IJERST

International Journal of Engineering Research and Science & Technology

ISSN : 2319-5991
Vol. 2, No. 3
August 2013

www.ijerst.com

Email: editorijerst@gmail.com or editor@ijerst.com

Int. J. Engg. Res. & Sci. & Tech. 2013

International Journal of Engineering Research and Science & Technology

ISSN 2319-5991 www.ijerst.com
Vol. 2, No. 3, August 2013

Research Paper

LOCATION SELECTION OF CHARGING STATIONS FOR BATTERY ELECTRIC VEHICLES IN AN URBAN AREA

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Every day countless miles are driven on the millions of miles of roads. This general trend continues to climb and it has led to an increasing demand in the diminishing oil supply and an increase in greenhouse gas production. Battery electric vehicles are emerging as an alternative to internal combustion engine based vehicles. As these vehicles enter the consumer market, the supporting infrastructure, such as charging stations, must be provided to reduce the driving range anxiety due to limited battery power and a long charging time. The readiness of this fundamental infrastructure is critical to the future market growth of such vehicles. The main objective of this paper is to determine the number of charging stations needed and the ideal locations to put them in order to meet the charging demand in an urban area. In this study, we developed a facility location model aided by a GIS based geometric reasoning method to help resolve the problem. By means of integrated modeling and mathematical optimization, it is demonstrated that the proposed model is capable of selecting proper locations for electric charging stations based on constraints in a given socioeconomic environment.

Keywords: Battery electric vehicles, Charging stations, Location selection, Geometric reasoning method, Constraints

INTRODUCTION

For the past 100 years, oil has become the dominant power source for the transportation industry. Demand for oil is expected to increase, gradually making it an unaffordable commodity. This presents an opportunity to adopt a more economical, environmentally sound, and dependable source of energy. Among the available forms of alternative energies such as solar, wind, hydrogen fuel cells, and electricity, the increasing momentum of the latter to power transportation in the form of Battery Electric Vehicles (BEVs) has gained widespread and increasing support throughout the US and China.

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As many places prepare for BEVs, an emphasis is placed on developing supporting infrastructure such as charging stations. This is due to the limited distance these vehicles can travel as opposed to conventional gasoline vehicles. Currently, BEVs can only travel around 100 miles on a full charge, which causes range anxiety, whereas a gasoline vehicle can travel up to 350 to 400 miles on a full tank. Once consumers start using BEVs, city or state governments will need to deploy charging stations at convenient and efficient locations.

In addition to improving the market growth and reducing the range anxiety of BEVs, it is necessary to determine charging station locations so as to meet consumer demand while minimizing initial investment. In this study, we have developed a mathematical model to help identify ideal locations in commercial districts (business/offices) with the support of block group data, zoning data and building footprint data on a Geographic Information System (GIS) platform. The block group is used by the US Census Bureau to indicate a small geographic unit, which lies between the census tracts and census blocks and divides the entire city or county into smaller blocks. The zoning data in GIS depicts the permitted use of land and also separates one set of land use from another. The zoning classification data in GIS mainly includes: residential (houses), commercial/business office (restaurants, shopping malls, offices, etc.), as well as conservation and recreation (i.e., national parks, community recreation centers), etc. The building footprint data in GIS shows the building data in a city or county, including the boundary of a building, the type of building (such as restaurant, office or movie theater), and the size of the building.

BACKGROUND

There are three types of charging stations: Level I (120 V, 16 A), Level II (240 V, 30 A) and DC charging (480 V, 125 A). These charging stations are categorized based on their power requirement and the time needed to charge the entire battery of the vehicle. The greater the charging power requirement, the less time it takes to charge the battery.

Level I (120 V, 16 A) charging stations require 10 – 15 h to charge the entire battery. They are most suitable for residential charging because a person spends around 12 h a day in the house. Level II (240 V, 30 A) charging stations require 4 – 6 h to charge the entire battery in a vehicle and are most suitable in workplace parking lots as well as garages at home (US Bureau of Labor Statistics, 2010). Lastly, DC (480 V, 125 A) charging uses direct current and takes around 15 – 30 min to charge the entire battery in the vehicle. This type of charging station is ideal for places where people shop, eat, participate in leisure activities, etc.

Many facility location models have been developed, but few have focused primarily on public places. In 2002, Ribeiro and Antunes integrated GIS and optimization models for locating the public facilities with minimum distance travel cost. Chan *et al.* (2007) adopted the same minimum distance optimization technique to locate gas stations based on gasoline demand and price. Sadeghpour *et al.* (2004) proposed locations for deploying temporary facilities around construction sites based on the minimum distance optimization technique and also by using the geometric reasoning methodology. Using hierarchical clustering analysis, Ip *et al.* (2010) found demand clusters for electric vehicles and used the optimization techniques for locating charging stations with minimum operating costs. The technique includes assigning identical stations to each demand cluster, assigning stations to demand clusters by different demands and capacities, and assigning stations to demand clusters based on a given limited capital and constraints. Frade *et al*. (2011) used the maximum covering optimization technique for locating electric vehicle charging stations in order to satisfy both daytime and nighttime demand.

