# Contents

# 1 Introduction

## 1.1 Background

### 1.1.1 Overview of The Problem

Electric vehicles are gradually developing towards a niche market as a cleaner promising alternative of transportation. Acknowledge of alleviating the dependency of fuel and reducing green house emissions has brought control use of gas cars a serious position and production of electric vehicles has been raised since they are more effective and less polluted(Li et al., 2016). Unlike gas cars, electric vehicles require frequent charges due to limitation of their causing ability especially for a remote trip over provinces. Therefore, how to distribute chargers stations is a main concern for providing cars owners a more convenient and safe experience. Tesla Inc, an energy company, has already produced several models of technologically electric vehicles successfully and created routes of charges for customers to keep their vehicles charged all the time. However, there are still places to improve for the future development.

The first problem for Tesla is that the current design of charging routes in America might not still be reasonable when Tesla cars become numerous. Secondly, for other countries, population density and geographies are different, the charging routes deign varies as well. Moreover, numbers of charging stations in a country are different when it owns different vehicles quantities so charging routes might evolve all the time. Therefore, it makes great sense to consider the main influential factors of a charging route design and to improve the Tesla charging network.

### 1.1.2 Current Tesla Charging Design

At present, there are two types of charging stations in addition of at-home chargers. Destination charging is for once charge lasting for several hours or over night. It is always set near a restaurant or in a hotel spot where owners could have couple hours break. The other type is supercharger which is allocated most in well-traveled routes. This charger is to provide longer trips that are up to 170 miles and is within 30 minutes of charging. Both of charging stations are built up in different areas so that people living in urban places can also charge their cars without traveling. The density of charging station s could sufficiently support local Tesla cars usage.

Tesla charging stations could be spotted from in-vehicle navigation map and owners could control battery charging condition from application. Navigation design in the vehicle could search the closet charging station and after setting the destination, it will automatically design a proper route along with charging station for driver in case non-sufficient power. Tesla cars are charged by costing network credits so it is convenient for users. Also, the battery condition could be monitored by the car or applications all the time and users are able to check it for charging or for when completing charging at stations.

It could be seen that the technology of Tesla cars is advanced and intelligent. One way to facilitate the development of electric car is to pursue a more effective design of charging stations routes. Since there will be expansion of charging station to fit fleet grows of electric vehicles, it is worth evaluating and analyzing main factors to design a suitable route for different countries and areas.

### 1.2 Main Tasks

- Study the current charging network in America and design a distribution plan for different areas.
- Create a network of charging stations in one of countries of South Korea, Ireland or Uruguay, find factors of determining when and how to develop a charging network and purpose a timeline for a whole evolution of electric vehicles.
- Improve previous model and generate more advanced models that could fit different conditions.
- Analyze how other techniques might influence use of electric cars.
- Prepare a national plan to migrate gas cars to electric vehicles and make specific ban date.

## 2 Assumptions and Related Notations

### 2.1 Model Assumptions and Justifications

In order to simplify the process of modelling and draw a reasonable conclusions with main factors, we make assumptions as follows:

- The data we use for numerical analysis and future prediction is reliable. The results processed by statistics methods are used for evaluation of current situation and to predict future trend.
- To predict future quantity of chargers of America, we use average increasing rate according to the present number of charging stations and the number of coming soon ones.
- When considering the chargers distribution, we assume each one we design works normally.
- All chargers could work for 24 hours in each station.
- Since it is additional chargers to consider, we consider the situation that each user has an at-home charger and electric cars would be charged to 100% before setting off.
- Queuing time is not taken into account in our circumstance.
- Along the electric cars' evolution, we consider there are sufficient products for commands and we assume the resource to build up charging stations is abundant.

### 2.2 Notations

| Symbol | Description |
|---|---|
| $N_U$ | urban population |
| $N_S$ | suburban population |
| $N_R$ | rural population |
| $L$ | highway length |
| $d$ | EV's driving range |
| $\alpha$ | charging requirement$0 < \alpha \leq 1$ |
| $\beta$ | real EV proportion, $0 < \beta \leq 1$ |
| $\beta_i$ | imagine EV proportion for development |
| $n_U$ | number of chargers in urban area |
| $n_S$ | number of chargers in suburban area |
| $n_R$ | number of chargers in rural area |
| $N$ | the total number of charging station |

*Table 1*

## 3 Model Analysis of Stations Network in the U.S.

Tesla has already sold more than 50,000 EVs in the United States and built 1,130 supercharger stations, as well as abundant destination charging stations. The concept of supercharger stations is relatively similar to the gasoline stations in our daily life: 30 minutes to go, only the time to grab a cup of coffee; according to Tesla, it takes around 1.5h to recharge the battery of Tesla model S from almost 0% to 100% with supercharger. Though the increasing sales of Tesla EV, it remains questionable that whether Tesla's charging stations are sufficient and more stations in schedule will cope with the increasing demands.

We first need to estimate the total number of the charging stations in the United States. Moreover, the number of chargers in different stations will be significant to estimate the number of stations. By analyzing the information of charging stations provided by Tesla, we retrieve the statistical results in Table 2.

