Incentivizing the Adoption of Electric Vehicles under Subsidy Schemes: A Duopoly Analysis[a]

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Abstract

We analyze the competition between an electric vehicle (EV) manufacturer and an internal combustion vehicle manufacturer, under a government's subsidy scheme that provides a per-unit subsidy to the EV manufacturer or a price discount subsidy to EV consumers. The government should adopt the per-unit subsidy scheme, because, compared to the price-discount scheme, the government under the per-unit scheme can achieve the same EV sales and social welfare but pay for a smaller total subsidy.

Key words: electric vehicles; subsidy; driving range; game theory; duopoly.

1 Introduction

The logistics industry is an indispensable part of any economic system, but its further development usually generates more air pollution and noises. For these negative issues, an effective solution is the deployment of electric vehicles (EVs), as such vehicles have no tailpipe emissions with a lower noise level than traditional vehicles [15]. In North America, some large fleet operators (including Coca-Cola, FedEx, UPS, and others) have become the members of Business for Social Responsibility, and cooperated with other firms to jointly develop the Sustainable Fuel Buyers' Principles for expansion of the market for green vehicles. In addition, France had more than 67,000 plug-in, electric light-duty vehicles in 2016 (Morganti and Browne [14]), and the city of Shenzhen in China has adopted 70,417 electric light vehicles by the end of 2019 (Wang et al. [19]).

To stimulate the EV adoption, some countries have implemented price discount incentive schemes with an aim to improve the competitiveness of EVs in markets. For example, the UK government [17] has implemented a subsidy program to help reduce the purchase price of an eligible van by 20%, with a limit of maximum reduction £8,000. In practice, governments usually offer subsidy schemes to EV manufacturers (e.g., Tesla, as revealed by Yu, Tang, and Shen [20]). Although the EV has drawn a great attention, we observe only a limited adoption of EVs in real logistics systems. For example, in 2015, around 0.5% of newly registered vans in Europe were plug-in electric vans [14]. High purchase prices and insufficient driving ranges are commonly viewed as major barriers that hinder the diffusion of EVs. As discussed by Cecere, Corrocher, and Guerzoni [2], the price reduction and the improvement in driving range are the most and second most important to arousing firms and consumers to adopt EVs, respectively. Accordingly, the Chinese government has provided subsidies based on the vehicle type and driving range of EVs. For example, the Ministry of Finance of China [13] reports that, in

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2020, the unit subsidy was ¥315/kwh for each pure electric freight vehicle (up to 3.5t) with the ceiling of ¥18 000. The above exposes that the subsidy decision for EVs should be dependent on their driving ranges, which, however, has not been investigated in literature.

We consider a sequential-move game under two subsidy schemes: (i) under the manufacturer subsidy scheme, a unit subsidy for the driving range is given to EV manufacturers; (ii) under the consumer subsidy scheme, a price discount incentive is provided to EV consumers. For simplicity, we call schemes (i) and (ii) "subsidy scheme m and "subsidy scheme c," respectively. In our game, the government first determines the optimal subsidy policy to maximize the social welfare. Then, an EV manufacturer and an internal combustion vehicle (ICV) manufacturer make their pricing decisions "simultaneously." Our paper is relevant to the publications regarding government subsidies in the EV supply chain analysis. We summarize the relevant publications in Table 1 in which, for the publications, we specify decision variables, subsidy types, and other issues such as consumer heterogeneity and the driving range.

Literature	**Decision variables**	**Subsidy types**	**Consumer heterogeneity**	**Driving range?**
Huang et al. [8]	Wholesale and retail prices of ICVs and EVs	A fixed subsidy	Consumption gain of EVs and ICVs	No
Luo et al. [12]	Wholesale and retail prices of EVs	A subsidy ceiling and a price discount rate	EV valuation	No
Cohen, Lobel, and Perakis [5]	Subsidy, price, and quantity	Subsidies	-	No
Fu, Chen, and Hu [7]	Wholesale and retail prices and order quantity of EVs	Linear and fixed subsidies	-	No
Shao, Yang, and Zhang [16]	Subsidy, price discount rate, and prices of EVs and ICVs	Fixed and price discount subsidies to consumers	Valuation of EVs and ICVs	No
Wang and Deng [18]	Wholesale and selling prices and charging station distance	Fixed subsidies to the producer or consumers	Greenness valuation of EVs	No
Chakraborty, Kumar, Bhaskar [3]	Subsidy or green tax, prices of EVs and ICVs	A fixed subsidy and a green tax to consumers	Valuation of EVs and ICVs	No
Deng, Li, and Wang [6]	Subsidy, price and production quantity of EVs	Fixed subsidies to the EV manufacturer or consumers	-	No
Chen and Fan [4]	Wholesale price and driving range of battery, the EV price	A fixed subsidy to the battery manufacturer	-	Yes

Table 1: Review of major relevant publications.

As shown in Table 1, Chen and Fan [4] considered the driving range and assumed an exogenous subsidy and a monopolistic EV manufacturer. Differently, we investigated subsidy strategies for EVs in a duopoly setting with the driving range. In addition, our paper differs from extant publications by allowing consumer heterogeneity in usage needs (e.g., miles traveled). This enables us to distinguish between environmental impacts of EVs and ICVs in accordance with their productions and usages. We aim to address the following research questions. First, can we achieve the same EV sales, social welfare, and total subsidy amount under the two subsidy schemes? Secondly, what is the impact of the driving range on the EV sales and the government's optimal subsidy policy? We delegate all proofs to online Appendix A.

