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Team Control Number
83625

Problem Chosen
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2018
MCM/ICM
Summary Sheet

The environment issues prompt the global government to encourage more electric vehicles. The switch to electric vehicles must be enforced in the coming years and the policy makers are facing the problem how to build a charging station network. Our goal is to help managing the problem from different aspects.

United States is a pioneer on building charging networks powered by Tesla which currently offers two types of charging stations: destination charging and supercharging. We evaluate the number of charging stations needed in US by considering the amount of electricity and running a run-charge model.

Then we apply the knowledge of network science to design a network cascade model in order to propose a charging station plan for other nations which is still at an early stage of building charging stations. Many factors are considered like early adopters, the optimal location and distribution of charging stations, wealth distribution, and so forth.

Finally, we make a step forward to discuss the influence of future technologies and in the end we propose a handout to international energy summit which identify key factors and give detailed suggestions.

Planning the Transition to Electric Vehicles

ICM Contest Question D

Team # 83625

February 13, 2018

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1 Introduction

1.1 The Problem

As the world's seeing probably the greatest shift in energy structure this century, more and more enterprises and consumers commence seeking alternatives to traditional gasoline and diesel vehicles, among which a favored choice is electric vehicles (EV). This newly adopted form of transport is gaining worldwide support due to the substantial environmental and economic benefits it brings. Some countries, such as China, have even set a goal to eliminate the use of gasoline and diesel completely in recent years.

With the growth of EV industry comes the challenge to feed the demand of charging stations. Therefore, nations have a pressing need to develop a mature structure of a charging network that could supply the full transition to electric vehicles, and set a moderate pace towards this final design.

In response to this problem, we seek to develop several mathematical models to determine key factors, propose future networks, and indicate potential setbacks. We hope our work offers a valid solution to the problem of interest.

2 Exploring Current Charging Stations in the U.S.

We consider the chargers and Electric Vehicles provided by Tesla, a U.S. company with the largest market share in the EV industry.

Besides chargers installed at home and in private workplace, there are currently two types of public Tesla chargers in the U.S.:

- Destination Charging Station
  It takes several hours to charge, normally requiring occupation of parking space for half a day or overnight.
- Supercharging Station
  It takes less than $1h$ to charge, delivering a 72 kilowatts (kW) of power.

Table 1: Vehicles-miles in the US *(Billion miles)*

Time	Rural	Urban	Total	Time	Rural	Urban	Total
16.NOV	77.2	186.4	263.6	17.JAN	69.1	173.2	242.3
17.FEB	67.4	166	233.4	17.MAR	79.8	192.1	271.9
17.APR	81.1	190.6	271.7	17.MAY	85.6	195.6	281.2
17.JUN	87.4	193.6	281	17.JUL	91.4	192.2	283.6
17.AUG	88.7	194.6	283.3	17.SEP	80.9	181.7	262.6
17.OCT	83.7	191.3	275	17.NOV	78.1	183.3	261.4

2.1 Current Tesla Charging Network

With less than 200,000 electric cars sold (And nearly one third of cars sold are in California). So if all vehicles are magically switch to all-electric, there will be a lot of problems.

2.1.1 The Amount of Electricity

We first consider the amount of electricity to charge all the vehicles if there is a complete switch to all-electric in the US.

And from Tesla's website, we find that 30 minutes charging can make your car driving for 170 miles. To deal with an average of 8.8 billion vehicles-mile per day, we need 103,000,000 hours of charging every day. With less than 10000 chargers in the US, this is surely the MISSION : IMPOSSIBLE for Tesla.

2.1.2 Current Stations in Rural Areas

And when we look at some rural areas, the charging stations are far from enough, with some states having less than ten chargers. And the total length of all road in the US is 4,150,000 miles, with less than 10000 chargers. So there are surely some dead place for electric vehicles : these places' nearest charging station are too far that a vehicle can not get there without charging. Let's hope electric car owner don't live there.

2.2 Predicted Final Charging Network: A Run-Charge Model

As we mentioned above, our final charging network should at least meet two requirements.

- The charging network can match the total electricity vehicles need.

