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Game Theory Analysis of Electric Vehicles Adoption in Beijing under License Plate Control policy

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ABSTRACT

To mitigate traffic congestion and improve environment condition, license plate control(LPC) policy has been implemented in Beijing since 2011. For instance, almost 100,000 vehicle license plates are distributed in 2019, including 60,000 electric vehicle (EV) license plate and 40,000 gasoline vehicle (GV) license plate. This paper tends to quantify the optimal EV license plate under the LPC policy in Beijing. A two-level Stackelberg game is proposed to model the interaction between vehicle consumers and the government. The equilibrium allocation of EV and its market share are derived from the Stackelberg model. According to the optimal result, the government should adjust the license plate distribution in order to maximize social utility. Once the government plans to enlarge the total quota to meet the excessive demand in the future, more quotas should be allocated to EV to promote EV adoption. Sensitive analysis is conducted to illustrated the impact of certain influential factors such as gasoline price, electricity price, and renting cost, on EV adoption. The result shows that when gasoline price is in a comparatively low level, consumers are more sensitive to the electricity price. Nevertheless, it becomes less significant if gasoline price goes higher. Besides, the impact of car-renting cost variation on EV adoption is studied. To be specific, if the car-renting cost declines from 2377 CNY/month to 1577 CNY/month due to the mature of renting market, the market share of EV will increase by 0.3%.

Keywords: Electric Vehicle, License plate control(LPC) policy, Stackelberg game theory, EV market share

1. INTRODUCTION

Beijing has been facing certain challenges such as decreasing air quality and deteriorated traffic congestion for a long time. Under this circumstance, replacing GV with EV becomes a prevalent trend in the transportation sector (Yuan and Liu et al., 2015). Theoretically, policies aiming to improve EV penetration include demand-based policies and supply-based policies (Zhuge and Wei et al., 2020). This paper will mainly focus on the demand-based policies which can be classified into economic and non-economic policies. In fact, certain economic incentives had been implemented by Beijing government such as GV purchasing tax increment in 2004, public transportation fares reduction in 2007, subsidies for EV and infrastructure since 2011, and EV purchasing tax exemption in 2014. There is no doubt that in the short term, these economic incentives increase the competitiveness of EV more or less. However, each of them has flaws and cannot limit vehicle quantity effectively in the long run (Zhuge and Wei et al., 2020). Consequently, economic incentives are inadequate to improve EV adoption in metropolitans such as Beijing, Shanghai, and Guangzhou.

Non-economic incentives, license plate control (LPC) policy in particular, should be taken into the consideration by the authority. To be specific, each year, LPC policy regulates license plate quota of GV and EV respectively. Under LPC policy, Beijing government distributes purchase permits to EV consumers, whereas GV consumers need to compete for the permits each year within a lottery system conducted by Beijing Municipal Commission of Transport on 26th every two months. Each lottery winner receives a nontransferable certification to purchase a vehicle (Yang and Liu et al.,

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2014). The annual license plate allocation in Beijing is shown as below:

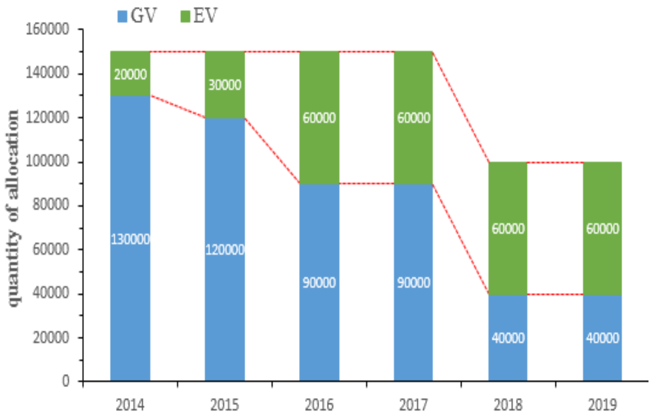

Fig. 1. License plates allocation from 2014 to 2019 in Beijing

In 2019, for instance, over 3350500 GVs applicants have registered on the website according to the statistical result of eBeijing, whereas the annual quota of GV license plate is 40000. Approximately, the probability of winning a GV license plate is 0.2%, which means that a consumer need to spend almost 41 years winning a GV license plate. By contrast, it would take a EV consumer only 9 years to obtain a EV license plate by queuing up.

