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Optimal Location Determination of Electric Vehicle Charging Stations: A Case Study on Turkey's Most Preferred Highway

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Abstract

Today, electric vehicles are seen as one of the most suitable and environmentally friendly alternatives to internal combustion engine vehicles. An important issue related to the dissemination of electric vehicles is the location of the vehicle charging network and specifically the optimum location selection of the charging stations. Generally, most of the studies focus on popular destinations such as city centers, shopping areas, bus stations, and airports. Although these places are often used in normal life, they can usually provide an adequate solution for daily charging needs due to the number of alternative charging stations. However, finding adequate charging stations is not possible in intercity travels especially in highways. In this paper, we proposed a decision model to determine the location of electric car charging stations in highways. We create an optimization model to decide the optimum locations for the charging stations that can meet the customer demands on the Istanbul-Ankara highway. The proposed model determines optimum charging stations that enable passengers traveling with their electric vehicles to travel in Istanbul-Ankara highway in the shortest time.

1. Introduction

People prefer to use a wide variety of tools to make everyday life easier. From the first human to nowadays, people have used many vehicles such as feet, domestic horses, and bicycles to move from one location to another for different reasons such as finding food, meeting, and doing business. However, in the last two centuries, more technological means of transportation have been invented and more usage has gained popularity. One of these means of transportation is the traditional fossil fuel-dependent cars, which are used for many things.

The technology of internal combustion engine vehicles that have been on the streets since the 19th century, which we have been using almost every day of our lives, is developing day by day and the number of uses is constantly increasing with an exponential acceleration. However, with the effect of air pollution and global warming, the place of vehicles using fossil fuels in our lives is questioned [1], [2]. According to The World Bank, as of 2014, transportation has more than 20% proportion of CO2 emission in the world [3]. These adverse situations brought different opportunities, one of which is the increase in alternative energy vehicle usage trend [4]. As examples to this trend Figures 1 and 2 are shared below. This trend not only increased vehicle sales, but also supported the development of the necessary infrastructure and by-products. For more sustainable fossil energy usage in transportation industry, vehicles that energized with alternative-fuel, especially electric vehicles (EVs), are seen more logical and suitable way [5].

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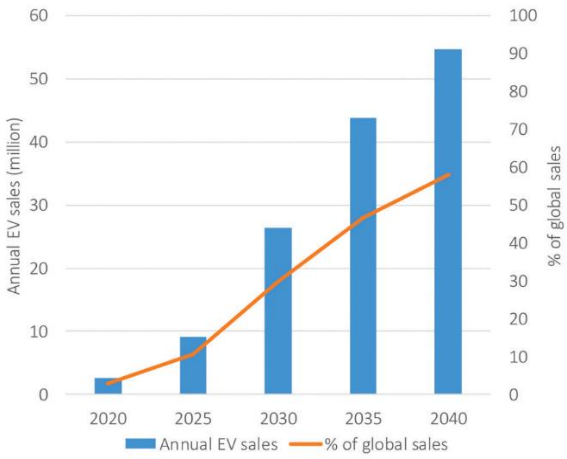

Figure 1. EV Sales' Forecast (Adopted From [17])

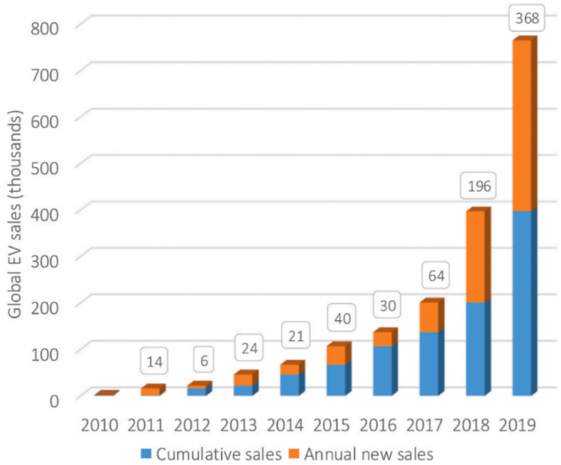

Figure 2. Global EV Sales (Adopted From [17])

The most important infrastructure requirement is undoubtedly charging stations in order to provide the maintenance and support of electric vehicles. However, it is important to understand that the infrastructure has just begun to be established, therefore the priorities and requirements are needed to be determined and an action plan must be created in the consumption of the related necessary resources. On account of the fact that, an important issue for extensive usage of EV is lack of charging stations which barrier to alternative fuel vehicles popularity [6, 7, 8]. To have an effective and useful plan for determining sites, several cases from different aspects are analyzed and various methods hold out.

