

Jingjing XUE, Bin ZHENG, Sijie LI

Optimal production strategy for auto manufacturers with government subsidies in competitive environments

© Higher Education Press 2023

Abstract Using the Hotelling model and evolutionary game theory, this paper studies the optimal production strategy of duopoly auto manufacturers and explores the impacts of two government policies (manufacturer and consumer subsidies) on strategies related to the production of electric vehicles (EVs) or fuel vehicles (FVs). The study finds that consumers' environmental preferences have direct effects on manufacturers' market shares and profits, which in turn, affect the manufacturers' production strategy selection. Specifically, when consumer environmental preference is sufficiently high, both auto manufacturers will eventually choose to produce EVs; when it is moderate, only one with a cost advantage will choose to produce EVs. Finally, when it is low, neither auto manufacturer will produce EVs. The findings further reveal that the more significant the difference in EV production costs is, the more inclined auto manufacturers are to choose a different final stable strategy. Regardless of whether the government subsidizes manufacturers or consumers, the policy only works if subsidies reach a certain threshold. The study also identifies the conditions under which government subsidies are considered more cost-effective.

Keywords supply chain management, low-carbon emission, electric vehicle, subsidy, evolutionary game theory

Received Dec. 29, 2022; revised Apr. 13, 2023; accepted May 2, 2023

Jingjing XUE
School of Economics and Management, Nanjing Tech University,
Nanjing 211816, China

Bin ZHENG, Sijie LI (✉)
School of Economics and Management, Southeast University, Nanjing
211189, China
E-mail: sjli@seu.edu.cn

This research was supported by the National Natural Science Foundation of China (Grant Nos. 71871058 and 72271054), and the Fundamental Research Funds for the Central Universities (Grant No. 2242023K40025).

1 Introduction

The transportation sector, which mainly relies on fuel vehicles (FVs), is one of the most polluting industries worldwide. It is responsible for approximately 23% of global greenhouse gas (GHG) emissions, and this is projected to increase by up to 50% by 2050 (Bunsen et al., 2018). In recent years, electric vehicles (EVs) have emerged as a more efficient alternative due to their zero tailpipe emissions (Kieckhäfer et al., 2014). If effectively and continually adopted, EVs will result in a significant decrease in GHG emissions, thereby contributing to environmental health to some extent (Gu et al., 2017; Bahrami and Amini, 2018). For example, in the UK, the average lifetime emission per km of driving a Nissan Leaf EV in 2019 was almost three times lower than those of conventional vehicles (Hausfather, 2019). Unlike other green products (e.g., solar equipment and environmentally friendly clothing), vigorously promoting EVs can help significantly reduce environmental pollution.

Governments worldwide are actively promoting EVs as a major technology to reduce GHG emissions and combat climate change. Amidst this background, we explore auto manufacturers' production strategies (i.e., FV or EV) in a competitive market environment, as well as government subsidies that effectively promote the development of EVs. However, the current development of EVs is still relatively slow, and their global penetration remains lower than that of FVs. In 2018, EVs represented just 0.7% of the overall market share in the auto industry, and the percentage is significantly less in developing countries (Rietmann et al., 2020). One of the reasons for this is consumers' low awareness of environmental protection, which directly affects their purchase valuation and demand for EVs (Zhang and Huang, 2021). Another major reason is that traditional auto manufacturers are not motivated to participate in the development and production of EVs, because their market share is too small to bring further benefits. Therefore, even if EVs are the future of the automotive industry, large automakers prefer to

produce FVs (Zarazua de Rubens et al., 2018) due to the high production cost and low market share of EVs in the current market (Zhang, 2014; Gao and Leng, 2021). Some executives of auto manufacturers have stated that the future of FVs should be determined by market demand and consumer preference. On the contrary, new entrants to the automotive industry, such as BYD, NIO, Li Auto, and Xiaopeng, prefer to engage in the research and development (R&D) and production of EVs. However, the development and future of EVs require the active participation of large automakers. In this context, auto manufacturers in the competitive setting must carefully choose their production strategies in the face of increasing consumer environmental awareness.