License plate allocation influences the purchasing decision of each consumer, which can exert an impact on individual utility, cost of waiting time as well as fuel consumption, and even social utility. However, given a fixed annual total quota, how to allocate the license plates between EV and GV in order to maximize social utility has not been analyzed in the current literature. Different from the existing literature, this paper aims to identify the optimal license plate allocation between EV and GV. The main contributions of this study are: First, Optimal license plate distribution of EV and GV under Beijing's LPC policy is quantified. Second, the influence of license plate distribution on the promotion of EVs is detected. Third, influential factors and their impact on EV adoption are explored and discussed, corresponding implications are offered to the authority.

The rest of this paper is organized as follows: In section 2, we propose the methodology including the formation of Stackelberg model and proves the existence of equilibrium results. In section 3, we obtain practical equilibrium results by inserting real value of parameters. In section 4, we discuss the results and explore further implications in order to improve EVs adoption.

2. Literature review

2.1. Policies for improving EV adoption

Policies aiming to improve EV adoption can be classified into two categories: economic related incentives and non-economic related incentives. Economic incentives mainly include purchasing tax reduction or exemptions, subsidy for EVs as well as charging infrastructures ((Zhang, 2014); (Yang and Liu et al., 2014); (Helveston and Liu et al., 2015); (Zhu and Wang et al., 2019)). In particular, subsidy policy is the most widely-discussed economic incentive. (Jenn and Springel et al., 2018) proposed three distinct generalized models to investigate the effect of different incentives and found that every $1000 subsidy would increase the sales of EV by 2.6%. Similarly, using a large random sample of individual, (Sheldon and Dua, 2020) demonstrated that if the subsidy had been halved without countervailing policies, EV market share in China would have declined by 21%.

Although the subsidy policy has been regarded as an effective approach to improve EV diffusion, flaws and disadvantages still exist and cannot be ignored either: Firstly, Effect of the subsidy policy could only increase the competitiveness of EV in a short run. In the long run, as EV adopter increases, government tends to reduce the level of subsidy to alleviate financial burden, which weakens the effect of subsidy consequently (Zhuge and Wei et al., 2020). Secondly, the implementation of subsidy policy is comparatively complicated. Once the incentive policy was conducted improperly, it would interrupt the vehicle market or even cause a backfire to it (Gneezy and Meier et al., 2011). Having witnessed the fluctuation of Sweden EV market in 2014 that EV market share in Sweden declined from 2.1% in August to less than 1.0% in November because of the rebate shortage, (Tietge, 2017) implied that subsidy might result in unexpected damage to the EV improvement under certain extreme circumstance.

By contrast, as a typical non-economic policy, LPC policy will be mainly discussed in this study. After the first LPC policy was implemented in Shanghai in 1994, in 2010, Beijing proposed a unique LPC policy which simultaneously regulated the license plate allocation of EV and GV within lottery systems (Wang and Zhao, 2017). Specifically, given fixed quantity of EV and GV license plates, consumers who would like to purchase EVs or GVs had to attend separate lottery systems in order to achieve license plates. However, to stimulate the EV adoption, Beijing government has cancelled the lottery mechanism on EV consumers and required them to queue up for obtaining EV license plates since October 2015. However, those who plan to purchase GV still need to enter a lottery system and compete for the purchase certificate (Zhang and Bai et al., 2018).

