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T3 ________________	Problem Chosen	F3 ________________
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2018
MCM/ICM
Summary Sheet

The Decision Model of Electric Vehicle Charging Stations

Summary

Recently, the trend of replacing gasoline and diesel cars with electric vehicles is becoming more intense. To deal with the increasing demand for electric vehicles, the determination of charging stations is especially important.

In order to work out a network of charging stations, we need to decide the number, distribution and timeline of Tesla destination charging and supercharging stations.

We begin with the quantitative analysis of present demand from the perspective of number of traditional and electric vehicles. Then we make use of the **Queuing Model** to figure out the relationship between the expected waiting time and arrival rate so as to predict the amount of charging stations with reasonable adjustment.

Taking the difference between rural and urban areas, we establish **Charging Station Distribution Model**. At first we build a basic model, referring to the **Coverage Theory**. Then we apply **Monte Carlo Method** to solve the model. Then we obtain the number and locations of charging stations. Also, much emphasis should be laid in urban areas and chargers should be built ahead of more purchase for electric cars.

When it comes to the comprehensive application of model, we take Ireland for instance. We start from the distance between blocks and population density. We illustrate the coverage area with figures at the timeline of 10%, 30%, 50% and 100% of the switch to all-electric cars.

As for the evolution of the model, we take the dominant factor in the differences between countries into account and establish a **Population/Income/Geographic-led Model**. In the Population-Led Model, we refer to the **Population Block Model**. After that, then we build **classification system** based on these three models to help countries decide which model is appropriate for the complete switch to electric vehicles. What's more, we apply this system to countries like Australia, etc.

With regard to further discussion of the model, we consider the possible effects the development of technology has on our model.

Last but not least, we take possible sudden increase of traffic flow into consideration to make assessments. It turns out that the model is sensitive to changes to traffic flow at the early stage but dull at the late stage. Also, we list the overall strengths and weaknesses of our model.

Contents

1 Introduction

1.1 Background

Since the invention of modern automobiles and wide use of fossil fuels, more and more environmental and economic problems come up. In this case, the trend of replacing conventionally fuelled cars with electric vehicles is becoming more intense. One of the representative corporations of electric vehicles is Tesla.

The Tesla established a charging network for endurance of driving. There are two types of charging stations: supercharging station and destination charging station. Supercharger works for long-road trips, only costing a few dozens of minutes to the full while destination charger is designed for several hours. The charging station is usually located near the restaurant, the shopping center, the WiFi hot spot and so on. Each charging station is built with a number of charging piles.

Aware of the public enthusiasm to electric vehicles and the problems conventionally fuelled cars bring about, the government of the US and other countries tend to develop policies to ban gasoline and diesel cars in the near future.

However, there are several real-life factors affecting the timeline and spatial structure of transition when people deploy the establishment of charging stations. To support the full adoption of all-electric vehicles, Tesla should consider final network of charging stations along with the growth and evolution of the network of charging stations over time.

1.2 Restatement of the Problem

We are required to provide a layout for the charging network to realize the complete transition from gasoline and diesel cars to electrical vehicles. In terms of the research object, we will focus only on personal passenger vehicles and later expand to the commercial vehicles briefly in this paper. In this process, we have to deal with the number and distribution of charging stations, the number of charging piles, and the future development of this network as the transition expands. The variables that may influence the transition and demand for charging stations are traffic flow, population density, economic factor, geographical features and so on. As to model building, we should consider an abstract urban model first and then do more expansions and improvements based on this primary model.

Here are our tasks:

- Build a model to predict whether Tesla on track in the United States meet the demand after full conversion according to current trends.
- Establish principles and models for selection of proper sites of charging stations and arrangements for the timeline. Decide the number and distribution of stations at each stage.
- Expand the model in a larger scale to find out whether it is suitable for different countries. Ameliorate the original model and make classification system.
- Make analysis and assessment of our models to find the strength and weakness of them and make future predictions.

1.3 Literature Review

When it comes to site selection of charging stations, the key factors previous research results focused on include: electric vehicle charging demand, technological development, charging mode, charging station operation mode, charging station service radius, city power grid planning, city road network planning, policy support and so on.

The location of electric vehicle charging station is a typical problem of research on site selection of network facilities. Main theories in this field are P-median problem, coverage problem, P-center problem and flow interception problem.

P-median problem mainly studies the location of P facilities. The goal is to make the weighted distance minimum with the weight of demand. **Hakimi**(1964) first proposed this concept, and pointed out "Hakimi characteristics", which assumed that the one optimal solution at least when all the candidate points are on the nodes, is equal to the best solution without assumptions. As a result, P- median can be simplified to discrete location problem.

The coverage problem includes the set cover problem (**Toregas**, 1971) and the maximum coverage problem (textbfChurch, 1974). The main concern is how to set up P sites to meet the maximum demand when the radius and the number of stations are known.

As for the flow interception problem (textbfHodgson, 1990), it suggested that consumer demand for service sites is composed of point demand and path demand instead of that based on network nodes in the traditional sites selection problem.

2 General Assumptions

To simplify our problems, we make the following basic assumptions:

- **All the vehicles are on an ideal plat, on which any two point can reach each other.** We don't consider extreme road or other environmental conditions. The plat is similar to connectivity diagram.
- **Power consumption in a mile and driving distance have a positive linear relationship.** The longer the driving distance is, the more the electricity vehicles consume in a mile.
- **The population concentration area is considered as a demand point while demand points of similar geographical locations as a demand block.** The demand points constitute a demand block, and each demand block is connected by a path. The destination charging stations lie in the demand point and the supercharging stations are located on the paths. Since the owner won't spend a night charging while traveling, we can assume that there is no need for destination charger on the paths.
- **Treat the aggregation area of Tesla electric vehicles as points.**

3 Notions and Symbol Description

We will define the following variables here as they are widely used throughout our paper. Additional variables may be defined later in particular sections.

