Adoption of Electric Vehicles: Manufacturers' Incentive and Government Policy

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Abstract: In the literature, auto manufacturers' incentives for adopting electric vehicles and their interactions with government policies are understudied, especially through an analytical approach. We develop a game-theoretic model to investigate what vehicle types should be produced from both private firm's and social perspectives. We then propose an EV-subsidy/environmental-tax policy and derive the optimal policy parameters that maximize social welfare. The monopoly and duopoly markets are examined and compared, and it is shown that the government should charge a higher environmental tax while offering a lower EV subsidy in the duopoly market than in the monopoly market. More complex market structures and the case of EV production capacity constraints are also investigated.

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1.0 Introduction

Electric vehicles (EVs) are seen as a potential solution to the growing environmental problem caused by gasoline vehicles (GVs). In 2016, the German and Indian governments announced that all new cars registered must be EVs by the year 2030 (Hayes, 2016). The United Kingdom, France, Norway, and the Netherlands have similar plans that replace GVs by EVs (Petroff, 2017). China, the world's largest car market, is preparing a plan to ban the production and sale of vehicles powered only by fossil fuels (Pham, 2017).

Although the global EV sales have rapidly grown from about 50,000 in 2011 to 1,281,000 in 2017 (EV Obsession, 2015; EV-Volumes, 2018), the adoption rate of EVs still remains relatively low. In the top three leading auto markets, namely, China, Europe, and the United States (US), EVs have a market share of about only 1 per cent (Cobb, 2017). The global market share of EVs was 1.34 per cent of total new car sales in 2017 (EV-Volumes, 2018). Among the barriers to consumers' EV adoption, empirical research has identified the two most important factors: EVs' high prices, mostly driven by the high cost of battery packs, and limited driving ranges (Larson *et al.*, 2014). Both factors result in a lower consumer net utility of an EV relative to that of a GV, which hinders the increase of EV demands. On the other hand, the high production cost, negative margin, and yet-to-be-growing demand of EVs result in auto manufacturers' hesitation in mass adoption of EVs. Under the current technology, in general, only with government subsidies is an EV manufacturer able to survive (Pappas, 2014; Colias, 2017).

Hence, to boost the EV adoption governments all over the world have come up with a variety of incentive schemes, such as support for EV R&D (research and development), investment on charging stations, free parking (Denmark), allowing EVs to use bus lanes and creating convenient parking zones (Germany), and exemption from license plate lottery (China) (Pappas, 2014). Yet the most common are financial incentives such as subsidies, tax exemption, and tax credit for EV purchasing. For example, Germany recently announced a €4,000 discount for all-electric vehicles (Lambert, 2016).

Under both the low adoption rates of EVs and vast government supportive efforts, three research questions arise naturally: First, under a given government policy, what are auto manufacturers' incentives for EV adoption? Second, is the ban on GV sales socially optimal? In other words, is it socially optimal to mandate all new vehicle sales to be electric? Third, how should a social planner design policies to elicit the social optimum?

Previous studies mainly adopt optimization and empirical approaches to investigate the effects of government policies on EV adoption and development; however, research using analytical, economic models is quite sparse. To fill this research gap, we develop a game theoretic model to address the above three research questions, which we believe adds a good contribution to the existing literature on government policies for EVs and associated consequences.

More specifically, we consider two types of markets. One is a monopoly market where a single auto manufacturer may produce GVs, EVs, or both. The other is a duopoly market where a GV manufacturer and an EV manufacturer compete; at equilibrium, one or both manufacturers may survive and remain in the market. In each market, we assume that consumers have heterogeneous valuations for both products (GVs and EVs). Consumers generally have lower valuation for an EV than a GV due to concerns about EVs' driving range, usage convenience, reliability, charging infrastructure availability, etc. (Larson *et al.*, 2014). Nonetheless, a consumer's usage cost for an EV is lower than that for a GV due largely to the low price of electricity relative to the fuel price. Each consumer makes the purchasing decision by evaluating his/her utility from a GV and an EV. Based on consumers' choices (hence, the demand functions), the manufacturers determine the price of each product to maximize their own profits.

However, the decisions of the private firms and consumers generally deviate from the socially optimal ones. In order to maximize social welfare, a government takes into account of the incentives of both the private firms and consumers, as well as the environmental impact of different vehicle types. At the social optimum, we show that a single or both vehicle types should be provided in the market, depending on an evaluation of the relative values of GVs' and EVs' marginal net social benefits. To attain the social optimum, we propose an EV-subsidy/environmental-tax policy that can align both the manufacturers' and consumers' incentives with the socially optimal decisions in terms of EV adoption.

In the rest of the paper, we first review related literature in Section 2, and then set up the model in Section 3. In Section 4, we consider a monopoly market and analyze the manufacturer's incentives for EV adoption, derive social optimum, and propose government policies. Section 5 examines a duopoly market where a GV manufacturer and an EV manufacturer compete; we derive market equilibrium and show policies that achieve social optimum. In Section 6, we discuss parameter estimations and policy implications. Section 7 extends the model to more complex market structures. Finally, Section 8 concludes the paper.

2.0 Literature Review

Several streams of literature study EV related issues. First, since the limited range is a major hurdle in EV adoption, a good number of research papers employ mathematical programming and other optimization approaches to study problems such as charging station deployment, battery swapping, and EV touring (He *et al.*, 2013; Avci *et al.*, 2015; Chen *et al.*, 2016; Liao *et al.*, 2016; Li *et al.*, 2016). The second research stream is concerned with consumers' attitude and choice for EVs. For example, Larson *et al.* (2014) conducted a survey on consumer attitudes toward EVs and found that consumers are unwilling to pay a large premium for EVs. Using experimental design data, Rasouli and Timmermans (2016) adopted a mixed-logit model to study the influence of social networks on latent choice of EVs. Lim *et al.* (2015) examined, through an analytical model, the impact of consumers' anxieties over range and resale on EV adoption. Plötz *et al.* (2014) identified that middle-aged men with technical professions living in rural or suburban multi-person households are most likely to buy EVs in Germany. Based on online surveys in Denmark and Sweden and regression analysis, Haustein and Jensen (2018) identified profiles of users who purchase EVs and GVs such as sex, education, and income.

While the above research helped us with the setup of our model capturing EV attributes and consumer preference, we focus on the interactions among government policy, firm strategy, and consumer choices concerning EVs, while abstracting away the issues of network deployment and technology development. Our goal is to understand private firms' incentives for EV adoption and propose public policies that elicit the socially optimal strategies associated with EVs.

Our work is related mostly to two strands of literature. One is the studies on various government policies and incentive schemes for EVs based on data and empirical or simulation approaches. In particular, several papers studied the financial incentives such as EV subsidies, tax exemption, and tax credits. For example, Gallagher and Muehlegger (2011) studied the relative efficacy of state sales tax waivers, income tax credits and non-tax incentives that induce consumer adoption of hybrid EVs. Beresteanu and Li (2011) found that gasoline price and income tax incentive program significantly affected the demand for hybrid EVs in the US. Shepherd *et al.* (2012) examined the impact of factors such as subsidies, range, and emission rates on future EV demand. Hao *et al.* (2014) reviewed China's EV subsidy scheme and estimated the impact on EV demand. Helveston *et al.* (2015) measured consumer preferences for EVs and examined whether subsidies drive EV adoption. Using a survey, Bjerkan *et al.* (2016) identified that exemptions from purchase tax and VAT are critical incentives for EV purchasing decisions in Norway. Using simulation, Gnann *et al.* (2015) compared the impact of several monetary policy options on EV stock in 2020, and found that a €1000 subsidy is most effective and efficient in EV diffusion.

While all the above papers used empirical or simulation approaches to investigate government policies' effects on EV adoption and development, research using game-theoretic, analytical models to study government policies for EVs are quite limited. Notice that in the above papers, depending on data collected, results on the effect of certain policies may vary across regions and/or time regarding. Whereas, our theoretic modelling framework enables us to provide an explanation for the variation in results regarding certain policies as well as manufacturers' incentives for EV adoption. We further suggest the socially optimal policy design under different conditions.

The other research strand uses analytical models to study auto manufacturers' strategies concerning EVs under the impact of EV policies (Luo *et al.*, 2014; Huang *et al.*, 2013; Wang *et* *al.*, 2015). Luo *et al.* (2014) showed that the manufacturer's profit is increasing in the discount rate and subsidy ceiling for EVs, which is consistent with our findings. However, Luo *et al.* (2014) assumed that the government's objective is solely to increase the manufacturer's EV production incentive, and set the "optimal" policy parameters accordingly. In contrast, we solve the welfare maximization problem to determine the optimal policies. Huang *et al.* (2013) assumed that the government adopts EV subsidy policy and examined the impact of EV subsidy on welfare *numerically*. We instead use a game-theoretic model to characterize, analytically, the effective policies to achieve the social optimum. Wang *et al.* (2015) abstracted away and treated the manufacturer's and government's decisions such as price, quantity, subsidy and tax as exogenous. On the other hand, we consider these decisions as endogenous and derive their optimal values in equilibrium. Moreover, in contrast to Wang *et al.*, we derive demand functions based on a consumer utility and choice model that reflects differences between GVs and EVs, and propose a public policy that elicits the social optimum concerning EV adoption.

3.0 The Model

Consider a market where two types of consumer vehicles may be available: a gasoline vehicle (GV) and an electric vehicle (EV). A consumer's valuation for the GV is V, which is a random variable with a uniform distribution on $[0,1]$.[1] The realization of V is denoted by v. A consumer's valuation for the EV is αv, where $\alpha \in (0,1)$.[2] The discount in consumers' valuation for the EV is mainly due to consumers' disutility from the perceived limited driving

[1] The assumption that consumers' valuation follows a uniform distribution reflects heterogeneity in consumers' perception toward the vehicles. In reality, consumers' valuation is not necessarily distributed uniformly; more complicated distributions can be utilized to simulate consumers' behavior, e.g., normal, exponential, etc. However, the uniform distribution assumption facilitates our analytical derivation and ensures closed-form solutions.

[2] We adopt the Mussa-Rosen model as the basis of our consumer choice model (Mussa and Rosen, 1978). The merit of this consumer choice model is its simplicity and the ability to capture the heterogeneous consumer behavior when facing vertically differentiated products. The demand functions derived from the Mussa-Rosen based model are linear in prices, which ensures the tractability of our model.

ranges of electric batteries, charging time of batteries, inconvenience in usage, and lack of charging infrastructure (Larson *et al.*, 2014; Rezvani *et al.*, 2015). However, since the fuel cost is much higher than the electricity cost, consumers pay a higher usage cost for a GV than for an EV. We denote by ω a GV consumer's usage cost over the life-time of the GV discounted to present, while normalizing this cost for EVs to zero. For analytical tractability, we focus on consumers' heterogeneous valuation for a vehicle while abstracting away their heterogeneity in other dimensions such as usage costs. Let s be the government's subsidy to a consumer who purchases an EV.[3]

The prices of GVs and EVs are denoted by p_1 and p_2 respectively (the subscripts indicate the type of the vehicle: "1" for GV and "2" for EV). Denote by c_1 and c_2 the per-unit production costs of GVs and EVs respectively. Empirical research shows that producing an EV is more costly than producing a GV (Parks *et al.*, 2007). This is mainly due to the high cost of EV batteries. Hence, we assume that $c_1 > c_2$.

Consider two market structures. First, a monopoly manufacturer maximizes its profit by choosing from three potential product mix strategies: (i) producing GVs only, (ii) producing EVs only, and (iii) producing both GVs and EVs. Second, an EV manufacturer competes with a GV manufacturer; three market outcomes are possible in equilibrium: (i) only the GV manufacturer stays in the market, (ii) only the EV manufacturer stays in the market, and (iii) both the GV and EV manufacturers stay in the market. We assume that when a GV manufacturer is out of the market, it cannot transfer to produce EVs; vice versa.[4]

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[3] A tax credit is mathematically equivalent to a subsidy. Also, one can assume that the subsidy is offered to the EV manufacturer rather than consumers, which will not affect our results either.