2 The Analysis for the EV and ICV Manufacturers

A government implements subsidy scheme m or c to promote EVs in city logistics. Under subsidy scheme m, the EV manufacturer enjoys the subsidy $G_m \equiv rs$, where r is the driving range of an EV and s is a unit subsidy for the driving range. Here, the driving range is defined as the maximal distance that an EV can run on a single full charge (Lin [11]). Under subsidy scheme c, each EV consumer obtains the subsidy $G_c \equiv \beta p_{1c}$, where $\beta \in [0, 1)$ denotes a price discount rate and p_{1c} is the sale price of an EV. Such subsidy can be viewed as an "ad valorem" subsidy (Yu, Tang, and Shen [20]); or, subsidy scheme c can be regarded as a price discount incentive scheme (Shao, Yang, and Zhang [16]). There are two decision-making stages. In the first stage, the government determines the optimal subsidy scheme policy. In the second stage, the EV and ICV manufacturers make optimal pricing decisions simultaneously. After observing the prices, consumers decide to buy an EV, or an ICV, or nothing. We subsequently use the backward induction approach to find solutions.

2.1 Consumer Utility

Consumers (e.g., freight drivers) are heterogeneous in their usage needs such as daily vehicle miles traveled. We denote the consumer usage need by u, which is uniformly distributed on the interval $[0, 1]$, similar to, e.g., Agrawal and Bellos [1]. The limited driving range and insufficient charging network usually cause significant inconvenience to EV users, as the users may have to go out-of-route to find a charging infrastructure and spend a waiting time. According to Kuppusamy, Magazine, and Rao [10] and Kontou et al. [9], the inconvenience cost of an EV per day, denoted by $I(r)$, decreases with the driving range but increases with the usage needs. Such cost can be computed as $I(r) = \alpha(u - r)$, where α is the time cost for recharging. The total inconvenience cost of an EV is $nI(r)$, where n denotes the total working days in the time horizon. In the end of time horizon, the resale value of vehicle i is ξ_i, where the vehicle is an EV if subscript $i = 1$ and it is an ICV if $i = 2$.

We let V represent the revenue per mile, w_i $(i = 1, 2)$ denote the unit operating cost of vehicle i. A consumer's utility from buying an EV and that from buying an ICV are $\Pi_{1j}(u) = n(V - w_1)u - nI(r) - P_{1j} + \xi_1$ and $\Pi_{2j}(u) = n(V - w_2)u - p_{2j} + \xi_2$, respectively. Here, subscript j denotes subsidy scheme m or c; $P_{1m} \equiv p_{1m}$ and $P_{1c} \equiv (1 - \beta)p_{1c}$, where p_{1j} and p_{2j} denote the prices for the EV and the ICV under subsidy j, respectively; and, β is the price discount rate. If the consumer buys neither the EV nor the ICV, his or her utility is 0. The consumer is indifferent between buying an ICV and buying an EV, when $\Pi_{1j}(u) = \Pi_{2j}(u)$, or, $u = u_m \equiv b(n\alpha r + p_{2m} - p_{1m} + \xi_1 - \xi_2)$ under subsidy scheme m and $u = u_c \equiv b[n\alpha r + p_{2c} - (1-\beta)p_{1c} + \xi_1 - \xi_2]$ under subsidy scheme c, where $b \equiv 1/[n(w_1 + \alpha - w_2)]$. Similarly, the consumer is indifferent between buying an EV and buying nothing, when $\Pi_{1j}(u) = 0$, or $u = \underline{u}_m \equiv \eta(p_{1m} - n\alpha r - \xi_1)$ and $u = \underline{u}_c \equiv \eta[(1 - \beta)\, p_{1c} - n\alpha r - \xi_1]$, where $\eta \equiv 1/[n(V - w_1 - \alpha)]$. In the above, b and η are two parameters reflecting the customer sensitivity to the sale price.

It thus follows that the consumers with their usage needs in $[u_j, 1]$ and those with their usage needs in $[\underline{u}_j, u_j]$ should purchase the ICVs and the EVs, respectively. Under subsidy scheme m, the sales of EVs and those of ICVs are $q_{1m} = u_m - \underline{u}_m = a_1 - (b+\eta)p_{1m} + bp_{2m}$ (where $a_1 \equiv (b+\eta)(n\alpha r + \xi_1) - b\xi_2$) and $q_{2m} = 1 - u_m = a_2 + bp_{1m} - bp_{2m}$ (where $a_2 \equiv 1 - b\,(n\alpha r + \xi_1 - \xi_2)$), respectively. Here, $b > 0$

and $\eta > 0$, according to the fact that the sales of EVs (ICVs) are decreasing in the EV (ICV) price but increasing in the ICV (EV) price. Note that a_1 (a_2) can be viewed as the demand potential of EVs (ICVs), which is increasing (decreasing) in the driving range r. Under subsidy scheme c, the sales of EVs and ICVs are computed as $q_{1c} = u_c - \underline{u}_c = a_1 - (b+\eta)(1-\beta)p_{1c} + bp_{2c}$ and $q_{2c} = 1 - u_c = a_2 + b(1-\beta)p_{1c} - bp_{2c}$, respectively. We observe that q_{1c} and q_{2c} are sensitive to the discounted price of buying an EV, i.e., $(1-\beta)\,p_{1c}$.

2.2 Price decisions of EV and ICV Manufacturers

We denote the production cost of an ICV and that of an EV by k_2 and $k_1(r) = k_{BD} + k_{BT}(r)$, respectively, where k_{BD} and $k_{BT}(r)$ are the body cost and battery cost of the EV. Similar to Lin [11] and Kontou et al. [9], we compute the battery cost as $k_{BT}(r) = re(r)w_{BT}(r)/h$, where $e(r)$ is the energy consumption rate (kwh/mile), $w_{BT}(r)$ is the unit battery cost (\$/kwh), and h is the ratio of the battery's available capacity to its total capacity. The term $re(r)$ can be explained as the usable capacity of an EV in terms of kwh. Naturally, the battery cost is increasing in the driving range, i.e., $\kappa \equiv \partial k_{BT}(r)/\partial r > 0$. The EV manufacturer's and the ICV manufacturer's objective functions are $\max_{p_{1j}} \pi_{1j}(p_{1j}) = q_{1j}\,(p_{1j} - K_{1j})$ and $\max_{p_{2j}} \pi_{2j}(p_{2j}) = q_{2j}\,(p_{2j} - k_2)$, respectively, where $j = m, c$; $K_{1m} \equiv k_1(r) - rs$, and $K_{1c} \equiv k_1(r)$.