Notations

Symbols	Definition
i	demand point
j	candidate point of destination charging station
d	demand
X_j	binary variable, whether to build station at j
Y_{ij}	binary variable, whether j meets the demand of i
R	service radius of charging station
α_{ij}	the distance of i and j less than R_j
N_D	number of destination charging stations
N_S	number of supercharging stations
k	candidate point of supercharging station
P_i	binary variable, whether the demand of i is satisfied
E	safe distance, half of reachable miles after being charged to the full
q	demand path
t_i	stages during construction of network, denoted as $t_1, t_2, ..., t_m$
A_j	the distance between station j and the closest charging station to station j
Z	the number of Tesla the charging station can serve
N_{t_m}	the number of charging piles at t_m

4 Analysis of Macro Demand for Tesla

4.1 Current Demand

To find out the current situation of complete switch to Tesla and future construction of charging stations, we intend to focus on the macro demand for Tesla. Since destination charging stations are suitable for short-distance driving and supercharging stations are for long-road trip, we decide to discuss these two types separately.

For long-road driving, we refer to the American Intercontinental Highway System. The total length of highway is 77,017 kilometers [1] while the current number of Tesla supercharging stations is 452 [2] . So, we should consider the distribution of supercharging stations and intercontinental highways.

These two figures illustrate that the locations of supercharging stations coincide with the outline of intercontinental highways. That is, the average service area of a supercharging station is 170km. We might as well assume that the average charging time for each Tesla driver is 30 minutes. According to the description in the task, 30min of charging allows Tesla electric vehicles to travel less than 170 miles, which is 273km. Therefore, the average time a driver spends at a supercharging station is 18.6 minute, which is obviously acceptable.

As to short-distance driving, considering the total population of 323,000 in the United States,

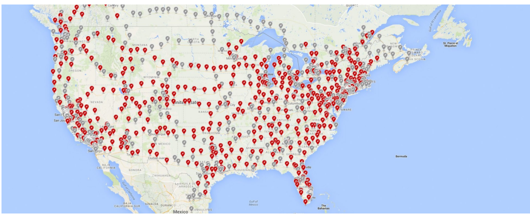


Figure 1: Supercharging stations in the U.S.

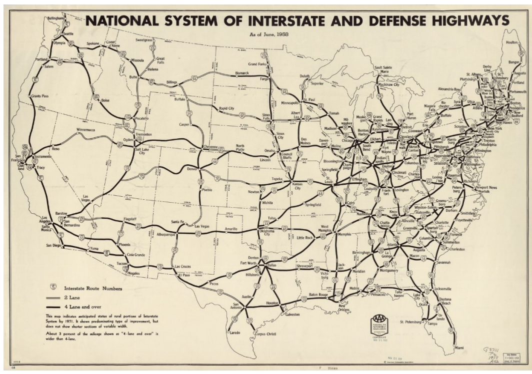


Figure 2: National system of interstate and defense highways

the average number of cars per thousand people possess is 812. Through calculation we can obtain the total number of cars in the United States, which is 262,272,000. Then we take the market share of Tesla in 2017(0.29%) into consideration to get the sum of Tesla electrical vehicles, which is 760,000. On the basis of media estimates, the number of destination charging piles is about 150,000. That is to say, on average every charging pile needs to serve about 5 cars. Considering destination charging station allows overnight charging, the working time of charging piles is almost 24 hours. Thus, every car can get charged for 4.5 hours. As a result, we can conclude that the number of Tesla matches that of charging stations at present.

4.2 Amount Prediction

In the United States, the market shares of electric vehicles in 2016 was only 0.91%. If all the vehicles turn into electric vehicles, the number of electric vehicles will be increased by 110 times. In this case, we need to consider queuing and efficiency problems in the station.

Electric cars: Market share

Table 10 • Electric cars (battery electric and plug-in hybrid), market share by country, 2005-16

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Canada								0.15%	0.20%	0.29%	0.39%	0.59%
China						0.01%	0.04%	0.06%	0.09%	0.38%	0.99%	1.37%
France						0.01%	0.13%	0.34%	0.55%	0.72%	1.22%	1.46%
Germany						0.00%	0.05%	0.11%	0.23%	0.42%	0.72%	0.73%
India				0.02%	0.01%	0.01%	0.02%	0.05%	0.01%	0.02%	0.04%	0.02%
Japan					0.03%	0.06%	0.35%	0.53%	0.63%	0.68%	0.58%	0.59%
Korea							0.02%	0.04%	0.05%	0.09%	0.21%	0.34%
Netherlands					0.01%	0.02%	0.16%	1.02%	5.38%	3.89%	9.74%	6.39%
Norway			0.01%	0.22%	0.15%	0.31%	1.33%	3.27%	6.00%	13.71%	23.63%	28.76%
Sweden						0.00%	0.05%	0.31%	0.53%	1.44%	2.37%	3.41%
United Kingdom	0.01%	0.01%	0.02%	0.01%	0.01%	0.01%	0.06%	0.13%	0.17%	0.60%	1.11%	1.41%
United States	0.01%			0.01%		0.01%	0.17%	0.44%	0.75%	0.74%	0.67%	0.91%
Others	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.04%	0.06%	0.10%	0.21%	0.38%	0.52%
Total	0.00%	0.00%	0.00%	0.01%	0.01%	0.01%	0.10%	0.23%	0.38%	0.54%	0.85%	1.10%

Note: The total market share is calculated on the basis of the total market size of all the countries covered in this report.

Figure 3: Electric cars: Market share [5]

4.2.1 Destination charging

Obviously, people do not want to wait for a few hours queuing up at places with destination chargers, such as hotels, shopping malls, office buildings. Time needed for supercharging is only half an hour, and the distribution of customer arrival is more random.