Despite many studies on facility location, additional research on location selection of electric vehicle charging stations is needed to accommodate the emerging BEV market growth. Our paper contributes to this effort by presenting a GIS-based user utility maximization model in which choice factors such as accessibility, time of charging, neighborhood safety, and method of charging, etc., are considered. After the optimizations, the locations with higher utility scores are recommended as ideal locations for deploying BEV charging stations.

METHODOLOGY

We propose a geometric reasoning method for finding the ideal charging station locations in commercial districts for Level II and DC charging. In this study, we focused on block groups (smallest geographic units by census data) where a charging station may be located (US Census Bureau, 2010). The geometric method is comprised of two modules: (1) Planning Module; (2) Facility Location Module. The Planning Module defines the variables and the Facility Location Module determines the collective user utility of the charging stations.

Planning Module

To find out the ideal locations of charging stations, we need to define the basis (variables) for the selections and the conditions on which the variables are evaluated. The variables that we considered include:

a. Accessibility – walking (for Level II charging) or driving (for DC charging) distance to a charging station; this variable affects the coverage of BEV demand.

b. Time Availability – hours the charging station is open, which rely on the capacity of the power grid and the load of electricity in the local network.

c. Power Grid Capacity – ability to charge multiple vehicles at the same time.

d. Neighborhood Safety – safety concerns against vandalism and street crime.

Each of the above variables is evaluated for every potential location in the decision process. For accessibility, a two-tier range specification method is used, where a distance of 1000’ (comfortable range) and 2000’ (acceptable range) are adopted for Level II charging stations. The selection of such range values is based on a person’s indifference to walking within short distances and maximum willingness to walk to a parking facility (Bossard, 2002). For DC charging, people generally will drive to charge the battery quickly and leave. Therefore, the corresponding range values are set as 1 mile and 2 miles, respectively, according to a consumer choice study on locations of gasoline stations (Chan, 2007). To differentiate the quality of service associated with accessibility, a weight factor of 1.0 is used for the comfortable range and 0.5 for the acceptable range in the testing process. Time availability affects the effective use of a charging station. A longer open time is expected to be more convenient for the users, whereas limited open hours during the day due to power grid (load) restrictions reduce the ability of the charging station to serve the community. Thus, we used a weight factor of 1.0 for charging stations that do not have time restrictions and 0.5 for those open only part-time. Similarly, a charging station with more Power Grid Capacity (ability of the charging facility) will allow more vehicles to charge simultaneously. Therefore, the weight factor given to the charging stations with multiple charging connectors vs. single connector is 1.0 and 0.5, respectively.

Furthermore, safety concern affects people's choice of charging facility, especially for Level II charging where the vehicle requires 4 to 6 h to charge. A location with a high crime rate can discourage people from coming, resulting in ineffective use of the facility. Accordingly, we used 1.0 and 0.5 to separate the locations with a low vs. high crime rate index. Table 1 lists the weight factors for the variables discussed above.

Besides the above variables, there is a budget constraint that limits the total number of charging stations to be installed in a given area. Although DC charging can serve a larger area it is more costly to install than Level II charging. Thus, a dynamic facility location process under constraint should be followed to determine the number and distribution of different types of charging stations, which collectively meet the charging demand for the users.

Facility Location Module

Using the variables defined above, this module employs a mathematical optimization process to determine the number and ideal locations of charging stations under a given budget. The objective is to maximize the collective user utility (U) from many prospective while satisfying all the requirements on location, power grid restriction, and financial budget. The outcome of the optimization is a set of location and type-specific charging stations in the study area. The mathematical model is formulated as follows:

$$\text{Max } U = \sum_{i}^{n} Zi + \sum_{j}^{m} Zj \qquad \text{...(1)}$$

$$\text{S.t.} \quad Z_k = \sum_{l=a}^{d} \sum_{p=1}^{2} A_{klp} B_{klp} \qquad \text{...(2)}$$

$$\sum_{i}^{n} C_i + \sum_{j}^{m} C_j \leq C \qquad \text{...(3)}$$

where,

Z_k is the user utility score for location k; k = i or j.

n, m are the number of Level II and DC charging stations to be determined; $n, m \geq 0$.

A_{klp} is the satisfaction score for variable *l* at location k.

B_{klp} is the weight factor for variable *l* at location k.

$l \in (a, b, c, d)$, variables as specified in the Planning Module and Table 1.

p is the level of valuation; *p* = 2 for variable *a*, *p* = 1 for variables *b, c*, and *d*.