[4] More complex market structures such as an oligopoly market may be more realistic in the real world. However, for analytical tractability of the model, we consider the monopoly and duopoly markets in our model. In the duopoly market, we also assume that each manufacturer produces only one product. In Section 7.1 we consider an extension where two competing manufacturers

We assume that each GV incurs a per-unit environmental cost e, and the environmental cost of EVs is normalized to be zero.[5] So, e represents the difference in the per-unit environmental cost between GVs and EVs. We also assume that $1 - \omega - c_1 - e > 0$ and $\alpha - c_2 > 0$ to avoid the trivial outcomes that it is never socially beneficial to produce GVs or EVs. (Since the environmental cost of EVs is normalized to be zero, when $\alpha - c_2 > 0$ is satisfied, we avoid the outcome that EVs should never be produced at social optimum.)

The sequence of events is as follows: (i) the social planner determines and announces relevant policies including EV subsidy s; (ii) the manufacturer(s) determine the product mix strategy, and the price and quantity of each product; and (iii) consumers make purchasing decisions.

4.0 A Monopoly Market

We first examine the market with a monopoly auto manufacturer. We solve the game backwards. Specifically, we first determine the manufacturer's optimal product mix strategy for a given government subsidy to EVs. We then examine the social optimum. And finally, we propose government policies that attain the social optimum, given the monopoly manufacturer.

4.1 The Manufacturer's Optimal Strategy

We denote the manufacturer's three potential product mix strategies as "G" for producing GVs only, "E" for producing EVs only, and "B" for producing both GVs and EVs. Under strategy G, the manufacturer chooses an optimal price of the GV, p_1^G, to maximize its profit

produce both GVs and EVs each.

[5] The environmental impacts of GVs and EVs include air pollution caused by emissions, noise, congestion, and accidents (Jochem *et al.*, 2016). While the other impacts do not differ significantly between GVs and EVs, EVs have considerable advantage in reduction of tank-to-wheel emission, local air pollution and noise. However, the well-to-tank emission of EVs highly depends on the electricity generation method to charge the batteries. If the share of renewables in energy generating increases, then EVs may cut greenhouse gas emissions by 25-50 per cent relative to GVs (Archsmith *et al.*, 2015).

$\pi^G = (p_1^G - c_1)D_1^G(\,p_1^G)$ (the superscript represents the corresponding strategy). The demand function $D_1^G(\,p_1^G)$ is derived as follows: If the manufacturer sets the price of GV to p_1^G, then consumers whose valuation for the GV is greater than their total cost $p_1^G + \omega$ will purchase the product. Since consumers' valuations are uniformly distributed, this implies that $1 - (p_1^G + \omega)$ consumers will purchase the GVs. Therefore, the demand for the GV is D_1^G=$1 - p_1^G - \omega$.

We take the first derivative of π^G with respect to p_1^G and equalize it to zero. Solve and obtain the firm's optimal price, demand, and profit ("*" indicates the firm optimum):

$$p_1^{G*} = \frac{1+c_1-\omega}{2},\ D_1^{G*} = \frac{1-c_1-\omega}{2},\ \pi^{G*} = \frac{(1-c_1-\omega)^2}{4} \tag{1}$$

If the manufacturer adopts strategy E, then a consumer's utility from purchasing an EV is $\alpha v - p_2^E + s = 0$. The marginal consumer who is indifferent from buying an EV and not buying satisfies $\alpha v - p_2^E + s = 0$. This marginal consumer therefore has a valuation $(p_2^E - s)/\alpha$. Thus, the total number of consumers who are willing to buy the EV is $D_2^E(p_2^E) = 1 - (p_2^E - s)/\alpha$. The manufacturer's profit function is hence $\pi^E = (p_2^E - c_2)D_2^E(p_2^E)$.

We solve the manufacturer's profit maximization problem and obtain the manufacturer's optimal price, demand, and profit under strategy E:

$$p_2^{E*} = \frac{\alpha+c_2+s}{2},\ \ D_2^{E*} = \frac{\alpha-c_2+s}{2\alpha},\ \ \pi^{E*} = \frac{(\alpha-c_2+s)^2}{4\alpha} \tag{2}$$

Furthermore, if the manufacturer adopts strategy B, then the manufacturer's profit, π^B, consists of the profit from both GV and EV sales, that is, $\pi^B = (p_1^B - c_1)D_1^B(\,p_1^B, p_2^B) + (p_2^B - c_2)D_2^B(p_1^B, p_2^B)$. To derive the demand functions, consider a consumer's whose valuation for the GV is v. Then this consumer's utility from a GV is $v - p_1^B - \omega$; and his/her utility from purchasing an EV is $\alpha v - p_2^B + s$. The marginal consumer who obtains equal utility from purchasing GV and EV satisfies $v - p_1^B - \omega$= $\alpha v - p_2^B + s$. Solve and get $v = (p_1^B - p_2^B +$

$\omega + s)/(1-\alpha) \equiv v_1$. Furthermore, the marginal consumer who is indifferent between purchasing an EV and nothing satisfies $\alpha v - p_2^B + s = 0$; solve and get $v = (p_2^B - s)/\alpha \equiv v_2$. Thus, the demand for GVs is $D_1^B = 1 - v_1 = (1 - \alpha - \omega - s - p_1^B + p_2^B)/(1-\alpha)$; and the demand for EVs is $D_2^B = v_1 - v_2 = (\alpha\omega + s + \alpha p_1^B - p_2^B)/(\alpha(1-\alpha))$.

For a given subsidy s, the manufacturer determines the prices, p_1^B for GVs and p_2^B for EVs, to maximize its profit. We solve the two FOCs, $\frac{\partial \pi^B}{\partial p_1^B} = 0$ and $\frac{\partial \pi^B}{\partial p_2^B} = 0$, and obtain:

$$p_1^{B*} = \frac{1+c_1-\omega}{2},\ D_1^{B*} = \frac{1-\omega-\alpha-c_1+c_2-s}{2(1-\alpha)},\ p_2^{B*} = \frac{\alpha+c_2+s}{2},\ D_2^{B*} = \frac{\alpha\omega+\alpha c_1-c_2+s}{2\alpha(1-\alpha)} \quad (3)$$

We can now compare the manufacturer's profit under the three strategies and derive the manufacturer's optimal strategy under a given s. Note that in Eq.(3), two conditions must be satisfied such that the demands D_1^{B*} and D_2^{B*} are non-negative; that is, $s \le 1 - \omega - \alpha - c_1 + c_2$ and $s \ge c_2 - \alpha c_1 - \alpha\omega$. We hence obtain two thresholds $s_1 \equiv c_2 - \alpha c_1 - \alpha\omega$ and $s_2 \ge 1 - \omega - \alpha - c_1 + c_2$. If $s < s_1$, then $D_2^{B*} = 0$, which implies that strategy B reduces to strategy G. If $s > s_2$, then $D_1^{B*} = 0$; and strategy B reduces to E. For $s_1 \le s \le s_2$, we can show that strategy B dominates both G and E. Therefore, we have the following lemma:

Lemma 1 *For a given subsidy s, the manufacturer's optimal strategy is*

a) to only produce GVs if $s < s_1$*;*

b) to produce both GVs and EVs if $s_1 \le s \le s_2$*;*

c) to only produce EVs if $s > s_2$

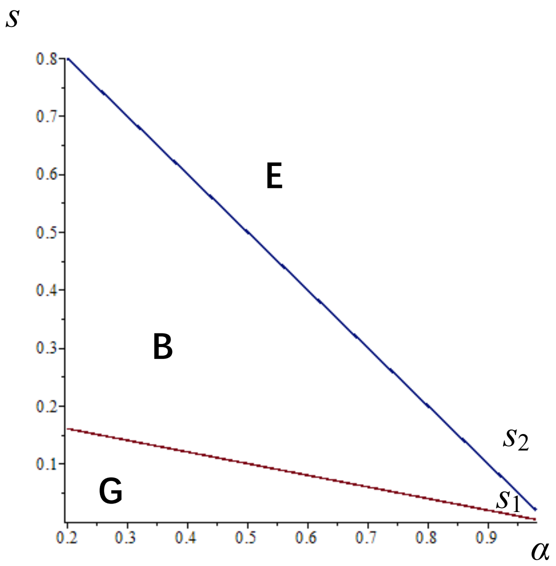
All the proofs are given in the Appendix. Lemma 1 indicates that all three strategies can be optimal depending on the value of the subsidy to EVs, s, relative to the other parameters. Specifically, if s is sufficiently large, then it is profitable for the manufacturer to produce EVs only. If s is too small, then the manufacturer would produce GVs only. Only if s is neither too large nor too small, is the benefit-cost ratio of producing GVs and EVs balanced; and it is optimal for the manufacturer to produce both products.

We then examine the thresholds s_1 and s_2, which consist of parameters α, ω, c_1, and c_2 See Figure 1 for illustrations. As consumers' perceived value for an EV relative to a GV increases (to the right of Figure 1 (a)), or consumers' usage cost for GVs increases (to the right of Figure 1 (b)), or the difference in the production costs between EVs and GVs decreases (to the left of Figure 1 (c)), EVs are more profitable compared with GVs. Both thresholds s_1 and s_2 are small in this case, which indicates that for a large range of parameter values ($s > s_2$), the manufacturer should produce EVs only. In the opposite case, that is, α or ω is small, or the difference between c_1 and c_2 is large (to the left of Figure 1 (a) or (b), or to the right of Figure 1 (c)), both s_1 and s_2 are large. GVs are relatively more profitable than EVs, and so for a large range of parameter values ($s < s_1$), the manufacturer produces GVs only.

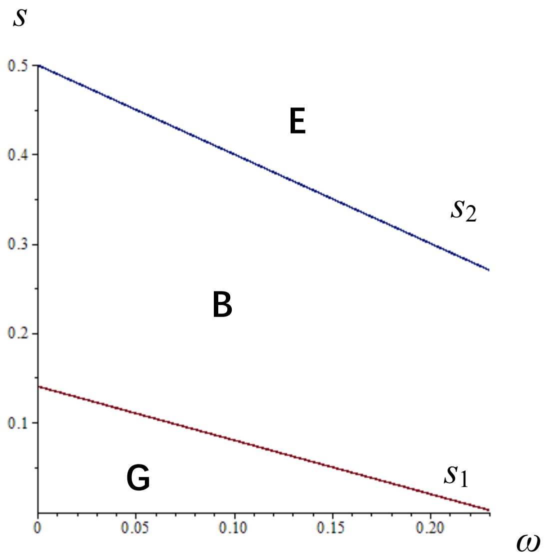
The implication of Lemma 1 is that the manufacturer's incentive for EV adoption highly depends on the government's subsidy to EVs and the relative profitability of EVs and GVs. Furthermore, we analyze how a change in the government subsidy to EVs affects the manufacturer's profit and consumer surplus and find the following property:

Remark 1 *If the manufacturer produces EVs (adopting strategy E or B), then both the manufacturer's profit and consumer surplus increase in EV subsidy s.*

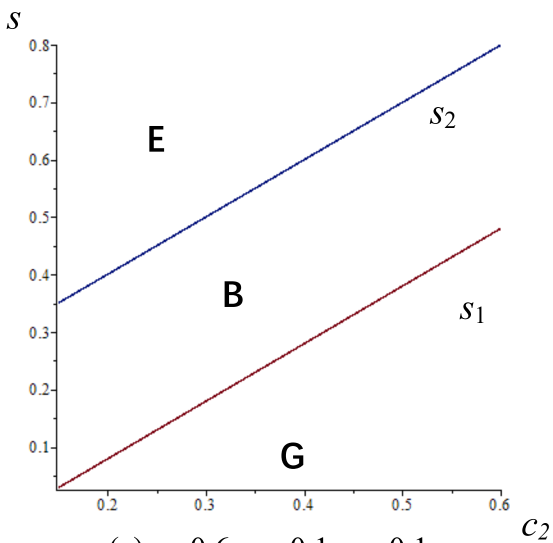
It is intuitive that if EVs are produced and sold in the market, then both the manufacturer and consumers benefit from an increase in the subsidy to EVs. Remark 1 implies that the EV subsidy is effective in promoting EVs by boosting both the manufacturer's profit and consumer surplus. However, to maximize social welfare, the social planner should consider not only firm profit and consumer surplus, but also the social cost of the policy and impact on the environment. In the next subsection, we derive the social optimum, which is followed by determination of the optimal policy that elicits the social optimum in Section 4.3.