Proposition 1 *Under subsidy $j = m, c$, the optimal EV and ICV prices are uniquely obtained as*

$$p_{1m}^* = \frac{2\,(b+\eta)\,(k_1(r) - rs) + A}{3b + 4\eta},\; p_{1c}^* = \frac{2\,(b+\eta)\,(1-\beta)\,k_1(r) + A}{(1-\beta)\,(3b+4\eta)};\text{ and } p_{2j}^* = (b+\eta)\,\frac{2K_2 + bX_j}{b\,(3b+4\eta)} + \xi_2,$$

where $A \equiv (b+2\eta)\,(n\alpha r + \xi_1) + K_2$, $K_2 \equiv 1 + bk_2 - b\xi_2$, $X_m \equiv k_1(r) - rs - n\alpha r - \xi_1$, and $X_c \equiv (1-\beta)\,k_1(r) - n\alpha r - \xi_1$.

Using Proposition 1, we calculate the sales of the EV and those of the ICV under subsidy j ($j = m, c$) as

$$q_{1j}^* = (b+\eta)\,\frac{K_2 - (b+2\eta)\,X_j}{3b+4\eta} \text{ and } q_{2j}^* = \frac{3b + 4\eta - (b+2\eta)\,K_2 + b\,(b+\eta)\,X_j}{3b+4\eta}.$$

As the value of s (β) increases, the EV price under subsidy scheme m (the consumer's net payment for an EV under subsidy scheme c) decreases but the sales of the EV increase, whereas both the price and sales of the ICV decrease. When the production cost of an ICV (EV) increases, both the EV manufacturer and the ICV manufacturer should increase their prices, which then increases (decreases) the sales of the EV and decreases (increases) the sales of the ICV.

3 The Subsidy Scheme

3.1 The Social Welfare and Optimal Subsidy

Under subsidy $j = m, c$, the social welfare SW_j consists of the EV manufacturer's profit $\pi_{1j}(p_{1j})$, the ICV manufacturer's profit $\pi_{2j}(p_{2j})$, consumer surplus CS_j, the total subsidy $q_{1j}G_j$, and environment impact E_j. Note that $G_m = rs$ and $G_c = \beta p_{1c}$, as defined previously, represent the subsidies for each EV to the EV manufacturer and each consumer, respectively. That is,

$$SW_j = \pi_{1j}(p_{1j}) + \pi_{2j}(p_{2j}) + CS_j - q_{1j}G_j - E_j.$$

The consumer surplus CS_j is obtained by integrating the utilities of consumers with respect to the usage need u over buying ICVs, buying EVs, and buying nothing (Shao, Yang, Zhang [16]). Thus, $CS_j = \int_{u_j}^{1} \Pi_{2j}(u)du + \int_{\underline{u}_j}^{u_j} \Pi_{1j}(u)du$.

The environmental impacts of the EV production and ICV production are denoted by $q_{1j}^* e_1$ and $q_{2j}^* e_2$, respectively, where e_i ($i = 1, 2$) represents the unit environmental impact of the production of vehicle i. Although any EV does not generate exhaust emissions, there still are some emissions resulting from the use of the EV. For example, the electricity used to charge EVs may be delivered by burning coal. Let $\hat{e}_1$ and $\hat{e}_2$ denote environmental impacts of using EVs and ICVs, respectively. For the consumer with the usage need u, the environmental impact of his or her vehicle usage depends on the environmental impact per mile (i.e., $\hat{e}_i$, $i = 1, 2$), the total working days (i.e., n), and the miles traveled per day (i.e., u). Similar to Agrawal and Bellos [1], we compute the total environmental impact as $E_j = q_{1j}^* e_1 + q_{2j}^* e_2 + n\hat{e}_1 \int_{\underline{u}_j}^{u_j} u du + n\hat{e}_2 \int_{u_j}^{1} u du$. Letting $\hat{E}_j \equiv n\hat{e}_1(u_j^2 - \underline{u}_j^2)/2 + n\hat{e}_2(1 - u_j^2)/2$, we specify the social welfare under subsidy scheme m and that under subsidy scheme c as $SW_m = q_{1m}(p_{1m} - k_1(r)) + \pi_{2m}(p_{2m}) + CS_m - q_{1m}e_1 - q_{2m}e_2 - \hat{E}_m$ and $SW_c = q_{1c}[(1-\beta)p_{1c} - k_1(r)] + \pi_{2c}(p_{2c}) + CS_c - q_{1c}e_1 - q_{2c}e_2 - \hat{E}_c$, respectively. The optimal solutions can be nonnegative, for which the proof is straightforward.

Proposition 2 *The optimal unit subsidy s^* under subsidy scheme m and the optimal price discount rate β^* under subsidy scheme c are computed as*

$$s^* = \frac{k_1(r)}{r} - \frac{\varphi(3b + 4\eta) + \rho K_2 - \zeta\,(n\alpha r + \xi_1)}{r\delta(b + \eta)},\ \beta^* = 1 - \frac{\varphi(3b + 4\eta) + \rho K_2 - \zeta\,(n\alpha r + \xi_1)}{\delta k_1(r)(b + \eta)},$$

where $\varphi \equiv (b + 2\eta)\,(e_1 + \chi)$ with $\chi \equiv k_1(r) + (1 - be_2)/\,(b + 2\eta)$; $\rho \equiv (b+2\eta)\omega - b + 2\eta^2 n\hat{e}_1 - b - 4\eta$ with $\omega \equiv bn(V - w_2 + \hat{e}_1 - \hat{e}_2) - 1 - b/\eta$; $\zeta \equiv b^2 + \lambda(b+\eta)$; and $\delta \equiv 2b + 8\eta - \lambda$ with $\lambda \equiv 2(b + 2\eta + 2n\hat{e}_1\eta^2) - b\omega - b$.