To stimulate consumer demand for EVs and reduce the production costs incurred by auto manufacturers, governments worldwide have actively launched various subsidy programs to heighten the viability of EVs as more attractive options. Unlike in other industries, the coexistence of manufacturer and consumer subsidies is quite common in the EV industry (Zhang, 2014; Safarzadeh and Rasti-Barzoki, 2019). For instance, consumers who purchase Tesla vehicles are eligible for US government subsidies (Yu et al., 2018). Furthermore, Chinese automakers, such as BYD and BAIC Motor, have received government subsidies to boost the production of EVs (Srivastava et al., 2022). To this end, from the perspective of government policy, it is essential to understand the effectiveness of different subsidy programs in the highly competitive auto market.

In this paper, we use evolutionary game to investigate the strategic interplay of auto manufacturers' production strategies in considering the characteristics of EVs and consumers' environmental preferences. Considering the characteristics and stability of the auto industry (Liu et al., 2017; Ji et al., 2019; Ma et al., 2021), we propose an evolutionarily stable strategy (ESS) for competitive auto manufacturers as we attempt to answer the following four questions:

- (1) Under what conditions would auto manufacturers adopt EVs?
- (2) What are the optimal prices for auto manufacturers in different competitive settings?
- (3) How do consumers' environmental preferences influence the ESS of auto manufacturers?
- (4) How do different subsidy strategies affect auto manufacturers' production strategies and ESS, and which subsidy program is more cost-effective?

In considering the production strategies (FVs or EVs) of two competing auto manufacturers with different production costs, we propose an evolutionary game model of the interactions between two asymmetrical auto manufacturers and identify the evolutionarily stable conditions. By performing numerical analysis, the impacts of the production cost on the evolutionary equilibrium are also discussed. Our research yields the

following significant findings, which bring valuable insights for auto manufacturers and environmental policy-makers engaged in promoting EVs.

First, when consumer environmental preference is sufficiently high, both auto manufacturers will eventually choose to produce EVs, whereas when consumer environmental preference is sufficiently low, both auto manufacturers will choose to produce FVs. Meanwhile, when consumer environmental preference is moderate, auto manufacturers with cost advantage will choose EVs, while auto manufacturers with cost disadvantage will choose FVs. Second, the differences in production costs between competing auto manufacturers have a considerable impact on their ESSs. In particular, the greater the difference in production costs is, the more inclined auto manufacturers will be to choose different production strategies in the long run. Finally, if the subsidies exceed a certain threshold, both manufacturer and consumer subsidy programs can effectively promote the adoption of EVs. Interestingly, the manufacturer subsidy program is more cost-effective than the consumer subsidy program when consumers have a high level of environmental awareness.

This paper makes two contributions to the field of operations management. First, we develop the one-shot game and evolutionary game models to explore the production strategy interactions of two asymmetrical and competitive auto manufacturers. Second, we explore the impacts of both the manufacturer and consumer subsidies on auto manufacturers' final stable strategies and discuss which type of subsidy program is more cost-effective for the government.

The remainder of the paper is organized as follows. Section 2 briefly reviews the related literature to identify research gaps and position our work. In Section 3, we introduce the problem and describe the assumptions. In Sections 4 and 5, we discuss the one-shot game model and present the evolutionary analysis of auto manufacturers' strategies, respectively. Section 6 considers the two types of government subsidies. Section 7 concludes the paper and provides future research directions.

2 Literature review

Our study focuses on the intersection of EVs and government subsidy policies. This work is related to two main research areas: EV-related operations management and environmentally friendly operations under government subsidy programs.

In recent years, an increasing number of scholars have explored EV-related topics from operations management perspectives, such as pricing strategies (Lim et al., 2015; Fan et al., 2020), battery capacity allocation and recycling (Gu et al., 2017; Zhu et al., 2020), and charging stations

(Yu et al., 2022). Fan et al. (2020) studied vertical cooperation and pricing strategies in a supply chain involving a battery supplier and two EV manufacturers. Considering an auto supply chain with a manufacturer and a retailer, Yu et al. (2021) studied the impacts of dual credit policy on the production and pricing strategies for EVs and FVs. Gao et al. (2022) investigated a logistics service provider's choice between offering only EVs or a mix of EVs and FVs. However, the above literature does not consider the competition between EVs and FVs or that between the automakers that manufacture them.