Generally, LPC policy includes auction and lottery (Yang and Liu et al., 2014), (Zhang and Bai et al., 2018), (Zhuge and Wei et al., 2020). Two reasons that lottery mechanism is chosen by Beijing government are illustrated by (Yang and Liu et al., 2014): Firstly, compared with the auction implemented by Singapore for the first time and followed by Shanghai in 1994 (Chen and Zhao, 2013), (Yang and Liu et al., 2014), lottery mechanism is more fair for all citizens. Without any requirement, applicants can register on government website for free. Secondly, having distributed the residential houses within lottery system successfully, Beijing government could apply a similar lottery system to vehicle market. So far, there are many literature focusing on the lottery mechanism implemented in Beijing. (Yang and Liu et al., 2014) analyzed the short term effect of lottery policy on Beijing's traffic situation and found that the congestion has been mitigated significantly because of the lottery policy. In more detail, they (Yang and Liu et al., 2020) estimated that the lottery mechanism would reduce the daily vehicle kilometers travelled and the usage of cars in rush hour by 15% and 10% respectively. By conducting survey on 332 respondents, (Zhang and Bai et al., 2018) assessed the influence of lottery policy on EV adoption and suggested that lottery policy was more suitable and powerful to promote EV penetration in Beijing. (Zhuge and Wei et al., 2020) proposed an agent-based model and asserted that not only did the lottery policy in Beijing influence the EV adoption significantly, but it also reduced the energy consumption and emission of vehicle.

Furthermore, due to Beijing's allocation mechanism that each vehicle consumer needs to attend the lottery system or queuing up system to obtain a GV or EV license plate, consumers are more sensitive to the specific allocation regulated by government which influences their vehicle usage utilities directly. However, research concentrating on this influential factor is still insufficient among current literature.

2.2. Models of EV incentive evaluation

Methodologies utilized to evaluate the efficiency of EV incentives are introduced by current literature, such as discrete choice model (Wang and Zhao, 2017), regression model (Sierzchula and Bakker et al., 2014) (Clinton and Brown et al., 2015) (Mersky and Sprei et al., 2016), agent-based model (Silvia and Krause, 2016) (Zhuge and Wei et al., 2020), multi-layer perspective model (Djalante and Djalante, 2012)(Figenbaum, 2017), and game theory model (Qin and Zhu, 2015)(Jang and Kim et al., 2018)(Zhu and Wang et al., 2019). To be specific, a discrete choice model involving 247 respondents is proposed by (Wang and Tang et al., 2017) to investigate the effectiveness of several potential policy incentives. The result shows that LPC and driving restriction policy in China have the most significant positive effects on EV penetration. By developing a multiple linear regression method, (Wang and Tang et al., 2019) found that direct subsidy scheme, could not account for the difference of EV penetration among countries. (Silvia and Krause, 2016) developed an agent-based model to stimulate and compare the effectiveness of four policies which aim to promote EV diffusion. Likewise, (Zhuge and Wei et al., 2020) proposed an agent-based spatial integrated urban model which was called SelfSim-EV to analyze the impact of incentive on individual consumer. The result showed that the purchase permits policy would exert significant impact on EV adoption.

Stackelberg model, as a type of game model, is applied frequently to model the hierarchical interaction among different stakeholders with distinct objectives (Zhu and Zhang et al., 2017) (Qin and Zhu, 2015) (Yu and Li et al., 2016) (Jang and Kim et al., 2018)). For example, in order to specify a robust strategy which improves the performance of EV market, (Qin and Zhu, 2015) established a trilateral Stackelberg game model including government, enterprises, and consumers. A sequential game was introduced by (Yu and Li et al., 2016) to model the interaction between charging infrastructure investor and EV consumer. (Zhu and Zhang et al., 2017) proposed a three-level Stackelberg game modeling the interaction between electricity supplier, the charging infrastructure operator, and crowdfunders. A stylized Stackelberg game within vehicle manufacturers, consumers, and energy suppliers was depicted and proposed by (Jang and Kim et al., 2018), aiming to identify strategic and policy implications for improving EV diffusion.

In this paper, we assumed that two players were involved in the vehicle market when allocating license plates under LPC policy: the government and vehicle consumers. The government regulates vehicle license plate allocation, then consumers decide to purchase EVs or GVs. Given this hierarchical interaction, a two-level Stackelberg game model is proposed by this paper which attempts to quantify EV license plate allocation and to explore influential factors and their influence on EV adoption.