As the value of e_1 decreases or the value of e_2 increases, the government should increase the optimal EV subsidies. The parameters $\hat{e}_1$ and $\hat{e}_2$ affect these subsidies in a nonlinear manner. The government should increase subsidies as a response to a higher value of $\hat{e}_1$, if the unit operating cost of the ICV w_2 is higher (lower) than W_2 and e_1 is greater (smaller) than ε_1, where $W_2 \equiv (3w_1 + 3\alpha - V)/2$, $\varepsilon_1 \equiv \left[(2\eta^2 + 2b\eta + b^2)\delta - \rho\gamma\right] K_2/(B\gamma) + \Gamma$, $\Gamma \equiv [\zeta + \delta\,(b + \eta)]\,(n\alpha r + \xi_1)\,/B - \chi$, $\gamma \equiv b^2 - 4\eta^2$, and $B \equiv (b + 2\eta)\,(3b + 4\eta)$. Otherwise, the government should reduce subsidies for the EV when the value of $\hat{e}_1$ increases. If the value of $\hat{e}_2$ increases and $e_1 < \varepsilon_2$ ($e_1 > \varepsilon_2$) where $\varepsilon_2 \equiv [(b + 2\eta)\,\delta - b\rho]\,K_2/(Bb) + \Gamma$, then the government should raise (lower) the subsidies for the EV to improve the social welfare. Using $s^*$and β^*, we can obtain the optimal pricing decisions, maximum profits, and social welfare under the two subsidy schemes.

Proposition 3 *We find that (1) $p_{1m}^* = p_{1c}^*(1 - \beta^*) \le p_{1c}^*$, $rs^* = \beta^* k_1(r) \le \beta^* p_{1c}^*$, $q_{1m}^* = q_{1c}^*$, and*

$\pi_{1m}(p^*_{1m}) \leq \pi_{1c}(p^*_{1c})$; (2) $p^*_{2m} = p^*_{2c}$, $q^*_{2m} = q^*_{2c}$, $\pi_{2m}(p^*_{2m}) = \pi_{2c}(p^*_{2c})$; and (3) $CS_m = CS_c$, $E_m = E_c$, and $SW_m = SW_c$.

Proposition 3 reveals that the EV price under subsidy scheme c is higher than that under subsidy scheme m. Note that the sales of the EV under subsidies schemes m and c are $q^*_{1m} = a_1 - (b+\eta)p^*_{1m} + bp^*_{2m}$ and $q^*_{1c} = a_1 - (b+\eta)(1-\beta)p^*_{1c} + bp^*_{2c}$, respectively. Compared to subsidy scheme m, the sales of the EV under subsidy scheme c decrease with the EV price at a lower rate because the government's subsidy βp^*_{1c} under scheme c can help offset negative effects of price increases on the EV sales. This motivates the EV manufacturer to increase the EV price. To ensure that a consumer's net payment for an EV is identical under the two subsidy schemes, the government offers a higher subsidy for an EV under subsidy scheme c than that under subsidy scheme m. Consequently, the EV sales and the other results (e.g., p^*_{2j}, q^*_{2j}, $\pi_{2j}(p^*_{2j})$, CS_j, and E_j, for $j = m, c$) are also the same under the two schemes. As the EV price under subsidy scheme c is higher than that under subsidy scheme m, the difference between the EV manufacturer's profits under the two subsidy schemes is $\beta^* q^*_{1c}(p^*_{1c} - k_1(r))$, which is also the difference between the total subsidies under these schemes. This implies that the government transfers this amount to the EV manufacturer under subsidy scheme c, which results in an identical social welfare under these two schemes.

3.2 Sensitivity Analyses and Managerial Insights

Proposition 4 *If the value of e_1 is higher than ε_{1m} (ε_{1c}), then s^* (β^*) increases with r; otherwise, s^* (β^*) decreases with r, where $\varepsilon_{1m} \equiv \kappa r - \chi + (\zeta\xi_1 - \rho K_2)/B + \delta\,(b+\eta)\,(k_1(r) - r\kappa)\,/B$, $\varepsilon_{1c} \equiv [(n\alpha r + \xi_1)\,\zeta - \rho K_2]\,/B - \zeta n\alpha k_1(r)/(\kappa B) + k_1(r) - \chi$, and $\kappa = \partial k_{BT}(r)/\partial r$.*

Proposition 4 indicates that e_1 influences the impact of driving range r on s^* and β^*. If $e_1 > \varepsilon_{1m}$ ($e_1 > \varepsilon_{1c}$), then s^* (β^*) would be low because it decreases with e_1. Thus, if the EV manufacturer produces a longer-range vehicle, then the government should increase its optimal subsidy. When $e_1 < \varepsilon_{1m}$ ($e_1 < \varepsilon_{1c}$), the government may still decrease the subsidy, even if the EV manufacturer produces a longer-range vehicle.

The EV price under subsidy scheme m increases (decreases) with r, if the marginal battery cost κ is larger (smaller) than $K^p_m \equiv n\alpha(3b+4\eta)(\lambda - 4\eta)/[4(b+4\eta)(b+\eta) + 2b^2]$. However, the impact of r on the price under subsidy scheme c is not monotone. This results in an uncertain relation between r and $\pi_{1c}(p^*_{1c})$. In addition, each consumer's net payment for an EV increases (decreases) with r, if the value of κ is higher (lower) than $K^p_c \equiv n\alpha(\lambda - 4\eta)/[2(b+2\eta)]$.

Proposition 5 *If κ is larger (smaller) than K^q_j ($j = m, c$) where $K^q_m \equiv n\alpha$ and $K^q_c \equiv n\alpha[2(b+\eta)(b+4\eta) + b^2]/B$, then the EV sales q^*_{1j} decrease (increase) with r but the ICV sales q^*_{2j} increase (decrease) with r.*

If $\kappa > K^q_j$ ($\kappa < K^q_j$), for $j = m, c$, then a higher driving range can decrease (increase) the EV sales, but it causes an increase (a decrease) in the price and sales of the ICV. For a longer driving range, the EV manufacturer's profit under subsidy scheme m decreases (increases), if $\kappa > K^q_m$ ($\kappa < K^q_m$).