Huang et al. (2013) discussed a duopoly competition between an FV supply chain and an EV and FV joint supply chain. Zhu et al. (2019) analyzed a product differential model on traditional gasoline vehicles and new energy vehicles under a cap-and-trade regulation system, finding that both the market share of EVs and manufacturers' profits increase with the increase in carbon quota for EVs. Ma et al. (2021) considered a competitive market consisting of an EV manufacturer and an FV manufacturer and found that government intervention policies can maximize social welfare. Our paper also considered a duopoly setting between two auto manufacturers, although we focused on the production strategy in which each auto manufacturer can choose to produce FVs or EVs.

Another stream of related research pertains to environmentally friendly operations under government subsidy programs or environmental policies (Raz and Ovchinnikov, 2015; Yu et al., 2018; Taylor and Xiao, 2019; Bian et al., 2020; Ye et al., 2021). Ma et al. (2019) examined two forms of government subsidies (service infrastructure and product subsidies) that aim to promote clean-technology products. Their results reveal that it is best to provide a product subsidy when the infrastructure cost is sufficiently high or low; nevertheless, it is ideal to provide both subsidies when this cost is moderate. Ye et al. (2021) investigated the optimal subsidy (farmers or bioenergy producers) in the bioenergy supply chain considering the subsidy budget and land capacity constraints.

In contrast to the aforementioned research, our work is closely tied to recent literature, which investigates various government subsidies designed to support the adoption of the EV industry (Luo et al., 2014; Shao et al., 2017; Chemama et al., 2019; Gu et al., 2019; Fan et al., 2020; Gao et al., 2022). For example, Narassimhan and Johnson (2018) studied 2008–2016 US car purchasing data and demonstrated that purchasing subsidies and the quantity of charging stations have considerable impacts on EV sales. Shao et al. (2017) studied both per-unit subsidy and price discount schemes for consumers to promote EVs under monopoly and duopoly settings. Fan et al. (2020) examined the optimal pricing strategies of domestic/imported EV manufacturers, as well as the optimal consumer subsidy and tariff policies implemented by the government. Srivastava et al. (2022) built a noncooperative

game to examine how manufacturer subsidies and differential taxation schemes may boost the market adoption of EVs. In the context of consumer and manufacturer subsidies, Zhang and Huang (2021) examined vehicle manufacturers' decisions on whether to produce traditional FVs and/or EVs/hybrid vehicles. Their results show that the economic and environmental interests of the subsidy programs may not always be aligned. Similar to Zhang and Huang (2021), we considered both manufacturer and consumer subsidies in this study. Our work, however, focused on the impacts of these subsidy policies on the production strategies of two competitive auto manufacturers under bounded rationality assumption.

3 Problem description and consumer demands

This study considers a duopoly in which two auto manufacturers (M1 and M2) sell their new vehicles, which are substitutable, to consumers on the market. Each auto manufacturer faces alternative production strategies: EVs or FVs. When both auto manufacturers choose the FV strategy (*FF*), there is only competition in price between them. When only one of them chooses the EV strategy (*FE* or *EF*), the auto manufacturer producing the EVs is more competitive among consumers who care about the environment. When both auto manufacturers choose the EV strategy (*EE*), there is competition between them regarding the price and emission reduction levels of EVs. The two auto manufacturers are supposed to move simultaneously in a Nash game and can constantly make decisions based on their observations and learnings of their rival's strategies. We also assume that all parameters are completely transparent to all participants.

Furthermore, we assume that consumers are uniformly distributed over the range $[0, 1]$ and that M1 and M2 compete for these consumers. Employing the Hotelling model with linear transportation cost and full market coverage, without loss of generality, we assume that M1 is located at 0, and M2 is located at 1. In addition, consumers make purchasing decisions based on utility, and they need at most one product. Thus, the consumers' utilities are respectively expressed as follows:

$$\begin{cases} u_1^j = v + m\theta e - p_1^j - \lambda x^j \\ u_2^j = v + n\theta e - p_2^j - \lambda(1 - x^j) \end{cases}, \quad (1)$$

where u_i^j ($i = 1, 2; j = FF, FE, EF, EE$) denotes the consumers' utility by purchasing the vehicle from M1 or M2 under different competitive cases, $x^j \in [0, 1]$ denotes the consumers' distance to M1, $\lambda > 0$ is the marginal cost of transportation or mismatching cost, p_i^j represents the sale price of the vehicle set by the auto manufacturers, and v is the basic value for EVs and FVs, which is the same for all consumers. To ensure full market coverage,

we assume that v is sufficiently high. The emission reduction levels of FV and EV are e_0 and e , respectively. Compared with FVs, EVs have great environmental advantages. Without loss of generality, we assume that $e > e_0 = 0$ (Ji et al., 2019; Srivastava et al., 2022), and $\theta > 0$ denotes the consumer environmental preference. The higher the θ is, the greater the likelihood that the consumers are environmentally conscious. Here, m and n are binary variables, $m = 0$ ($n = 0$) indicates that M1 (M2) chooses FVs, and $m = 1$ ($n = 1$) means that M1 (M2) chooses EVs.