(a) ω=0.1, c_1=0.1, c_2=0.2



(b) α=0.6, c_1=0.1, c_2=0.2



(c) α=0.6, ω=0.1, c_1=0.1

Figure 1: Thresholds s_1 and s_2 and the monopolist's optimal strategies G, B, and E.

4.2 Social Optimum

Consider a centralized economy, where the manufacturer is state-owned and the products are provided to consumers based on their utility from consumption (as well as on the production and environmental costs). A social planner makes decisions on what product(s) to produce and the production quantity of each product to maximize social welfare.

Consider three product mix schemes: In the first scheme, only GVs are produced and provided (referred to as "scheme G"). Under this scheme, the total social benefit (TSB) comes from the aggregate of utility of each consumer who obtains and uses a GV. Suppose that q_1^G GVs are produced and offered. The consumer who has the largest utility from consumption is the one with the highest valuation for a GV, that is, $v = 1$. (Recall that consumers' valuation for GVs V follows a uniform distribution on [0,1].) The utility of the "last" consumer who obtains the GV has a valuation equal to $1 - q_1^G$. Therefore, the total consumer utility when q_1^G GVs are offered equals $(1 - \omega + 1 - q_1^G - \omega)q_1^G/2 \equiv TSB^G$ and the marginal social benefit equals $1 - \omega - q_1^G$. The total social cost (*TSC*) consists of the production cost and environmental impact of GVs, that is, $TSC^G = (c_1 + e)q_1^G$. The marginal social cost is then $c_1 + e$. Equalizing the marginal social benefit and cost yields the socially optimal quantity of GVs, which is $1 - c_1 - \omega - e \equiv q_1^{G\dagger}$ (superscript $\dagger$ indicates the social optimality). We can then obtain the optimal social welfare $SW^{G\dagger} = (1 - c_1 - \omega - e)^2/2$.

In the second scheme, only EVs are produced and provided ("scheme E"). The social benefit is consumers' utility of using EVs, which is $TSB^E = (\alpha + \alpha(1 - q_2^E))q_2^E/2$. The total social cost equals the cost of producing EVs, that is, $TSC^E = c_2 q_2^E$. Equalizing the marginal social benefit and cost gives us the optimal quantity of EVs: $q_2^{E\dagger} = 1 - c_2/\alpha$. And the optimal social welfare is $SW^{E\dagger} = (\alpha - c_2)^2/(2\alpha)$.

Finally, the third scheme refers to the situation where both GVs and EVs are produced and provided ("scheme B"). The total social benefit is the sum of the utility of both GV and EV consumers, that is, $TSB^B = \big(1 - \omega + (1 - q_1^B - \omega)\big)q_1^B/2 + \big(\alpha(1 - q_1^B) + \alpha(1 - q_1^B - q_2^B)\big)q_2^B/2$. And the total social cost consists of the environmental cost of GVs and production cost of EVs, that is, $TSC^B = (c_1 + e)q_1^B + c_2 q_2^B$. The social planner will choose the optimal quantities q_1^B and q_2^B to maximize social welfare $SW^B = TSB^B - TSC^B$. Solving the first order conditions with respect to q_1^B and q_2^B, we obtain the socially optimal quantities of GVs and EVs:

$$q_1^{B\dagger} = \frac{1-\omega-\alpha-c_1+c_2-e}{1-\alpha},\ q_2^{B\dagger} = \frac{\alpha c_1+\alpha\omega+\alpha e-c_2}{\alpha(1-\alpha)}. \tag{4}$$

We now compare the three schemes and derive the product mix that achieves the maximum social welfare. Let $e_1 \equiv c_2/\alpha - c_1 - \omega$ and $e_2 \equiv 1 - \omega - \alpha - c_1 + c_2$; we have the following proposition:

Proposition 1 *It is socially optimal to*

a) produce GVs only, if $e < e_1$*;*

b) produce both GVs and EVs, if $e_1 \le e \le e_2$*;*

c) produce EVs only, if $e > e_2$*.*

Note that in a centralized economy, there is no subsidy for EVs. A key parameter is *e*, that is, the environmental cost incurred by GVs relative to EVs. It is intuitive that as *e* increases, the social planner should decrease the quantity of GVs while producing more EVs. At the same time, consumers' perceived value for EVs, GVs' usage cost, and the production cost difference between EVs and GVs still play important roles in determining the socially optimal product mix. Specifically, a high consumers' perceived value for EVs or a low additional production cost of EVs relative to GVs indicates a high net social benefit that an EV can provide; whereas a low GVs' usage cost or a low environmental cost of GVs relative to EVs indicates a high net social benefit of a GV. So, the socially optimal product mix is determined by balancing the marginal net social benefits of EVs and GVs. In particular, only if the marginal net social benefits of GVs and EVs are fairly balanced, should both products be produced.

4.3 Policy Inducing Social Optimum

In order to attain the social optimum, the planner should induce the manufacturer to choose the socially optimal product mix as well as socially optimal quantities of the products. Note that the social planner only needs two policy instruments to align the private firm's incentives, one for the quantity of each product. This is because once the quantities of both products achieve social optimum, the product mix is also socially optimal. For example, if the socially optimal strategy is E, then we only need to induce the manufacturer to produce the socially optimal quantity of EVs and zero quantities of GVs.

Therefore, we propose an EV-subsidy/environmental-tax policy to elicit the optimal quantities of both EVs and GVs. Specifically, the government offers a subsidy s to each EV buyer; and for each GV, the government charges the manufacturer an environmental tax, denoted by t, for each GV sold.[6]

We first consider the case where it is socially optimal for the manufacturer to produce EVs only (scheme E is socially optimal). Suppose that the social planner offers a subsidy s for each EV; then from Section 4.1, the manufacturer will produce $D_2^{E*}(s) = (\alpha - c_2 + s)/(2\alpha)$ number of EVs. Recall the socially optimal quantity in Section 4.2, $q_2^{E\dagger} = 1 - c_2/\alpha$. Compare the two quantities, we find that $q_2^{E\dagger} > D_2^{E*}(s)$ if s=0. So, in order to induce the manufacturer

[6] Environmental taxes have been applied to auto manufacturers for producing and selling cars in many countries (ACEA (European Automobile Manufacturers Association), 2017; People's Daily Online, 2010). Alternatively, the environmental tax can be charged to GV consumers for the usage of gasoline, rather than the GV manufacturer, for example, the California Carbon Tax Law imposes a carbon tax on suppliers of fossil fuels (California Legislative Information, 2014). In our model, the two setups will lead to the same result.

to produce $q_2^{E\dagger}$, we need to offer a positive EV subsidy. Equalizing the two quantities, that is, $D_2^{E*}(s) = q_2^{E\dagger}$; we can solve and obtain the optimal subsidy, that is, $s^{E\dagger} = \alpha - c_2$.

Furthermore, in order to elicit the socially optimal product mix, the social planner should also eliminate the manufacturer's incentive for producing GVs. To achieve this purpose, the social planner can charge a sufficiently high environmental tax for GVs so that it is non-profitable for the firm to produce any GV. The following lemma summarizes the above analysis:

Lemma 2 *If it is socially optimal for the manufacturer to produce EVs only, then the social planner should offer a subsidy to each EV user,* $s^{\dagger} = \alpha - c_2$ *, and charge the manufacturer a sufficiently high environmental tax for GVs.*

We then consider the case where it is socially optimal for the manufacturer to produce GVs only (scheme G is socially optimal). Suppose that the social planner charges the manufacturer an environmental tax *t* for each GV. The profit of the manufacturer then becomes $\pi^G = (p_1^G - c_1 - t)D_1^G$. We calculate the manufacturer's optimal quantity and obtain that $D_1^{G*}(t) = q_1^{G\dagger}$. Compare it with the socially optimal quantity, $q_1^{G\dagger} = 1 - c_1 - \omega - e$. In order to have $D_1^{G*}(t) = q_1^{G\dagger}$, we must set the environment tax at $t = c_1 + \omega + 2e - 1 \equiv t^{G\dagger}$.

Note that $t^{G\dagger}$ is negative if $e < (1 - c_1 - \omega)/2$. That is, when the emission of a GV is sufficiently low such that its environmental cost is sufficiently small, the optimal environmental tax for GVs becomes negative. This negative tax in fact becomes a subsidy. The reason is that in our model we consider a monopoly market. It is readily verified that a monopolist tends to set a too high price and produce a too low quantity relative to the social optimum. This "monopoly effect" drives the manufacturer to produce less GVs than the socially optimal level. On the other hand, the manufacturer ignores the externality that it exerts on the environment when producing GVs. This "environmental externality effect" drives the manufacturer to produce GVs more than the socially optimal level.

Hence, whether the private firm will produce too many or too few GVs compared with the social optimum depends on the relative strengths of the two opposite effects, that is, the monopoly effect and environmental externality effect. If the environmental externality effect outweighs the monopoly effect, then the social planner should charge an environmental tax $t^{\dagger}$ to reduce the firm's production quantity of GVs. If the opposite is true, then the social planner ought to offer a subsidy $|t^{\dagger}|$ to boost the too low quantity of GVs.

Moreover, if strategy G is socially optimal, then other than the tax/subsidy $t^{\dagger}$, we only need to set *s* at zero to prevent the manufacturer from producing EVs; that is, the government does not offer a subsidy to EV consumers. This is because compared with a GV, an EV has a lower consumer valuation and a higher production cost. So, if *s*=0, it is always less profitable for the manufacturer to produce an EV compared with a GV. We have the following lemma:

Lemma 3 *If it is socially optimal for the manufacturer to produce GVs only, then the social planner should charge the manufacturer an environmental tax* $t^{\dagger} = c_1 + \omega + 2e - 1$ *for each GV, while offering zero subsidy to EVs.*

We finally consider the case where it is socially optimal to produce both GVs and EVs (scheme B is socially optimal). Suppose that the social planner offers a subsidy *s* to each consumer who purchases an EV, and charges the manufacturer an environmental tax t for each GV. Then the manufacturer's profit function becomes $\pi^B = (p_1^B - t)D_1^B(s) + (p_2^B - c)D_2^B(s)$. We solve the manufacturer's optimization problem, and obtain the optimal quantities of GVs and EVs as functions of *s* and *t*:

$$D_1^{B*}(s,t) = \frac{1-c_1-\omega-\alpha+c_2-s-t}{2(1-\alpha)}, \tag{5}$$

$$D_2^{B*}(s,t) = \frac{\alpha c_1+\alpha\omega-c_2+s+\alpha t}{2\alpha(1-\alpha)}. \tag{6}$$

The social planner needs to elicit the socially optimal quantities of both products, that is, $q_1^{B\dagger}$and $q_2^{B\dagger}$. Notice that from Eq.s (5) and (6), the total quantity of the two products that the private firm produces, $D_1^{B*}(s,t) + D_2^{B*}(s,t) = (\alpha - c_2 + s)/(2\alpha)$, which only depends on *s* but not on *t*. Suppose that we do not offer any subsidy, that is, *s*=0, then $(D_1^{B*} + D_2^{B*})|_{s=0} < q_1^{B\dagger} + q_2^{B\dagger}$; that is, with no EV subsidy, the private firm would produce a lower total quantity of the two products than the socially optimal level. In order to achieve the social optimum, we need to offer a positive EV subsidy. To determine the amount of the EV subsidy, as Figure 2 illustrates, we just need to "move" the marginal consumer "Y" who is indifferent between buying an EV and nothing "downward" such that the total demand for both GVs and EVs increases to $q_1^{B\dagger} + q_2^{B\dagger}$.