- There should be charging stations in every area with a certain diameter.

If the charging station meet these two requirements, we can say it is workable in theory, but just in theory. Imagine a situation : There are only some really big charging station every 300 miles(so every Tesla can drive to one station technically) and the number of supercharger is accurately calculated to make sure if they work 24/7, they can match the electricity demand. But we surely need to come up with a better idea, otherwise Tesla will lose all their users due to the long waiting.

Our idea is simple, we can compare gas station with charge station. So we need to define these following variables.

L is for Road Length. we can simply imagine the longer road is, the more charger we need.

F is for the traffic flow through the road. The more vehicles go through it, the more electricity is needed.

E is for the Effectiveness, it is the ratio between the time vehicles get charged or refueled and the time vehicles can run. For a tanker, E is so small that it can even be ignored. a vehicle can get lots of gas in one or two minutes, which can support hours of driving. But for a charger, E has a great influence. A supercharging can provide up to 170 miles in 30 minutes of charging. But 170 miles is only 3 hour driving on highways. E for Tesla is at least 10 times larger than usual cars.

H is for home-charging, it is the proportion of people using home-charging. Tesla do have a big advantage that usual vehicle do not have : people can charge their Tesla at home. That means if you park your cars in your garage every night (which is really common in urban and suburban area), you don't have to charge you Tesla outside.

2.2.1 Urban and Suburban

In urban areas, there are many destinations for drivers like park, mall or office. And in suburban areas, there are enough space for garage. So the user living in suburban area can just use home-charging for daily drive. So we can see only a little amount of people need to charge their car on the way. And a charger can work 12 hours a day. Thus there's a really big H in these two area. Let's just define $H = 0.75$. And we get: $L = 1{,}200{,}000$ *miles*

$F = 6.7$ *billion vehicle miles / day*

$E = 0.0625$ (Average speed is about 20 miles per hour)

$H = 0.8$ (Lots of home-charging)

The easiest way is to change every gas station in urban and suburban area into charge station. So we got about 90,000 charge station. On average, there is one station every 13 miles. And there are about $F/20 * E * (1 - H) = 4,200,000$ charging hours per day. That means we need at least 350,000 super chargers. So Tesla need about 90,000 charge station with 350,000 superchargers (on average, is 4 super charger per station) in urban and suburban area.

As for destination chargers, the demand is much bigger. A restaurant, a mall, a office building, they all need some destination chargers. Destination chargers has a really bad effectiveness(Even if your car is fully charged, the charger is not available until you leave, which may take few hours, so a destination charger can charge about three or four cars a day). With about 8,000,000 parking lots in the US, and one eighth of them is changed into destination chargers. So that's 1,000,000 destination chargers.

2.2.2 Rural

In rural areas, the trip tend to be long, and there can't be many home-chargers or destination chargers. The charging stations are going to be like the gas stations, they should be placed on the road. We just imagine that there is a charge station every 50 miles. And most people drive on rural road during daytime, so let's imagine that a super charger works for 8 hours a day.

In rural areas, we get:

L = 3,000,000 miles

F = 3 billion vehicle miles / day

E = 0.125 (Average speed is about 40 miles per hour)

H = 0.1 (Few cars can have home-charging on rural area)

So for the first requirement, we need at least $L/50 = 60,000$ charge stations to make sure Tesla drivers will not having problem find the nearest charge station. And there are $F/40 * E * (1 - H) = 8,500,000$ charging hours per day. That means we need at least 1,050,000 super chargers.

So we finally make our conclusion : Tesla need about 60,000 charge station with 1,050,000 superchargers (on average, is 17.5 super charger per station) in rural area. On average, our charge station can serve 35 vehicles per hour, and the fact is that in some really big charge station in expressway, there need to be hundreds of chargers.

2.2.3 Conclusion

So our conclusion is : If everyone switched to all-electric personal passenger vehicles in the US, we need about 15,000 charging stations with 1,400,000 super chargers, and 1,000,000 destination chargers on parking lots.

And 90,000 charging stations are in urban or suburban area, just in the place of gas station, with an average of 4 super chargers per station. The rest of 60,000 charging stations are in rural area, a station per 50 miles of road and 17.5 super chargers per station.