The only way to increase EV (Electric Vehicle) drivers' service satisfaction is not to place new charging stations, but the regulate the schedules and places of the charging stations is a proper way to observe more satisfaction [9]. To be able to deal with that, waiting times are analyzed and revision of the locations of the charging stations is offered by Qin and Zhang, 2011 [9]. On the other hand, having broad service network is inevitable and sine qua non for the EV industry founders and customers. Therefore, in the literature new studies are seen frequently like implementation offerings in South Korea. One of the dramatic technological improvements still being observed in the South Korea, and that leads to EV network's proliferation. That give a raise to studies that focuses on to locating new EV charging stations like conducted case study by Chung and Kwon, 2015 [8]. They proposed a case study based on the actual traffic flow data of the Korean Expressway network. Three different methods are used to offer solution and comparison as multi-rotation optimization, forward myopic and backward myopic optimization. At the end, outcomes of the multi-rotation optimization model were observed as the most suitable method for large scale network problems.

Considering the traffic density and the capacity of the charging stations, another alternative study was conducted to reduce the time lost by electric vehicle drivers while reaching the charging stations [10]. The region is divided into nine different sub-regions using the Genetic Algorithm to find the best locations and successfully propose a solution to satisfy customers with EV drivers.

Another approach to deal with charging station siting problem is proposed by Erbaş et al., 2018 [11]. The approach in this study is Geographic Information System (GIS) based Multi Criteria Decision Analysis to choose places to implant charging stations. For criteria prioritization fuzzy analytical hierarchy process (AHP), for ranking between potential places technique for order preference by similarity to ideal solution (TOPSIS) are used. These approaches are applied for the inner-city of Ankara, and alternative site places are suggested as the result of the study.

The problem investigated in this paper is not just a theoretically created problem but also a globally discussed affair as mentioned. This widespread issue is taking place in actions of companies working on this related industries, non-governmental organizations, even statesmen of the countries. Recently, Scotland hosted the United Nations Climate Change Conference (COP26) between the 31st of October and the 12th of November 2021. The main focus of these conferences were the climate change and the global warming. Declaration about the zero emission cars and vans till 2035 is signed by 33 countries, 40 cities, 11 automotive manufacturers and 27 fleet owners [12].

One another motivation of this study is that the investment of TOGG (Turkey's Automobile Joint Venture Group) on the EV technology and manufacturing in Turkey. The manufacturing process is expected to start in 2022 [13]. Therefore, burst of demand will be observed for the charging station in the region. On the other hand, when the literature checked, there exist not much study on this topic that covers possible optimum locations for charging stations in Turkey especially on highways. This study is going to be offering optimum locations for the charging stations that can meet the customer demands on the given highway.

Our main motivation in this study is the use of electric vehicles in Turkey is increasing exponentially. Especially, considering the TOGG investment and Turkey signed the agreement to come out of diesel and gasoline vehicles in Turkey by 2035, the infrastructure of charging stations is of great importance. So, based on the future progress on electric cars in Turkey, a suitable and environmentally friendly model is needed to build proper infrastructure for the electric car vehicle.

Charging is not a big problem in urban transportation. In daily life, people can usually provide an adequate solution for daily charging needs due to the number of alternative charging stations in urban areas and the range that they travel is limited. However, when traveling between cities, considering the distance to be traveled, it is not possible for electric vehicles to complete their travel with a single charge. Electric vehicle battery technology currently has a range of approximately 200 km. For this reason, vehicles may need to be charged twice in a trip of approximately 500 km, such as İstanbul – Ankara. Our contribution in this study is to create an optimization model to decide the optimum locations for the charging stations that can meet the customer demands. The proposed model determines optimum charging stations that enable passengers traveling with their electric vehicles to travel in İstanbul – Ankara highway in the shortest time.

The remainder of this article is structured as follows: In section 2, used methodology is presented and in the 3rd section basic notations and definitions in the article is given. Formulation of the mathematical model is also covered in the section 3. In section 4, the outputs of the applied methodology and the explanation of them are given. In section 5, conclusion of the article is done and suggestions for future studies is expressed.