For example, the distribution of customers who charge at the destination charging station near the office is apparently regular on weekdays, not an ideal random model. So, we won't apply queuing model when analyzing the number of destination charging stations but through analogizing parking lot and parking space.

According to the previous macro estimate, if a charging pile can serve only five cars, 110 times of the present charging piles are needed. It's negligible compared with the scale of destination charging stations right now. The data on Tesla official website reveals that the United States currently has 3804 destination charging stations. The number will become 418,440 after expansion.

4.2.2 Supercharging

To maintain the average usage time of each supercharging station at 30 minutes, we need to consider the queuing problem. We establish a **queuing model**, assuming that

- The process of customers arriving at the supercharging station is in accordance with the Poisson Distribution.
- Supercharging station service time, which is the range consumers arrive, is 8.am.-10.pm. (because almost no one will come late at night)
- A supercharging station has 8 charging piles (This is based on the data *1,130* supercharger stations with *8,496* superchargers from the Tesla official website.
- The limit of charging station capacity is infinity, and the number of customer sources is determined by the local traffic flow. Service rule is first come, first served.

The details of queuing model are as follows [3]:

Symbol	Definition
μ	The number of electric cars a supercharger can serve per hour
λ	The number of cars a supercharger station expected to receive per hour
c	The number of superchargers in a supercharger station
ρ	The number of electric cars a supercharger station can serve per hour
P_0	The probability of the case that all superchargers are idle
P_{inf}	The probability of the case that all superchargers are busy
L_q	The expected number of cars waited to be served
L	The expected number of cars stayed in the charging station
W	The expected time a car stayed in the charging station
W_q	The expected time a car waited in the charging station

$$P_0 = \{[\Sigma_{n=0}^{c-1}\frac{(c\rho)^n}{n!}] + [\frac{(c\rho)^c}{c!(1-\rho)}]\}^{-1}$$

$$\rho = \frac{\lambda}{c\mu}, P_{\text{inf}} = \frac{(c\rho)^c P_0}{c!(1-\rho)}$$

$$L_q = \frac{\rho P_{\text{inf}}}{1-\rho}, L = c\rho + \frac{\rho P_{\text{inf}}}{1-\rho}$$
$$W = \frac{L}{\rho}, W_q = W - \frac{1}{\mu}$$

With multiple calculations compiled by MATLAB, we successfully work out the relationship between arrival rate and expected time in queue. The function curve is shown in Figure 5.

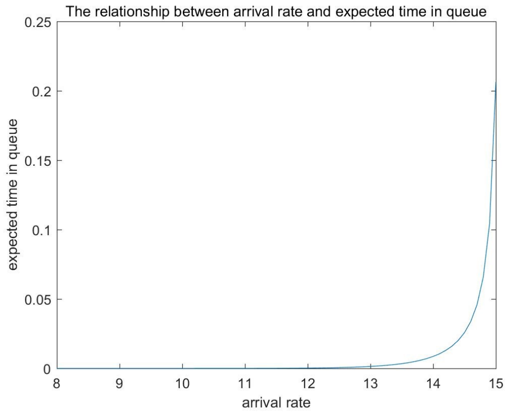


Figure 4: The relationship between arrival rate and expected time in queue

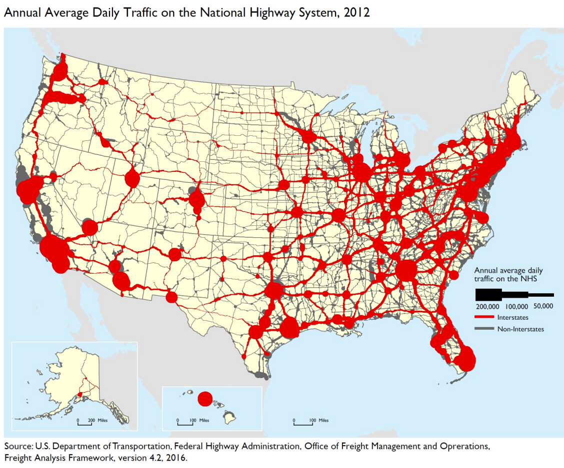


Figure 5: Annual Average Traffic on the National Highway System

The figure implies that the expected waiting time is not long when the arrival rate of the customers is within the (13,14) interval. However, while the arrival rate is within the (14,15) interval, waiting time will have a dramatic increase. Therefore, we may wish to set 14 as the standard of acceptable arrival rate. That is to say, we expect the arrival rate in every charging station to be 14/h.

Then we consider the queuing model on the above. The mode and median of intercontinental highway system are about 100,000 per year. We set 150,000 as the standard reference conditions. Each day about 273 vehicles pass either section of any intercontinental highway, so on average, each supercharging station will be interviewed 273 times. At this point, the customer arrival rate is 19.5 / h, approximately equal to 20 / h. It is larger than our expectation of 14 / h, which leads us to thinking of building more charging stations between existing stations to achieve shunting. Despite the 276-kilometer distance between stations and extra thirty-minute charging for the driving, it's obvious that the added stations will still become the choice of people if there are other stations within the 276 kilometers. The probability of choosing which station is relevant to geographic location but we may wish this probability to be average. In other words, if we want to make arrival rate of each charging station is 14 / h, it is necessary to build 1.42 times of the existing charging stations.

Since we have 453 supercharging stations, we expect the number of stations to be 643(453*1.42) to meet customer demand. In fact, according to the statistics at the Tesla official website, the number of super charging stations opening soon is 432, which is much larger than the result we got. One possible reason is that our investigation is based on the scale of the vehicles in recent years. We think Tesla's future network of supercharging stations takes the possible expansion of the total scale of vehicles into account, which is a reflection of Tesla's marketing strategy. Besides, considering that thirty minutes is too long for those who are in a hurry, we think in the reality the service time is better to be 5 minutes. In this case, the distance between stations should be shorten by 6 times, so the total number of supercharging stations is 3858.