C_i, C_j is the cost of Level II and DC charging station in the current market, respectively.

C is the total budget available.

In the above formulation, the user utility score (Z) for a given location is determined by a combination of conditions defining the variables from *a* to *d* in the Planning Module, and the weight

Table 1: Weight Factors for Variables

Variables	Conditions	
	Comfortable	**Acceptable**
Accessibility (a)	Comfortable range, 1.0	Acceptable range, 0.5
Time availability (b)	No time restriction, 1.0	Part time, 0.5
Number of connectors (c)	Multiple connectors, 1.0	Single connector, 0.5
Neighborhood safety (d)	Low crime rate area, 1.0	Higher crime rate area, 0.5

factors (B_{klp}) are defined in Table 1. A_{klp} are calculated from the following equations:

$$A_{kap} = \frac{\text{BEV demand covered by station k}}{\text{highest BEV demand covered at the valuation level p}} \quad \text{...(4)}$$

$$A_{kb} = \frac{\text{hours station k is open}}{\text{longest hours a station is open in the weighting group}} \quad \text{...(5)}$$

$$A_{kc} = 0.5\left(1 + \frac{\text{No. of charing connectors at station k}}{\text{max No. of charging connectors in the weighting group}}\right) \quad \text{...(6)}$$

$$A_{kd} = \frac{\text{highest block crime rate index in the wt. group-crime rate index at block k}}{\text{highest block crime rate index in the weighting group}} \quad \text{...(7)}$$

The crime rate on the block group is determined by comparing with the US average crime rate index level for different areas, ranging from 0 to 100% (Geographic Research Inc., 2011).

In Equation (4), A_{kap} refer to the satisfaction score for the accessibility variable at location k. To determine its value, for a Level II charging station a comfortable range circle of 1000 feet (p=1) is drawn from the center point of a block group in a GIS map. The area enclosed by the circle is measured to find its proportional size to the entire block area. The areas covered in each of the adjacent blocks are also measured in the same way. Based on each block's BEV demand obtained from the local transportation authority, those proportions are multiplied by the BEV demand at the respective block group to convert the area coverage into BEV demand coverage. Similarly, an acceptable range circle of 2000 feet (p=2) is drawn from the same center point to estimate the additional BEV demand covered. Then, the two demands are combined to yield the total BEV demand covered by the two circles.

To help determine the areas covered by a circle in different blocks, a series of GIS tools are incorporated in the modeling process, including the Select by Location Tool, Feature to Point Tool, Buffer Tool, and Intersection Tool (Chang, 2006). The Select by Location Tool is used to select at first the block groups that overlap with the commercial districts specified in the zoning data. In this tool, the target layer in a GIS map is the block group information and the source layer is the land use type of commercial/office spaces; the criterion in the selection is for the target layer feature to intersect with the source layer feature.

After selecting the block groups that are overlapping with commercial districts by using the Select by Location Tool, the Intersection Tool is then used with the building footprint data to identify the buildings that are overlapping with the commercial districts for potential charging station deployment based on the building type. The Feature to Point Tool is used to generate the center point of each selected block group using the centroid of the polygon. The Buffer Tool is used to generate a polygon enclosing point, line or a polygon within a specified distance (i.e., miles, feet). In our model, we used this tool to generate the two circular rings (p=1, 2) around the central point of each block group to define the different levels of BEV demand coverage (Figure 1), where the number inside each circle represents the BEV demand. Lastly, the Intersection Tool is used to determine the number of circles that intersect a block group and how the block group is divided into smaller segments by a given circle (Figure 2). All these steps and the optimization process are integrated in the computer model.

Figure 1: Accessibility Circles Intersecting Block Groups with BEV Demand

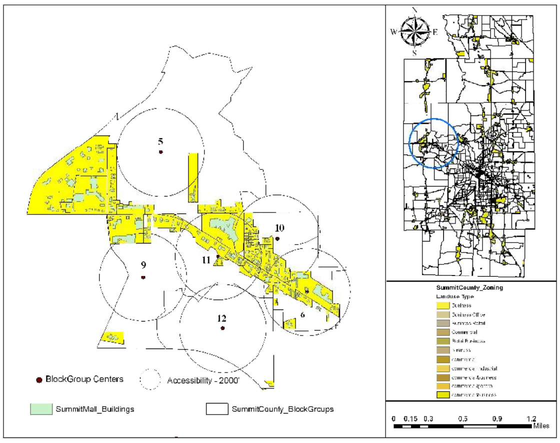
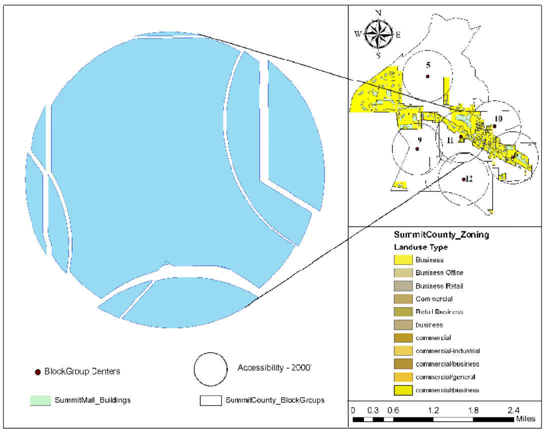


