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Determination of the level of service and customer crowding for electric charging stations through fuzzy models and simulation techniques

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HIGHLIGHTS

- A new method to assess service level for electric charging stations is proposed.
- A big-data traffic source allows the identification of a drivers' sample.
- A fuzzy model that mimics the drivers' behavior for station choice is presented.
- A simulation procedure to stack and queue in time the charging requests is shown.
- The instantaneous crowding and energy load for charging stations are obtained.

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ABSTRACT

Electric mobility is regarded as an important option for reducing environmental impacts of transport. State incentives and planning efforts for the mass deployment of a public charging infrastructure (CI) are in hand in many countries; in particular, public CIs based on the Level 3 DC fast charge are most likely to become commercially viable in the short to medium term, as the drivers are more likely to view the operation as traditional refuelling.

The aim of this work is to develop a procedure for the evaluation of the level of service of a configuration of electric fast charging stations (CI scenario), located in a selected urban area of the city of Rome. By varying the configuration of the stations in the area, and taking into account a charge demand inferred from real-world traffic data, we are able to make comparative analyses among different CI scenarios, and to determine the best one in terms of average and maximum waiting time to recharge (demand-side analysis). The steps considered included: creation of realistic CI scenarios based on lists of existing car parks and petrol stations; estimation of the potential battery electrical vehicle (BEV) users in the selected urban area using a Big Data analysis procedure; development of a fuzzy model to assign BEV users to stations with a criterion of convenience; use of a simulation procedure of all the charge events, in order to obtain a time profile of customer crowding at stations.

1. Introduction

Greenhouse gases are of primary concern for people and governments because of the rising awareness of their potential detrimental effects on the environment. In this arena, electric mobility is regarded as an important option to reduce environmental impacts and climate gas emissions from transport. Road vehicles are acknowledged to be significant sources of a range of pollutants, and have been estimated to contribute to about one-fifth of the EU's total carbon dioxide (CO_2) emissions, the main greenhouse gas [1]. Even if the emission-reduction benefits of the BEV depend on many variables, such as availability and location of charging points [2], electric mobility is recognized as being energy-efficient, does not cause local emissions, reduces noise, may benefit in the future from increased renewable energy production [3], and could also provide auxiliary storage capacity for the electrical grid through on-board batteries, further reinforcing the integration of renewable energy conversion technologies in the electrical grid.

Despite all these advantages, the penetration of the electric vehicle market is still very low. Many factors influence this narrow pervasiveness, such as electric vehicle cost and usability, which involves customer concerns about range [1–5] and a lack of widespread charging networks [6]. The key importance of an appropriate charging infrastructure for the successful penetration of alternative fuels was also recognized by the CARS 21 High Level Group on the Competitiveness

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and Sustainable Growth of the Automotive Industry in the European Union, in its recent report [7], in the European Commission communication on clean power for transport [8], and in the proposal for the directive on the deployment of alternative fuels' infrastructure [9], which provides a legal framework to promote the deployment of the recharge network for BEVs on a European basis. Many other national authorities and international organizations have been issuing reports or guidelines to provide essential information and resources required to implement electric vehicle CIs [10,11]; we use the terms CI and electric charging station interchangeably.

Many studies deal with the problem of planning CIs in different contexts and from different perspectives. In Funke et al. [12], the problem of public CIs is considered: in particular, the paper deals with the problem of selecting effective criteria for the set-up of CIs in different contexts, taking into account user needs and geographical constraints. In Gkatzoflias et al. [13] a methodology is proposed to optimally locate CIs within a spatially extended region, both in a city network and in a regional or national network. For city and regional roads, high-potential areas for the installation of CIs are identified, whereas for highway networks, the CIs should be located in already built petrol stations or rest areas, to minimize additional investment costs. In Viswanathan et al. [14], the approach to the optimization of the CI location problem is based on city-scale traffic simulation, whose results are used in spatio-temporal planning.

A hybrid approach that uses a genetic algorithm (GA) and an improved Particle Swarm Optimization (PSO) has been proposed by Awasthi et al. [15] to optimize the size and locations of CIs for the case of a city in India. In Ghamami et al. [16] a CIs planning approach has been studied that includes factors such as infrastructure investment, battery cost and user cost to support long-distance intercity travel along highways.