Hence, under strategy FF , the consumers' utilities by purchasing FVs from M1 and M2 are $u_1^{FF} = v - p_1^{FF} - \lambda x^{FF}$ and $u_2^{FF} = v - p_2^{FF} - \lambda(1 - x^{FF})$, respectively. By letting $u_1^{FF} = u_2^{FF}$, the location of the marginal consumer who is indifferent between buying from M1 and M2 is expressed as $\bar{x}^{FF} = (p_2^{FF} - p_1^{FF} + \lambda)/(2\lambda)$. Thus, the demands of M1 and M2 under strategy FF are $D_1^{FF} = (p_2^{FF} - p_1^{FF} + \lambda)/(2\lambda)$ and $D_2^{FF} = 1 - (p_2^{FF} - p_1^{FF} + \lambda)/(2\lambda)$, respectively. Similarly, we can obtain the consumer demands of the two auto manufacturers under other strategies.

4 One-shot duopoly game

In this section, we model a one-shot duopoly game between the two manufacturers and determine the prices of FVs and EVs in different competitive cases. Currently, EVs are significantly more expensive than FVs due to the high cost of batteries (Egbue and Long, 2012). We assume that the production cost of EVs is higher than that of FVs, and the unit production costs of FVs and EVs are c and $c + k_i e^2$, respectively. The increasing unit production cost in efficiency captures the reality that vehicles with fewer carbon emissions are usually more expensive to produce. This quadratic cost function in emission reduction is prevalent in the literature (Han et al., 2022). Here, k_i is the cost coefficient for producing EVs, which represents the auto manufacturers' R&D ability in designing and producing EVs. The higher the k_i , the lower the efficiency

of auto manufacturers. To capture the difference in the efficiency of EV R&D capabilities between the two auto manufacturers, we assume that $k_1 < k_2$, which means that M1 possesses an advantage in the production cost of EVs compared with M2. Here, M1 (M2) represents auto manufacturers with EV R&D cost advantages (disadvantages). To simplify our models and sharpen our findings, we further assume $c = 0$ because c does not affect the main results.

Based on the above discussion, the profit functions of M1 and M2 are respectively summarized as follows:

$$\begin{cases} \pi_1^j = (p_1^j - mk_1 e^2) D_1^j \\ \pi_2^j = (p_2^j - nk_2 e^2) D_2^j \end{cases}, \tag{2}$$

where $m = 0$ ($n = 0$) indicates M1 (M2) chooses FVs, whereas $m = 1$ ($n = 1$) means M1 (M2) chooses EVs.

In the market, two auto manufacturers simultaneously announce their sale prices and reach a Nash equilibrium. With the objective of maximizing manufacturers' profits, we obtain the optimal prices p_i^* , demands D_i^* , and profits π_i^* of M1 and M2 under four strategies, which are summarized in Table 1.

Note that, to ensure that the equilibrium solutions of M1 and M2 under four competitive cases are non-negative, consumer environment preference should satisfy the following two conditions: $(e^2 k_2 - 3\lambda)/e \leq \theta \leq (e^2 k_1 + 3\lambda)/e$ and $e^2 k_1 + 3\lambda \geq e^2 k_2$.

From Table 1, we obtain the following proposition, which shows two manufacturers' production strategies.

Proposition 1.

- (1) Under strategy EF , when $\theta > (e^2 k_1 + 3\lambda)/e$, M1 will monopolize the market by producing EVs;
- (2) Under strategy FE , when $\theta > (e^2 k_2 + 3\lambda)/e$, M2 will monopolize the market by producing EVs;
- (3) $p_1^{FF*} = p_2^{FF*} < p_1^{EE*} < p_2^{EE*}$;
- (4) $D_2^{EE*} < D_2^{FF*} = D_1^{FF*} < D_1^{EE*}$.

