Transportation Research Part C xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Review

Survey of the operation and system study on wireless charging electric vehicle systems

Young Jae Jang

Department of Industrial and Systems Engineering, KAIST (Korea Advanced Institute of Science and Technology), Republic of Korea

ARTICLE INFO

Keywords:
Wireless charging
Electric vehicles
Transportation systems
Transportation planning
Research survey

ABSTRACT

This survey investigates the state-of-the-art in operations and systems-related studies of wireless charging electric vehicles (EVs). The wireless charging EV is one of emerging transportation systems in which the EV's battery is charged via wireless power transfer (WPT) technology. The system makes use of charging infrastructure embedded under the surface of the road that transfers electric power to the vehicle while it is in transit. The survey focuses on studies related to both dynamic and quasi-dynamic types of wireless charging EV – charging while in motion and while temporarily stopped during a trip, respectively. The ability to charge EVs while in transit has raised numerous operations and systems issues that had not been observed in conventional EVs. This paper surveys the current research on such issues, including decisions on the allocation of charging infrastructure; cost and benefit analyses; billing and pricing; and other supporting operations and facilities. This survey consists of three parts. The first provides an orienting review of terminology specific to wireless charging EVs; it also reviews some past and ongoing developments and implementations of wireless charging EVs. The second part surveys the research on the operations and systems issues prompted by wireless charging EVs. The third part proposes future research directions. The goal of the survey is to provide researchers and practitioners with an overview of research trends and to provide a guide to promising future research directions.

1. Introduction

As electric vehicles (EVs) have become increasingly popular as a mainstream transportation solution, opportunities to recharge the vehicle away from home have become a critical issue. *Wireless charging EV* is a type of EV in which charging is done using wireless power transfer (WPT) technology, which does not require any physical contact in the process of transferring electric energy. WPT has been successfully applied for charging various handheld devices, such as medical devices, electronic toothbrushes, and smartphones. It has also been widely used for automated material handling systems in semiconductor fabrication and flat-panel display production lines (Covic and Boys, 2013). Wireless charging technology was first commercialized for automobiles to eliminate the conventional charging of 'plug-in' EVs – charged by connecting a wired cable from a charger to the vehicle. The first wireless charging technology to be deployed was *stationary*, the system having been designed to charge EVs in garages or public parking spaces, when the vehicle is not operating for an extended period. Because a physical connection is not required, there has been major interest in the possibility of charging EVs while they are in transit. Charging an EV while in motion is called *dynamic wireless charging*. A typical dynamic wireless charging EV is a pure, battery-only EV that takes its electrical charge in motion, remotely, from a wireless charger installed underneath the road surface. Roads capable of supplying electric power to wireless charging EVs are called *electrified roads* or *charging*

E-mail address: yjang@kaist.ac.kr.

https://doi.org/10.1016/j.trc.2018.04.006
Received 7 November 2017; Received in revised form 20 March 2018; Accepted 9 April 2018

lanes. There is also a third wireless charging category, *quasi-dynamic wireless charging*, in which the charging takes place when the EV decelerates to or accelerates from a resting position.

For both dynamic and quasi-dynamic wireless charging, charging can be done while the EV is in transit. These new charging mechanisms extend the operational range of EVs with both rapid boost charging during brief station stops and dynamic or "on the fly" charging opportunities.

Stationary wireless charging makes the charging process safer and more convenient (Cirimele et al., 2016). However, in terms of charging time, frequency, the operation of the vehicle, and charging station allocation, stationary charging is not significantly different from conventional plug-in conductive charging. In contrast, dynamic and quasi-dynamic wireless charging enable the EVs battery to be charged while in operation. This capability has raised new operations and infrastructural design issues that had never been raised for conventional plug-in EVs. These issues are the focus of this paper. Note that in this paper, references to "wireless charging EV" indicate dynamic and quasi-dynamic wireless charging EVs, if not specified. For the readers interested in the static charging technology, refer to the following work: (Abe et al., 2000; Birrell et al., 2015; Wu et al., 2012; Foley et al., 2010). It should also be stated that although the term wireless charging EV suggests a single vehicle unit, it should be understood as a system comprised of EVs and the charging infrastructure. Further terminological and categorical distinctions are discussed in subsequent sections.