Since electric mobility could significantly contribute to emission reduction only if renewable energies are used [17,18], the integration among BEV demand and renewable supply is quite relevant. In [19], a charging control model based on a Multi-Agent System (MAS) is developed to control a decentralized scheduling algorithm for electric vehicle charging. The problem of the optimal sizing of CIs considering energy produced by solar photovoltaic is examined in Hung et al. [20]. The potential impact of BEVs charging demand on distribution network is another important issue: in Xydas et al. [21], the analysis of real charging events produced an input to a fuzzy model that evaluates the potential spatial impact of the BEV load on the distribution network in a mid-term future; in Arias and Bae [22], historical real-world traffic distribution data and weather conditions are used to predict the electric vehicle charging demand.

An approach to the optimal sizing and placing of charging stations, taking into account the distribution network and the transportation network, is presented in Xing et al. [23]. Dong et al. [24] studied the impact of CI deployment on the consumers' acceptance of the BEV market; they analysed GPS travel data from 445 conventional petrol vehicles, and made the hypothesis of a complete switch to BEVs. A genetic algorithm-based optimization was applied to the charger placement problem, subject to certain budget constraints and considering both Level 1 and Level 3 DC fast charges.

The purpose of the present work is to identify a sample of private vehicle drivers, extracted from a large database of floating car data and referred to a particular urban area, in order to determine how the charge requests are distributed over time in a local scenario of charging stations, supposing that all the drivers in the sample will convert to electric mobility. The scenario is composed of a fixed number of stations and plugs-in/charging points, whose number and distribution is given arbitrarily a priori, and the assignment of each charge request to an electric station is driven by a fuzzy model that mimics the decision-making process of a human driver, based on considerations of maximum convenience and attractiveness.

Once the charge events are assigned to the electric stations and stacked respecting the exact arrival times, we are able to determine the time trend of the level of service (LoS) for a fixed scenario, expressed in terms of driver crowding and charge waiting times. The LoS can be related to the inverse of the time a costumer has to wait at the CI before starting to charge the battery (waiting time) or to the percentage of costumers served with zero waiting time. In this way we can evaluate the performance of a scenario with respect to a pre-set level of customer acceptance through a classic simulation approach.

By repeating the simulation procedure over different scenarios, it is possible to determine the situation that best matches the user needs among the proposed ones (demand-side analysis).

Our analysis only took into account the Level 3 DC fast charge, because in our opinion in the future it will assume a prevalent importance in the context of the 'on the road' and extemporaneous charging operations: the relative speed of charging can encourage drivers to make deliberate stops for charging and enable them to view the operation as traditional refuelling.

Our work is based on the integration of Big Data analysis, fuzzy modelling and simulation techniques, in order to make possible a comparison among different scenarios of CI distribution, and to identify which one provides the best customer LoS. More in detail, the rational basis of our methodology consists on the step-by-step application of the following procedures: the utilization of specific techniques of reconstruction of road trajectories from successive GPS driver positions; the original procedure of building up a fuzzy model driven by two objective parameters (distance from the charge station, time to plug into the charger) to produce a subjective output (the driver choice of station); a simulation technique which stacks the times of the charge requests to evaluate their consequent time distribution and to produce the level of crowding in an assumed scenario of stations.

The novelty of our work lies in the integration of these diverse techniques and in the modeling of the BEV drivers' behaviour when in need to choose a station using a fuzzy model.

There are several works that use fuzzy logic controller, as for example, in systems that govern the implementation of vehicle to grid infrastructure [25], in the design of battery charging system for slow [26] and fast charge [27], and in residential distribution systems [28]. A fuzzy technique for order of preference by similarity to an ideal solution was applied as a multi-criteria decision analysis method to the problem of ranking a set of possible charge station locations to select the optimal site, when the different alternatives are judged by expert panels [29]. A fuzzy matter element analysis was applied to obtain the optimal fuzzy matter element sequence for a sequence of features of urban BEV charging stations, as a reference sequence [30]. The weighted gray correlation degree of each planning scheme is calculated to obtain the order of relevance degree of the BEV charging stations. To the best of our knowledge, no work used the fuzzy logic approach to simulate the hypothetical BEV drivers decisional process for the selection of the CI.

The paper is organized as follows: in Section 2 we illustrate the proposed methodology; Section 3 presents the simulation results for some realistic charge infrastructure scenarios. The case study considered the data collected in a week in a urban area of the city of Rome; in Section 4 we draw our conclusions.

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2. Proposed methodology

In this paper, we propose a methodology to investigate the problem of the correct sizing for the charging infrastructure in an urban area that is based on the following steps: selection of a representative sample of potential BEV users; creation of a local scenario of CI; construction of an appropriate fuzzy model to mimic users' behaviour when a charge is needed; and finally, utilization of a simulation procedure in order to