Some data shows the distribution of gas stations and population distribution are almost the same in urban area. So we can describe our result in this way :

- In urban and suburban area, there is one charge station for every 3,000 people with 4 super chargers, and a destination charger for every 2,80 people.
- In rural area, there is one charge station for every 50 miles with an average of 17.5 super chargers.

2.3 Further Discussions

From our data, we can see that all-electric vehicles is really great for urban and suburban area due to the convenient home charging. But when it comes to rural area, the lack of high-performance battery makes all-electric vehicles a nightmare.

Average cars per household in the US is about 2.0, that means a typical US Tesla family may have one Tesla cars for urban using and another normal one for rural area. That means the pressure for rural charging isn't growing as fast as the number of electric vehicles. Which may be a good news for Tesla and our model because we don't need so many chargers in real world.

3 Determining Optimal Charging Stations in Other Countries: Network Cascade Model

Planning an optimal charging network for a nation at an early stage like Korea is definitely different from evaluating an existing charging network for a prepared nation like the U.S. Not only does the optimal number of charging stations need to be decided, but also the best location and the growth strategy. So we should consider Task 2 in a local network level rather than a population level. In this section, we take social behaviors into account, like spread of innovation, individual's decision-making and the influence of a facility.

3.1 The Diffusion of Electric Vehicles

There is already a number of studies on *Diffusion of Innovation*, which is a theory that attempts to explain why, how and in what speed new technologies, ideas, behaviors and trends are spread from person to person. Researchers have found that in a social network, there are always early adopters who are open to certain innovation, like the early customers of iPhone X, and there are also followers who are convinced to switch based on their observation of others' decisions.

As an innovation, Electric Vehicle is supposed to follow a similar pattern. Car owners who are concerned about environment and new buyers in consideration of the policy (encouraging electric vehicles as well as banning gasoline and diesel cars) can be the early adopters of EV. As people observe more and more of their neighbors and colleagues switch to electric vehicles, they are likely to imitate one day.

However, not all car owners can afford a private charger. The need of public charging station prompts them to take the distance to the charging stations within reach as an important factor. Therefore, when a facility like public charging station has been placed, residents around must be more or less influenced.

3.2 Model Description: How Cascades Form

3.2.1 Network Structure

We build the network on a two-dimension grid where each node is connected to its eight nearest neighbors. It is suitable for modeling the reality because a residential district naturally looks like a grid and a map with longitudes and latitudes is also a kind of grid.

In our model, each node on the grid can be a site of a charging station.

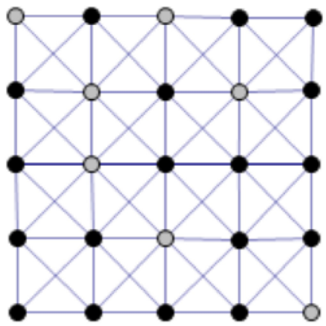

Figure 1: A grid with a set of car owners

There is also a certain probability p, say 0.7, that a car owner appears on this node. This parameter can be varied from urban areas to rural areas and the latter may have a lower probability due to the lower density of population. The car owners connected to him are his neighbors living in the same neighborhood or colleagues working at the same spot.

Here we assume that there are two types of potential EV buyers: day type who prefer to charge their EV at work and night type who prefer to charge their EV at home. Day type are more likely to be influenced by their colleagues and night type are more likely to be influenced by their neighbors. In either of the case, we can assign the potential EV buyer to some node and consider the influence by neighboring EV adopters and charging stations.

In general, the grid looks like Figure 1, where the black (white) node represents a spot with (without) a car owner. Take the black node in the middle as an example. It is connected with four black nodes while the black node on its left-down corner has six black nodes connect to it.

3.2.2 Threshold Rule

Our model is inspired by the natural network model proposed in [2], pg. 566 which derives a threshold rule from a *networked coordination game*. It says that if at least a $q = b/(a+b)$ fraction of neighbors follow the new technology then one would make a change, where a is the payoff if both he and his neighbor adopt the new technology and b is the payoff if both of them stick with the old one. The payoff matrix can be represented as Table 2.

	new	old
new	a,a	0,0
old	0,0	b,b

Table 2: A payoff matrix of homogeneous network coordination game

There is already a conclusion that given any finite set of early adopters who are contained in some rectangle of the grid, and if $q > 3/8$, no node outside this rectangle will ever become adopters.