The first commercial dynamic wireless charging electric vehicle, the On-Line Electric Vehicle ($OLEV^{TM}$), was deployed in 2009 by the Korea Advanced Institute of Science and Technology (KAIST), South Korea, and received ample media attention (Miller et al., 2015). A significant body of literature has been published specifically on the technical engineering challenges posed by wireless charging EVs. Some topics of the most highly cited papers include charging topology for wireless charging (Yilmaz and Krein, 2013); electric vehicle design and technologies (Li and Mi, 2015; Wu et al., 2011; Covic and Boys, 2013); hardware and systems design (Kim et al., 2013; Shin et al., 2014); road construction and pavement issues (Chen et al., 2015); power flow control (Miller et al., 2015); and efficiency optimization (Imura and Hori, 2011).

By contrast, research on *operations and systems* issues is still nascent. Definitions of operations and systems challenges remain somewhat broad. In this paper, however, they refer specifically to modeling, analysis, and methods that can be leveraged to support and enhance effective and efficient operations of wireless charging-based transportation systems. The term *system* is used explicitly because the research challenges are not limited to just vehicular components but also include: supporting facilities such as charging infrastructure; information handling in intelligent transportation systems (ITS); integration with smart grids; economic analyses for the pricing of charging; and other related managerial strategies and tactics.

Studies that deal with these issues tend to address the following questions:

- What are the long-term and short-term economic benefits of wireless charging EVs relative to other existing transportation systems?
- How much charging infrastructure should be allocated to maximize the economic benefit of this emerging transportation system?
- What are the critical design parameters for wireless charging EVs, given transportation requirements, and how do we determine them?
- How can policymakers design operational policies, rules, and regulations for new transportation systems?
- How can we design information systems to optimize the systems benefits?
- How would this new transportation system affect existing traffic and how should this be analyzed?
- What are the environmental benefits of wireless charging EV over conventional transportation systems in terms of stainability?

Operations and systems research for wireless charging EVs is a multidisciplinary research domain, the success of which depends on integrated efforts. There is little doubt that academic research on operations and systems perspectives is critical, particularly in the current stage of the technology's development. WPT technology, the key enabler of the wireless charging EV, has been improving rapidly. As mentioned previously, several commercialized WPT systems have already been made available. Given that the technology has reached this phase so rapidly, systematic investigations of its operations and systems implications for wireless charging EVs are needed. Several reasons can be given for why such an investigation is appropriately timed.

- First, there is high demand for surveys from government sectors, particularly policymakers and regulators, in addressing the operations and systems challenges posed by wireless charging EVs, especially for understanding the state-of-the-art. For example, in South Korea, one of the first countries where wireless charging EVs have been commercialized for public transportation, traffic and transportation administration agencies have funded research on analyzing the economic value of such systems. Similarly, the Transport Research Laboratory in the UK investigated the feasibility of dynamic WPT for EVs and published *Feasibility study: powering electric vehicles on England's major roads* (Highway England, 2015) on behalf of Highways England, the government agency in charge of operating, maintaining, and improving England's motorways and major roads. The European Union has also launched FABRIC (feasibility analysis and development of on-road charging solutions for future electric vehicles) a project to investigate the technological feasibility, economic viability, and socio-environmental sustainability of dynamic on-road charging of EVs (de Blas, 2017). In 2012, the US Department of Transportation (DOT) recognized the emergence of WPT charging of vehicles and the need to understand the implications of in-motion charging of vehicles on highways (Miller et al., 2015). This research considered what approaches might be adopted to best analyze the economic benefits of the technology and served as a guideline for electricity pricing. International scientific and technical communities, such as the SAE and IEEE, have also created working groups to draft recommendations for standardizing parts and components of the wireless charging system and to write