In order to estimate the number of the charging stations in the United States, we introduce a model based on the statistic (Table 2) and parameters (Table 1).

$$\sum_j \sum_i \frac{m_j}{d\mu} \frac{\mu N_{ij}}{\frac{T_s}{t_c} n_i} \tag{1}$$

The statistic in Table 2 is retrieved form the United States Census Bureau. Moreover, we introduce another parameter: charging requirement Rj , to improve this model. Charging Requirement Rj is different in each state. It has a positive correlation with the person traveling miles per day of each state and it has a negative correlation with the cruise range of EV. To acquire approximate total number of stations, we assume all EVs are Tesla Model S, with a 335 miles cruise range (due to the range anxiety problem, we shrink it to 300 mi). In addition, the charging station network will develop in advance to ensure the stations will be sufficient for the growing number of EVs. Therefore, we will first set a real EV proportion of all passenger vehicle and the formula will output the desired network capacity with an imagine EV proportion (Fig 1).

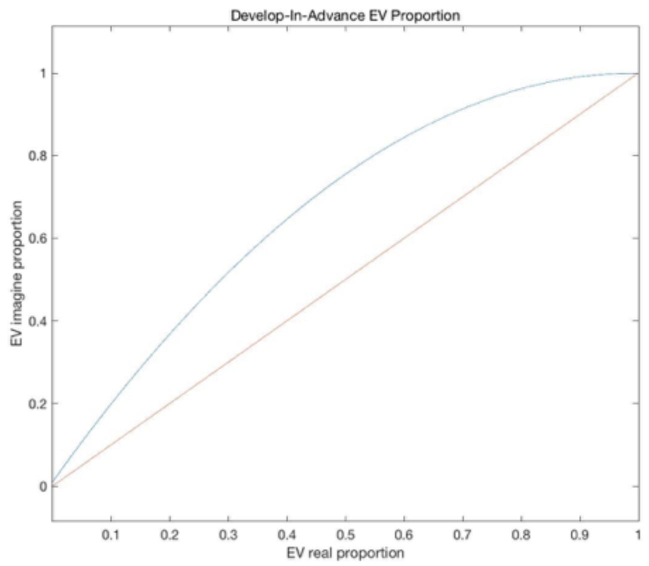



Figure 1: EV proportion

Table 4 and Figure 2 demonstrate the estimated number of supercharger station in the U.S. as well as their distribution in urban, suburban and rural areas. Moreover, when we study the Tesla current charging network in the U.S., the number of supercharger stations is 1,130 and Tesla EV market share is around 0.04% in the U.S. (only considering the number of passenger vehicle). Our estimation is 1,502 and increasing rate at this point (double the EV number, considering the sale growth of Tesla all models) is 9.85%. After analyzing Tesla's data, we obtain the increasing rate of Tesla is 12.04% by the end of 2018. Therefore we may conclude that Tesla is on the right track to develop nationwide charging stations and the detailed distribution of stations in urban, suburban and rural area is demonstrated in the Table 4.

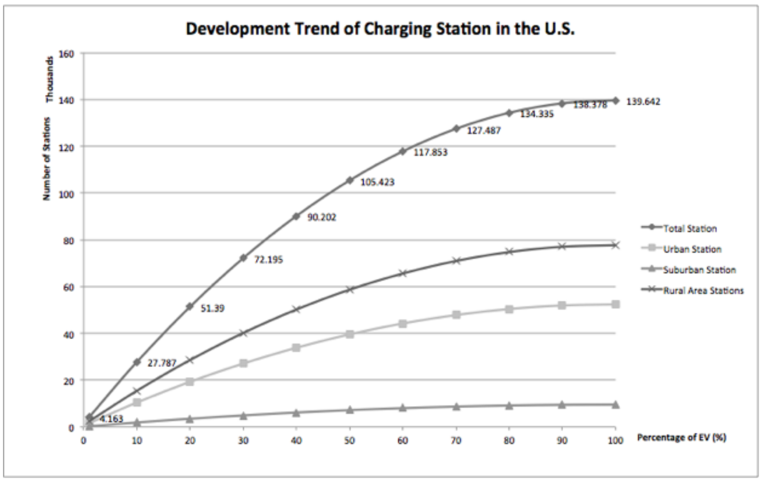



Figure 2: DTCS in the U.S.

| EV (%) | Total | Urban | Suburban | Rural |
|---|---|---|---|---|
| 1 | 4163 | 1564 | 282 | 2316 |
| 10 | 27787 | 10430 | 1893 | 15465 |
| 20 | 51390 | 19288 | 3499 | 28596 |
| 30 | 72195 | 27093 | 4915 | 40181 |
| 40 | 90202 | 33853 | 6145 | 50210 |
| 50 | 105423 | 39568 | 7179 | 58684 |
| 60 | 117853 | 44233 | 8025 | 65597 |
| 70 | 127487 | 47846 | 8682 | 70959 |
| 80 | 134335 | 50418 | 9148 | 74767 |
| 90 | 138378 | 51937 | 9423 | 77026 |
| 100 | 139642 | 52404 | 9506 | 77724 |

Figure 3:

# 4 Model Modification

## 4.1 Overview of Advanced Models

Comparing to the basic model based on America, the total number of current and coming soon charging stations are already sufficient for 100% cover of electric cars. Since different country has variant geographic features and population distribution, the basic model and algorithm we create for America might also suit for other countries. Hence, our model needs further modification by considering some key factors. Our advanced models are designed by considering a countryâĂŹs population distribution and local highway network as main factors. When analyzing model one, we found a linear relationship between population in a state denoted x and number of its current charging stations, y, by calculating their correlation coefficient

$$r_{xy} = \frac{S_{xy}}{S_x S_y}$$

and = 0.895, which showed a strongly positive linear relationship by comparing with , 0.28. Also, the classification of urban, suburban and rural areas is mainly based on local population and larger population means more potential purchasing. Thus, we list population density as the first factor. Moreover, charging stations are supposed to be on the main roads specially for highways due to more demands for long distance travelling and because of geographical influence, there would be more roads in cities and less in mountainous districts, so the second factor we consider as the current local highway routes.