5 Charging Station Distribution Model

5.1 Basic mode

This basic model mainly concentrates on the distribution between urban and rural areas, referring to **Coverage Theory**. We will base the following research on this model and then do more modifications and improvements to solve broader problems.

In this model, we assume the establishment of model is on a planar connected convex hull including urban, suburban and rural areas. We have n demand points i, the demand of each point is d_i.

As for destination charging stations, we will build m stations and N_j charging piles for station j. If a charging pile can satisfy the demand of 4 Tesla, station j can provide service for $4N_j$ Tesla.

- **Constraints**

$$R_j \leqslant E, A_j \leqslant E$$

$$\sum_i X_i = n, \sum X_{area} \times area \geqslant S$$

S = total acreage of the area

- **Objective function:**

$$MIN\{m * 15000 + \sum N_j * 1000\}$$

The cost of building a station is 15000 $

The cost of building a charging pile is 1000 $

m is the number of Charging Station

As the share of electric vehicles increases, the number of demand points and the demand at each point also increases, which shortens R_j. Thus, the holes of coverage come up again and more charging stations should be added to meet the demand.

In rural areas, $\frac{d}{dt}d_i(t)$ is relatively small while R_j is relatively big. Also, most charging stations have redundant service capabilities. So it's safe to conclude that we can lay emphasis on urban areas and add investment in rural areas when necessary.

Furthermore, it's possible that the constraint $A_j \leqslant E$ can be negligible when there are only 10% electric vehicles. So we can suppose that sparsely populated rural areas can not be reached considering the utilization of resources at the time when electric cars are scarce.

Regarding the **order** of buying electric cars and building chargers, we should adopt "building chargers first" to encourage people to purchase electric vehicles because in urban areas where the growth rate of demand develops fast, the speed of building chargers is slower than that of demand growth.

However, in rural areas where the growth rate of demand is slow, we should adopt "building chargers in response to car purchases" because the speed of building chargers is faster than that of demand growth. Building chargers first tends to cause unnecessary waste of resources.

As for supercharging stations, the figure of Supercharging stations in the U.S and National system of interstate and defense highways above illustrate that the supercharging stations usually lie in the cross places of highway network or along with the its outline.

We can lay the model on a connected undirected graph. With respect to each supercharging station, its area of coverage is a neighborhood. So it's more efficient to put the stations at the cross places. Then we can work out the distribution rule:

- Placing supercharging stations at the intersections of the highway first
- Determine the area of coverage according to the reachable distance after charging for 30 minutes and the current number of Tesla
- Make sure the coverage area can cover the dispersed points and lines as much as possible

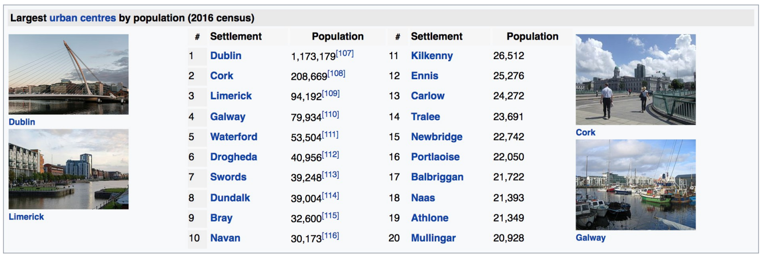
5.2 The Comprehensive Application of the Model

In this section we are about to make a combination of the model and analysis above. We will illustrate the model with a specific country, Ireland.

Since the terrain of Ireland can be roughly regarded as a connected convex hull on a plane, we can reasonably abstract it into a flat plane.

To calculate the structure of the charging stations, first we should determine the number macroscopically, the method of which is similar to theories applied in the previous analysis. Next, we will discuss short drive (mainly use destination charging) and long trip (mainly use supercharging) separately.

For short drive:


Largest urban centres by population (2016 census)

#	Settlement	Population	#	Settlement	Population
1	Dublin	1,173,179[107]	11	Kilkenny	26,512
2	Cork	208,669[108]	12	Ennis	25,276
3	Limerick	94,192[109]	13	Carlow	24,272
4	Galway	79,934[110]	14	Tralee	23,691
5	Waterford	53,504[111]	15	Newbridge	22,742
6	Drogheda	40,956[112]	16	Portlaoise	22,050
7	Swords	39,248[113]	17	Balbriggan	21,722
8	Dundalk	39,004[114]	18	Naas	21,393
9	Bray	32,600[115]	19	Athlone	21,349
10	Navan	30,173[116]	20	Mullingar	20,928

Figure 6: Population distribution figure of Ireland [4]

We can denote the number of Tesla in large cities as $\lambda \times pop$. $\lambda$is a constant, equal to $ca \times pro$. pop is the amount of population. ca is the number of cars per person possesses. pro is the proportion Tesla to cars.

Considering that the market share is 100%, the total number of Tesla is 2,586,966. As discussed above, each destination charger can satisfy the demand for 5 Tesla. So the number of destination chargers is 517,242.

For long trip: The Irish highway is 2500 kilometers long. On the basis of queuing model on the above, we can obtain that the number of supercharging stations is 1903 and the charging piles is 15218 after the complete switch to electric vehicles.

After deciding the overall structure of charging stations and chargers, we are supposed to move to the timeline of evolution to all vehicles in the country. We divide the construction of Ireland into four stages: 10%, 30%, 50% and 100%.

For each stage, in view of the fact that Ireland is a developed country with little change to population, we can consider it to be a constant. The key factors are population density and distance between blocks.

At the first three stages, we don't need to think about whether the safe area centered around the charging stations can cover the Ireland completely but consider the coverage of demand points. That is to say, the constraint $X_{area} \times area$ should be equal to the total acreage can be neglected.

