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Simulation-assisted exploration of charging infrastructure requirements for electric vehicles in urban environments[☆]

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ABSTRACT

High population densities in today's cities are leading to increasing congestion and air pollution. Sustainable cities of the future will require a large scale transition to electro-mobility. The development of electric vehicle charging infrastructure is necessary to enable this transition. Existing methods for determining charging infrastructure take an optimization approach that ignores existing traffic demands and infrastructure. Moreover, the dynamics of vehicle movement like stop-and-go traffic, congestion and the effect of traffic lights are not considered in determining energy consumption. In this paper, we propose a novel nanoscopic city-scale traffic simulation based method for determining charging infrastructure locations; subsequently, we demonstrate its usefulness in spatio-temporal planning through a case-study of Singapore. Through this method, existing traffic and road network data and the dynamics of individual vehicle movement can be taken into consideration in planning.

1. Introduction

Urbanisation is a trend which has been accelerating and is expected to continue doing so, ultimately leading to more densely populated cities across the world. Today, several mega-cities can be found in Asia, particularly in China. Due to high density, these cities are facing many problems like congestion and increasing air pollution. In most cities, traffic is a significant contributor to these problems. Future mobility will likely be characterized by a number of major transitions. One such transition will be the shift from fossil-fueled internal combustion engine vehicles to electric vehicles (EVs) which is already slowly taking place today and this trend is likely to accelerate. While EVs cannot be expected to solve the congestion problem, they can be a solution to the decreasing air quality in cities. EVs generate no local emissions. In addition, they also produce less noise since electric engines hardly generate any noise. Having an all-electric traffic system in densely populated cities is thus very attractive. However, a common problem in this vision coming to fruition for city planners is the installation of the required charging infrastructure. There seems to exist a type of chicken-and-egg problem here: vehicle users feel uncomfortable changing to EVs because sufficient charging infrastructure has not been developed; on the other hand, installing charging station infrastructure is costly and without a sizeable number of customers, the private sector may not see the business opportunity in even developing cars that would make use of this infrastructure.

However, despite the ostensible lack of business opportunities, the private sector has made significant progress in the development of EV technologies. For example, most major automobile companies do have vehicles with electric power-trains. Of these, the majority are hybrid solutions but more and more all-electric vehicles are entering the market (e.g., Tesla, BMW i-Series). However, as far as the required charging infrastructure is concerned, this generally has to be undertaken by the public sector. This is particularly true for large cities, such as Singapore, because most people live in high-rise buildings and do not have the luxury of their own garage for conveniently installing a charging station. Instead, large car parks would have to be equipped with a sufficient amount of charging stations.

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Therefore, for a city government to aim for a city-wide all-electric traffic system, various problems associated with the infrastructure for EVs need to be addressed first.

One issue concerning charging infrastructure is the issue of placement of charging stations. Ideally, charging stations would only have to be placed where there is sufficient demand. Depending on the assumed scenario (e.g., all vehicles in a city are electric, only certain fleets, etc.), the placement problem can become nontrivial [1]; in such cases, as traffic is not taken into consideration, existing methods [1–4] are likely to fall short. Traditionally, even when real world data is used, energy utilization is calculated based on the average speed on roads and this is used to predict ideal charging station placement. Studies have shown that taking into consideration the driving style of individual drivers or factors like congestion can have a significant effect on energy consumption [5,6]. Another problem that existing methods to not address is the issue of long term planning for development of charging infrastructure. Given the capital costs and time taken to build charging infrastructure, it is important to identify not only the locations where charging stations will have to be developed but also the order in which they will have to be built.

The major contribution of this paper is the description of a computational science approach, based on modelling and simulation, that allows us to evaluate both the spatial and temporal aspects of charging station placement based on available real world traffic data. We apply our method to the case of Singapore and discuss our findings with respect to the typical energy consumption of vehicles over the course of a typical day in Singapore; subsequently, we derive plans for charging station locations from this.