2. Methodology

Our main focus in this study is meeting the customer demand, which is reaching the intercity EV charging services. For that purpose, a place should be selected for analyzing. Therefore, Ankara-İstanbul highway was chosen and the reason behind is that network was one of the well-fitting routes because, it is one of the most used interurban highways in Turkey. Therefore, passenger data can be collected easily on this highway.

The chosen route, Ankara – İstanbul Highway, includes 23 different entrances to the highway for drivers. Candidate places are selected, the idea was very similar to the case study that has been done by Chung and Kwon, 2015 [8]. Stopovers and the mostly known gas stations are candidate places of the study. The reason that the inner-city places were not chosen is the ranges of the EVs are generally enough to recharge in any place in a city like houses, offices and so on.

Coordinates of the stopovers and gas stations were extracted from "Google Maps". Purpose of using these places is that they have suitable infrastructure to implant charging stations and customers willing to wait and rest there. At the end, combined number of the stopovers and gas stations were determined. These places are shown in Figure 3 below. In the Figure, pins are representing toll booths and the gas stations. On the other hand, data is received from Directorate of Highways of Ankara – İstanbul, and with 23 entrance the highway divided into the 24 parts. The traffic density information of those parts is obtained from the highway traffic volume map of 2016.

Other must have information for the study is ranges of the existing EVs. Without consideration of the ranges, mathematical model and its outcomes will only be irrelevant and useless. Thus, the ranges are gathered and shown in the Table 1, also while solving the problem, inevitably, ranges were one of the limitations.

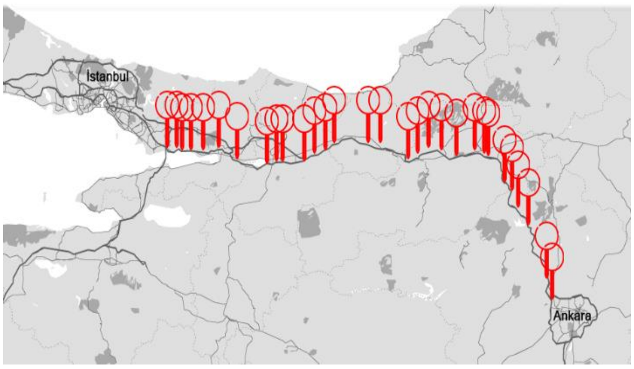

Figure 3. Toll Booths, Stopovers and Gas Stations

Brands have different strategies for the battery of an EV. Some seek for the long-distance coverage, however, several of them aim to offer lighter vehicle. Even the same brand can have different market plan for its models. Therefore, different brands and models should have been considered. In the Table below, its seen that the ranges alter within each brand and models. Ranges have a non-negligible effect on the results, they change the constraints status which also directly affects the satisfaction level of the customers.

Table 1. Ranges of the Various EVs

Brand	Model (year of 2017)	Range (Kilometers)
BMW	i3	183.4
Chevrolet	Bold EV	238
Fiat	500e	135.2
Ford	Focus Electric	185
Hyundai	Ioniq Electric	199.5
Kia	Soul EV	149.7
Mercedes	B250e	120
Mitsubishi	i-MiEV	160
Nissan	Leaf	172.2
Tesla	Model S	337.9
Tesla	Model X	383.1
Volkswagen	e-Golf	201
BYD	E6	300

The least range is considered as the standard range of an EV, the reason behind, if the least range EV user can be satisfied with the given service others also can be satisfied. With this way, one of the goals of the study will be reached as desired and the customer satisfaction will be improved. On the other hand, for each model year of 2017 is selected as seen in Table 1. The reason behind is to have more affordable EVs for people and it's not logical to consider only brand-new cars.

3. Mathematical Modelling

In this section, we are going to give mathematical model that solves the current problem. Following content is basically explanation of the data, made assumptions before running the mathematical model to handle reasonable model, notations and their definition, and lastly the formulation part.

3.1. Data

The considered highway, which is İstanbul – Ankara Highway, is divided into 24 parts according to entrances as mentioned. Parts that contain stopovers and gas stations are used as candidate areas for implementation. In the mathematical modelling part, it is desired to match minimum range coverage for each model of EVs. The idea behind is to achieve maximum satisfaction of customers.