We have two models that respectively focus on usage rates of stations and their rationality if they were built followed as our design, Population Distribution Trail model (PDT) and Shortest Route Preference model (SRP). In PDT model, the charging stations are distributed due to population distribution. Without considering how long it will take for a vehicle to reach destination if charging is required on the way, stations are placed in larger population density place as long as they could support the vehicleâĂŹs power.

The second model is based on the shortest route so that electric cars could be charged on the way to the destination as soon as possible.

Given a highway network of a country, we locate the main traffic hinge and districts. We simplify them to cross lines and points shown below

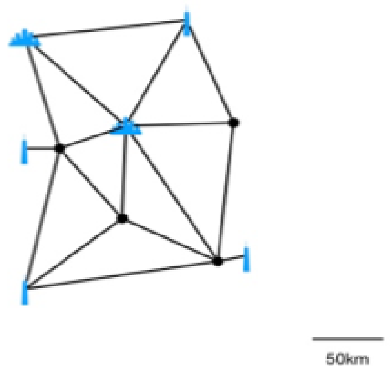



Figure 4:

Fig.1 A simplified highway network map in which dots mean the traffic hinge and blue marks represent provinces in different level.

As our assumption, we determine a constant cursing distance . As for the travel distance, we determine it as , which is obtained following the highway network from start to the end place. Our main concerns now are to set charging stations when reasonably and as our models are proposed, we create two methods to place stations. After that, we simulate as condition of several countries with different landscape and population distribution to evaluate its sensitivity for further classification and conclusion.

## 4.2 Population Distribution Trail Model (PDT)

The method could be briefly concluded as follows, denote :

- Condition: and start with full electric energy, which could be treated as a station;
- Selectable placements of charging stations: chosen by network points within ,
- Stations placement: at the furthest point to the current start point that within
- Repeat the previous process until , ;

The factors affected in this model is cities position and distance from each other. In corresponding algorithm, the citiesâĂŹ position or coordinates and distance between each two cities need to be recorded. Create a simplified highway network map as below. Black dots represent cities and traffic hinges demoted from A to I. Green circle has radius of cursing distance and destination traveling distance is randomized. Here we give an example when allocating the furthest point I as destination. Green dot, red dot, grey dots and blue flash represent start point, temporary end point and selectable placements for stations respectively. These denotes would be used in the following discussion.

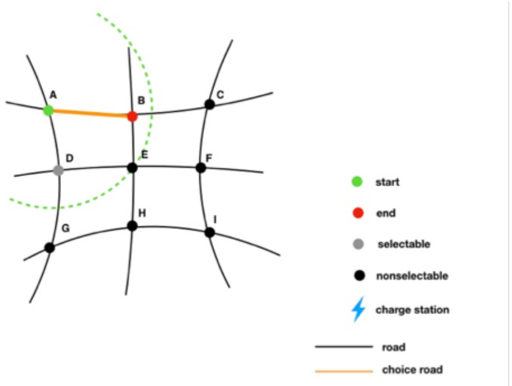
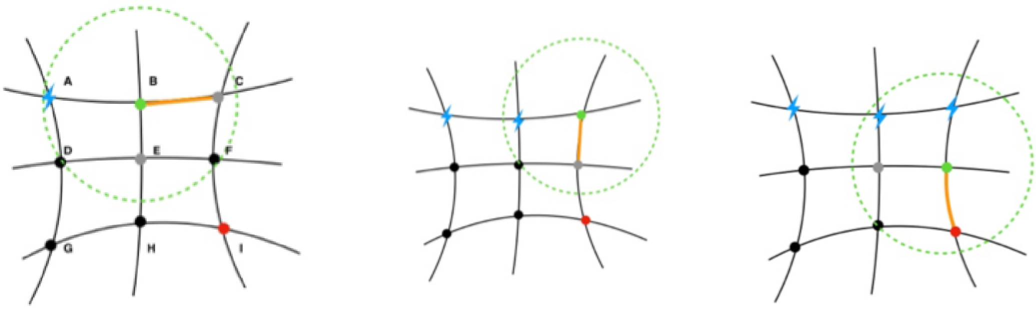



Figure 5:

Fig.2 Simplified Highway network map. Within the radius (green circle) , we mark by grey dots to present selectable placement for charging stations. Here we have point A as start point and B, D as selectable placement. Then we choose one of selectable points as station, also for an end point, B. Notice that, when there are several selectable placements, we choose the relatively farthest point to place station.

The whole process could be represented by Figure 3 below.