However, this model is based on *direct-benefit effects* which states that one can earn benefits when aligning themselves to neighbors. There is another effect named *informational effects* explaining our imitating behaviors, which seems to be more proper regarding the behavior of buying electric vehicles.

So we change the threshold rule as: each adopter has an influence on his neighbors with certain index, say $1/8$, and each charging station has influence with descending indexes on descending *Manhattan Distance*, say $3/8, 2/8, 1/8$. If a car owner is influenced by a sum of indexes larger than a threshold q, say $1/2$, he would decide to switch. Here the threshold can also be varied from rich to poor, depending on the payoff of switching.

The definition of Manhattan Distance here is also adapted to the grid structure. For instance, in Figure 2, the Manhattan Distance between A and B is 2 and the Manhattan Distance between A and C is 3. If the coordinates of two nodes are (x_1, y_1) and (x_2, y_2) respectively, then the Manhattan Distance between them is

$$\max\{|x_1 - x_2|, |y_1 - y_2|\}.$$

3.2.3 Network Dynamics

Now we consider the evolution of this network has atomicity, that is all events (the emergence of early adopters, the switch of car owners, the

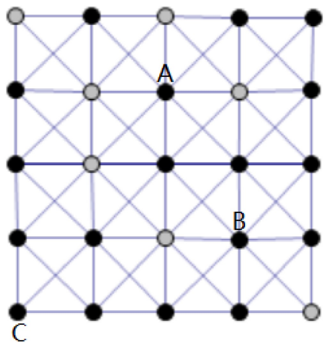

Figure 2: Adapted Manhattan Distance on gird

placement of charging stations) are occurred phase by phase.

At the initial phase, there are already a few randomly chosen early adopters who have private chargers (name it **private type**) and at each phase,

- with a small probability r, a non-adopter becomes a private type.
- with probability $1 - r$, a non-adopter observes the nearby car owners and charging stations, then follows the threshold rule in Section 3.2.2 to be an adopter.
- we can place public charging stations on some nodes.
- determine whether public charging stations are enough to meet the need of electric vehicles.

The logic of the above assumptions is very similar to the logic of rich-get-richer model in [2], pg. 561.

3.2.4 Charging Service

How to place the charging stations is a tricky part. This is a famous facility location problem. The shortest path from each node to the nearest charging station needs to be considered. Besides, the charging frequency of an EV determines how many EVs can a charging station serve given the number of chargers in each station. For example, according to [3], a public charging station in US can provide three chargers on average. If each EV belongs to either **day type** (charge whole day) or **night type** (charge overnight) and has to charge everyday, then a public charging station can serve six EVs roughly.

So here we make the problem simpler by reserving each public charging station we have placed to its nearest m EV adopters (**public type**) where m denotes the number of EVs it can serve.

3.3 Model Analysis: How Different Factors Influence Cascades

Rather than focusing on one nation, we develop a more general methodology to study the evolution of charging network and EV network cascades, which can apply to nations under different circumstances.

3.3.1 Early Adopter

It is not easy to find out who and where are the early adopters in reality. While in our model, an early adopter can appear in anywhere. Due to this uncertainty, placing public charging stations in different location may lead to different cascading speed.

3.3.2 Charger-first vs. Car-first

In 3.3.1 we have seen that the network cascade can come to a standstill or at a slow state. So the growth plan plays an important role in the duration of the cascade. In our model, if we place two charging stations close to each other, the cascade can be triggered without existing adopters. If we wait for the early adopters to cluster, the cascade can also be triggered. The former case can be viewed as **charger-first strategy** (build the chargers first and hope people buy the cars) while the latter case can be regarded as **car-first strategy** (build chargers in response to car purchases).