3.2. Assumptions of the Mathematical Model

A model is a representation of the real world to have better understanding on the actual situations [14]. Therefore, to solve a real-world problem, it is needed to be made some key assumptions. In this study, to make the problem able to be solved several assumptions have been made. Those assumptions are as followings:

- The drivers do not have extraordinary driving style,
- Driving ranges of the EVs are constant and invariable,
- The least range of the included EV models is applicable for every customer,
- Batteries of the EVs linearly run out,
- Neither electric-truck nor electric-motorcycle is existing in the system,
- Electricity in the charging system is not finite and not interruptible,
- No queue forms in front of the charging stations,
- The first and the last stopovers are not adequate to implant any chargers.

3.3. Modelling Sets/Indices

i *parts of the İstanbul – Ankara Highway* $i = \{1, 2, 3, \ldots, 24\}$,

j *parts of the İstanbul – Ankara Highway* $j = i = \{1, 2, 3, \ldots, 24\}$;

Data/Parameters

R_{ij} *Distance between parts of the İstanbul – Ankara Highway i and j,*

D_i *Expected demand of the İstanbul – Ankara Highway part i,*

M_i *Number of station (stopover or gas station) on the İstanbul – Ankara Highway part i;*

Decision Variables

$X_i =$ *Capacity of the station on the İstanbul – Ankara Highway part i,*

$Y_i =$ *{1, if the station (stopover or gas station) is selected to locate charger(s) on to the İstanbul – Ankara Highway part i; 0, otherwise},*

$N_i =$ *Not satisfied demand of the customers on the İstanbul – Ankara Highway part i;*

3.4. Formulation Objective Function Constraints

$$z^{*} = min\ \Sigma_i N_i \qquad (1)$$

$$99 \times Y_i \geq X_i \qquad \forall i, \qquad (2)$$

$$X_i \geq Y_i \qquad \forall i, \qquad (3)$$

$$M_i \geq Y_i \qquad \forall i, \qquad (4)$$

$$N_i = D_i - (99 \times X_i) \qquad \forall i, \qquad (5)$$

$$Y_3 \geq 1, \qquad (6)$$

$$Y_3 \leq \mathrm{Y}_4 + \mathrm{Y}_5 + \mathrm{Y}_6 + \mathrm{Y}_7 + \mathrm{Y}_8, \qquad (7)$$

$$X_i \in \mathrm{N} \qquad \forall i, \qquad (8)$$

$$Y_i \in \{0,1\} \qquad \forall i, \qquad (9)$$

Decision variable X_i is defined as capacity of the station *i*, which means that outcome of the model as the number of chargers in the given station. On the other hand, Y_i is binary variable that determines whether the station will have charger or not. Another decision variable N_i is defined to check the demand amount that is expected to observe but not met. With this way, model and the outcomes of it are being more persuasive for the counter party of this study.

Objective function (1) is minimizing the not satisfied demand of the customers on the İstanbul – Ankara Highway. Ordinarily, the most desired outcome is to have maximum customer satisfaction, which is the first necessity of the study. Constraint (2) defined for that the chargers are not located, if there exist no station on the highway part *i*. The reason of this constraint is any charger cannot be established onto not selected station intuitively. Also, this constraint prevents model to locate more than 99 chargers on any station. Constraint (3) prevents the model to not select any place as charging station which does not have any charger capacity. Constraint (3) also ensures decision variable Y_i to take value of 1, if the chargers are located at there. On the other hand, it archives and lists the chosen locations. Constraint (4) ensures that place can be selected to implement charging station(s) if there exist at least a stopover in that part of highway. Constraint (5) works as database to keep not satisfied customer numbers in a part. In the model 1st and the 2nd parts are entrance and the exit of the İstanbul – Ankara Highway. Therefore, in the Constraint (6) it set to be locate a charging station to the 3rd station which is the first stop for the highway users. This guarantees to start with a fully charged battery to the trip. Constraint (7) ensures that on the stations from 4 to 8 there should be at least one more station which is needed for the range of the model that offers least km range capacity. Constraint (8) and (9) are to define variable X as natural number and variable Y as a binary variable.

4. Results

Given model in section 2 is examined by using GAMS software as optimization tool. Formulation and constraints are coded properly to the platform and after running the model obtained results are as follows:

- Seven places are chosen as the charging station implementation area,
- Totally, 7 stations and 15 chargers are enough to meet the demand of the customers,
- One charger for 3rd station, one charger for 8th station, one charger for 9th station, two chargers for 14th station, four chargers four 17th station, four chargers for 19th station and two chargers in 22nd station is enough to satisfy the demands on those locations is seen as an outcome of the model,
- These outcomes are shared, as a bunch, in the Table 2 below.