2. Related work

A primary issue regarding the placement of charging stations is the range of vehicles, i.e., the distance that the EV can travel in one full charge. In EVs, the vehicle range is one of the fundamental specifications that is considered. In transportation engineering, energy consumption of vehicles is estimated using driving cycles [7,8]. A driving cycle is a time-series of data points indicating the speed of a vehicle. For a given environment, based on a given driving cycle and a specific type of vehicle, it is possible to estimate the energy consumption. There are a number of standard driving cycles that are used world-wide by the automobile industry. Although driving cycles allow the estimation of energy consumption, they do not provide spatial information, i.e., they cannot be used to estimate the temporo-spatial energy consumption and demand for an entire city. In contrast to this, as per SAE J1634 Recommended Practice, EV range is generally calculated separately for cities and highways by fully charging the battery and driving the vehicle through the particular conditions [9]. While this method is ideal for the purpose of determining vehicle range, it is not practical for determining energy demand of a city.

Despite recent vehicles, like Tesla Model S, having much larger battery capacities, *range anxiety* is still observed in EV drivers. Range anxiety is the phenomenon where EV drivers are continually concerned about becoming stranded with a limited range vehicle [10]. While the exact causes of range anxiety are unknown, studies have shown that most drivers need a *range buffer* of around 20 miles and that their behaviour starts noticeably changing once the State of Charge (SoC) of the EV drops below 50% [10].

This suggests that larger availability of charging stations may address the range anxiety concerns of EV drivers. However, at least initially, charging stations will have to be placed strategically to address these concerns. There have been several ways in which the problem of optimal placement of charging stations in a city has been approached. Some have tried to optimize charging station placement in order maximize coverage [1,2]. Lam et al. [1] analysed the problem of optimal placement of charging stations to get maximum coverage at minimum cost. Their approach was to consider a graph of all possible locations of charging stations and to find the optimal sub-graph of this graph that has complete coverage of all areas in the network. After proving the NP-hardness, the authors proceeded to demonstrate how a greedy algorithm is sufficient to solve this problem while being faster than a mixed integer approach. A similar approach was taken by Ge et al. [2] where the area was partitioned into grids and the optimal layout of charging stations determined. Xiong et al. [11] take a game theory based approach to the optimization problem that considers the mutual impact between allocation of charging stations and charging activities of EV drivers.

There have also been approaches that made use of existing travel data to determine ideal locations for charging stations [3,4]. These approaches used mixed integer programs to select charging station spots with an objective function that seeks to minimize the total access costs (walking distances) from the charging station to the driver's ultimate destination zone in selected US cities like Chicago and Seattle. Others have approached the problem from the power grid perspective, i.e., place stations such that the load on the power network is minimized [12]. Other aspects of the problem like the construction and environment costs of the project have been studied as well [13].

These mathematical approaches, however, by their nature, cannot take into consideration the effect of traffic. Also, while it would be ideal to have complete coverage, from a practical standpoint, city planners will have to determine which areas of the city should have a charging infrastructure built first. These kinds of questions are most easily answered through a modelling and simulation based approach.

Modelling and simulation is an interesting alternative to the mostly mathematical methods discussed above. Traffic simulations allow us to analyse in more detail the impact of individual vehicles, their route choices and driving behaviour [14–17]. Based on the level of detail in which the traffic flow is modelled traffic simulations are generally classified as macroscopic, mesoscopic and microscopic simulations. Macroscopic simulations [18] are used when fast simulations are required; this is generally the case for traffic control policy evaluation on the basis of aggregate properties like speed, density and flow of the traffic. These simulations are heavily inspired by fluid dynamics. On the other hand, speed density relationships and queuing theory form the basis of mesoscopic approaches [19] which, unlike macroscopic models, have individual vehicles as the basic units of the system. Microscopic models have an even higher level of detail than mesoscopic models in that they model individual driver–vehicle-units (DVU) occupying streets [15,17]. The movement of these DVUs is a result of a combination of car-following models, lane-changing and gap acceptance behaviours which are discussed in more detail in Section 3.

Besides the aforementioned three approaches, traffic modelling and simulation has recently been extended into, what is termed, the nanoscopic level [20]. In nanoscopic simulations, the DVUs themselves are considered to be a combination of drivers and vehicles. This enables the modelling of the effect of driver behaviours and a more detailed model of the vehicle and, more importantly, the interaction of these two detailed models. For example, drivers who drive brashly will tend to pull more energy from their batteries and drain their batteries faster than calmer drivers. The effect of such repeated microscopic, heterogeneous behaviour on the macroscopic city level can be explored using nanoscopic simulation engines like SUMO [21] and SEMSim traffic, used in this paper. We use the term "nanoscopic simulation" in the sense used by [22,23] of having models with detailed vehicle and driver models and their interaction. Other models, like the Commuter model [24],