It is obvious that waiting for the cluster of early adopters takes much longer time. Moreover, there should be a certain number of charging stations meeting the demand of the earliest public types (as mentioned in 3.2.4). So it is recommendable to build some chargers first.

However, there are also two strategies available in this case: **myopic strategy** (build chargers in response to the prediction of the next phase) and

farseeing strategy (get prepared for a few following phases and wait for the switches). There are both advantage and disadvantage of either strategies, the myopic strategy may fall behind the cascade of EV purchases and cause chargers in short supply to some extent, while the farseeing strategy may not optimally place the charging stations due to the lack of future cascade information and cause chargers idle to some extent. Both of the strategies are common in our daily life. For example, some companies place orders dynamically while other companies keep storages for the future.

In general, the **distribution of early adopters** and **cascading speed** are the key factors that shape the charging station plan.

3.3.3 Density of Charging Stations Network

In 3.3.2 we have already realized the trade-off between shortage and surplus. Actually, the **density of the network of charging stations** is a key factor. If the network is dense, then the growing speed of car purchases is fast, but it may result in surplus somehow. If the network is scattered, then some charging station is so isolated that it needs new adopters to trigger the cascade. So the trade-off is also a key factor to the **timeline**. Like the Dominoes, if they are narrowly placed, the falling speed is too fast and may not form the pattern as wanted; if they are sparsely placed, the falling speed is too slow and even stop at some point.

3.3.4 City-based vs. Rural-based

The network of car owners in urban areas is definitely denser than that in rural areas. We can set the probability mentioned in3.2.1 as 0.7, 0.5, 0.3 for urban, suburban and rural areas.

From the angle of demand, since the network in rural areas is sparser, the influence of adopters and charging stations are reduced, leading to a slower cascade. From the angle of supply, each charging station can provide service to a broader area and the pressure is reduced. In general, the number of charging stations should be in descending order regards to urban, suburban and rural areas.

To study whether to build all city-based chargers first, or all rural chargers, or a mix of both, we should generate a **"radial map"** for car owners where the center has a density of 0.7, the boarder has a density of 0.3 and the transition zone has a density of 0.5. Then run the **simulation** to see which has a notable cascading phenomenon: **from center to boarder** or **from boarder to center**.

3.3.5 Wealth Distribution

Different countries have different wealth distribution, the rural areas in developed countries like US is richer than that in developing countries like China. As 3.2.2 mentioned, the threshold q is lower as to richer car owners because EV is more affordable to them. So in less developed areas, the cascade is harder to sustain.

3.4 Simulation

The strength of our model is that all above reasonings can be validated by simulation. We provide a universal method suitable for all nations rather than give results and arguments for just one nation. To implement simulation, one should replace the random generating nodes of car owners with the actual geographical positions (even coordinates).

4 Further Discussions

4.1 New Technological Options

New technologies may offer more solutions to the proposed charging problem and more possibilities of transportation. We will discuss the impact of the following technologies.

4.2 Impacts of Technological Development

Different technology can pose a different impact on our analysis of the expansion of Electric Vehicle. Some influence charging options, some influence the production of EV, and some might even alter the whole network structure we discussed in Section 3.2 of Electric Vehicle. When predicting the impacts of these developments, we assess our model construction and identify key factors that are affected.

4.2.1 Carsharing

Carsharing allows people to drive cars that are not owned by themselves. There are generally two types of carsharing options.

Similar to ofo and *mobike*, the first option is to rent cars provided by private companies, for example, *car2go* and $Zipcar$. With the trend of Electric Vehicles worldwide, carsharing companies offering EV are coming to existence. *BlueSG* is the first such service in Singapore. Launched in December, 2017, the company establishes a self-service network of *BlueSG* stations, where users can reserve, rent, drive, and drop their cars at any time they choose. The shared EV technology does not have the same network structure as what we established in Section 3.2.1. Service users make an influence on other users or potential users through the online comment system instead of neighbors and colleagues. According to [1], online social networks reflects offline networks, distances cannot be explicitly defined.

The second option is shared car ride in self-organized groups. Either among friends, neighbors, or even complete strangers in a small community, people share a ride on privately-owned vehicles with each other. When electric car owners share their cars in this way, their neighbors are less inclined to transfer to electric vehicles, so the threshold is predictably higher. This can influence the spread of EV in an opposite direction.