3. Methodology

3.1. The formation of Stackelberg game

We assume that there are two players in the vehicle market: vehicle consumers and government. The government decides the specific allocation between EVs and GVs and carry it out. Given a fixed allocation, as a response, consumers have to choose whether to purchase EVs or GVs. The interaction between these two participants is illustrated in the diagram below.

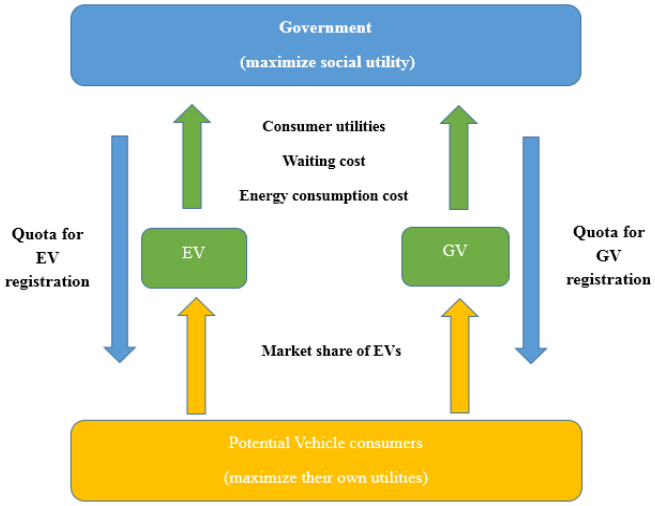

Figure.2. Diagram of the interaction between government and vehicle consumers

Typically, game theory is utilized to model the circumstance where decisions made by different participants would exert influence on others. In particular, a Stackelberg game is applied in this case in order to detect the interaction between the participants.

In this case, the government could regard as the leader, while the consumers are followers. The optimal decision of this scenario depends on both the government and consumers.

3.2. Consumers' decision model

To depict the choose faced by consumers, a binary choice model is proposed in this study. Consumers' utilities of purchasing electric vehicle and gasoline vehicle are shown respectively:

$$U_G = \beta1 * P_G + \beta2 * I_G + \beta3 * M_G + \beta4 * \frac{N_G}{(6*B_G)} + \varepsilon_G \quad (1)$$

$$U_E = \beta1 * P_E + \beta2 * I_E + \beta4 * \frac{(K-N_G)}{B_E} + \varepsilon_E \quad (2)$$

Where:

P_G, P_E are average prices of EVs and GVs; I_G, I_E are the quantities of fuel charging stations and charging piles in Beijing; M_G is the possibility of tail number restriction for a vehicle in Beijing; N_G is the specific allocation for GV; B_E describes the number of potential consumers who are willing to purchase EVs, whereas B_G is the number of consumers who tend to buy GVs; K is the total vehicle quota in Beijing 2020.

$\beta1$measures the consumer's sensitivity toward the price of vehicles; $\beta2$ refers to the consumer's sensitivity toward the number of infrastructures; $\beta3$ measures the impact of nail number restriction policy on consumer's utility; $\beta4$ refers to the sensitivity of consumer toward the possibility of achieving a license plate. Binary logit model(BNL) was used to assess the impacts of four factors on consumer purchasing behavior.

Besides, ε_G and ε_E are random variables, referring to the random preference of GVs and EVs consumers respectively. We assume that both ε_G and ε_E vary from 0 to 1 and that the relationship between two random variables is:

$$\varepsilon_G + \varepsilon_E = 1 \quad (3)$$

To maximize their own utilities, consumers need to decide individually which type of vehicle they would like to buy. For each person, the expected individual utility could be expressed as:

$$U_{consumer} = Max(U_G, U_E) \quad (4)$$

Combined the upper formula with the special property of ε_G and ε_E ($\varepsilon_G + \varepsilon_E$=1), the threshold of market share of GVs , η^*, can be deduced from it:

$$\frac{\left(\beta1*P_G+\beta2*I_G+\beta3*M_G+1-\beta1*P_E-\beta2*I_E-\beta4*\left(\frac{K}{B_E}\right)+\beta4*\left(\frac{1}{B_G}+\frac{1}{B_E}\right)*N_G\right)}{2} \quad (5)$$