Figure 2: A Block Group is Divided into Smaller Segments by Accessibility Circles



Implementation

To show how the proposed method is implemented, we conducted a case study in the greater Akron area of Ohio. We selected Summit Country as the study base to identify locations and types of BEV charging stations.

Our analysis utilizes the ArcGIS 2010 software and spatial data for Summit County. The commercial districts are defined as office buildings, shopping mall areas, restaurants, and other work related locations.

In addition to the block group, zoning and building footprint data from the local transportation planning organization, the BEV rollout plan for the greater Akron area (PEV Rollout Consortium, 2011) is also used. This provides not only the cost of installing charging stations, but also the potential public locations for Level II and DC charging. The daytime hours of operation based on the existing power load and the capacity of the local grid at each potential location are also suggested and subsequently incorporated by the research team in the GIS map. Further, the BEV information is obtained from the local auto dealer association (PEV Rollout Consortium, 2011) based on market surveys to determine the size and distribution of BEV demand from consumers in each census block group. This data is mapped on the GIS platform to obtain the block group based BEV information.

The above procedure is followed by first employing the GIS tools to define the service areas by each potential charging station, and then by steps to calculate the satisfaction score on each variable that influences the selection. The mathematical optimization is carried out interactively using the GIS data in the Facility Location Module, and the system compares and evaluates different combinations of charging stations in terms of type and location constrained by the local conditions. The output of the optimization process is one of those combinations that return the highest user utility (U) in Equation (1).

Due to spacing limitation, we cannot show the massive amount of information generated in the modeling process; instead, we presented the results in Table 2 through Table 3 to show the given conditions and calculated utility score of a sample block group. Table 4 shows the selected area-wide charging stations. By analyzing the results, we have made the following observations: (1) the accessibility variable contributes most among all four variables to the utility score. The maximum accessibility score can reach 1.5 whereas the other variables can each contribute at most 1.0. This is, however, a plausible result because of the importance of this variable; (2) Shopping malls/business centers tend to be good locations for DC charging stations due to longer open hours and the support by the power grid.

Table 2: Local Conditions for Block Group 3

Local Conditions	Variables							
	Type of Charging Station		Cost ($)		Hours Open		Number of Connectors Availability	Crime Rate Index Levels (%)
	Level II	DC	Level II	DC	Part Time	Not Restricted		
Block Group 3	Yes		10,000			Yes	3	10

Source: BEV Roll Out Plan, Greater Akron Area, Ohio

Table 3: Calculation of Utility Score for Block Group 3

Variables	Conditions	Satisfaction Score (A_i)	Weights (B_i)	Utility Score $Z_i = \Sigma A_i * B_i$
Accessibility	1000’	0.95	1.0	
	2000’	0.7	0.5	
Convenience	24 h	1	1	
Neighborhood Safety	10%	0.9	1	
Charging Connectors	3	0.1	1	
Total				2.95

Table 4: Utility Scores of Recommended Charging Stations Based on Budget Constraint

Total Budget Amount ($)	Level II ($10k)	DC ($50k)	Utility Score
$250,000	Block Group 3		2.95
	Block Group 15		2.85
	Block Group 31		2.50
	Block Group 42		2.90
	Block Group 53		2.88
		Block Group 102	4.05
		Block Group 115	3.60
		Block Group 125	3.55
		Block Group 141	3.52

(3) Hours open and power grid capacity may significantly affect the utility score of a station.

CONCLUSION

This paper developed and tested a geometric reasoning method for selection of BEV charging stations. Using maximization of utility score as the selection criterion, we built the optimization model on the basis of accessibility to the charging facility and other utilities provided to users. Preliminary tests of the model in the Summit County area showed that it is effective in identifying the proper number and locations of Level II and DC charging stations in public places under a budget constraint. It should be noted that the weight factors used in the test are arbitrarily set for the purpose of testing the model. The model is built in such a way that model parameters can be easily changed, for example, to emphasize a certain operation regulation or market condition change. In addition, the selection criteria (basic variables) can also be added or removed from the model based on strong consumer preference. In the interactive process, this model can be frequently fine-tuned as it is applied with the availability of market data to improve its effectiveness.

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ISSN 2319-5991
03
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