### 4.3 Shortest Route Preference model (SRP)

Instead of considering population distribution only, in SRP model, after the destination has been fixed, we determine the shortest route on highway network first and then only consider building charging stations along it. In this case, in spite of cities coordinates and distance between each two are needed, we also use Manhattan Distance to locate the points in a cityâĂŹs neighbourhood. The whole process is similar to PDT model:

- Condition: and start with full electric energy, which could be treated as a station;
- Determine the best route: comparing distance between start point and destination in different way by Manhattan Distance;
- Selectable placements of charging stations: chosen by network points on the chosen route within ,
- Stations placement: at the furthest point to the current start point that within

- Repeat the previous process until ,;

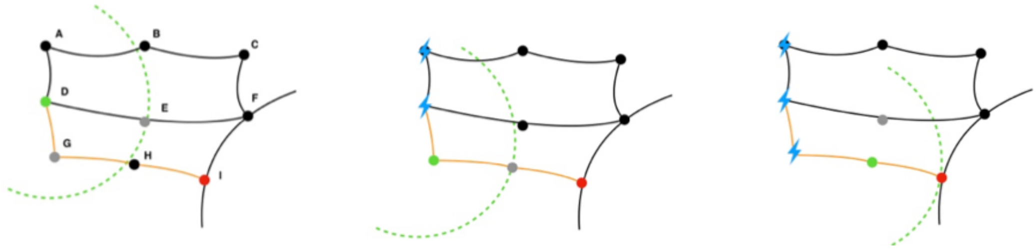



Fig.4 Three pictures from left to right orderly show the process to place the charging stations. At the beginning, the shortest route has been chosen, shown by orange in the figure. As a result, the chosen points to place stations are A, D, G.

### 4.4 Evaluation and Revisit of PDT&SRP Models

Intuitively, two models are modification of model based on Tesla charging stations in the USA. We generally consider the population distribution and highway network as main factors. However, there are many other influential elements to discuss, such as GDP in different district, average electric vehicle holding and other production of high technology that would influence demand for charging stations. These factors would be discussed in the later sections with the electric carsâĂŹ evolution specific to one example country.

Revisit the current charging stations in the USA of Tesla, data and figure show that most stations are built near highways and there are more stations in states holding larger population such as California and New York. Apparently, the distance and population density are two main factors Tesla considers that influence charging stations distribution. Therefore, the models we create are reasonable.

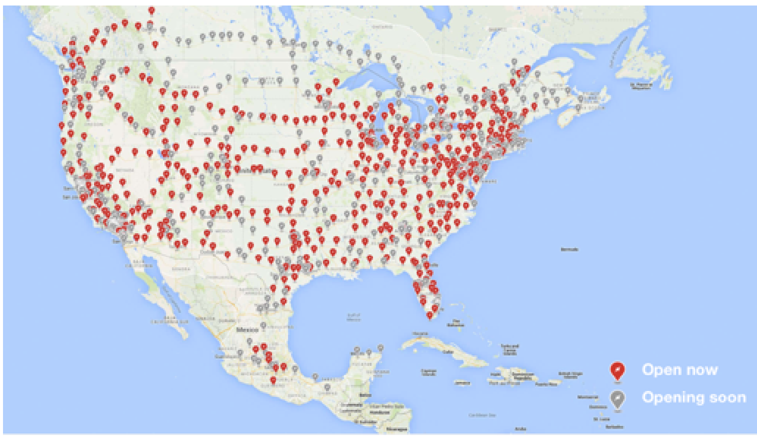



Figure 6:

# 5 Model Testing

## 5.1 HDT Model Testing and Evaluation Based On South Korea

At the beginning, we choose all traffic hinges from highway network. Adding grid to the origin map, we locate all considered hinges as shown below with their coordinates.

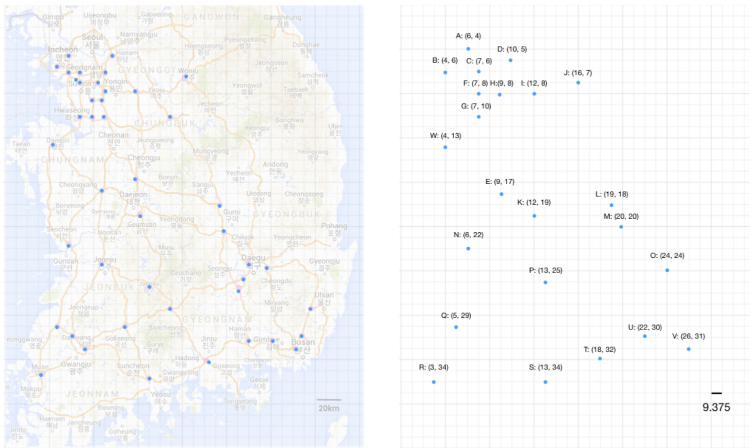



Figure 7:

Using Manhattan Distance algorithm to determine each pointâĂŹs neighbourhood, we connect those hinges by considering their relative shortest distance. The simulation is finally generated according to the following map.

