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Dynamic charging-while-driving systems for freight delivery services with electric vehicles: Traffic and energy modelling

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ABSTRACT

This paper presents a research on traffic modelling developed for assessing traffic and energy performance of electric systems installed along roads for dynamic charging-while-driving (CWD) of fully electric vehicles (FEVs).

The logic adopted by the developed traffic model is derived from a particular simulation scenario of electric charging: a freight distribution service operated using medium-sized vans. In this case, the CWD service is used to recover the state of charge of the FEV batteries to shortly start with further activities after arrival at the depot.

The CWD system is assumed to be implemented in a multilane ring road with several intermediate on-ramp entrances, where the slowest lane is reserved for the dynamic charging of authorized electric vehicles. A specific traffic model is developed and implemented based on a mesoscopic approach, where energy requirements and charging opportunities affect driving and traffic behaviours. Overtaking manoeuvres as well as new entries in the CWD lane of vehicles that need to charge are modelled according to a cooperative driving system, which manages adequate time gaps between consecutive vehicles. Finally, a speed control strategy is simulated at a defined node to create an empty time-space slot in the CWD lane, by delaying the arriving vehicles. This simulated control, implemented to allow maintenance operations for CWD that may require clearing a charging zone for a short time slot, could also be applied to facilitate on-ramp merging manoeuvres.

1. Introduction

Majority of fully electric vehicles (FEVs) currently satisfy the electric energy requirements for their motion with on-board batteries. Extensive literature on FEV limitations focuses on battery problems, particularly on limitations in size and power, battery weight, life and recharge time, and the lack of a wide network of electric charging points. These problems are even more relevant for freight distribution services, where the vehicle masses and daily distances are greater compared with those of passenger cars. In this case, a stationary recharge could require many charging stations not only located at depots, but also distributed in the service area, to provide more charging opportunities during the delivery routes. For this reason, the charging-while-driving (CWD) system could provide a technology to contain the battery sizes and recharging infrastructure costs without impacting on the vehicle autonomy. Wireless charging is based on the

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principle of inductive coupling. In this type of coupling, a circular magnetic field is generated as a result of the current through a wire coil. If another loop of coil, installed on the electric vehicle (EV), is placed near the first coil, current is induced in it. These coils are regulated to have identical resonant frequency in order to avoid energy leakage and reduce the risk of electrical shock (Bansal, 2015). Dynamic wireless charging (while driving) is implemented to provide energy to equipped vehicles while they are moving over charging pads, which are installed under the road surface. By using this dynamic charge, the idle time owing to possible stops for charging during the journey would decrease and the ratio of range distance over battery size would increase.

In this context, Boulanger et al. (2011) analysed the problems related to battery charging management that may cause range anxiety to drivers: uncertainty surrounding the monitoring of the state of charge (SOC), limited availability of charging infrastructure, and long time required to recharge. The use of intelligent transport systems (ITS), in particular vehicle-to-vehicle or vehicle-to-infrastructure communications, was evaluated to allow drivers to accurately and confidently locate charging stations where they could recharge the battery in the shortest period (Ezell, 2010). Johnson et al. (2013) evaluated how connected vehicle technologies can facilitate the rapid charging of FEVs at charging stations throughout the road network. The market acceptance of FEVs, travel requirements, and consumer choices, particularly for the first car in the household, were also analysed by Kirsch (2000). Moreover, extensive research on overcoming the drawbacks of battery inefficiency and its large space when used in FEVs is being conducted. One of the efforts is devoted to applying the wireless power transfer technology—Unplugged (2017), Fabric (2017), and eCo-FEV (2017) projects are recent examples—where the energy can be transferred to an electric device without any interconnecting media. The *Unplugged* project aims to investigate how the use of smart inductive charging of FEVs in urban environments improves the convenience and sustainability of car-based mobility. In *Fabric*, one of the objectives is the identification of technology requirements that may enable the implementation of wireless charging technology and the diffusion of wireless charging infrastructures. The *eCo-FEV* project aims at achieving an innovation in FEV introduction by proposing a general architecture for FEV integration into different infrastructure systems cooperating with each other, including CWD systems.

Chen et al. (2017) investigated the optimal deployment of charging stations and lanes along a long traffic corridor to serve the charging requirement of EVs as well as the competitiveness of charging lanes. When both charging stations and lanes are deployed along the corridor, EV drivers travelling from one end to the other are assumed to choose charging facilities that minimize their travel costs. A mathematical program is formulated to optimally deploy charging stations and lanes with regard to different operating regimes. The optimal location problem of wireless charging facilities is addressed as well to ensure that the captured traffic flow on these roads is maximized (Riemann et al., 2015). The multinomial logit model stochastic user equilibrium principle is employed to capture the routing choice behaviour of drivers. A case study (Fuller, 2016) evaluated the potential for a dynamic charging infrastructure to address range and recharge issues of FEVs by considering travel to regional destinations in California. Different combinations of wireless charging power (dynamic charging levels from 20 kW to 120 kW) and vehicle range (vehicle ranges between 100 miles and 300 miles) were evaluated using a Geographic Information System (GIS) tool and an optimization model. Dynamic charging, coupled with strategic static charging, proves to be more cost effective than gasoline over a 10-year period. At very low battery prices of $100 per kWh, the research showed that dynamic charging can be a more cost effective approach to extending the range than increasing the battery capacity.

To overcome the FEV range limitation problem, many research activities are focusing also on new electric charging technologies. Ahn and Kim (2011) proposed several techniques for the reduction of CWD electromagnetic fields from the power line and the vehicle itself by applying a metallic plate shield. Suh (2011) presented an application of the shaped magnetic field in resonance technology for future urban transportation. Finally, another important element that supports a battery charging modality with frequent and low energy transfer while driving is that the SOC must be managed carefully and the batteries should never be fully discharged to avoid excessive shortening of the battery life cycle.

The aim of this research is to support preliminary studies on one of the possible future technologies that could enhance FEV use in freight transport. One of the goals of the European white paper is to achieve essentially CO2-free city logistics in major urban centres by 2030, and CWD technology could be one of the possible ways to meet this target. Beginning with an EV supply equipment (EVSE) layout defined and analysed in previous studies (Deflorio et al., 2013, 2015), a model for the traffic flow simulation is implemented to quantify and describe the traffic performance (useful for both drivers and fleet operators), SOC variations for the fleet, and also the electric power that should be provided by an energy supplier for the proper management of the charging system.

With respect to the model described in the aforementioned studies, in the simulation model presented here, the relationships between the simulated traffic and the charging operations have been extended, enabling the model to simulate even critical situations in high traffic conditions. Specific improvements related to the functional requirements defined for the CWD system have been introduced to increase the reliability and efficiency of the simulation model. Finally, the model has been adapted to simulate a realistic road scenario with intermediate entrances, where traffic interruptions can also be generated for short time intervals. This paper provides extended analyses of the simulation scenarios previously presented by Deflorio and Castello (2015), including more details on the mathematical model approach (Section 3) on the simulation model and algorithms (Section 4).

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