4 Conclusions

We develop a sequential-move game, obtain optimal prices for an EV manufacturer and an ICV manufacturer, and derive the government's optimal subsidy strategy. Compared to subsidy scheme m, the adoption of subsidy scheme c induces the EV manufacturer to raise the EV price. Moreover, scheme c requires a greater subsidy amount to make the EV consumer's net payment identical to that under scheme m. The two subsidy schemes result in identical sales for the EV and the same social welfare. The above findings may explain why the Chinese government uses subsidy scheme m. When the environmental impact of the EV production is sufficiently high (low), the government should increase (decrease) its subsidy if the EV manufacturer increases the driving range for the EV. However, if the marginal battery cost is sufficiently high, a longer driving range of the EV may hinder the EV adoption. This holds regardless of what subsidy scheme is used.

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Online Appendix

Incentivizing the Adoption of Electric Vehicles under Subsidy Schemes: A Duopoly Analysis

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Appendix A Proofs

Proof of Proposition 1. The profit functions of the EV manufacturer and the ICV manufacturer are $\pi_{1m}(p_{1m}) = [a_1 - (b+\eta)p_{1m} + bp_{2m}](p_{1m} - k_1(r) + rs)$ and $\pi_{2m}(p_{2m}) = (a_2 + bp_{1m} - bp_{2m})(p_{2m} - k_2)$, respectively. Taking the first-order derivatives of $\pi_{1m}(p_{1m})$ w.r.t. p_{1m} and $\pi_{2m}(p_{2m})$ w.r.t. p_{2m}, we find the EV price and the ICV price under subsidy scheme m as given in this proposition. The resulting sales are $q_{1m}^* = (b+\eta)\left[K_2 - (b+2\eta) X_m\right]/(3b+4\eta)$ and $q_{2m}^* = [3b+4\eta-(b+2\eta) K_2 + b(b+\eta) X_m]/(3b+4\eta)$, where $X_m = k_1(r) - rs - n\alpha r - \xi_1$. Similarly, under subsidy scheme c, the optimal prices of the EV and the ICV are computed as in this proposition, and we compute the resulting sales as $q_{1c}^* = (b+\eta)[K_2 - X_c(b+2\eta)]/(3b+4\eta)$, and $q_{2c}^* = [3b+4\eta-(b+2\eta)K_2 + b(b+\eta)X_c]/(3b+4\eta)$, where $X_c = (1-\beta)\, k_1(r) - n\alpha r - \xi_1$.

Substituting the above optimal solutions into the EV manufacturer's and the ICV manufacturer's profit functions, we have

$$\pi_{1m}(p_{1m}^*) = (b+\eta)\frac{\left[K_2 - X_m\,(b+2\eta)\right]^2}{(3b+4\eta)^2},\ \pi_{1c}(p_{1c}^*) = (b+\eta)\,\frac{\left[K_2 - X_c\,(b+2\eta)\right]^2}{(3b+4\eta)^2\,(1-\beta)};$$

and,

$$\pi_{2j}(p_{2j}^*) = \frac{\left[3b+4\eta-(b+2\eta)\,K_2 + b\,(b+\eta)\,X_j\right]^2}{b\,(3b+4\eta)^2},\ \text{where } j = m, c.$$

■

Proof of Proposition 2. The social welfare under subsidy scheme m is written as $SW_m = q_{1m}(p_{1m} - k_1(r)) + \pi_{2m}(p_{2m}) + CS_m - q_{1m}e_1 - q_{2m}e_2 - \hat{E}_m$, where p_{1m}, p_{2m}, q_{1m}, and q_{2m} are defined as in Proposition 1, and $\hat{E}_m = n\hat{e}_1\left(u_m^2 - \underline{u}_m^2\right)/2 + n\hat{e}_2\left(1 - u_m^2\right)/2$. Letting $Y_m \equiv q_{1m}p_{1m}$, $Z_m \equiv \pi_{2m}(p_{2m}) - q_{1m}(k_1(r) + e_1) - q_{2m}e_2$, and $T_m \equiv CS_m - \hat{E}_m$, we compute the first-order derivative of SW_m w.r.t. s as

$$\frac{\partial SW_m}{\partial s} = \frac{\partial Y_m}{\partial s} + \frac{\partial Z_m}{\partial s} + \frac{\partial T_m}{\partial s},$$

where

$$\frac{\partial Y_m}{\partial s} = \frac{r\,(b+\eta)}{(3b+4\eta)^2}\left[4\,(b+\eta)\,(b+2\eta)\,(k_1(r) - rs) - b\,(b+2\eta)\,(n\alpha r + \xi_1) - bK_2\right].$$

Note that $CS_m = n(V - w_2)(1 - u_m^2)/2 - p_{2m}(1 - u_m) + (u_m^2 - \underline{u}_m^2)/(2\eta) + (n\alpha r - p_{1m})(u_m - \underline{u}_m)$. We rewrite u_m as

$$u_m = \frac{K_2\,(b+2\eta) - b\,(b+\eta)\,X_m}{3b+4\eta},$$

where $X_m = k_1(r) - rs - n\alpha r - \xi_1$ and $K_2 = 1 + bk_2 - b\xi_2$. We also rewrite $\underline{u}_m$ as

$$\underline{u}_m = \eta(p_{1m} - n\alpha r - \xi_1) = \eta\frac{K_2 + 2\,(b+\eta)\,X_m}{3b+4\eta}.$$