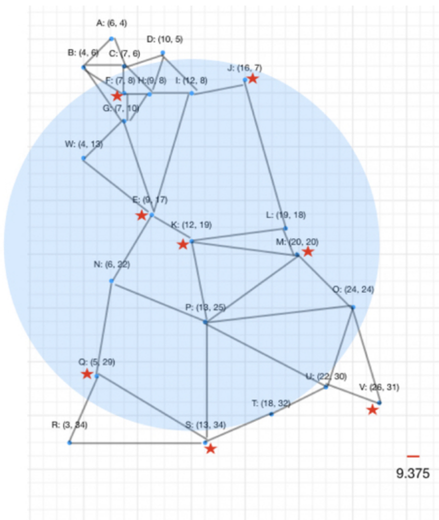



Figure 8:

Fig. 7 Our charging station route design based on HDT model. Here a length of a grid is 9.375 in km. Red stars represent the stationsâĂŹ positions.

Numerical method we sued for rationality of our HDT model on South Korea is evaluating the difference between the travelling path and the distance between two places. Basically we chose four points as start respectively from the most crowded province such as Seoul, less crowded, mountainous district such as Gyeongbuk and a central place such as Daejon. We evaluate waste rate, defined as,

$$W = \frac{S - d_s}{d_s} .100\%$$

where is travelling path and is the distance between two places, with relationship of different , which means different destination in our simulation. The result could be seen as below.

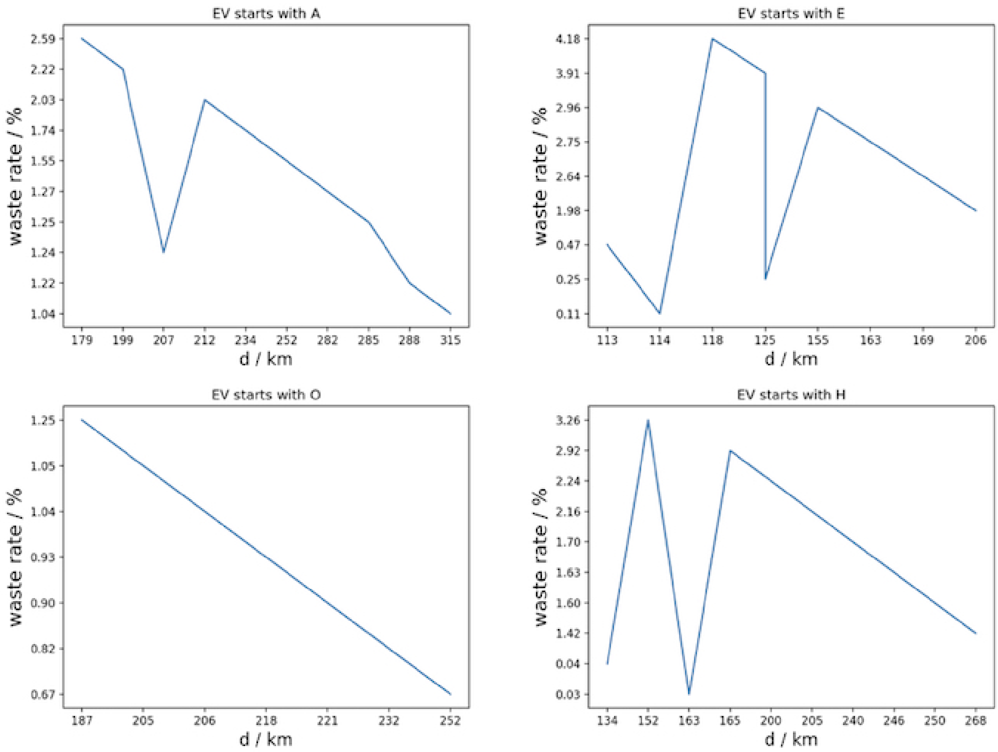



Figure 9:

Fig. 8 Four charts orderly show the relationship between and waste rate considering different starting point.

It could be seen that as is getting larger, the less waste path a car would travel. For a province that has high population density and rich traffic network, such as point A, it would waste less travelling for reaching more remote places such as R, S, V. For place like O that not many hinges to place stations, it indicates a standard negative linear relationship between waste rate and .

This indicates that our HDT model is not suitable for small country or country who has short distance between each two cities. Since our model is based on local highway network and stations are built up at traffic hinges, if two cities are close, which means surrounding traffic hinges are close, our algorithm might cause detour.

### 5.2 SRP Model Testing for South Korea

Here we briefly introduce the application in our SRP model. The choosing process is similar to HDT model and the only difference is that in this model the first step is fixing the relative shortest route and then considering build up stations as the furthest hinge point. The whole process could be shown as below.

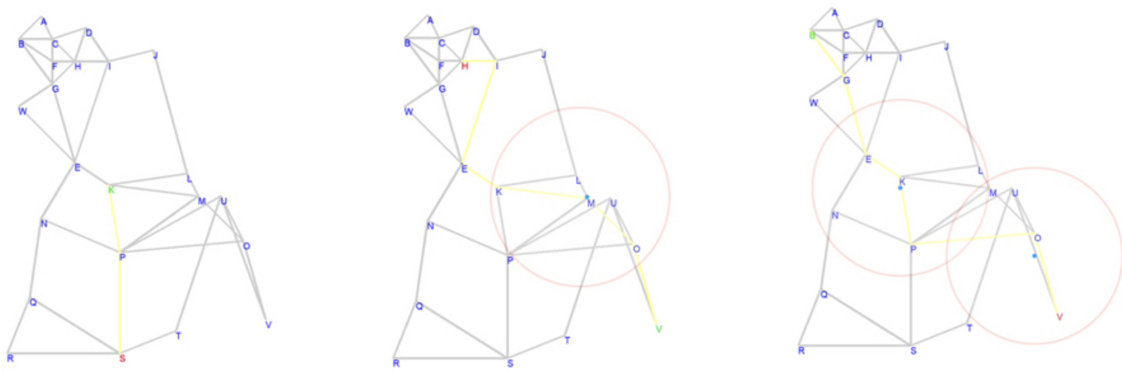


Figure 10:

Three examples of choosing the shortest route. Yellow line is shortest route chosen for each start point.

