is no specific requirement in terms of the minimum route length for a DWC lane. Furthermore, at its early stages of deployment, the system is expected to be installed in the right lane since trucks mostly travel on this lane and the system's connection to the roadside equipment and thus the grid would be more effective. As the market penetration grows, the installation of the system can be expanded to more lanes.

e. Other criteria: Locations that commonly experience problems related to water accumulation or flooding should be avoided, since there may be a risk of damage to the DWC system [73]. Moreover, DWC technology is expected to reduce emission levels in the long run based on studies (e.g., [23, 45]). Therefore, areas with high levels of emissions can be identified and considered as candidate locations in order to alleviate their environmental problem in the long run. It is important to mention though that the identification of areas with high levels of emissions can be directly related with the traffic demand patterns and the environmental impacts may extend to the vicinity of the network. Based on the literature (e.g., [65, 73]), the DWC technology has been tested and showed durability against extreme weather conditions; hence, other weather factors may not cause problems to the system from a technical perspective.

2.3. Summary

By closely examining the existing literature regarding DWC (subsections 2.1 and 2.2), the deployment of the DWC technology on a road freight transportation network has not been examined to date. Past work has mainly examined the deployment of this technology on bus transit routes only (e.g., [42, 47]). However, trucks are also considered to be among the first adopters of this technology [15]. Additionally, previous studies applied mathematical programming techniques to achieve the optimal deployment of DWC lanes at either a micro- or a macro-level by considering only some implementation factors and by including assumptions in their models for a technology that has not been implemented yet and about which, there is limited practical knowledge. However, a state-level GIS approach for the problem of locating DWC lanes has not yet been implemented, although it is highly appropriate for high-level screening, can easily combine all the necessary location criteria, and can make the resulting information more accessible and interpretable for stakeholders-especially at the earliest stages of the technology. Furthermore, the GIS approach may indicate not only the most desirable locations for DWC lanes but also provide agencies with more information about the less desirable locations.

To address these gaps, this study proposes a multi-criteria decision-making GIS approach for determining the optimal statewide deployment of DWC on road freight transportation networks. This is the first study that provides a comprehensive list of all the location criteria and corresponding values as reported in the literature. This way, the paper can provide a beneficial tool for transportation planners and decision makers who would like to establish effective and appropriate measures for designing and deploying the DWC system. The approach followed can be easily accessible and interpreted by transportation planners or other stakeholders and help them decide the most suitable locations of DWC lanes in any setting by examining the generated maps and then visiting the locations as a second step to ensure their appropriateness.

3. Empirical setting and data

3.1. Empirical setting

The study area for this analysis is the state of Indiana in the USA. Indiana has been characterized as the crossroads for the nation's transportation systems [10], since it includes 13 pass-through interstates. According to the Indiana Department of Transportation [35], approximately 229 million total vehicle miles and 28 million commercial vehicle miles were traveled daily on the state's roads in 2017. The state consists of 97,553 public roadway miles (including 11,175 state highway miles), making Indiana the 19th highest ranking state in the USA in terms of roadway mileage [10]. The trucking industry especially is of vital importance for the state's revenue, since Indiana is among the leaders in truck tons originated and received through its interstates [18]. For these reasons, Indiana has invested billions of dollars in infrastructure, leading to expanded capacity, improved road quality, and increased connectivity throughout the state. Among these infrastructure improvement efforts is the examination of developments and opportunities for Indiana's corridors, such as the concepts of truck platooning and truck-only lanes that would accommodate the heavy truck traffic that passes through the state.

Indiana has also been proactive in terms of the adoption of EVs, based on the number of EVs and the availability of public charging stations and energy networks. Specifically, the total light-duty EV market in Indiana (hybrid, battery, plug-in EVs) reached 3.07% in 2019 [2]. These EVs are served by the state's 239 public charging stations. Hybrid, battery, and plug-in EVs constituted around 71%, 22%, and 7% of the light-duty EV sales in 2019, respectively [2]. Several transportation infrastructure projects in Indiana involve the cooperation of national utilities and state agencies to accelerate the adoption of EVs and explore "green" transportation technologies. These initiatives, combined with the state's high annual average daily truck traffic and the global need for lower emissions, necessitate the development of new systems to accommodate EVs and the demand of the trucking industry. Investigating the concept of DWC lanes for truck traffic in Indiana is a fitting response to this need.