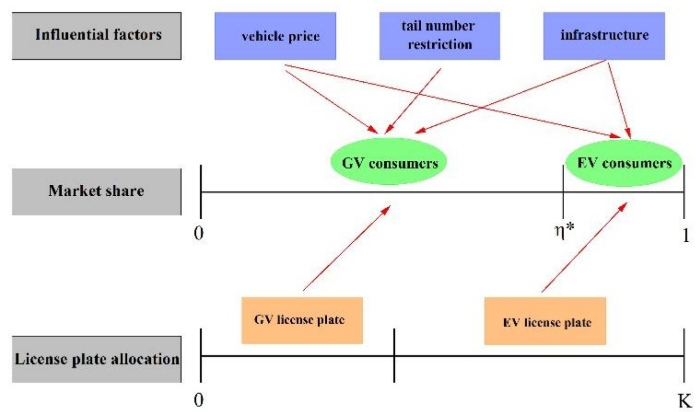

Figure.3. Diagram of the vehicle consumers' decision

The consumer's decision could be:

when $\eta > \eta^*$, $U_{consumer}$ = Max(U_G, U_E) = U_G , consumer chooses gasoline vehicle;

when $\eta < \eta^*$, $U_{consumer}$ = Max(U_G, U_E) = U_E , consumer chooses EV;

Consequently, the expected utility function for each consumer could be deduced:

$$U_{consumer} = \int_0^{\eta}\left(\beta1 * P_G + \beta2 * I_G + \beta3 * M_G + \beta4 * \frac{N_G}{(6*B_G)} + \varepsilon_G\right) d\,\varepsilon_G + \int_{\eta}^{1}(\beta1 * P_E + \beta2 * I_E + \beta4 * \frac{(K-N_G)}{B_E} + \varepsilon_E)\, d\varepsilon_E \quad (6)$$

3.3. Waiting time cost

Waiting time cost is the cost of consumers who are willing to purchase vehicles but do not achieve the license plates because of the license plates control(LPC) policy. We assume that they choose to rent vehicles in order to obtain similar experiences as those who have gotten their license plates and purchase vehicles.

However, the mechanism of distributing EVs and GVs are significantly distinct. Specifically, for GVs, Beijing government distributes license plates within a publicly held lottery, whereas EVs consumers need to queue up to obtain the license plates. Based on this fact, the expected waiting time for EVs and GVs consumers are formulated respectively.

3.3.1. expected waiting time of GVs consumers

To calculate the waiting time of consumers who tend to purchase GVs, a novel model is adopted in this paper. The expected waiting time is formulated as below:

$$[\int_0^{\infty} t * p * (1-p)^t * e^{\left(p*\left[1-\frac{(1-p)^t}{\ln(1-p)}\right]\right)} dt] * \frac{1}{6} \quad (7)$$

p is the expected chance of winning a license plate successfully in one lottery. To obtain the theoretical value of waiting time, practical value of probability would be input in the model.

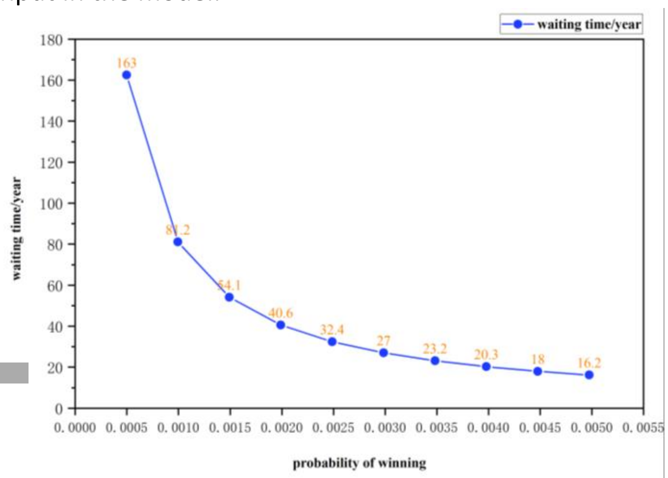

Figure.4. The relationship between the probability of winning and waiting time.