Then, consumer surplus CS_m can be reduced to

$$CS_m = n(V - w_2)\left(1 - u_m^2\right)/2 + (\xi_2 - p_{2j})(1 - u_m) + \left(u_m - \underline{u}_m\right)^2/(2\eta)\,,$$

where $u_m - \underline{u}_m = (b+\eta)[K_2 - X_m(b+2\eta)]/(3b+4\eta)$. Substituting CS_m and $\hat{E}_m$ into T_m, we find that s affects T_m only via X_m, and have

$$\begin{aligned}
T_m &= CS_m - n\hat{e}_2\frac{1-u_m^2}{2} - n\hat{e}_1\frac{u_m^2 - \underline{u}_m^2}{2} \\
&= n(V - w_2 - \hat{e}_2)\frac{1-u_m^2}{2} + (\xi_2 - p_{2j})(1-u_m) + \frac{\left(u_m - \underline{u}_m\right)^2}{2\eta} - n\hat{e}_1\frac{\left(u_m^2 - \underline{u}_m^2\right)}{2}.
\end{aligned}$$

Since $\partial u_m/\partial X_m = -b(b+\eta)/(3b+4\eta)$, $\partial p_{2m}/\partial X_m = (b+\eta)/(3b+4\eta)$, and $\partial\underline{u}_m/\partial X_m = 2\eta(b+\eta)/(3b+4\eta)$, we calculate the first-order derivative of T_m w.r.t. X_m as

$$\begin{aligned}
\frac{\partial T_m}{\partial X_m} &= -n(V - w_2 - \hat{e}_2)u_m\frac{\partial u_m}{\partial X_m} - \frac{\partial p_{2m}}{\partial X_m}(1-u_m) - (\xi_2 - p_{2j})\frac{\partial u_m}{\partial X_m} \\
&\quad + \frac{(u_m - \underline{u}_m)}{\eta}\left(\frac{\partial u_m}{\partial X_m} - \frac{\partial \underline{u}_m}{\partial X_m}\right) - n\hat{e}_1\left(u_m\frac{\partial u_m}{\partial X_m} - \underline{u}_m\frac{\partial \underline{u}_m}{\partial X_m}\right) \\
&= \frac{b+\eta}{3b+4\eta}\left[\omega u_m - 1 - b\left(p_{2m} - \xi_2\right) + \underline{u}_m\left(\frac{b}{\eta} + 2 + 2n\eta\hat{e}_1\right)\right],
\end{aligned}$$

where $\omega = bn(V - w_2 + \hat{e}_1 - \hat{e}_2) - 1 - b/\eta$.

We substitute p_{2m}, u_m, and $\underline{u}_m$ into $\partial T_m/\partial X_m$, and have

$$\frac{\partial T_m}{\partial X_m} = \frac{(b+\eta)}{(3b+4\eta)^2}\left[\tau K_2 + \lambda\,(b+\eta)\,X_m - 3b - 4\eta\right],$$

where $\tau \equiv \omega(b+2\eta) - b + 2\eta^2 n\hat{e}_1$ and $\lambda = 2(b + 2\eta + 2n\eta^2\hat{e}_1) - b\omega - b$. The first-order derivative of Z_m w.r.t. X_m is computed as

$$\frac{\partial Z_m}{\partial X_m} = \frac{\partial \pi_{2m}(p_{2m})}{\partial X_m} - \frac{\partial q_{1m}}{\partial X_m}\left(k_1(r) + e_1\right) - \frac{\partial q_{2m}}{\partial X_m}e_2.$$

The first-order derivative of $\pi_{2m}(p_{2m})$ w.r.t. X_m is

$$\frac{\partial \pi_{2m}(p_{2m})}{\partial X_m} = \frac{2\,(b+\eta)\left[3b + 4\eta + b\,(b+\eta)\,X_m - (b+2\eta)\,K_2\right]}{(3b+4\eta)^2}.$$

As

$$\frac{\partial q_{1m}}{\partial X_m} = \frac{-\,(b+2\eta)\,(b+\eta)}{(3b+4\eta)} \text{ and } \frac{\partial q_{2m}}{\partial X_m} = \frac{b\,(b+\eta)}{(3b+4\eta)},$$

the first-order derivative of Z_m w.r.t. X_m is

$$\begin{aligned}\frac{\partial Z_m}{\partial X_m} &= \frac{\partial \pi_{2m}(p_{2m})}{\partial X_m} - \frac{\partial q_{1m}}{\partial X_m}(k_1(r)+e_1) - \frac{\partial q_{2m}}{\partial X_m}e_2 \\ &= (b+\eta)\,\frac{\{(3b+4\eta)\,[2+(b+2\eta)\,(k_1(r)+e_1)-be_2]-2\,(b+2\eta)\,K_2+2b\,(b+\eta)\,X_m\}}{(3b+4\eta)^2}.\end{aligned}$$

Then,

$$\frac{\partial T_m}{\partial X_m}+\frac{\partial Z_m}{\partial X_m}=\frac{(b+\eta)\,\{[\tau-2\,(b+2\eta)]\,K_2+(\lambda+2b)\,(b+\eta)\,X_m+\varphi\,(3b+4\eta)\}}{(3b+4\eta)^2},$$

where $\varphi=(b+2\eta)(k_1(r)+e_1)+1-be_2$.

The first-order derivative of SW_m w.r.t. s is

$$\begin{aligned}\frac{\partial SW_m}{\partial s} &= \frac{\partial Y_m}{\partial s}+\frac{\partial T_m}{\partial s}+\frac{\partial Z_m}{\partial s} \\ &= \frac{r\,(b+\eta)\left\{\delta\,(b+\eta)\,(k_1(r)-rs)-\rho K_2+(n\alpha r+\xi_1)\left[\lambda\,(b+\eta)+b^2\right]-\varphi\,(3b+4\eta)\right\}}{(3b+4\eta)^2},\end{aligned}$$

where $\delta=2b+8\eta-\lambda$ and $\rho=\tau-b-4\eta$. The second-order derivative of SW_m w.r.t. s is $\partial^2 SW_m/\partial s^2 = -r^2(b+\eta)^2\delta/(3b+4\eta)^2$. Assume $\delta>0$. The optimal subsidy under subsidy scheme m is

$$s^*=\frac{k_1(r)}{r}-\frac{(3b+4\eta)\,\varphi+\rho K_2-\zeta\,(n\alpha r+\xi_1)}{r\delta\,(b+\eta)}.$$