4.2.2 Self-driving Cars

Self-driving cars, like Tesla Model S with the Tesla Autopilot system, are another extension of electric vehicles. According to proceedings in [4], self-driving vehicles prove to be much more energy efficient due to the consistency in operation. Moreover, self-driving cars work with On Line Electric Vehicles (OLEVs), an inductive power transfer technology that allows charging while driving on the road. This will significantly reduce the demand for roadside charging stations and total electricity.

4.2.3 Battery-swap Stations

In 2013, Tesla launched its Battery Swap Event, introducing a new technology implemented in Model S which features swaping an empty battery with a fully charged one in approximately three minutes, reducing the time of charging to almost 1/10. We think this technology can boost the number of electric car owners, a lot of whom will otherwise be dissuaded due to the long charging time and the shortage of vacant parking spaces.

However, Tesla finally decided to shut down the battery swap stations and replace them with supercharging Stations. Possible causes might include:

- Car owners are unwilling to replace their batteries when the condition and milleage of the batteries swapped in are unknown.
- The cost of having sufficient battery packs ready in the stations is too high.
- The equipment operation has higher cost than superchargers.

4.2.4 Flying Cars

While just a fantasy up to now, flying cars might be another great evolution of short distance transportation. Given that the technology is available, impacts of flying cars can be illustrated as follows:

- A charging station has relatively little or no influence over its neighborhood's decision to switch, as farther charging stations are available within a short period of time.
- The network of supercharging stations in suburban and rural areas are subject to change, because drivers can choose to take a longer detour in the air to get charged.
- Electric Vehicles will likely expand, as the high energy consumption of flying cars can arouse serious environmental issues, and electricity is cleaner than gasoline and diesel.

4.2.5 Hyperloop

Hyperloops offer an approach opposite to flying cars. Instead of trying to 'go up', innovators and engineerings are seeking to 'go down' by digging tunnels for high-speed transportation. According to [5], Hyperloop tubes are drawn near vacuum inside to reduce air friction to the lowest possible level. The cabins can travel at a speed of 600 miles per hour, taking a small group ($8-16$) of people or a personal vehicle to their destination with no pause. With regard to economic and environmental benefits, Hyperloops are enhancing public transport to a completely new level. Considering the suggested speed and convenience to travel door-to-door, the number of private vehicles can be largely reduced. It is predictable that EV will mostly be needed for short trips like daily routines, so the destination charging stations and supercharging stations will likely be gathered in urban areas.

The 'electric skate', a vehicle within a Hyperloop, is powered by multiple electric motors. Charging enough skates to run become the central concern. However, such chargers won't be distributed among roads, but will be installed inside several operation stations. Our future analysis will then turn from privately owned electric vehicles to the network of Hyperloop and its charging centers.

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Handout

Preparing for a Smooth Transition

—From Gas to All-Electric

Stage 1: Identifying Early Adopters

1. Locate early adopters of Electric Vehicles and nearby regions
2. Implement initial charging stations
3. Find out stagnation in the spreading cascade
4. Build additional stations to enhance car purchase, thus releasing the cascade

Stage 2: Expanding Charging Network

1. Predict the growth of adopters
2. Build stations according to prediction
3. Repeat the cycle until the final network is established

Factors to Consider

1. For each cycle in Stage 2, a few more stations than the amount predicted can be built to avoid shortage of demand
2. Numbers of stations built each cycle: if the network becomes too dense, it may finally result in surplus; if the network is too scattered, some isolated areas might need new adopters to trigger the cascade
3. Urban or rural areas: urban network should be denser than rural network, grow faster, and have less pressure providing service
4. Wealth distribution: in less-developed countries, threshold is higher, and cascade is more difficult to sustain
5. Expanding from urban to rural areas (or adversely): setting p = 0.7, 0.5, 0.3 respectively, draw radiation charts to decide which direction supports a faster cascade

Suggested Time Line

1. The gas vehicle-ban date should be set when Stage 2 has almost been finished.

5 Appendices