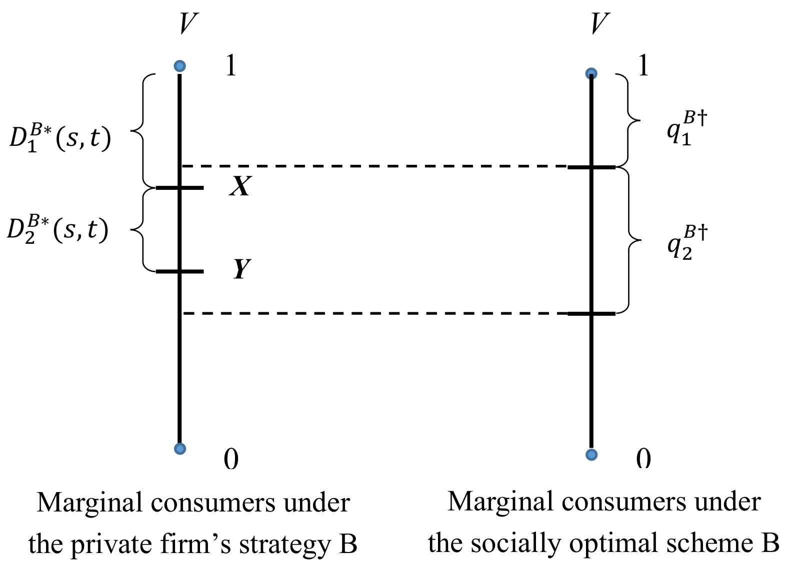


Figure 2: Illustration of the marginal consumers under the private firm's strategy B and the socially optimal scheme B (Note that while $D_2^{B*}|_{s=0,t=0} < q_2^{B\dagger}$and $(D_1^{B*} + D_2^{B*})|_{s=0,t=0} < q_1^{B\dagger} + q_2^{B\dagger}$, $D_1^{B*}|_{s=0,t=0}$ can be greater or smaller than $q_1^{B\dagger}$, which indicates a positive/negative $t^{\dagger}$respectively.)

Note that $D_1^{B*}(s,t) + D_2^{B*}(s,t) = D_2^{E*}(s)$ and $q_1^{B\dagger} + q_2^{B\dagger} = q_2^{E\dagger}$. This implies that the amount of the subsidy to increase the firm's total demand $D_1^{B*}(s,t) + D_2^{B*}(s,t)$ to the socially optimal total quantity $q_1^{B\dagger} + q_2^{B\dagger}$ under strategy B should equal the subsidy that increases the private firm's production quantity $D_2^{E*}(s)$ to the socially optimal total quantity $q_2^{E\dagger}$ under strategy E; that is, under strategy B, the optimal subsidy should equal that under strategy E, $s^{\dagger} = \alpha - c_2$. Furthermore, under strategy B, we also need to fix the marginal consumer "X" who is indifferent between buying a GV and an EV. Specifically, we need $D_1^{B*}(s,t)|_{s=\alpha-c} = q_1^{B\dagger}$. Solve the equation for *t* and we obtain that $t = c_1 + \omega + 2e - 1$, which equals the environmental tax under strategy G. We have the following lemma:

Lemma 4 *If it is socially optimal for the manufacturer to produce both GVs and EVs, the social planner should offer each EV consumer a subsidy* $s^{\dagger} = \alpha - c_2$*, and charge the manufacturer an environmental tax* $t^{\dagger} = c_1 + \omega + 2e - 1$ *for each GV.*

We now summarize Lemmas 2, 3, and 4 and characterize the socially optimal policy in the monopoly market as follows:

Proposition 2 *In a monopoly market, the social planner can elicit the socially optimal product mix and quantities through a subsidy to EVs and an environmental tax for GVs. Specifically,*

a) for $e < e_1$*, the social planner charges the GV manufacturer an environmental tax* $t^{\dagger} = c_1 + \omega + 2e - 1$ *for each GV and does not offer any subsidy for EVs;*

b) for $e_1 \le e \le e_2$*, the social planner charges the GV manufacturer an environmental tax* $t^{\dagger} = c_1 + \omega + 2e - 1$ *for each GV, and offers a subsidy* $s^{\dagger} = \alpha - c_2$ *for each EV;*

c) for $e > e_2$*, the social planner offers a subsidy* $s^{\dagger} = \alpha - c_2$ *for each EV and charges a sufficiently large environmental tax for GVs.*

Under the policy proposed in Proposition 2, the social planner not only induces the manufacturer to choose the proper product mix, but also elicits the socially optimal quantities of both GVs and EVs.

5.0 Competition between GV and EV Manufacturers

In this section, we consider a market where two auto manufacturers compete. Suppose that one manufacturer produces GVs only and the other produces EVs only. Consumers may choose to buy from either manufacturer or nothing. In the following, we first derive the market equilibrium; then based on the social optimum that we derived in Section 4.2, we propose policies that attain social optimum in the duopoly market.

5.1 Market Equilibrium

In equilibrium, there can be three outcomes: (1) only the GV manufacturer survives in the market (while the EV manufacturer is out of the market because it cannot make a profit); (2) only the EV manufacturer survives in the market and; (3) both the GV and EV manufacturers survive and compete in the market. In either outcome (1) or (2), since there is only one manufacturer in the market, the equilibrium price and quantity are the same as in the monopoly case (see Section 4.1). So, we focus on outcome (3) where the two manufacturers compete in the market.

For a fixed EV subsidy, the two manufacturers' profit functions are as follows: $\tilde{\pi}_1^B$=$(p_1 - c_1)D_1(p_1, p_2)$ for the GV manufacturer, and $\tilde{\pi}_2^B$=$(p_2 - c_2)D_2(p_1, p_2)$ for the EV manufacturer. Each manufacturer chooses the price of its product to maximize its own profit. We solve two simultaneous equations, that is, $\partial\tilde{\pi}_1^B/\partial p_1 = 0$and $\partial\tilde{\pi}_2^B/\partial p_2 = 0$, to obtain the equilibrium prices, demands, and profits as follows:

$$\tilde{p}_1^{B*} = \frac{2+2c_1-2\omega-2\alpha+c_2+\alpha\omega-s}{4-\alpha}, \qquad \tilde{p}_2^{B*} = \frac{\alpha-\alpha^2+\alpha c_1+\alpha\omega+2c_2+2s-\alpha s}{4-\alpha}, \tag{7}$$

$$\tilde{D}_1^{B*} = \frac{2-2\omega-2\alpha+\alpha c_1-2c_1+c_2+\alpha\omega-s}{(1-\alpha)(4-\alpha)}, \ \tilde{D}_2^{B*} = \frac{\alpha-\alpha^2+\alpha c_1+\alpha\omega+2c_2+2s-\alpha s}{\alpha(1-\alpha)(4-\alpha)}, \tag{8}$$

$$\tilde{\pi}_1^{B*} = \frac{(2-2\omega-2\alpha+\alpha c_1-2c_1+c_2+\alpha\omega-s)^2}{(1-\alpha)(4-\alpha)^2}, \ \tilde{\pi}_2^{B*} = \frac{(\alpha-\alpha^2+\alpha c_1+\alpha\omega+2c_2+2s-\alpha s)^2}{\alpha(1-\alpha)(4-\alpha)^2}. \tag{9}$$

We next examine which product mix will be the equilibrium outcome. In particular, if both the GV and EV manufacturers compete in the market (outcome (3)), the subsidy *s* for EVs cannot be too high or too low. If *s* is too low, then the EV manufacturer cannot make a profit; and the GV manufacturer takes all the market. On the other hand, if *s* is too high, then the GV manufacturer will be out of the market. Specifically, we show that if outcome (3) is the equilibrium, then s should be within a range, that is, $\tilde{s}_1 \leq s \leq \tilde{s}_2$, where$\tilde{s}_1 = (2c_2 - \alpha + \alpha^2 - \alpha\omega - \alpha c_1 - \alpha c_2)/(2-\alpha)$ and $\tilde{s}_2 = 2 - 2\omega - 2\alpha - 2c_1 + c_2 + \alpha c_1 + \alpha\omega$. We then have the following lemma:

Lemma 5 *Suppose that a GV manufacturer and an EV manufacturer compete in the market. In equilibrium,*

a) only the GV manufacturer produces and sells the product in the market if s < $\tilde{s}_1$*;*

b) both the GV and EV manufacturers produce and sell the product in the market if $\tilde{s}_1 \leq s \leq \tilde{s}_2$*;*

c) only the EV manufacturer produces and sells the product in the market if s > $\tilde{s}_2$*.*

Note that the equilibrium product mix in the duopoly market is similar to that in the monopoly market; whereas the thresholds are different. We compare the thresholds in the monopoly and duopoly markets and find that:

Remark 2 Comparing the thresholds in the monopoly and duopoly markets, we have that $\tilde{s}_1 < s_1$, and $\tilde{s}_2 > s_2$.

Figure 3 illustrates Remark 2 graphically. Remark 2 indicates that for $s \in (\tilde{s}_1, s_1)$ or $s \in (s_2, \tilde{s}_2)$, only one product will be produced and sold in the monopoly market, while in the duopoly market, both GVs and EVs are sold. This is because for $s \in (\tilde{s}_1, s_1)$, the subsidy to EVs is not high enough; the monopoly firm will not produce EVs since the additional profit generated by EVs cannot offset the profit loss of GVs due to cannibalization between the products. However, under competition, the EV manufacturer intends to enter the market since it makes a positive profit even though the profit is low; it also ignores the profit loss that it causes to the GV manufacturer. Similarly, for $s \in (s_2, \tilde{s}_2)$, the subsidy to EVs is high enough such that the monopoly manufacturer will stop producing GVs and only sell EVs in the market. However, in the duopoly market, the GV manufacturer would not withdraw from the market. At equilibrium, both GVs and EVs are sold in the market although the profits of the GV and EV manufacturers are both low. The implication of Remark 2 to the policy maker is that under the same policy, the duopoly market will produce a more diversified product mix than the monopoly market.

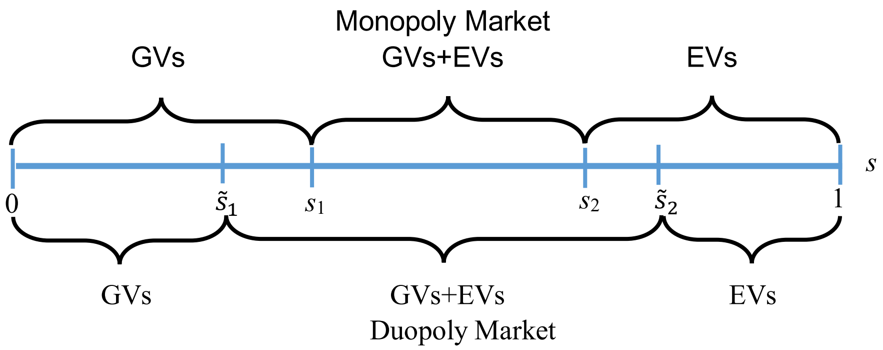


Figure 3: Optimal/equilibrium product mix in the monopoly and duopoly markets.

5.2 Policy Eliciting Social Optimum under Competition

Since the social optimum does not depend on the market structure, we still use the social optimum derived in Section 4.2 as our benchmark; we only need to determine the policy that aligns the manufacturers' incentives in the duopoly market. Note that if it is socially optimal to produce GVs or EVs only, the policies that we propose in Proposition 2 a) and b) still work. Specifically, if it is socially optimal to produce GVs only, then the social planner does not offer any subsidy to EV consumers; this will drive the EV manufacturer out of the market. In the meantime, the social planner charges the GV manufacturer a proper environmental tax to induce it to produce the socially optimal quantity of GVs. If it is socially optimal to produce EVs only, the social planner can offer a proper EV subsidy while charging the GV manufacturer a sufficiently high environmental tax.

Hence, we focus on the case where it is socially optimal to produce both GVs and EVs. The social planner should align the two competing manufacturers' incentives with the socially optimal decisions. Under policy (s, t), the two manufacturers' profit functions are now $\tilde{\pi}_1^B = (p_1 - c_1 - t)D_1(p_1, p_2)$ for the GV manufacturer, and $\tilde{\pi}_2^B = (p_2 - c_2)D_2(p_1, p_2)$ for the EV manufacturer. From the best response functions of the two manufacturers, we can solve for the Nash equilibrium of the game. As a result, the equilibrium quantities are functions of *s* and *t*, which we denote by $\widetilde{D}_1^{B*}(s,t)$ and $\widetilde{D}_2^{B*}(s,t)$. Then based on the socially optimal quantities derived in Eq. (4), we solve two simultaneous equations, $\widetilde{D}_1^{B*}(s,t) = q_1^{G\dagger}$ and $\widetilde{D}_2^{B*}(s,t) = q_2^{G\dagger}$, for the optimal values of s and t. The following lemma provides the policy that elicits the socially optimal quantities of both GVs and EVs:

Lemma 6 *Suppose that the GV and EV manufacturers are competing in the market. In order to induce the firms to produce the socially optimal quantities of GVs and EVs, the social planner should offer a subsidy* $\tilde{s}^\dagger = \alpha c_1 + \alpha\omega + \alpha e - c_2$ *to each EV consumer, and charge the GV manufacturer an environmental tax* $\tilde{t}^\dagger = \omega - 1 + \alpha + c_1 - c_2 + 2e$ *for each GV.*

Note that in Lemma 6, the environmental tax $\tilde{t}^{\dagger}$ is negative if $e < (1 - \omega - \alpha - c_1 + c_2)/2$, which implies that $\tilde{t}^{\dagger}$ is a subsidy rather than a tax in this case. Similar to the monopoly market, if the GVs' environmental cost is sufficiently small, then the social planner may have to subsidize the GV manufacturer for producing more GVs. It is because although with competition, the GV manufacturer produces more than a monopolist does, the quantity of GVs under duopoly competition may still be in short relative to the social optimum as the two products are vertically differentiated.