The figures are shown above are three examples of how to determine the shortest routes for a car. Example one is route for R to S. The second figure is for H to V and the last one is for B to V.

### 5.3 HDT Model Testing Based On Australia

As mentioned before, a countryâĂŹs landscape and traffic hinges distribution also influence the efficiency of charging stations which is evaluated by waste rate. The second test is based on traffic network of Australia. By choosing some start and end points, we repeated same process for comparison.First we present the traffic hinge map we set for later simulation.

It could be seen that waste rate fluctuated a lot as destination distance is increasing but the general result shows that our model works well in both of these countries but it suits better for Australia. However, one point to pay attention to is that since the property of electric vehicle is also important, we propose that when constructing network for the charging stations, fully consider the cursing distance and build up stations as our model does.

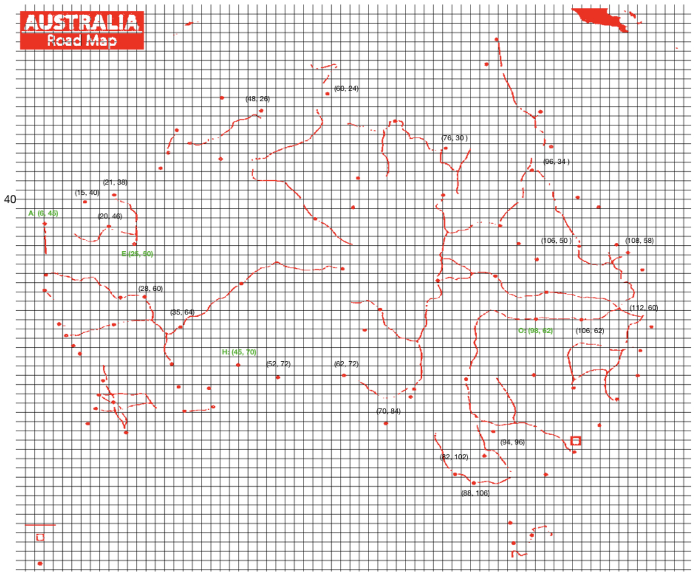



Figure 11:

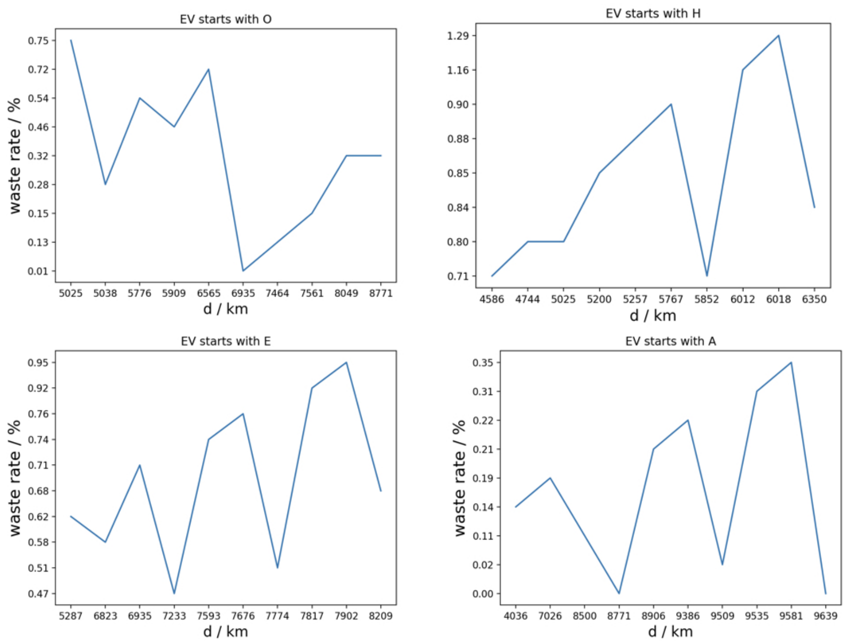



Figure 12:

# 6 Other Models

## 6.1 Neural Distribution Network Model (NDN)

From example of South Korea, we discover that the country who has intuitive traffic hinges distribution, HDT model is not very suitable. In the Seoul area, there are dense hinges and high population, then there would be more selectable stations placement around the start point in Seoul but the relative furthest one might cause detour. In this case, we construct another model that is simply based on latitude of hinges. We split hinges into several groups due to their positions and belonging provinces.