Data about the distance between the main cities in Ireland [4]

City	Dublin	Cork	Fingal	Galway	Kildare	Limerick	Meath	Kerry
Dublin	0	266	208	192	204	54.4	224	189
Cork	266	0	206	202	105	299	384	85.4
Fingal	208	206	0	177	98.1	190	203	139
Galway	192	202	177	0	147	99.5	232	132
Kildare	204	105	98.1	147	0	242	285	40.2
Limerick	54.4	299	190	99.5	242	0	177	228
Meath	224	384	203	232	285	177	0	325
Kerry	189	85.4	139	132	40.2	228	325	0

With calculations compiled by MATLAB, we successfully work out the figure revealing radiant range. The codes are in the **appendix**.

5.3 Evolution of Charging Station Distribution Model

The basic model above mainly discusses certain countries and do specific research. However, the trend of complete switch to electric vehicles is worldwide, not limited to several areas. So, we should think about the evolution of charging station distribution model from a global perspective. The key factors that constrict the development of electric vehicles industry:

- Economic factors. The electric vehicles are often expensive and only a few can afford.
- Geographical factors. Harsh environment is not suitable for driving and maintenance of electric vehicles.
- Demographic factors. Purchasing power is often less in sparsely populated areas.

In a country that is developed flat-terrain but has uneven population distribution, the key determinant of the demand for electric vehicles is the population. However, in a country where population is evenly distributed and has flat terrain but the economy is unevenly developed, the key factor is about economy. Therefore, based on the economic, geographical and population distribution of each country, we set up the following three models:

Figure 7: 10%

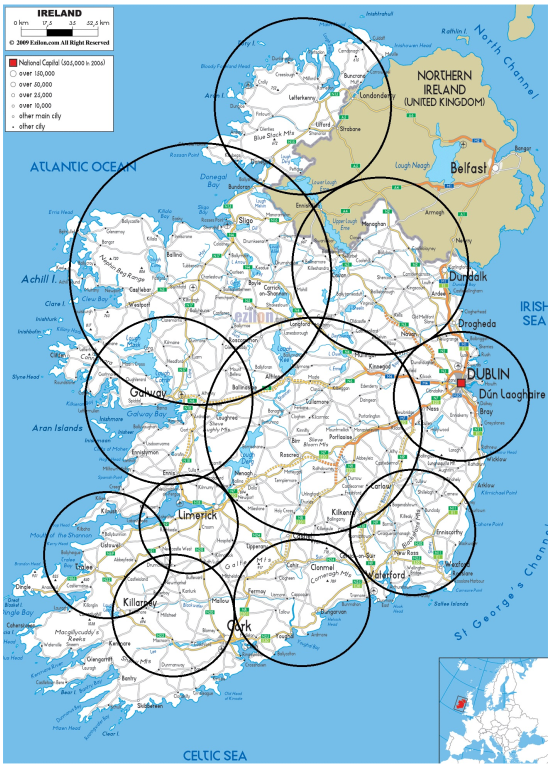


Figure 8: 30%

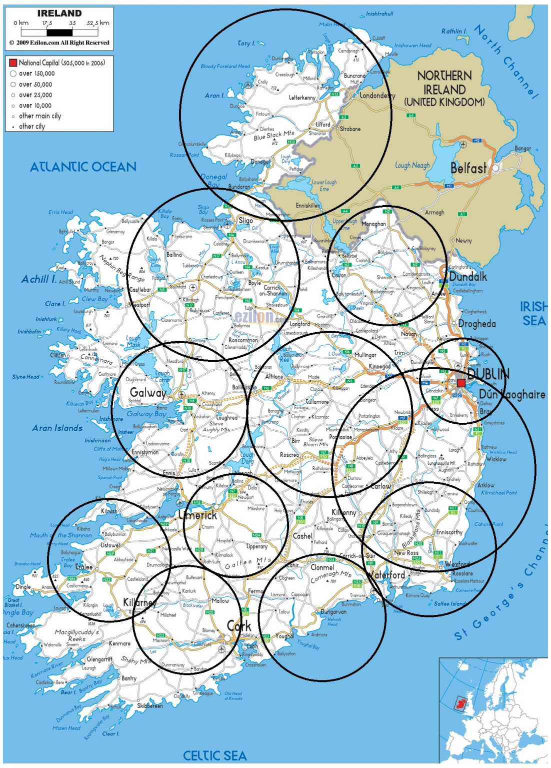


Figure 9: 50%

Figure 10: 100%

- Income-led demand model
- Geography-led demand model
- Population-led demand model

Although economy, geography, and population have mutual effects, we can assume that they do not affect each other.

In our models above, point demand is defined as an income-related variable so the model can be considered as an income-led demand model. Therefore, the model can not be applied completely in Australia, China, Indonesia, Saudi Arabia and Singapore.

Then we summary three models based on different characteristics:

- Income-led demand model: Consider the average income level around each demand point. In simple terms, the regions with high income levels have high demand for electric vehicles, which reveals the positive linear relationship. Suppose the demand is D and the local average income is x. $D = ktx$. k is only related to the average consumption capacity of the host country and t denotes time.
- Geography-led demand model: We consider the livable point as the demand point. Suppose the demand is D, $D = kt$; k is related to the consumption capacity of the host country.
- Population-led demand model: Consider the **model of population retardation growth**. $\frac{dx}{dt} = xR(x)$, $x(0) = x_0$; $R(x) = r - sx$; decompose the differential equation to obtain $x = \frac{m}{1+ne^{-rt}}$, set the demand to be D, $D = kx = \frac{km}{1+Ce^{-rt}}$. k is related to the consumption capacity of the country, related to the population base of the country.

Next, we will work on the feasibility of applying this model system to practice.