From Lemma 6 and Proposition 1, we can obtain the policy that elicits social optimum under duopoly competition:

Proposition 3 *In a market where a GV and an EV manufacturers compete, the social planner can attain the social optimum through a subsidy for EVs and an environmental tax for GVs. Specifically,*

a) for $e < e_1$*, the social planner charges the GV manufacturer an environmental tax* $\tilde{t}^{\dagger} = c_1 + \omega + 2e - 1$ *for each GV and does not offer any subsidy for EVs;*

b) for $e_1 \leq e \leq e_2$*, the social planner charges the manufacturer an environmental tax* $\tilde{t}^{\dagger} = \omega - 1 + \alpha - c_2 + c_1 + 2e$ *for each GV and offers a subsidy* $\tilde{s}^{\dagger} = \alpha c_1 + \alpha\omega + \alpha e - c_2$ *for each EV;*

c) for $e > e_2$*, the social planner offers a subsidy* $\tilde{s}^{\dagger} = \alpha - c_2$ *for each EV and charges the GV manufacturer a sufficiently high environmental tax.*

From Propositions 2 and 3, we compare the policies in the monopoly and duopoly markets and obtain Proposition 4.

Proposition 4 *Comparing the optimal policy parameters in the monopoly and duopoly markets,* *we have that* $\tilde{t}^{\dagger} > t^{\dagger}$, *and* $\tilde{s}^{\dagger} < s^{\dagger}$.

Proposition 4 shows that the social planner should charge the competing GV manufacturer a higher environmental tax than the monopoly manufacturer. This is because the competing manufacturer tends to produce more than a monopolist, which deviates even more from the socially optimal quantity of GVs. (In the case where GVs are subsidized rather than taxed, the duopoly GV manufacturer should be offered a smaller subsidy than the monopoly manufacturer.) For a similar reason, the EV subsidy should be lower in the duopoly market than in the monopoly market. This is because under competition, a duopoly EV manufacturer has an incentive for producing more EVs than a monopolist, which pushes the EV quantity in the duopoly market closer to the social optimum than in the monopoly market. Figure 4 illustrates the social optimum and corresponding ranges, as well as the policies that elicit the social optimum in the monopoly and duopoly markets.

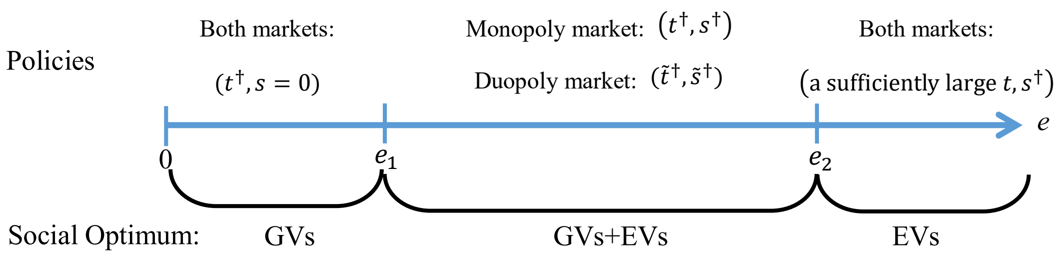


Figure 4: Social optimum and policies in the monopoly and duopoly markets.

6.0 Discussions

In this section, we discuss possible ways for estimating parameters in our model and several policy implications of our analysis.

6.1 Parameter Estimation

Empirical estimation of parameters is critical to the implementation of our model. In this subsection, we review and discuss approaches in related studies that can be used adaptively to estimate the parameters in our model. Our goal is to make a first effort in suggesting possible ways for parameter estimation in our model. Data collection and empirical study on parameter estimation is beyond the scope of the present paper, and so we leave it for future research. The main parameters in our model include the discount in consumers' valuation for EVs relative to GVs (α), the production costs of GVs and EVs (c_1 and c_2), consumers' usage cost for GVs (ω), and the environmental impact parameter (e).

(i) Estimation of Discount in Consumers' Valuation for EVs α

Estimation of consumers' perceived value for EVs relative to GVs is typically based on surveys (Lebeau *et al.*, 2013; Larson *et al.*, 2014). For example, Lebeau *et al.* collected 1,196 responses to an online survey from people older than 18 years in Flanders, Belgium. They found that about 50% of the respondents were willing to pay EVs a comparable price with current conventional cars. In addition, 20% of the respondents would purchase EVs if EVs are €2,500-10,000 cheaper than GVs; while about 27% were willing to pay more for EVs than for GVs.

Consumers' willingness to pay for a premium for an EV is driven by several reasons, including savings in fuel and maintenance costs of EVs, subsidy/tax-relief, less noise and tailpipe emission produced by EVs, environmental consciousness and concerns, etc. For example, Hidrue *et al.* (2011) showed that the respondents of a US national survey capitalized 5 years of fuel savings into their willingness-to-pay for EVs. Note that in our model, two factors, i.e., savings in usage costs and subsidy/tax, are separated from consumers' willingness-to-pay. In particular, parameter ω in our model represents the usage cost savings of EVs relative to GVs; also, subsidies and taxes are explicitly modeled. Therefore, surveys for our model should exclude such factors. Specifically, we may design a questionnaire with two hypothetical vehicle types, i.e., GV and EV, specifying attributes such as performance, driving range, level of difficulty for battery charge, product life, and levels of noise and tailpipe emission. Subjects are to be asked to determine their willingness-to-pay for the two vehicle types.

Notice that in practice there are a good number of EV and GV types available. However, in our theoretic model, we abstract away any difference between types within each category and consider only a representative GV and a representative EV. What we can do in the survey is to ask subjects to compare several pairs of GVs and EVs of similar sizes and functions and take an average for the estimate of α weighted by sales of vehicle types.

(ii) Estimation of Cost Parameters c_1, c_2, and ω

Estimation of c_1 and c_2 can be obtained from contact with auto manufacturers. Some research papers reported their estimates. For example, Leurent and Windisch (2015) broke down the vehicle manufacturing cost into 26 categories and estimated the costs of €14,600 for a conventional vehicle (Renault Clio 3 Diesel) and €23,600 for an EV (Renault Zoe). Lipman and Delucci (2006)'s estimates were $15,100 for a GV and $17,797 for a hybrid EV.

Consumers' usage costs for a vehicle (both GVs and EVs) are mainly composed of energy consumption cost and maintenance cost. The US Federal Highway Administration posted the age-weighted annual driving mileage of 13,476 miles (21,688 km) per driver (Tseng *et al.*, 2013). Some research therefore assumed 120,000 miles (193,120 km) to 150,000 miles (241,400 km) life-time mileage for a vehicle for 10 to 12 years (Ogden *et al.*, 2004; Tseng *et al.*, 2013). Dividing the total life-time mileage by the vehicle life and vehicle efficiency yields the amount of gasoline/electricity that a vehicle needs each year. We then can multiply it by the per-unit retail price of gasoline or electricity (current or predicted), and sum up the net present value of the cost each year discounted by the interest rate to obtain the total energy consumption cost of a GV/EV. Furthermore, some research provided estimates of maintenance costs of GVs and EVs; see e.g., Table 2 in Tseng *et al*. (2013) and Leurent and Windisch (2015). Note that depending on the life-time of an EV's battery, the user may need to replace the battery during the life of the vehicle, the cost of which will have to be counted in the total usage cost of an EV (Lipman and Delucci, 2006).

(iii) Estimation of Environmental Impact Parameter *e*

Parameter e represents the difference in the environmental cost between GVs and EVs. As mentioned in Section 3, the environmental impacts of vehicles consist of emissions, noise, congestion, accidents, impact during production and distribution, etc. (Jochem *et al*., 2016). Empirical research mostly focuses on estimation of the emission difference between GVs and EVs. Estimation of EV emissions follows the following steps: First, the energy consumption rate of an EV is computed via a dynamic vehicle simulator such as ADVISOR by Argonne National Labs (Markel et al., 2002) and MOVES by EPA (Gardner et al., 2013) with inputs of vehicle miles traveled (VMT) and vehicle parameters. Then the emission rate of EVs equals the energy consumption rate of an EV multiplied by the emission rate of power plants. The method of electricity production at the power plants should be accounted for. If the power plants in a region use different sources, a weighted average should be taken to characterize emissions by the energy mix.

Energy consumption estimates of GVs can also be obtained from MOVES. For example, Gardner et al. (2013) extracted energy consumption and vehicle speed data from MOVES and produced a regression model. They then generated functions of CO_2, NOx, and SO_2 emissions as functions of vehicle speed. For simplicity, some research also uses the regulated upper limit for vehicle emissions as an estimate. For example, Hromádko and Miler (2012) used the EURO 5 standard that regulates the production of emission particles.

Note that the Argonne National Labs developed GREET model series that provide simulation-based life-cycle analysis and evaluation of emissions of both GVs and EVs for a number of vehicle classes (https://greet.es.anl.gov/net). The user can download the software for free and enter the fleet size, VMT, and fuel economy or fuel use to get an estimation of CO_2-equivalent greenhouse gases volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NOx), airborne particulate matter with sizes smaller than 10 micrometers (PM10), particulate matter with sizes smaller than 2.5 micrometers (PM2.5), and sulfur oxides (SOx) of a particular vehicle.

Results from some empirical papers are as follows: With the US data, Archsmith et al. (2015) found that replacing a midsize GV with an EV can reduce greenhouse gas emissions by 0.74 tons of CO_2 per year. Using data from the Czech Republic, Hromádko and Miler (2012) concluded that with electricity from the energy mix, EVs produce 56% of savings in CO_2 relative to GVs; and with coal-fired power plants, the saving reduces to 16%. These numbers, monetized, can serve as estimates of e in our model.

The final step is to estimate the monetary cost of emissions of GVs and EVs. The main cost caused by polluting emissions is human health damage. Maibach *et al.* (2008) reported two approaches to calculate health costs: The Impact Pathway Approach developed in the ExternE project traces the passage of a pollutant emitted to population; and the top-down approach developed in the WHO 1999 study allocates overall health costs (illness and death) caused by air pollution to different categories including transport.

However, note that the social planner may not value human health cost and economic effect of an auto product equally. In other words, the relative weights of the environmental and economic benefit/cost in the social welfare function may not be 1:1. This does not affect our model derivation since the relative weights can be captured with parameter e. However, in parameter estimation, one needs to take the weight of the environmental impact into consideration. In particular, some research invited policy-makers to assess policy measures for EVs (Bakker and Trip, 2013). Similar methods can be utilized to ask policy makers, public authorities, and specialists to score and comment on the relative weights between environment and economy when they make public policies.

With the above and other possible approaches, one can estimate the parameter values in our model for a particular region. We then can plug the parameter values into the equations derived in Sections 4 and 5 to make suggestions to firms and governments on strategic choices and policy-making.

6.2 Policy Implications

The invention of the first electric motor car could go back to the early 1800's (Todorova, 2012). However, EVs soon declined in the competition with internal combustion engine vehicles due to its short range, high cost, and low top speed. At the beginning of the 21st century, as the concern over air pollutants, greenhouse gas emissions, and other environmental damages caused by GVs increased, EVs reappeared as a solution to the environmental problems in the transport sector (Zhang *et al.*, 2004). More recently, several countries have announced plans to replace GVs with EVs completely (Pham, 2017; Petroff, 2017).