Table 2. Outcomes of the Mathematical Model (Selected Sites and Number of Chargers on Them)

Station:	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*
Y_i	0	1	0	0	0	0	1	1	0	0	0	0	1	0	0	1	0	1	0	0	1	0
X_i	0	1	0	0	0	0	1	1	0	0	0	0	2	0	0	4	0	4	0	0	2	0

In the Table 2, 1st and the 24th sites are not existed. The reason behind, they are the entrance and the exit parts of the İstanbul – Ankara Highway. In the row 2, Y_i values are seen as 0 and 1. What it means that, if the value is one then it's offered to select this site as a station. On the other hand, X_i values are the offered number of chargers at the station to put on the site. For example, station 19 is selected as a station (Y_i = 1), and because of the expected EV density in that place, it's offered to establish 4 chargers (X_i = 4) to meet the demand of the customers.

Number of sites and total number of chargers in these sites were the main expected outcomes of the study. Therefore, results written above are illustrated with the Figure 4 for better understanding. Charger icons in the Figure 4 are representing the sites that can optimally meet the customer demands. To travel between İstanbul and Ankara by an EV on the highway, these offered places are meet the requirements while minimizing the unsatisfied number of customers.

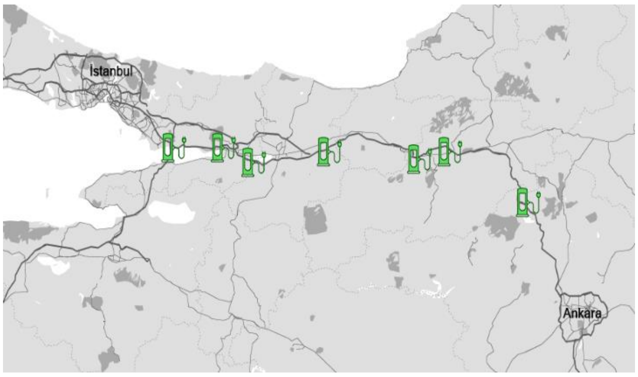

Figure 1. Charger Locations - Outcome of the Model

5. Conclusion and the Future Works

With the technological improvements, new tools are used to make life easier. Undoubtedly, the tools that are in our daily life have the most impact on establishing infrastructure network. Nowadays, EVs are one of the trending technologies to be used over the world and which is getting widely used in Turkey. The study done is born because of this necessity. Also, according to statement given by Fatih Dönmez, who is Minister of Energy and Natural Resources Ministry, shows that charging stations are going to be one of the critical infrastructure necessities. It is indicated by Minister; projections show that there is going to be more than 1 million EVs in Turkey until the 2030 [15]. However, Turkey is in the beginning of this EV era. In the first half of the 2021, only 894 EVs and 186 PHEVs (Plug-in Hybrid Electric Vehicle) are sold officially [16]. Recently, some encouragements are proposed by the government, but still the number of EVs in Turkey is very low to be appreciated by the Turkish community. Regulations and situation of infrastructure need to be supportive and satisfactory to stimulate EV usage.

One of the most used highways in Turkey, İstanbul – Ankara Highway, is selected and accordingly to traffic density potential charging station locations are determined by a mathematical modelling approach. As a result of the work done, its seen that the demand of the EV drivers can be satisfied by implementing 7 stations and 15 chargers through İstanbul – Ankara Highway.

This study had some assumptions as EVs are evenly distributed to the traditional combustion engine cars and they are using one of the most crowded highways in Turkey. For the coming studies its planned to forecast number of EVs in Turkey extending to years and their distribution. With the outcomes of forecasting approach, highways are going to be selected to work on and data will be up to date. Also, different scenarios like various charge status of EVs are going to be considered and analysis will be based on them. Lastly, the offered solution will not be stationary, it is going to be giving recommendations for several sequential years. This will help to cover real world more closely.

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Authors' Contribution

In this study, Author 1 contributed to literature review, evaluation of the data, building the mathematical model, analyzing the result of the mathematical model, article writing, while Author 2 contributed to formation of ideas, collection of the data, building the mathematical model, article writing and editing.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics.

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