Australia:

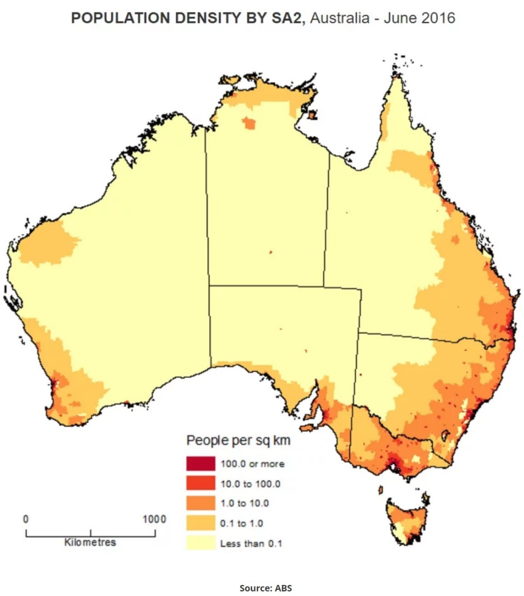


Figure 11: Population Density

Figure 12: Geographical Figure of Australia

Distribution of income in Australia

Western Australia	1004
Northern Territory	882
South Australia	812
Queensland	865
New south Wales	896
Victoria	865
Tasmania	754

The Table above imply that Australia is suitable for Population-led demand model.

China:

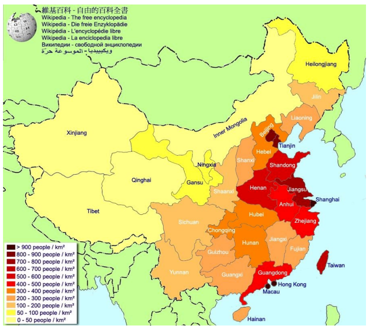


Figure 13: The demographical of China

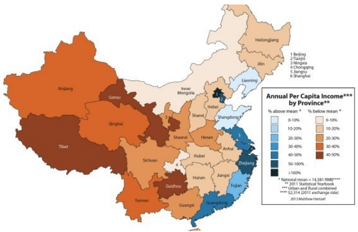


Figure 14: income figures of China

Figure 15: geographical figures of China

These figures indicate that China's income imbalance is quite serious. So Income-led demand model is appropriate here.

Indonesia:

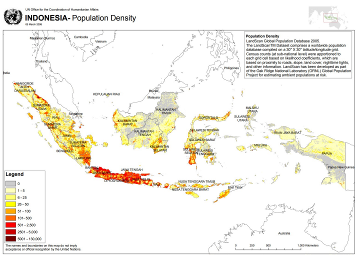


Figure 16: The demographica of Indonesial

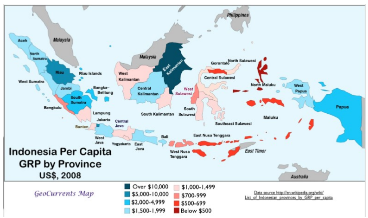


Figure 17: income figures of Indonesia

Figure 18: geographical figures of Indonesia

Geography-led demand model is suitable for research on Indonesia.

Saudi Arabia:

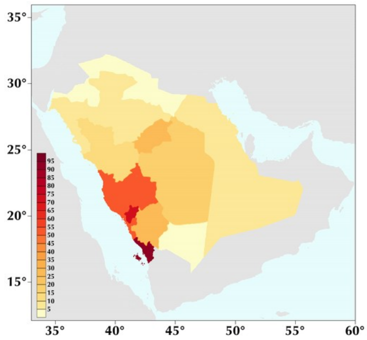
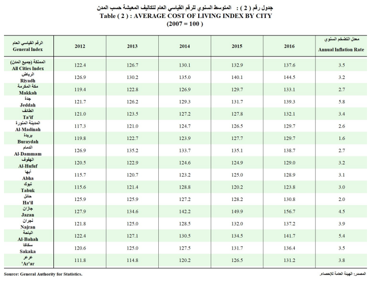


Figure 19: The demographica of Saudi Arabial



جدول رقم (2) : المتوسط السنوي للرقم القياسي العام لتكاليف المعيشة حسب المدن
Table (2) : AVERAGE COST OF LIVING INDEX BY CITY
(2007 = 100)

الرقم القياسي العام General Index	2012	2013	2014	2015	2016	معدل التضخم السنوي Annual Inflation Rate
المملكة (جميع المدن) All Cities Index	122.4	126.7	130.1	132.9	137.6	3.5
الرياض Riyadh	126.9	130.2	135.0	140.1	144.5	3.2
مكة المكرمة Makkah	119.4	122.8	126.9	129.7	133.1	2.7
جدة Jeddah	121.7	126.2	129.3	131.7	139.3	5.8
الطائف Ta'if	121.0	123.5	127.2	127.8	132.1	3.4
المدينة المنورة Al-Madinah	117.3	121.0	124.7	126.5	129.7	2.6
بريدة Buraydah	119.8	122.7	123.9	127.7	129.7	1.6
الدمام Al-Dammam	126.9	135.2	133.7	135.1	138.7	2.7
الهفوف Al-Hufuf	120.5	122.9	124.6	124.9	129.0	3.2
أبها Abha	115.7	120.7	123.2	125.0	128.9	3.1
تبوك Tabuk	115.6	121.4	128.8	120.2	123.8	3.0
حائل Ha'il	125.9	125.9	127.2	128.2	130.8	2.0
جازان Jazan	127.9	134.6	142.2	149.9	156.7	4.5
نجران Najran	121.8	125.0	128.5	132.0	137.2	3.9
الباحة Al-Bahah	122.4	127.1	130.5	134.5	141.7	5.4
سكاكا Sakaka	120.6	125.0	127.5	131.7	136.4	3.5
عرعر 'Ar'ar	111.8	114.8	120.2	126.5	131.2	3.8

Source: General Authority for Statistics. المصدر: الهيئة العامة للإحصاء.

Figure 20: income figures of Saudi Arabia

Figure 21: geographical figures of Saudi Arabia

We need population-led demand model here.