However, as indicated by our work, whether the governments have set proper goals (including the ones involving banning of GVs and replacement with EVs) depend on several critical factors. First, firms' profits and consumer surplus are the two very important components of social welfare, and both depend highly on the benefit-cost ratio of EVs relative to GVs. When technology is not mature enough, consumers' willingness-to-pay for EVs is relatively low while the production cost of EVs is relatively high. In this case, both firms' and consumers' incentives to adopt EVs are weak. It will not be socially optimal to promote EVs extensively in this case. This has been observed by empirical research. For example, collecting data from UK, Shepherd *et al.* (2012) found that subsidies under a budget have limited impact on EVs' market shares in both the short term and long term. Moreover, based on an investigation of China's Electric Vehicle Subsidy Scheme (EVSS), Hao *et al.* (2014) suggested that "China's current EVSS is not sufficient for the BEPV [battery and plug-in hybrid electric vehicles] market to take off." From our Lemma 1, if the government insists in promoting EVs, then it will have to subsidize heavily to stimulate manufacturers' EV incentives, especially if the government aims at replacing GVs by EVs completely. As Shepherd *et al.* (2012) showed, to achieve the targets on EV sales, the subsidy can be quite high and, "in many cases, exceeds the likely budget." Nevertheless, as consumer's valuation for EVs increases, the unit production cost of EVs drops, and the gasoline price rises, the threshold e_2 in Proposition 1 decreases, which explains the increasing interests in EVs globally.

On the other hand, the trend of replacing EVs for GVs may be largely driven by the third component, the environmental impact of the vehicles, in the social welfare. According to our result, as the difference in the environmental cost between GVs and EVs, e, increases above the threshold e_2, it will be socially optimal to have EVs only. In fact, the per-vehicle emission of GVs keeps falling in recent years due to more and more stringent regulations of the governments around the world (for example, in the EU, specific emissions of newly registered vehicles in the EU-15 states were reduced by 2.4 per cent (Jochem *et al.*, 2016)). However, the emissions produced by generation grid that charges the EV batteries (the main emissions caused by EVs) are also decreasing, as coal and fossil fuel are replaced by natural gas, nuclear, solar, hydro, and wind in electricity generation and EV technology and as efficiency improve (Archsmith *et al.*, 2015). Moreover, the increasing public concern over environmental problems pushes policy makers to add weight to the environmental impact in social welfare consideration, which also implies an increase in e in our model.

In summary, when a government is about to set a goal concerning EVs, it should rely on careful parameter estimation and threshold calculation. In particular, if the predicted consumer utility and firm profit from EVs are still too low due to EVs' disadvantages such as short ranges and high costs, then it may still be socially optimal to have both GVs and EVs produced and sold in the market. Only when consumers' perceived value of EVs becomes sufficiently high, the cost of EVs becomes sufficiently low, the GVs' and EVs' environmental cost difference grows very large, and/or the public and government's environmental concern is sufficiently high, is the ban of GVs socially optimal.

This result may be of particular interest to countries that have not come up with or are in the process of studying the timetable to eliminate the use of GVs, for example, the US and China. In these two countries, proportion of coal-fired electricity varies significantly among regions.

For example, coal-fired electricity accounts for 9 per cent in California but 54 per cent in the three Midwestern states. In China, 96 per cent electricity in the generation mix in the Beijing-Tianjin region is coal-based, while the number is 64 per cent in the pearl-river delta region (Huo *et al.*, 2015). However, in the regions where electricity generation is more polluting, the government tends to be more determined in promoting renewable electricity and EVs. For example, the Beijing-Tianjin-Hebei region planned to invest a total of RMB 5.9 billion (US$ 950 million) in 2015 to tackle air pollution and set a target of reducing PM 2.5 by 25 per cent in Beijing by 2017, which had been achieved according to recent reports (China Daily, 2015; Xinhua Net, 2018). This indicates that although EVs' reduction in environmental cost relative to GVs may still be moderate for now, e might become larger in the near future due to the government's strong will to clean the environment.

Once we determine the market and social conditions based on the estimated parameter values, we can then calculate the corresponding policy parameters, s and t, using formulae given in Propositions 2 and 3 for the government to apply. Currently, many countries are providing financial incentives for EV promotion. Our model considers an EV purchase subsidy, which can be easily adapted to other financial policies such as income tax credit, vehicle registration tax reduction, and vehicle license fee exemption (Bjerkan *et al.*, 2016). The environmental tax on GVs in our model has, in effect, also been adopted in practice. Examples include the carbon tax charged for gasoline and diesel (The Irish Times, 2009; The World Bank, 2015; The Province of British Columbia, 2018) and the extra charge on top of congestion fees for vehicles that do not meet emission standards (BBC News, 2017).

7.0 Extensions

Our research is a first step towards a complete analysis of firms' EV adoption incentives and government policies using a game-theoretic model. We now discuss several natural extensions of the analysis presented here.

7.1 Extension 1: More Complex Market Structures

In our model, we consider two types of markets where EVs are potentially sold. More complex market structures could be explored. For instance, a manufacturer who produces both GVs and EVs competes with a pure GV/EV manufacturer. A pure GV/EV manufacturer may also enter the production of the other vehicle type. We expect that as the complexity of the market structure grows, the equilibrium will be more complicated and there will be more sub-cases of the threshold results in the parameter domain. We next illustrate an extension to a more general case where the two manufacturers produce both GVs and EVs each.

Consider two manufacturers, indexed by 1 and 2, producing both GVs and EVs. The two types of vehicles are denoted by "G" and "E" for short. So, there are four products, i.e., G1, E1, G2, and E2, with both horizontal and vertical differentiation that compete/cannibalize with each other. We still use the Mussa-Rosen consumer choice model to depict the vertical differentiation, while adopting the Hotelling model to depict the horizontal differentiation between products (Hotelling, 1929). Since each manufacturer has two products, we have a unit square rather than a unit line in the original Hotelling model (see Figure 5 for an illustration).

Specifically, suppose that the two manufacturers are located at the left and right edges of the unit square respectively. Consumers are uniformly distributed on the square and heterogeneous in two dimensions, i.e., product performance (vertical differentiation between GVs and EVs) and product feature (horizontal differentiation between the manufacturers). The coordinates of a consumer C are denoted by (x, v). The vertical coordinate v has the same definition as in the main model, representing the consumer's preference for the two products. The horizontal coordinate x represents the consumer's preference for the two manufacturers; specifically, x is the "distance" between C and manufacturer 1, while the distance between C and manufacturer 2 is $1\text{-}x$. The per-distance "travel" cost (between the manufacturers) of a consumer is denoted by l, which represents the disutility of the consumer due to not obtaining his/her ideal manufacturer. Similar to the single-dimension Hotelling model, we assume that l is sufficiently small so that the two manufacturers compete with each other. (If the manufacturers do not compete, one can simply duplicate our results in the monopoly case in Section 4.) In addition, denote by p_i^X, i=1, 2, X=G, E, the price of product Xi. We obtain consumer C's utility U from the four products:

$$U_{G1} = v - lx - p_1^G - \omega, \quad \text{if C purchases G1;} \tag{10}$$

$$U_{G2} = v - l(1-x) - p_2^G - \omega, \quad \text{if C purchases G2;} \tag{11}$$

$$U_{E1} = \alpha v - lx - p_1^E + s, \quad \text{if C purchases E1;} \tag{12}$$

$$U_{E2} = \alpha v - l(1-x) - p_2^E + s, \quad \text{if C purchases E2.} \tag{13}$$

In order to obtain the demand functions of the four products, G1, E1, G2, and E2, we need to determine each consumer's purchasing preference for given prices of the products. Note that for any product Xi, the consumers who potentially purchase the product must satisfy $U_{Xi} \geq 0$. We can thereby define four "marginal consumer lines" as follows: $v=lx-p_1^G-\omega \equiv V_{G1}$, $v=l(1-x)-p_2^G-\omega \equiv V_{G2}$, $v=(lx-p_1^E+s)/\alpha \equiv V_{E1}$, and $v=(l(1-x)-p_2^E+s)/\alpha \equiv V_{E2}$.

We first look at the potential consumers who will purchase G1 or E1. The consumers who purchase G1 must be above the V_{G1} line. Furthermore, these consumers must obtain a higher utility from G1 than from E1, that is $U_{G1} \geq U_{E1}$. Solve and obtain $v \geq (p_1^G - p_1^E + \omega - s)/(1-\alpha) \equiv v_1$. Draw a horizontal line $v = v_1$ in Figure 5. We can see that consumers whose utility is greater or equal to $\max(v_1,\ V_{G1})$ may potentially buy G1, that is, above both the V_{G1} and $v = v_1$ lines, while consumers who are below $v = v_1$ and above $v=V_{E1}$ are the potential demand for E1. Similarly, we can define the indifference line $v = v_2$ between G2 and E2, which separates the demands for G2 and E2.

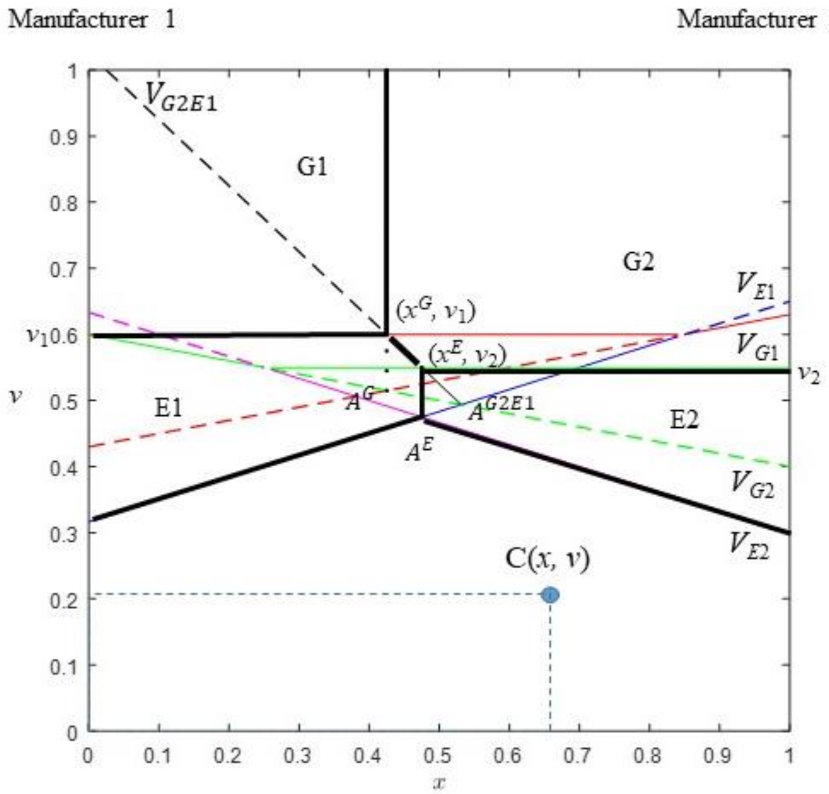


Figure 5: Illustration of two competing firms that produce both GVs and EVs (the bold lines are boundaries of the demands for the four products)

Furthermore, product G1 competes with G2. The consumers who are indifferent between G1 and G2 are located along a vertical line starting from the intersection of lines V_{G1} and V_{G2}, denoted by A^G with coordinates (x^G, v^G), till the upper edge of the unit square. The consumers to the left of this vertical line may purchase G1 while the consumers to the right may purchase

G2. Similarly, there is also a vertical indifference line between E1 and E2, starting from $A^E(x^E, v^E)$, which separates the demands for E1 and E2.

Finally, competition may also exist between G1 and E2, and G2 and E1. However, in our model, for given prices of the four products, only one pair of GV and EV across manufacturers will compete with each other. Specifically, suppose that $p_1^X \geq p_2^X, X = G, E$. If $v_1 > v_2$, then G2 and E1 compete with each other, while G1 and E2 do not compete; vice versa. Due to symmetry between the manufacturers, we only consider the case $v_1 > v_2$, while the other case will lead to the same equilibrium. We denote the intersection of lines V_{G2} and V_{E1} by A^{G2E1}. Then the indifference line between G2 and E1, denoted by V_{G2E1}, starts from A^{G2E1}. The area below V_{G2E1} are consumers who purchase E1 and the area above V_{G2E1} are demands for G2.