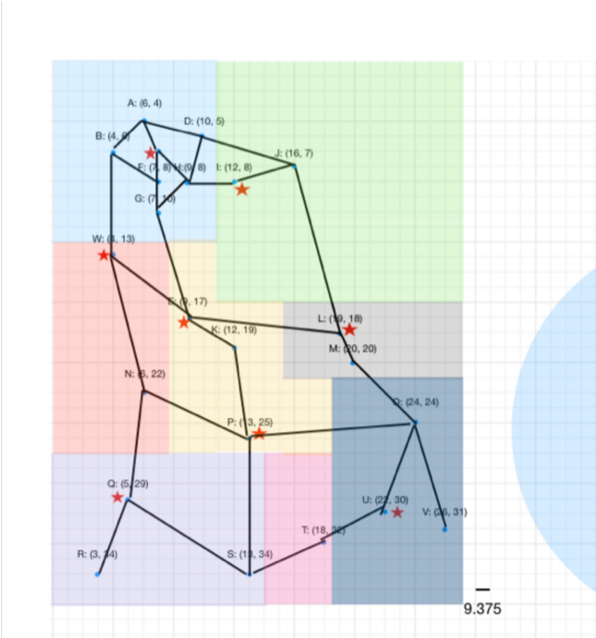



Figure 13:

The main idea is that within each group, since hinges are separated in groups by province, the more crowded the province is, there are more likely to be dense hinges. Thus we connect all hinges from above to the bottom vertically and connect neighbour hinges across provinces horizontally. In the blue area due to high population density and more travelling, we connect hinges like a neural network, so that route choosing is more flexible and waste rate could be reduced.

## 6.2 Population-City Base Model (PCB)

Generally, instead of considering highway network and hinges, we now could choose cities as our candidates for charging stations. The new network then will be created by the city location. Moreover, when several cities are within cursing distance, we compare each cityâĂŹs population density, denoted by , and then choose the city that holds the largest density as our station placement.

Start from city A, within the cursing distance, represented by the range of blue sphere, we have B, C two candidates, assume d2>d3, we choose B. Repeat the process until the destination is included in cursing distance sphere.

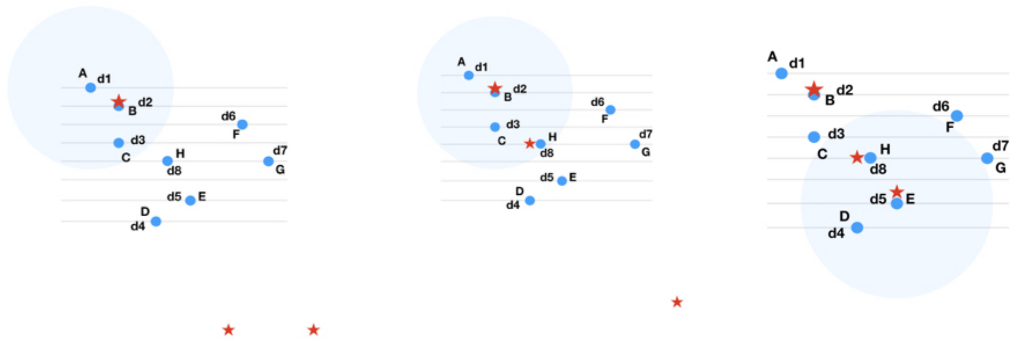



Figure 14:

# 7 Evaluation and Network Growing Plans

## 7.1 Strengths

Our models are mainly based on local current highway network which is already considered by the country landscape and richness of traffic. It could be seen that, placing charging stations at hinges of highways could increase usage of charging since travelling routes depend on main highways or roads and hinges apparently would have large traffic flow. Therefore, our models follow the traffic trend.

We also consider the waste route if travelling path is based our design. In aforementioned numerical analysis and plots, HDT model is more suitable for larger area country that hinges are less crowded and crossing states with larger distance. If the travelling path could be saved efficiently, the less demand for charging stations and better experience for users. In our first America model, we could see that in principle, for one country, the stations people need in total are much less than reality. This indicates that after satisfying basic demand, more stations could be set up in crowded places and metropolis. In those big cities, there more resources and financial support for the development of charging stations, which would also facilitate the growth of electric vehicles.

## 7.2 Weakness

At the beginning, we searched lots of data for a country such as its landscape, its traffic network and population. Also we predicted for its population increasing situation and used average cars holding percentage to determine the number of vehicles. These estimations might cause difference when applying to reality. The models we construct are in principle. We simplify the countries map to do analysis and reduce the complexity of highways. We convert curve to straight line to compute the distance which might cause mistakes and make it less realistic.

### 7.3 Plan of Development of EVâĂŹs Network

All models are based on different criteria that considers less waste rate and higher usage possibility. Since the construction cost is another factor to influence the development of electric network and its coverage, we do need to pay attention to the local demand for charging stations. In other words, begin from zero slate, we could consider to build up several charging stations according to the electric cars sales-planning. We distribute stations following planning sales number in positive proportion with local GDP to different areas.

We propose that in the process of evolution of electric cars, the total number of charging stations is meant to be determined by the sales-planning. The placements could be determined referenced by local highway network first and then the number of stations in each area depends on the local GDP with a positive relationship.

Considering there are numerous technologies that are changing our lifestyle and there more alternatives for travelling. The development of electric vehicle would be influenced by other advanced transportation but since the growing of other technologies takes time to enter the main market, so in near future we assume the main trend would be increasing in exponential way.