The social welfare under subsidy scheme c is

$$SW_c=(1-\beta)\,q_{1c}p_{1c}+\pi_{2c}(p_{2c})+CS_c-q_{1c}\,(e_1+k_1(r))-q_{2c}e_2-\hat{E}_c.$$

Letting $Y_c=q_{1c}p_{1c}(1-\beta)$, $Z_c=\pi_{2c}(p_{2c})-q_{1c}(k_1(r)+e_1)-q_{2c}e_2$, and $T_c=CS_c-\hat{E}_c$, we rewrite SW_c as $SW_c=Y_c+Z_c+T_c$. The first-order derivative of Y_c w.r.t. β is

$$\frac{\partial Y_c}{\partial \beta}=-\frac{(b+\eta)\,k_1(r)\,[bK_2+n\alpha rb\,(b+2\eta)-4\,(b+\eta)\,(b+2\eta)\,(1-\beta)\,k_1(r)]}{(3b+4\eta)^2}.$$

In addition, we have

$$\frac{\partial T_c}{\partial X_c}+\frac{\partial Z_c}{\partial X_c}=\frac{(b+\eta)\,\{[\tau-2\,(b+2\eta)]\,K_2+(\lambda+2b)\,(b+\eta)\,X_c+\varphi\,(3b+4\eta)\}}{(3b+4\eta)^2}.$$

Therefore,

$$\frac{\partial SW_c}{\partial \beta}=\frac{(b+\eta)\,k_1(r)}{(3b+4\eta)^2}\,[\delta\,(b+\eta)\,(1-\beta)\,k_1(r)-\rho K_2+\zeta\,(n\alpha r+\xi_1)-\varphi\,(3b+4\eta)]\,.$$

The optimal subsidy under subsidy scheme c is obtained as

$$\beta^* = 1 - \frac{(3b+4\eta)\,\varphi + \rho K_2 - \zeta\,(n\alpha r + \xi_1)}{(b+\eta)\,\delta k_1(r)}.$$

Substituting s^* and β^* into $X_m = k_1(r) - rs^* - n\alpha r - \xi_1$ and $X_c = (1-\beta^*)\,k_1(r) - n\alpha r - \xi_1$ yields

$$X_m = X_c = \frac{\varphi\,(3b+4\eta) + \rho K_2 - [\zeta + (b+\eta)\,\delta](n\alpha r + \xi_1)}{\delta\,(b+\eta)}.$$

To ensure $s^* > 0$ and $\beta^* > 0$, we let $e_1 < [\delta k_1(r)(b+\eta) + \zeta\,(n\alpha r + \xi_1) - \rho K_2]/B - \chi$, where $\chi = k_1(r) + (1-be_2)/\,(b+2\eta)$, $B = (3b+4\eta)\,(b+2\eta)$. To ensure $q^*_{1j} > 0$, $q^*_{2j} > 0$, and $\underline{u}_j > 0$, we need to make $e_1 \in (\underline{e}_1, \bar{e}_1)$, where $\underline{e}_1 \equiv \max\{e_{1A}, e_{1B}\}$, $e_{1A} \equiv \mu/B + \{[\delta\,(b+2\eta) - b\rho]\,K_2 - \delta\,(3b+4\eta)\}/(bB) - \chi$, $e_{1B} \equiv [2\mu - (\delta + 2\rho)\,K_2]/(2B) - \chi$, $\bar{e}_1 \equiv \mu/B + [\delta\,(b+\eta) - \rho\,(b+2\eta)]\,K_2/[(b+2\eta)\,B] - \chi$, $\mu \equiv [\zeta + (b+\eta)\,\delta]\,(n\alpha r + \xi_1)$. ■

Proof of Proposition 3. Substituting s^* and β^* into p^*_{1m} and p^*_{1c}, we have

$$\begin{cases} p^*_{1m} = \dfrac{2\,[\varphi\,(3b+4\eta) + \rho K_2 - \zeta\,(n\alpha r + \xi_1)] + \delta\,[(b+2\eta)\,(n\alpha r + \xi_1) + K_2]}{(3b+4\eta)\,\delta}, \\ p^*_{1c} = \dfrac{2\,[\varphi\,(3b+4\eta) + \rho K_2 - \zeta\,(n\alpha r + \xi_1)] + \delta\,[(b+2\eta)\,(n\alpha r + \xi_1) + K_2]}{(1-\beta)\,(3b+4\eta)\,\delta}. \end{cases}$$

We find that $p^*_{1m} = (1-\beta^*)\,p^*_{1c} \le p^*_{1c}$. Recalling $X_m = X_c$, we have $rs^* = \beta^* k_1(r) < \beta^* p^*_{1c}$. As $p^*_{1c} \ge k_1(r)$, $G^*_c \ge G^*_m$, where $G^*_m = rs^*$ and $G^*_c = \beta p^*_{1c}$. Because p^*_{2j}, q^*_{1j}, and q^*_{2j} are functions of X_j, we find that $p^*_{2m} = p^*_{2c}$, $q^*_{1m} = q^*_{1c}$, and $q^*_{2m} = q^*_{2c}$. We have $\pi_{1c}(p^*_{1c}) = \pi_{1m}(p^*_{1m})/(1-\beta^*)$ and $\pi_{1m}(p^*_{1m}) \le \pi_{1c}(p^*_{1c})$. In addition, $\pi_{2m}(p^*_{2m}) = \pi_{2c}(p^*_{2c})$. As s^* affects T_m and Z_m only via X_m and β^* affects T_c and Z_c only via X_c, where $T_j = CS_j - \hat{E}_j$, $Z_j = \pi_{2j}(p_{2j}) - q^*_{1j}[k_1(r) + e_1] - q^*_{2j}e_2$, for $j = m$, c. We find that $T_m = T_c$ and $Z_m = Z_c$. Since $p^*_{1m} = p^*_{1c}(1-\beta^*)$ and $q^*_{1m} = q^*_{1c}$, we have $Y_m = Y_c$. It thus follows that $SW_m = SW_c$. ■