In 2019, the quantity of license plates of GVs is 40000, which means that for an individual GV consumer, the possibility of winning a license plate is only 0.2%. It approximately takes him/her 41 years to win a license plate.

3.5. Government's decision model

The government's aim is to maximize social utility which is decided by three parts: vehicle consumers' utilities, cost of waiting time, and cost of fuel consumption by the vehicles distributed in 2020.

The vehicle consumer's utilities are the gain of utility, whereas the waiting cost as well as cost of fuel consumption could be regarded as the utility losses. The underlying assumption for this social welfare function is that different utilities could be compared. Consequently, the coefficients λ1, λ2, and λ3 are integrated into the social utility function in order to compare the gain and loss of the utility directly.

Here is the social utility function considered by the government: $U_{social} = \lambda_1 * (U_{consumers}) - \lambda_2 * (\text{waiting time cost}) - \lambda_3 * (\text{fuel consumption cost})$

3.6. Stackelberg equilibrium

As the distribution of GV, N_G, varies from 0 to 100000, the variation of total social utility is depicted as below:

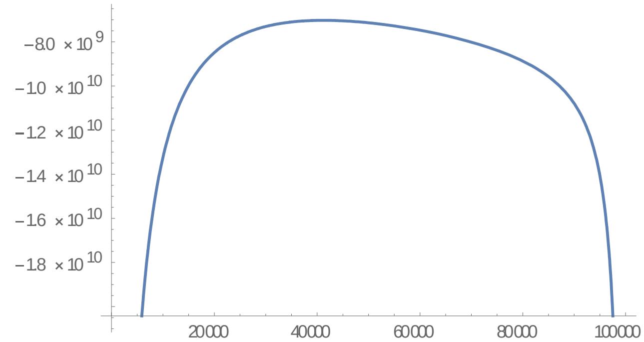

Figure.5. The impact of total vehicles distributed on total utility.

Theoretically, by analyzing the property of this curve, the optimal value (N_G^*) must exist. However, because of complexity of the formula itself, it is too demanding to calculate the exact algebraic result of N_G^* in this equation. Consequently, the optimal value of N_G^* is solved approximately with Wolfram Mathematica 11.3. The optimal market share of GV $\boldsymbol{\eta}^*$ can be expressed as:

$$\frac{\left(\beta1*P_G+\beta2*I_G+\beta3*M_G+1-\beta1*P_E-\beta2*I_E-\beta4*\left(\frac{K}{B_E}\right)+\beta4*\left(\frac{1}{6*B_G}+\frac{1}{B_E}\right)*N_G^*\right)}{2} \quad (8)$$

The market share of EV: 1-η^*

4. Estimation of parameter

Estimation of the key parameters involved in this study is shown in Table.1.as below:

Parameter	Estimated value	Parameter	Estimated value
λ1	1	P_E	15
λ2	0.046	P_G	10
λ3	10	I_E	6.1
β1	-0.32	I_G	0.904
β2	0.13	M_G	0.2
β3	-0.11	K	100000
β4	0.44	P_e	0.6
B_E	467400	P_g	5.31
B_G	3350500	c	2377

Table.1. The estimation of key parameters

5. Result analysis and implications discussion

5.1. Result of equilibrium

With the values inserted into the equation, the following equilibrium results can be obtained: The Optimal distribution for GVs, N_G^*, is 41200, whereas the Optimal distribution for EVs, k-N_G^*, is 58800; The market share of GVs is 92.60%, while the market share of EVs is 7.397%.

To better understand the final results and provide implications for policy-maker, this paper discusses the policy implications of total quota in 5.2. Then impacts of some vital factors on vehicle market will be introduced from 5.2.1. to 5.2.3.