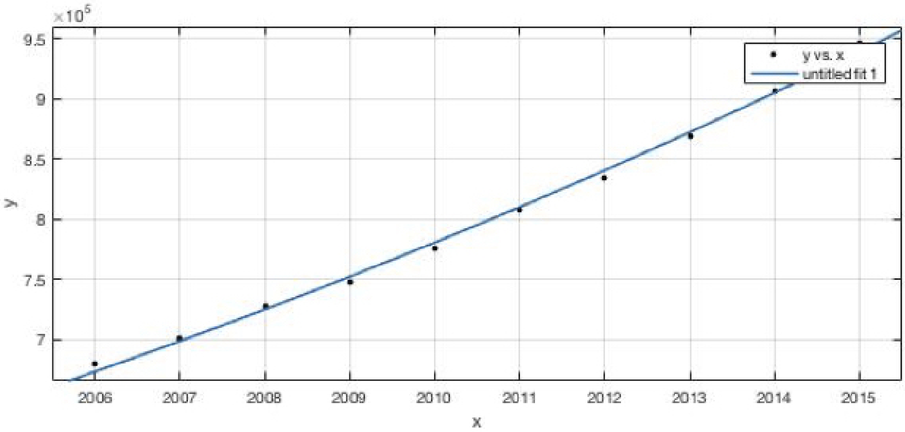



Figure 15:

By searching for average GDP and EV production, the total trend of EV increasing trend could be concluded as

$$N = 3.8^{-27} exp(0.037t)$$

where t is time in year and N is prediction of total number of EVs.

## 8 Conclusion

According to previous numerical analysis and model testing, we conclude that main model HDT is suitable for country with large area. It could basically reduce travelling waste path to offer a reasonable experience and construction idea. Other models, SRP is another further modification based on both model one and HDT. When considering the hinge position, we also add shortest route as first factor and condition. Then based on these conditions, we could make sure the waste rate is almost zero and also all charging stations could support any path to the destination.

For the future study, we propose simulations for other models and based on different countries who have different population distribution and landscape. Also, when comparing results, we could consider the waste rate and its relative usage efficiency according to surrounding areaâĂŹs traffic flow to test the necessity. Then when analysing the results, we can compare each modelsâĂŹ strengths and weakness with simulations on different countries.

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# Appendices

## Appendix A simulation code

Here are simulation programmes based on dijkstra algorithm in our SRP model to find the shortest path as follow.

## python simulation

```
# the shortest distance
    def find_shortest(self, start, end):
        # org, not will be replaced
        org_start = start
        org_end = end

        # set costs inf
        costs = {}
        inf = float("inf")
        # first to 0, or it will endless
        costs.setdefault(start, 0)
        for i in list(self.co_map):
            costs.setdefault(i, inf)

        # process for filter unprocessed point
        process = []
        parens = {"A": None}
        while start != end:
            # if end in neighbors, end program, get the dis
            if end in self.ne_map[start]:
                break
            # update neighbors weight
            for i in self.ne_map[start]:
                if i not in process:
                    current_dis = self.compute_dis(self.co_map[start][0], self.co_map[i][0],
                                                   self.co_map[start][1], self.co_map[i][1])
                                                   # find the smallest weighted neighbor as the
                                                   if current_dis + costs[start] < costs[i]:
                                                       costs[i] = current_dis + costs[start]
                                                       parens.setdefault(i, start)
            # add this point as processed
            process.append(start)
            # return the smallest
            start = [i[0] for i in sorted(costs.items(), key=lambda x: x[1], reverse=False) if
                     i[0] not in process][0]
                parens[end] = start
                costs[end] = costs[start] + self.compute_dis(self.co_map[start][0], self.co_map
                                                             self.co_map[start][1], self.co_map
                return self.find_path(parens, org_start, org_end)

    '''
    work principle likes this(end: F, start: A)
    F B D E A
    B D E A None
    F has a special key for link the start
    '''
        def find_path(self, link_dict, start, end):
        path = []
        while end != start:
            path.append(end)
            end = link_dict[end]
path.append(start)
path.reverse()
return path
```

# Appendix B Handout

## B.1 Findings from Our Research

After having studied on planning charging station network in three different types of country: the United States, South Korea and Australia, we can conclude there are three factors concerning with developing nationwide charging station network:

- Population
  - The distribution of population
  - The density of population
  - Vehicle per person
- Traffic network
  - Traffic flow
  - Tendency of residentsâĂŹ movement
- The Average Performance of EV
  - Cruise Range
  - Charging Time

In addition, there are key factors that influence the planning schedule for migrating the motor vehicles to EVs:

- Wealth distribution
  - Monthly income per capita
  - Average EV price
  - Cost of recharging
  - Subsides from government
  - Sales rate of EV
- Development of electric charging infrastructure
  - Coverage rate of charging stations network
- Current policy

## B.2 Summary

In conclusion, to migrate personal transportation to all-electric cars, two aspects are mainly considered. First, population, traffic network and property of EV are key factors. A strong charging electric power support is an essential condition. Secondly, developing schedule depends on local financial condition, construction period and policy. Based on these factors, a proper plan could be arranged according to specific circumstance. Reasonably, efficiently and systematically to expand advanced trip mode is current pursuit and efforts are taken for a better place. The gas vehicle-ban date is set when evolution of migration reaches 96%.