Propositions 1(1) and 1(2) indicate that when consumers' environmental preferences are sufficiently high, the auto manufacturer who first adopts the EVs can

Table 1 Equilibrium solutions under different strategies

	Strategy FF	Strategy FE	Strategy EF	Strategy EE
p_1^*	λ	$\frac{e(ek_2 - \theta) + 3\lambda}{3}$	$\frac{e(2ek_1 + \theta) + 3\lambda}{3}$	$\frac{e^2(2k_1 + k_2) + 3\lambda}{3}$
p_2^*	λ	$\frac{e(2ek_2 + \theta) + 3\lambda}{3}$	$\frac{e(ek_1 - \theta) + 3\lambda}{3}$	$\frac{e^2(k_1 + 2k_2) + 3\lambda}{3}$
D_1^*	$\frac{1}{2}$	$\frac{e(ek_2 - \theta) + 3\lambda}{6\lambda}$	$\frac{e(\theta - ek_1) + 3\lambda}{6\lambda}$	$\frac{e^2(k_2 - k_1) + 3\lambda}{6\lambda}$
D_2^*	$\frac{1}{2}$	$\frac{e(\theta - ek_2) + 3\lambda}{6\lambda}$	$\frac{e(ek_1 - \theta) + 3\lambda}{6\lambda}$	$\frac{e^2(k_1 - k_2) + 3\lambda}{6\lambda}$
π_1^*	$\frac{\lambda}{2}$	$\frac{(e^2 k_2 + 3\lambda - e\theta)^2}{18\lambda}$	$\frac{(3\lambda - e^2 k_1 + e\theta)^2}{18\lambda}$	$\frac{(e^2(k_2 - k_1) + 3\lambda)^2}{18\lambda}$
π_2^*	$\frac{\lambda}{2}$	$\frac{(3\lambda - e^2 k_2 + e\theta)^2}{18\lambda}$	$\frac{(e^2 k_1 + 3\lambda - e\theta)^2}{18\lambda}$	$\frac{(e^2(k_1 - k_2) + 3\lambda)^2}{18\lambda}$

gain a significant advantage in a competitive market, thus occupying a monopolistic position. In this case, if the strong manufacturer (M1) still chooses to produce FVs, it will also be squeezed out of the market by the weak manufacturer (M2).

Proposition 1(3) indicates that when both manufacturers decide to produce EVs, consumers must pay a higher purchase price. This is intuitive because manufacturers must invest in additional production technologies to produce EVs compared with the production of FVs, and as a result, the production costs increase. Additionally, both manufacturers have half the market when they produce FVs. However, under strategy *EE*, M1 will be able to set a lower price to capture a greater market share and maximize profits due to the cost advantage. Accordingly, compared with strategy *FF*, M1 can achieve greater profits under strategy *EE*, while M2's profits are reduced.

5 Evolutionary analysis of manufacturers' strategies

5.1 Stable points in the evolutionary

According to the bounded rationality assumption, the one-shot game may not be optimal for auto manufacturers when the decisions of the game players are interdependent. In the long run, auto manufacturers determine the best stable equilibrium strategy by continuously learning and imitating the tactics of their competitors. Therefore, it is necessary to investigate the repeated dynamic adjustment of auto manufacturers in the market. Based on the one-shot game, two auto manufacturers have two pure strategies (i.e., FVs and EVs). Their payoff matrix is shown in Table 2.

Table 2 Payoff matrix of M1 and M2

M1	M2	
	EV strategy	FV strategy
EV strategy	$(\pi_1^{EE*}, \pi_2^{EE*})$	$(\pi_1^{EF*}, \pi_2^{EF*})$
FV strategy	$(\pi_1^{FE*}, \pi_2^{FE*})$	$(\pi_1^{FF*}, \pi_2^{FF*})$