Singapore:

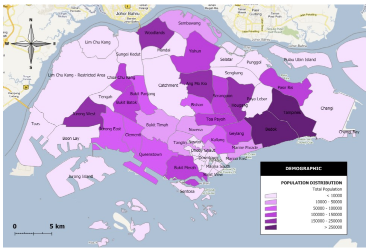


Figure 22: The demographica of Singapore

Figure 23: income figures of Singapore

Figure 24: geographical figures of Singapore

Population-led demand model is needed to study Singapore.

Through the analysis above, we can work out a **classification system** to help determine the growth model to successfully migrate away from gasoline and diesel vehicles to all electric cars: To each country, we apply three indexes:

- p-Population restriction index
- g-Geography restriction index
- e-Income restriction index

Each of the indexes should satisfy:

- In the same interval
- Have the same distribution in the interval

Order the countries according to these three indexes and get rankings of three aspects for all the countries. Give priority to the corresponding model of the highest-ranking index when determining which model to apply.

6 Exogenous Effects on the Electrical Vehicles

Technological development has continuous impact on our world and is impacting transportation options. This also holds true in the world of electric cars. Car-sharing and ride-sharing industry would reduce the transportation expanse, as you could share an expensive electric car with others. Car-share service and ride-share service would leave pressure on the charging station network, and increase the usage rate for electric cars.

Self-driving electric cars can take you to your destination, and find charger station itself. By big data immediate analysis, electric car traffic can be well organized, avoiding traffic jam. You don't have to worry about the electric quantity by yourself. Self-driving cars would motivate people's desire to travel by cars, promoting the sales numbers of electric cars. Charging stations would be used with higher efficiency and thus, reduce the number of destination charger stations and supercharger stations. Demands would be greater than we have expected, and charger stations can be distributed.

Rapid battery-swap stations can make your battery quantity change from 0 to 100 percent in just 5min, but battery-swap means big cost. Battery-swap stations would have larger coverage area, and greater cost. Rapid battery-swap stations may not be their first choice for a short travel. But if their trip covers a long distance, the battery-swap stations may be attached higher priority. The rapid battery-swap stations network would not be intense and usually set along main highway.

Flying cars equipped with electric battery would need more electricity, for flying would consume more energy than riding on the road. Ground conditions would not be important for flying cars, so the candidate charger stations don't have to be lay out along roads. The charging station network may have better structure.

Hyperloop technology has not been well developed nowadays, but if hyperloop ways are built. We may expect to see more demand, larger and more intense network. The way we consider to set stations may change and the traffic flow may be easier to count, so that we could get more precise data.

7 Handout

Electric Vehicles Contributes to Green Future

Electric cars

Electric cars uses energy stored in rechargeable batteries. No greenhouse gas would emit when driving and no gas is required for electric cars. According to Tesla Stastics, about 2,988,000 tons of carbon dioxide has been saved in US. Also, driving electric would save about 55% fee for energy. With the development of charging technology, 30min charging can make electric cars travel 170 miles at most. Electric cars can replace traditional cars by improving current charging network. Electric car industries have bright future, and now, it is time to promote electric cars in your country and investing on the infrastructure of electric cars.

Full Evolution to Electric Vehicles Needs Time

Despite the fact that we are eager to see the full evolution to electric vehicles, it is still a long time before setting a total gas vehicle ban. We suggest that government sectors in your country shoud do research first. Our Stastics shows that economic conditions, population density, the development of charging technology are the key factors determining the timeline. We hope governments in your country provide policy assistance to electric car enterprises and electric car owners, including reducing taxes and giving finacial support. Electric cars are relativly expensive, we hope you government could relief people's burden for purchasing an electric car.

Population in your country determine the basic demand for electric cars. And the population density determine the infrastructure constructing progress. We hope the construction of electric cars be in pace with the number of the electric vehicles in your country. Additionally, the development of charging technology determines the cost and efficiency of charging. We hope you could support the scientific research on charging technology.

Pcitures from Internet.

8 sensitivity Analysis

Our model applies queuing theory and coverage theory, so the result of the first model will depend on the volume of each area. However, the size of the traffic is relevant to time. Next, we will analyze the impact of traffic flow on the model.

As **Figure 5** mentioned above, the trend of function of expected time in queue -arrival rate is close to exponential growth in the interval [13,15] and is relatively smooth in the interval [13,14]. This demonstrates that the result of the model is dumb to the change of flow when it is less than 14 times /h. Correspondingly, the results are sensitive when traffic volume is more than 14 /h.

Although a long queue can be diverted by adding sites, a sudden increase of traffic flow will make the whole charging network vulnerable. Therefore, if the technological problem concerning charging efficiency can not be fully solved, the network of complete electric vehicles will be weaker than that of gasoline vehicle system.

Then we intend to analyze the sensitivity of distribution of demand points. Since our model work out the distribution of charging stations from the that of demand points, the density of demand points and demand of single demand point have enormous effects on the results.

The service radius is undoubtedly small in the area where the total demand is large (it means the demand points are dense or the demand of single demand point is large) according to its definition. Besides, with the spread of electric vehicles the service radius will be smaller.

To study the relationship between service radius and the density of demand points, we will define a measure relevant to density.

ρ: Take an area with an acreage of S, making the total demand *sum* on S >10; the density $\rho = \frac{sum}{S}$ We successfully work out the figure showing the relationship between density and service radius through MATLAB.