Thus, we have determined the consumers for each product:

Demand for G1: $D_1^G = \int_0^{x^G} \int_{v_1}^1 dF(v)dF(x)$, (14)

Demand for E1: $D_1^E = \int_0^{x^G} \int_{V_{E1}}^1 dF(v)dF(x) + \int_{x^G}^{x^E} \int_{V_{E1}}^{V_{G2E1}} dF(v)dF(x)$, (15)

Demand for G2: $D_2^G = \int_{x^G}^{x^E} \int_{V_{G2E1}}^1 dF(v)dF(x) + \int_{x^E}^1 \int_{v_2}^1 dF(v)dF(x)$, (16)

Demand for E2: $D_2^E = \int_{x^E}^1 \int_{V_{E2}}^{v_2} dF(v)dF(x)$. (17)

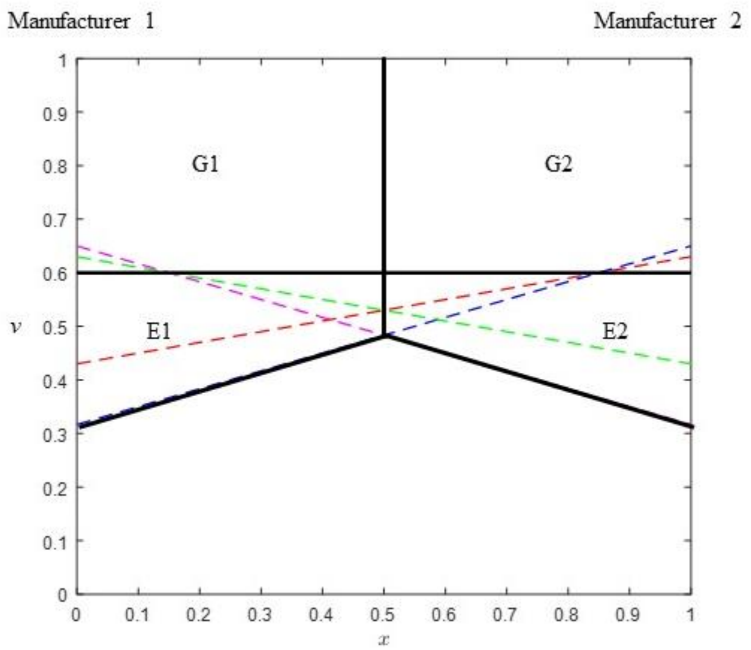


Figure 6: Equilibrium of the two competing firms that produce both GVs and EVs (the bold lines are boundaries of the demands for the four products)

We then plug the demand functions into the two manufacturers' profit functions:

$$\pi_1 = (p_1^G - c_1)D_1^G + (p_1^E - c_2)D_1^E,\ \ \pi_2 = (p_2^G - c_2)D_2^G + (p_2^E - c_2)D_2^E. \tag{18}$$

In order to characterize the equilibrium clearly, we focus on the case where the two manufacturers are symmetric. The demands for the four products are illustrated in Figure 6.

We next derive the social optimum of the two-manufacturer-two-product market. Suppose that in a centralized economy, the government determines the quantities of the four products, G1, E1, G2, and E2, to maximize the social welfare. In order to calculate the socially optimal quantities, we first need to determine how to distribute the four products to consumers (analogous to the determination of "demands" for the products in the private-firm case). Note that a consumer $(\tilde{x}, \tilde{v})$ who is distributed a unit of G1 will obtain utility $\tilde{v}-l\tilde{x}-\omega$. If this consumer obtains a G1, then all consumers with the same utility as his/hers should be distributed a unit of G1 as well. Hence, all these consumers constitute an "iso-utility" line $v=lx+b_{G1}$, where b_{G1} is determined by $(\tilde{x}, \tilde{v})$; that is, $\tilde{v}=l\tilde{x}+b_{G1}$, which yields $b_{G1}=\tilde{v}-l\tilde{x}$.

We can similarly obtain the iso-utility lines for E1, $v=\alpha lx+b_{E1}$, G2, $v=l(1\text{-}x)+b_{G2}$, and E2, $v=\alpha l(1\text{-}x)+b_{E2}$. Denote by V_{G1}^{s} the "last-consumer" line for product G1, that is, the consumers whose utility is the lowest among all consumers who get a G1, where V_{G1}^{s} also has a slope equal to l. Since the slopes of the iso-utility lines of G1 and E1 are different (l and αl), the last-consumer lines of G1 and E1 must have an intersection, the coordinates of which are denote by (x_1^s, v_1^s). Similarly, denote by (x_2^s, v_2^s) the coordinates of the intersection of the last-consumer lines of G2 and E2. We next express the quantities of the four products, denoted by $q_1^G, q_1^E, q_2^G,$ and q_2^E, in terms of $x_1^s, v_1^s, x_2^s,$ and v_2^s. In other words, we essentially substitute the decision variables $q_1^G, q_1^E, q_2^G,$ and q_2^E by x_1^s, v_1^s, $x_2^s,$ and v_2^s in the social welfare optimization problem. With the new decision variables x_1^s, v_1^s, $x_2^s,$ and v_2^s we can determine the last-consumer lines for the four products. For example, for G1, we plug (x_1^s, v_1^s) into $v=lx+b_{G1}$, and get $b_{G1}=v_1^s - lx_1^s$; so the last-consumer line of G1 is $v=lx+v_1^s - lx_1^s \equiv V_{G1}^s$. Similarly, we can define the last-consumers lines $V_{E1}^s, V_{G2}^s,$ and V_{E2}^s for E1, G2, and E2 respectively.

Furthermore, consumer $(\tilde{x}, \tilde{v})$ who obtains utility $\tilde{v}-l\tilde{x}-\omega$ from G1 may alternatively be distributed with E1 and obtain utility $\alpha\tilde{v}-l\tilde{x}$. In fact, consumers who obtain equal utility from G1 and E1 satisfy $v-lx-\omega=\alpha v-lx$, which yields $v = \omega/(1-\alpha) \equiv v^s$; and the horizontal line $v = v^s$ is the indifference line between G1 and E1. Note that products G2 and E2 also share this indifference line. We then derive the indifference line between G1 and G2 by equalizing $v-lx-\omega$ and $v-l(1\text{-}x)-\omega$, which yields $x=1/2$. Similarly, the indifference line between E1 and E2 is also $x=1/2$. This means consumers in the left half of the unit square should not be given G2 or E2, because they are dominated by G1 or E1. Similarly, consumers in the right half of the unit square should not be distributed G1 or E1.

Now we can obtain the quantities of the four products. Define (x_{Ei}^s, v^s) the intersection of lines V_{Ei}^s and $v = v^s$; and we have the following:

Quantity of G1: $q_1^G = \int_0^{\frac{1}{2}} \int_{\max(v^s, V_{G1}^s)}^1 dF(v) dF(x),$ (19)

Quantity of E1: $q_1^E = \int_0^{x_{E1}^s} \int_{\max(0, V_{E1}^s)}^{v^s} dF(v) dF(x),$ (20)

Quantity of G2: $q_2^G = \int_{\frac{1}{2}}^1 \int_{\max(v^s, V_{G2}^s)}^1 dF(v) dF(x),$ (21)

Quantity of E2: $q_2^E = \int_{x_{E1}^s}^1 \int_{\max(0, V_{E2}^s)}^{v^s} dF(v) dF(x).$ (22)

We can also calculate the aggregate consumer utility for each product:

Aggregate utility from G1: $AU_1^G = \int_0^{\frac{1}{2}} \int_{\max(v^s, V_{G1}^s)}^1 (v - lx - \omega) dF(v) dF(x),$ (23)

Aggregate utility from E1: $AU_1^E = \int_0^{x_{E1}^s} \int_{\max(0, V_{E1}^s)}^{v^s} (\alpha v - lx) dF(v) dF(x),$ (24)

Aggregate utility from G2: $AU_2^G = \int_{\frac{1}{2}}^1 \int_{\max(v^s, V_{G2}^s)}^1 (v - l(1-x) - \omega) dF(v) dF(x),$ (25)

Aggregate utility from E2: $AU_2^E = \int_{x_{E1}^s}^1 \int_{\max(0, V_{E2}^s)}^{v^s} (\alpha v - l(1-x)) dF(v) dF(x).$ (26)

The aggregate utility of all the products constitute the total social benefit, while the social cost consists of the production and environmental costs of the four products. The social welfare then equals $SW = \sum_{i=1,2, X=G,E} AU_i^X - (c_1 + e_1)(q_1^G + q_2^G) - (c_2 + e_2)(q_1^E + q_2^E)$. Since we have substituted the quantity variables with $x_1^s, v_1^s, x_2^s,$ and v_2^s, we take the first derivative of *SW* with respect to $x_1^s, v_1^s, x_2^s,$ and v_2^s respectively. Given a set of parameter values, we can solve the four first order conditions for the optimal values of $x_1^s, v_1^s, x_2^s,$ and v_2^s in a computation software such as Maple; the socially optimal quantities of the four products can be consequently calculated from (19)-(22).

The final step is to derive a policy that achieves the social optimum. In the main model we proposed an EV-subsidy/environmental-tax policy. Since in the extended model, there are four variables of the private firms, i.e., the quantities of the four products, we need four policy instruments to achieve the social optimum. Suppose for each manufacturer, the government charges an environmental-tax t_i for GVs while offering a subsidy s_i for EVs. Then the manufacturers' profit functions become:

$$\pi_1 = (p_1^G - c_1 - t_1)D_1^G(s_1) + (p_1^E - c_2)D_1^E(s_1), \tag{27}$$

$$\pi_2 = (p_2^G - c_2 - t_2)D_2^G(s_2) + (p_2^E - c_2)D_2^E(s_2). \tag{28}$$

The demand functions in the above equations are the same as (14)-(17). We again can solve for the optimal prices and demands numerically for given values of the parameters. However, in order to calculate the optimal policy parameters $t_i^\dagger, s_i^\dagger$, we need to develop the following algorithm:

Step 1: Parameters α, ω, c_1, c_2 and e are set with reasonable values;

Step 2: Solve the four first order conditions simultaneously that maximize the social welfare SW, and get the socially optimal quantities $q_i^{X\dagger}$;

Step 3: For s_i=0:1 (with a reasonable step such as 0.001; due to symmetry, we only consider cases where $s_1 = s_2$)

For t_i=-1:1 (with a reasonable step such as 0.001; due to symmetry, we only consider cases where $t_1 = t_2$)

Solve the two manufacturers' four first order conditions simultaneously and get $p_i^{X*}, i = 1,2, X = G, E$;

Plug p_i^{X*} into the manufacturers' demand functions and get D_i^{X*};

If $D_i^{X*} = q_i^{X\dagger}$

$s_i^\dagger \equiv s_i, t_i^\dagger \equiv t_i$;

End (of if)

End (of the t_i loop)

End (of the s_i loop)

The outputs of the above algorithm are thus the optimal EV-subsidy/environmental-tax policy parameters $t_i^{\dagger}, s_i^{\dagger}$ for any given set of values of parameters α, ω, c_1, c_2 and e. From the above calculation and analysis, we can see that the policy structure from our main model continues to work in the extended model.

7.2 Extension 2: EV capacity constraint

Limited by capacity in production and logistics, the delivery issue may have an impact on manufacturers' profit from selling EVs. Suppose that in the monopoly case, the manufacturer's production of EVs is subject to a capacity, denoted by C. Then the manufacturer maximizes its profit under a constraint $D_2 \leq C$. When the manufacturer adopts strategy E, i.e., producing EVs only, if the optimal quantity $D_2^{E*} \leq C$, then the manufacturer can still attain the optimal profit π^{E*} by producing D_2^{E*} (a corner rather than interior solution). However, if $D_2^{E*} > C$, then the manufacturer can only produce up to C EVs. The price of the EV is determined by $D_2^E(p_2^E) = 1 - (p_2^E - s)/\alpha = C$, which yields $p_2^E = \alpha(1\text{-}C) + s \equiv \widetilde{p^{E*}}$; and the manufacturer obtains a profit $(\alpha(1\text{-}C) + s - c_2)C \equiv \widetilde{\pi^{E*}}$, which is lower than π^{E*}.