5.2.1 Implication of total quota variation

In reality, the quota of total vehicles distributed in each year is not constant. Since 2018, government begins to reduce the quota up to 100000 in order to satisfy the need of emission reduction appealed by central government. it is important to analyze the impact caused by the variation of total quota on the EVs adoption. Beijing government tends to increase the total quota in the future.

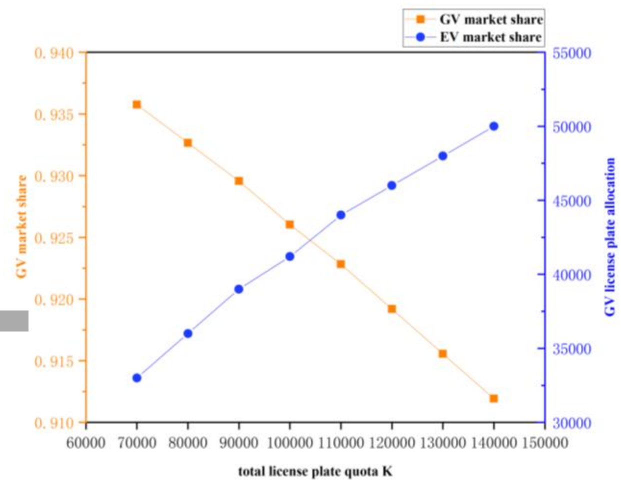

Fig.6. The influence of total quota on GVs market share and allocation

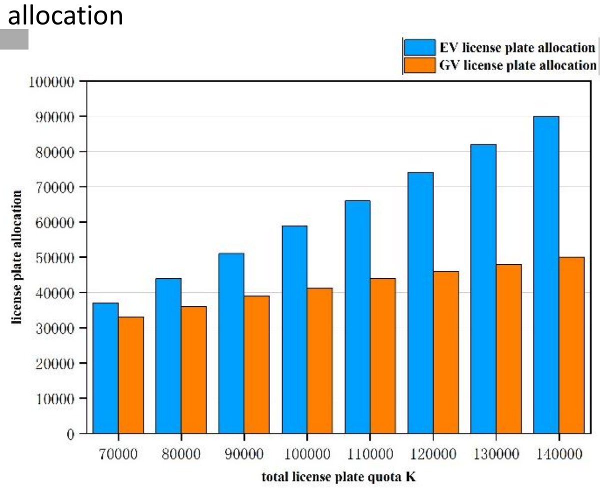

Fig.7. The influence of total quota on the allocation of EVs and GVs

Figure.7. shows that although the allocation of GVs increases, the market share of GVs declines as the total quota increases. For example, if total quota in future varies from 100000 to 140000, the absolute variation in EVs allocation is 24000, which is much higher than that of GVs (6000). Although the total quota has a tendency to enlarge, government prefers to meet the need of EVs consumers in order to control the energy emission as much as possible. Consequently, the government should enlarge the distribution of EVs license plate if it plans to increase the total quota in the future.

5.2.2. Implication of fuel price variation

In order to explore the impact of price of gasoline and electricity on the adoption of EVs, different levels of electricity prices are established. Setting the electricity price P_e to be 0.4 CNY/kWh, 0.6 CNY/kWh, and 0.8CNY/kWh respectively.

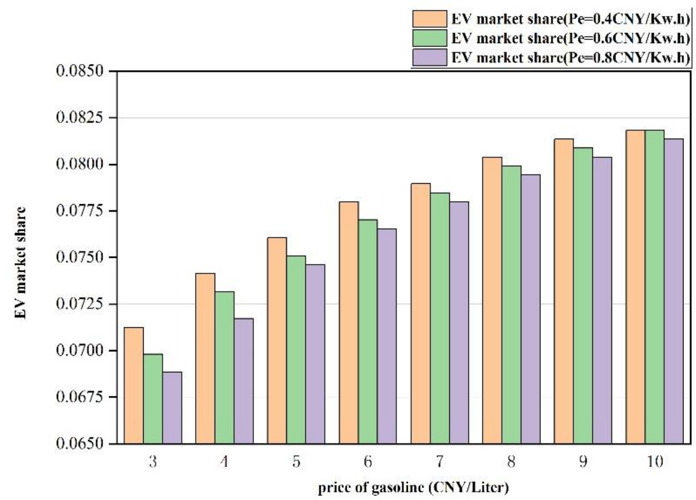

Figure.8. The impact of gasoline price on EVs market share under different electricity prices