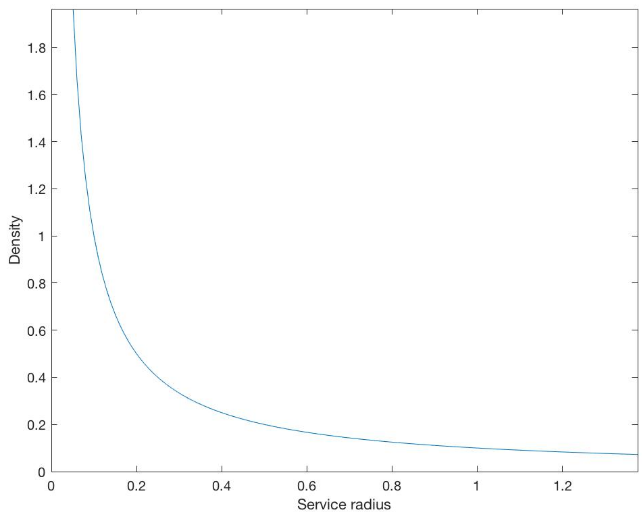


Figure 25: the relationship between density and service radius

Obviously, we can see that the demand density has great influence on the service radius in the start-up stage of the electric vehicle. When the charging vehicle is more popular, the service radius of each charging station tends to a relatively stable value. On the other hand, according to our model, the number of new sites added and the increase of demand has a linear relationship. In the early and late stages of the development of charging vehicles, the rate of demand change is relatively small. The result of the model is slow to the demand density. However, in the middle period of development when the demand is increasing rapidly, the service radius and the number of added stations rise greatly.

To conclude, at the early stage of the charging network, the results of the model are sensitive to the demand density while the response to the demand density is slow in the later period.

As a consequence, in actual planning we need to predict the demand accurately especially in urban area. We need to improve the charging infrastructure in advance, so as to avoid the overload of the charging station. Considering the growth rate of the cost and the speed of building the station, coping with the abrupt increase in demand is an advantage charging vehicle network has to gasoline vehicle system.

9 Strengths and Weaknesses

Our macro prediction model uses statistics numbers including population, total road length, average traffic flow numbers to evaluate this problem. Major strength and weakness are posted below:
Strength:

- Data used in this prediction model is easily accessible.
- Having considered the waiting time for customers, which means than our model considered more reliable factors.
- We use probability theory to evaluate this problem, which means that the result may be closer to the expected number.
- We use Matlab to draw figures and calculate numbers.
- We post detailed numbers, including the number of superchargers and destinationchargers.

weakness:

- Our prediction is theoretical to certain extent, and cannot respond fast towards the changes in source data.
- Our prediction model would not perform well in source-unbalanced country, despite the fact that we have considered to construct a classification system.
- Our model just consider the typical usage of the two charger station, in reality supercharger stations may also function like destination charger stations.
- We assume an average number of chargers in a charger station, but in reality, number of chargers in charger station may differ much from this average number.
- The growth of population, income increase, and the development of charging technology are not taken into consideration.

Our micro-evaluation model uses statistics like the distribution of electric car demand, the serve ability of each charger station, and the timeline of the evolution towards electric cars. Major strength and weakness are posted below: **Strength:**

- We simplified the demand area as a point on the map, which is easier to be get when putting a real map into theoretical map.
- Our model could reveal the evolution of the network of the charger station network including the supercharger network and the destination charger network.
- Our model fits well with both city charger station network and the country charger station network.
- We turn data into visual graph to show the result of our model.
- We use Matlab and Python for computation when analyzing the charger station distribution in Ireland.

Weakness:

- The demand cannot be easily described by usual data.
- We treat it as a quasi-static model when analyzing the distribution of charger stations.
- Our description towards demand is too simple, which may cause big difference from reality.
- The way we compute the distance between two points is not precise, but the traffic condition is complex in mot cases.

10 Conclusion

We evaluate this problem by macro-analysis and micro-analysis. When considering the whole distribution of charger station network, we use statistic data to construct our model, despite the fact that the distribution in reality may differ from what we have expected, the number we obtain was still reliable to some extent. The source data we obtain is easily accessible, making this model easier to solve.

Our micro-analysis focus on the detailed distribution of charger stations. We put the real traffic map into ideal graph by adapting graph theory using vertices to represent demand areas on the map. We designed a Monte-Carlo-based algorithm to solve our model, but computers cannot solve immediately. We estimated that if we got enough data with the CPU of personal computers, we have to wait for over 20 hours to get our result. So we simplified our model to get our result.

We spend a lot of time in dimming the data we need. In fact, some data are not easy to get, and we have to find some data for replacement. This is a tough process. We hope that more statistic data can be accessible to public and search engines could have solution to this demand.

Prediction model have to take many factors into consideration, and may rapidly change due to the development of new technologies. At present, the electric cars have only 0.91% market share. It is a long time before the age of full electric cars. We still have to wait, and later reports is still needed to evaluate this problem.

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Appendix

MONTE-CARLO-TRAINING(M,S,w,D,r)

$t \leftarrow 0$
$MinCost \leftarrow \inf$
while $t \leq 3000$
    $(N,R,j,C) =$ SET-COVER-ALGORITHM(M,S,w,D,r)
    $cost \leftarrow$ COST-COMPUTE(N,j,C)
    if $cost < MinCost$
        $(N',j',C') = (N,j,C)$
return (N,j,C)

DIST(x,y)

return the distance between x and y

SET-COVER-ALGORITHM(M,S,w,D,r)

$N \leftarrow \emptyset$
$T \leftarrow \emptyset$
$j \leftarrow 0$
while $|T| \neq n$
$i \leftarrow random - select(M/T)$
$N \leftarrow N \cup \{i\}$
$T \leftarrow T \cup \{i\}$
$j \leftarrow j+1$
$R_j \leftarrow 0$
$C_j \leftarrow w - S_i$
while ($C_j > 0$ and $R_j < D$)
    $R_j \leftarrow R_j + r$
    for $\forall k \in M/T$
        if (DIST$(k,j) < R_j$ and $R_j < D$)
          $C_j \leftarrow C_j - S_k$
          if $C_j \geq 0$
              $T \leftarrow T \cup k$
return (N,R,j,C)

COST-COMPUTE(N,j,C)

$cost \leftarrow 0$
for $\forall i \in N$
    $cost \leftarrow cost + (W - C_i)$
return cost