Similarly, under strategy B, if $D_2^{B*} \leq C$, the manufacturer produces D_1^{B*} GVs and D_2^{B*} EVs and achieves the maximum profit π^{B*} as in the incapacitated case. However, if $D_2^{B*} > C$, then the manufacturer can only produce C EVs, while the quantity of GVs should be determined by plugging $D_2^B = C$ into the profit function and maximizing it over the prices. We thereby obtain the optimal solutions when the EV capacity constraint is binding as follows:

$$\widetilde{p_1^{B*}} = \frac{1+c_1-\omega}{2},\ \widetilde{D_1^{B*}} = 1 - \omega - 2\alpha C - c_1\ ,\ \widetilde{p_2^{B*}} = \frac{2\alpha^2 C + (1+\omega+c_1-2C)\alpha + 2s}{2},\ \widetilde{D_2^{B*}} = C. \quad (29)$$

Furthermore, when capacitated, the optimal strategy may change. For example, if C is very small, then producing EVs only may lead to a very small profit; the manufacturer may thereby produce some GVs to increase its profit, which turns strategy E into strategy B. Nevertheless, when C is relatively large, the optimal strategy that we proposed in Lemma 1 remains the same, with only the prices and quantities of the products being adjusted. Denote $\bar{C} \equiv (\alpha - c_2 + s)/(2\alpha)$; we have the following result:

Proposition 5 *When the EV capacity* $C \geq \bar{C}$*, the manufacturer's optimal strategy is*

a) to only produce GVs if $s < s_1$*;*

b) to produce both GVs and EVs if $s_1 \leq s \leq s_2$*;*

c) to only produce EVs if $s > s_2$.

When the EV capacity $C < \bar{C}$*, the manufacturer's optimal strategy is*

a) to only produce GVs if $s < s_1$*;*

b) to produce both GVs and EVs if $s \geq s_1$.

Therefore, when the EV production is subject to a capacity constraint, compared with the unconstrained case, in general, the manufacturer's production quantity will be lower, its price will be higher; and its profit will be lower. In addition, when the EV capacity is small, it may never be profitable for the manufacturer to adopt the EV only strategy; rather, the manufacturer will produce both GVs and EVs to make a higher profit.

8.0 Conclusions

In this paper, we have developed a game-theoretic model to investigate auto manufacturers' incentives for adopting EVs and governments' policy towards EV adoption. We consider both a monopoly market and a duopoly market. In the monopoly market, we characterize the firm's optimal product mix and quantity of each product under a fixed government subsidy for EVs. We find that as the EV subsidy increases, the manufacturer's optimal product mix changes from producing GVs only, to producing both GVs and EVs, and then to EVs only. In the duopoly market, we derive the equilibrium and show that at equilibrium, the product mix in the market also depends on the EV subsidy relative to the benefit-cost ratio of the two products. Comparing the two markets, we find that consumers are more likely to see both GVs and EVs in the market in the duopoly case than in the monopoly case.

Furthermore, we derive the socially optimal product mix and quantities. We show that it is socially optimal to produce and provide EVs if the environmental cost of GVs relative to EVs is sufficiently large. In order to attain the social optimum, we propose an EV-subsidy/environmental-tax policy to align private firms' incentives. In both the monopoly and duopoly markets, our policy is sufficient to elicit both the socially optimal product mix and socially optimal quantity of each product. We also compare the policy parameters in the two markets and find that with duopoly competition, the government can offer a lower subsidy while charging a lower environmental tax than in the monopoly market. Finally, we discuss parameter estimation, policy implications, and possible extensions to our model for future research directions.

Our research is a first step towards a full analysis of firms' EV adoption incentives and government policies using a theoretic model. Future research can go in several directions to extend our work. First, more possible market structures should be explored when examining EV incentives and policies such as oligopoly markets. Furthermore, as charging infrastructure has an impact on the adoption of EVs, we may consider an extension where the government invests on charging infrastructure to encourage EV adoption. Finally, our model considers consumers' heterogeneity in their valuation for EVs and GVs. Future research may consider consumers' heterogeneity in other dimensions such as environmental consciousness and usage cost of GVs.

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Appendix: Proofs

Proof of Lemma 1: The manufacturer's profit under strategy G is $\pi^G = (p_1^G - c_1)(1 - \omega - p_1^G)$. Calculate $\partial\pi^G/\partial p_1^G = 1 + c_1 - \omega - 2p_1^G$. Let it be zero to get $p_1^G = (1 + c_1 - \omega)/2$. Similarly, we can get the optimal prices and demands under strategies E and B. We then calculate and find that $\pi^{B*} - \pi^{G*} = (\alpha\omega + s + \alpha c_1 - c_2)^2/(4\alpha(1-\alpha))$, which is non-negative. However, $s \geq s_2 \equiv 1 - \omega - \alpha - c_1 + c_2$ must be satisfied such that the manufacturer obtains non-negative demand for EV. If $s < 1 - \omega - \alpha - c_1 + c_2$, then the demand for EV becomes zero; it is optimal for the manufacturer to produce GVs only. Similarly, $\pi^{B*} - \pi^{E*} = (1 - \alpha - \omega - s - c_1 + c_2)^2/(4(1-\alpha))$. Condition $s \leq s_1 \equiv c_2 - \alpha c_1 - \alpha\omega$ must be satisfied; otherwise, the demand for GVs becomes zero, and it is optimal for the manufacturer to produce EVs only.

Proof of Remark 1: We need to prove the monotonicity under the manufacturer's two strategies: E and B. Under strategy E, from Eq. (2), the manufacturer's profit is $\pi^{E*} = (\alpha - c_2 + s)^2/(4\alpha)$. It is clear that $\partial\pi^{E*}/\partial s > 0$. Calculate consumer surplus $CS^{E*} = (\alpha + s - p_2^{E*})D_2^{E*}/2 = (\alpha + s - c_2)^2/(8\alpha)$. We can get that $\partial CS^{E*}/\partial s > 0$.

Next consider strategy B. From Eq. (3), we can get the manufacturer's profit. Calculating its partial derivative with respect to s, we have that $\partial\pi^{B*}/\partial s = (\alpha\omega + s + \alpha c_1 - c_2)/(2\alpha(1-\alpha))$. From Lemma 1, one condition under which B is optimal is $s \geq s_1$. Under this condition, $\partial\pi^{B*}/\partial s \geq 0$. Furthermore, consumer surplus equals $CS^B = (1 - \omega - p_1^B + v_1 - \omega - p_1^B)D_1^B/2 + (\alpha v_1 - p_2^B + s + \alpha v_2 - p_2^B + s)D_2^B/2$. Calculate $\partial CS^{B*}/\partial s = (\alpha\omega + s + \alpha c_1 - c_2)/(4\alpha(1-\alpha))$. Since $s \geq s_1$, $\partial CS^{B*}/\partial s \geq 0$.

Proof of Proposition 1: Calculate and find that $SW^{B\dagger} - SW^{G\dagger} = (\alpha\omega + \alpha e + \alpha c_1 - c_2)^2/(2\alpha(1-\alpha))$ and $SW^{B\dagger} - SW^{E\dagger} = (1 - \omega - \alpha - c_1 + c_2 - e)^2/(2(1-\alpha))$, which are both non-negative since $\alpha < 1$. However, note that under scheme B, condition $e_1 \leq e \leq e_2$ must be satisfied such that the quantities of GVs and EVs are non-negative. Otherwise, scheme B will reduce to either scheme G or E. Specifically, if $e < e_1$, then $q_2^{B\dagger} < 0$, indicating that the social optimum becomes scheme G. Similarly, if $e > e_2$, then $q_1^{B\dagger} < 0$, indicating that the social optimum becomes scheme E.

Proof of Proposition 2: Follows directly from Proposition 1 and Lemmas 2, 3, and 4.

Proof of Lemma 5: From Eq. (8), two conditions must be satisfied such that the demands for both GVs and EVs are non-negative. From $\widetilde{D}_1^{B*} \geq 0$, we get that $s \leq \tilde{s}_2$. From $\widetilde{D}_2^{B*} \geq 0$, we get $s \geq \tilde{s}_2$. If the two conditions are satisfied, then the GV and EV manufacturers both stay and sell in the market. Otherwise, either GVs or EVs are out of the market due to zero demand.

Proof of Remark 2: We can calculate and get that $\tilde{s}_1 - s_1 = \alpha(1 - \omega - c_1)(1-\alpha)/(2-\alpha) > 0$; $\tilde{s}_2 - s_2 = -(1 - \omega - c_1)(1-\alpha) < 0$ from assumption that $1 - \omega - c_1 - e > 0$.

Proof of Lemma 6: We solve two simultaneous equations, $\widetilde{D}_1^{B*}(s,t) = q_1^{G\dagger}$ and $\widetilde{D}_2^{B*}(s,t) = q_2^{G\dagger}$, for the optimal values of s and t. Then we get $\tilde{s}^\dagger = \alpha c_1 + \alpha\omega + \alpha e - c_2$ and $\tilde{t}^\dagger = \omega - 1 + \alpha + c_1 - c_2 + 2e$.

Proof of Proposition 3: If the condition in b) is satisfied, i.e., $e_1 \leq e \leq e_2$, then it is socially optimal to produce both GVs and EVs. We hence should apply the policy in Lemma 6. Otherwise, it is socially optimal to produce one product only. From Lemmas 2 and 3, the corresponding policies follow.

Proof of Proposition 4: We calculate and get that $\tilde{s}^\dagger - s^\dagger = -\alpha(1-\omega-c_1-e)$ and $\tilde{t}^\dagger - t^\dagger = \alpha - c_2$. It follows that $\tilde{s}^\dagger < s^\dagger$ and $\tilde{t}^\dagger > t^\dagger$ from our assumptions in Section 3.

Proof of Proposition 5: With the EV capacity constraint, the manufacturer's decisions under strategy G remains unchanged. We only need to consider strategies E and B. Under strategy E, if $D_2^{E*}>C$, then the manufacturer's optimality is at a corner solution $\widetilde{D^{E*}} = C$, $\widetilde{p^{E*}} = \alpha(1\text{-}C) + s, \widetilde{\pi^{E*}} = (\alpha(1-C)+s-c_2)C$; denote this optimality by $\widetilde{E^*}$, in contrast to the interior solution of the manufacturer's optimization problem E^*. Write the condition $D_2^{E*}>C$ in terms of s and have $s > 2\alpha C - \alpha + c_2 \equiv s^E$. Similarly, denote by $\widetilde{B^*}$ the manufacturer's optimality when the capacity constraint is binding. Two conditions must be satisfied: $C < D_2^{B*}$ and $\widetilde{D_1^{B*}} \geq 0$. The former can be re-written into $s > 2\alpha C(1-\alpha) - \alpha c_1 - \alpha\omega + c_2 \equiv s^B$; and the latter yields $C < (1-\omega-c_1)/(2\alpha) \equiv \bar{C}$. Note that $\widetilde{\pi^{B*}} - \widetilde{\pi^{E*}} = (1-\omega-c_1-2\alpha C)^2/4 \geq 0$; that is, $\widetilde{B^*}$ dominates $\widetilde{E^*}$ when it is valid. If $C < \bar{C}$, then $s_1 < s^B < s_2$ and $s^B > s^E$. We know that if the manufacturer produces EVs only, then for $s \leq s^E$, its optimal solution is E^*; while for $s > s^E$, its optimal solution is $\widetilde{E^*}$. However, for $s > s^E$, we must have $s > s^B$ and $\widetilde{B^*}$ is also valid in this region; so $\widetilde{E^*}$ is dominated by $\widetilde{B^*}$. Whereas, for $s \leq s^E$, E^* is dominated by either B^* or G^*. In summary, if $C < \bar{C}$, then the optimality is G^* for $s < s_1$, B^* for $s_1 \leq s \leq s^B$, and $\widetilde{B^*}$ for $s > s^B$ (in the last two cases, the manufacturer produces both GVs and EVs).

If $C \geq \bar{C}$, $\widetilde{B^*}$ is not valid. So the optimality is G^* for $s < s_1$ and B^* for $s_1 \leq s \leq s_2$. For $s > s_2$, the optimality is either E^* or $\widetilde{E^*}$. In either case, the manufacturer produces EVs only.