Figure.8. shows that both the price of electricity and gasoline could exert influence on EVs adoption. However, the extent of influence of electricity price reduces as the gasoline price increases. Given a relative low level price of gasoline, 3 or 4 CNY/liter, the difference of electricity price influences EVs adoption significantly. The gap of market shares is almost 0%, where price of gasoline is 9 or 10 CNY/liter. It is because when making purchase decision, consumers are more sensitive to the electricity price when gasoline, as a substitute of electricity, is at quite a low level. However, if the price of gasoline becomes too high, compared with that of electricity, most of consumers would choose EVs without hesitate.

5.2.3. Implication of renting cost variation

Because of the LPC policy, only a small part of candidates could win the license plates fortunately, whereas the rest of them need to rent vehicles to gain similar usage experience. Therefore, the value of renting cost, as an important factor, is analyzed as below:

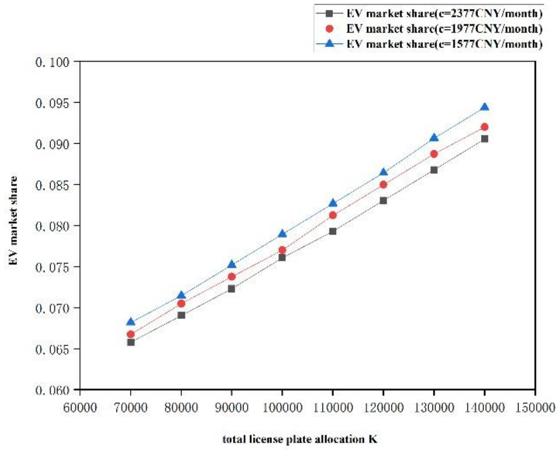

Fig.9. The impact of the renting cost on market share of EVs.

Figure.9. shows the influence of variation in renting cost on EVs adoption. Decreasing renting cost will further enlarge the EVs adoption. Lower renting cost means that consumers could stand relative longer waiting time and lower waiting cost. Under this condition, although the total quota increases, government inclines to allocate more license plates on EVs. Assume that the total quota in the future still equals to 100000, if the cost of renting a vehicle declines from 2377 CNY/month to 1577 CNY/month as the result of the mature of renting market, the EVs market share will increases from 7.4% to 7.9%.

6. Conclusion

This study quantified EV adoption in Beijing under the license plate control policy. A two-level Stackelberg game was proposed to model the interaction between vehicle consumers and government. The results that we obtain as follows indicate some implications to policy maker.

(1) Given a total quota of 100000 in 2020, the optimal license plate distribution to GV is 41200, whereas the allocation to EV is 58800. The market share of GV is 92.60%, while EV market share is 7.397%.

(2) If Beijing government were to enlarge the total quota in the future, the increment of EV license plate would be comparative larger than that of GV. Therefore, more licenses should be distributed to EVs, compared with GVs.

(3) Besides total quota, there are other factors which exert influence on the EVs adoption such as the fuel price and the renting cost. To be specific, when gasoline price is relatively low, the lower electric price would attract more consumers; when the gasoline price is too high, consumers would not be sensitive to electricity price and the market share of EVs increases significantly.

(4) It is important for government to keep renting cost in a low level in order to promote EVs adoption. For example, assume that the total quota in the future still equals to 100000, if the cost of renting a vehicle declines from 2377 CNY/month to 1577 CNY/month as the result of the mature of renting market, the EVs market share will increases up to 7.9%.

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