Proof of Proposition 4. The first-order derivative of s^* w.r.t. r is

$$\frac{\partial s^*}{\partial r} = \frac{1}{r^2}\left[\frac{\varphi\,(3b+4\eta) + \rho K_2 - \zeta\xi_1}{\delta\,(b+\eta)} - k_1(r)\right] + \frac{\kappa}{r}\left[\frac{\delta\,(b+\eta) - (3b+4\eta)\,(b+2\eta)}{\delta\,(b+\eta)}\right].$$

Then, $\partial s^*/\partial r > 0$ if $e_1 > \varepsilon_{1m}$ and $\partial s^*/\partial r \le 0$ if $e_1 \le \varepsilon_{1m}$, where ε_{1m} is defined as in this proposition . The first-order derivative of β^* w.r.t. r is

$$\frac{\partial \beta^*}{\partial r} = \frac{\kappa\,[\varphi\,(3b+4\eta) + \rho K_2 - \zeta\,(n\alpha r + \xi_1)] - [\kappa\,(3b+4\eta)\,(b+2\eta) - \zeta n\alpha]\,k_1(r)}{(b+\eta)\,\delta k_1(r)^2}.$$

If $e_1 > \varepsilon_{1c}$ where ε_{1c} is defined as in this proposition, $\partial\beta^*/\partial r > 0$. If $e_1 \le \varepsilon_{1c}$, $\partial\beta^*/\partial r \le 0$. ■

Proof of Proposition 5. The first-order derivative of p^*_{1m} w.r.t. r is

$$\frac{\partial p^*_{1m}}{\partial r} = \frac{2\kappa\left[2\,(b+4\eta)\,(b+\eta) + b^2\right] - 2n\alpha\zeta + n\alpha\delta\,(b+2\eta)}{\delta\,(3b+4\eta)}.$$

Defining K_m^p as in this proposition, we find that, if $\kappa > K_m^p$, then $\partial p_{1m}^*/\partial r > 0$; otherwise, if $\kappa \leq K_m^p$, then $\partial p_{1m}^*/\partial r \leq 0$, where $\kappa = \partial k_{BT}(r)/\partial r$. The first-order derivative of X_m w.r.t. r is

$$\frac{\partial X_m}{\partial r} = \frac{2\,(b+4\eta)\,(b+\eta)+b^2}{\delta\,(b+\eta)}(\kappa - n\alpha).$$

Under subsidy scheme c, the first-order derivative of $(1-\beta^*)p_{1c}^*$ w.r.t. r is

$$\frac{\partial\left[(1-\beta)\,p_{1c}^*\right]}{\partial r} = \frac{2\,(b+2\eta)\,\kappa + n\alpha\,(4\eta-\lambda)}{\delta}.$$

If $\kappa > K_c^p$, $\partial(p_{1c}^*(1-\beta^*))/\partial r > 0$; otherwise, if $\kappa \leq K_c^p$, $\partial(p_{1c}^*(1-\beta^*))/\partial r \leq 0$. The first-order derivative of p_{1c}^* w.r.t. r is computed as

$$\frac{\partial p_{1c}^*}{\partial r} = \frac{2\kappa\,(b+\eta)}{3b+4\eta} + \frac{n\alpha\,(b+2\eta)\,(1-\beta^*) + \left[(n\alpha r+\xi_1)\,(b+2\eta)+K_2\right]\partial\beta^*/\partial r}{(3b+4\eta)\,(1-\beta^*)^2},$$

which may be positive or may be negative. This result is similar to $\partial\pi_{1c}(p_{1c}^*)/\partial r$.

The first-order derivative of X_c w.r.t. r is

$$\frac{\partial X_c}{\partial r} = \frac{B\kappa}{\delta\,(b+\eta)} - n\alpha\frac{2\,(b+\eta)\,(b+4\eta)+b^2}{\delta\,(b+\eta)}.$$

Note that the sign of $\partial q_{1j}^*/\partial r$ depends on $-\partial X_j/\partial r$, and the signs of $\partial p_{2j}^*/\partial r$, $\partial q_{2j}^*/\partial r$, and $\partial\pi_{2j}(p_{2j}^*)/\partial r$ are contingent on $\partial X_j/\partial r$, where $j = m, c$. We find that if $\kappa > K_m^q = n\alpha$, $\partial p_{2m}^*/\partial r > 0$, $\partial q_{2m}^*/\partial r > 0$, $\partial\pi_{2m}(p_{2m}^*)/\partial r > 0$, $\partial q_{1m}^*/\partial r < 0$, and $\partial\pi_{1m}(p_{1m}^*)/\partial r < 0$. If $\kappa \leq K_m^q$, $\partial p_{2m}^*/\partial r \leq 0$, $\partial q_{2m}^*/\partial r \leq 0$, $\partial\pi_{2m}(p_{2m}^*)/\partial r \leq 0$, $\partial q_{1m}^*/\partial r \geq 0$, and $\partial\pi_{1m}(p_{1m}^*)/\partial r \geq 0$. We find if $\kappa > K_c^q$, $\partial X_c/\partial r > 0$, $\partial p_{2c}^*/\partial r > 0$, $\partial q_{1c}^*/\partial r < 0$, $\partial q_{2c}^*/\partial r > 0$, and $\partial\pi_{2c}(p_{2c}^*)/\partial r > 0$. Otherwise, if $\kappa \leq K_c^q$, then $\partial X_c/\partial r \leq 0$, $\partial p_{2c}^*/\partial r \leq 0$, $\partial q_{1c}^*/\partial r \geq 0$, $\partial q_{2c}^*/\partial r \leq 0$, and $\partial\pi_{2c}(p_{2c}^*)/\partial r \leq 0$. ■