Let x and $(1 - x)$ denote the probability of M1 choosing the EV and FV strategies, respectively, whereas the probabilities of M2 adopting the EV and FV strategies are y and $(1 - y)$, respectively. The two probabilities $x, y \in [0, 1]$ are functions of time t . In addition, U_1^E and U_1^F denote the expected payoffs of M1 choosing the EV and FV strategies, respectively, and \bar{U}_1 denotes the average expected payoff. According to the payoff matrix in Table 2, the expected and average expected payoffs of M1 are respectively given by:

$$U_1^E = y\pi_1^{EE*} + (1 - y)\pi_1^{EF*}, \tag{3}$$

$$U_1^F = y\pi_1^{FE*} + (1 - y)\pi_1^{FF*}, \tag{4}$$

$$\bar{U}_1 = xU_1^E + (1 - x)U_1^F. \tag{5}$$

According to evolutionary game theory, the replicator dynamics equation of M1 is given by:

$$F(x) = \frac{dx}{dt} = x(1 - x)[y(\pi_1^{EE*} - \pi_1^{FE*}) + (1 - y)(\pi_1^{EF*} - \pi_1^{FF*})], \tag{6}$$

where $F(x)$ represents the change rate of M1 choosing EV strategy. Furthermore, $F'(0) < 0$ shows that the proportion of M1 adopting the EV strategy evolves to 0 over time, while $F'(1) < 0$ indicates that it evolves to 1 (Xiao and Chen, 2009).

Similarly, the replicator dynamics equation of M2 is given by:

$$F(y) = \frac{dy}{dt} = y(1 - y)[x(\pi_2^{EE*} - \pi_2^{EF*}) + (1 - x)(\pi_2^{FE*} - \pi_2^{FF*})]. \tag{7}$$

Following the definition of the stable strategy for an evolutionary game, let $F(x) = 0$ and $F(y) = 0$, which mean that the system will no longer evolve and achieve equilibrium. Therefore, the replicator dynamics system has five stable equilibrium points: $(0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, and (x_0, y_0) , where $x_0 = \frac{\pi_2^{FF*} - \pi_2^{FE*}}{\pi_2^{EE*} - \pi_2^{EF*} - \pi_2^{FE*} + \pi_2^{FF*}}$, $y_0 = \frac{\pi_1^{FF*} - \pi_1^{EF*}}{\pi_1^{EE*} - \pi_1^{FE*} - \pi_1^{EF*} + \pi_1^{FF*}}$, $0 \leq x_0 \leq 1$, and $0 \leq y_0 \leq 1$.

5.2 Stability analysis

When a stable point of the replicator dynamics equation is an evolutionary equilibrium, which equals the locally asymptotically stable point, it is judged as the ESS of a system. The standard Jacobian matrix is used to evaluate whether the equilibrium strategy pairs are asymptotically stable, and it can achieve ESS when the stable points satisfy $\det(\mathbf{J}) > 0$ and $\text{tr}(\mathbf{J}) < 0$ (Friedman, 1991). The Jacobian matrix \mathbf{J} is expressed as:

$$\mathbf{J} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1 - 2x)(yM + (1 - y)N) & x(1 - x)(M - N) \\ y(1 - y)(P - Q) & (1 - 2y)(xP + (1 - x)Q) \end{bmatrix}, \tag{8}$$

where $M = \pi_1^{EE*} - \pi_1^{FE*}$, $N = \pi_1^{EF*} - \pi_1^{FF*}$, $P = \pi_2^{EE*} - \pi_2^{EF*}$, and $Q = \pi_2^{FE*} - \pi_2^{FF*}$. Then, we have $\det(\mathbf{J}) = (1 - 2x) \cdot (yM + (1 - y)N)(1 - 2y)(xP + (1 - x)Q) - x(1 - x)(M - N) \cdot y(1 - y)(P - Q)$ and $\text{tr}(\mathbf{J}) = (1 - 2x)(yM + (1 - y)N) + (1 - 2y)(xP + (1 - x)Q)$.

The evaluations of the equilibrium strategy pairs are shown in Table 3.

Table 3 Analysis of the local stabilities between M1 and M2

Point	det (J)	tr (J)	Result
Case 1: $(e^2k_2 - 3\lambda)/e \leq \theta < ek_1$			
(0, 0)	+	–	ESS
(0, 1)	–	±	Saddle point
(1, 0)	–	±	Saddle point
(1, 1)	+	+	Unstable point
Case 2: $ek_1 \leq \theta < ek_2$			
(0, 0)	–	±	Saddle point
(0, 1)	+	+	Unstable point
(1, 0)	+	–	ESS
(1, 1)	–	–	Saddle point
Case 3: $ek_2 \leq \theta \leq (e^2k_1 + 3\lambda)/e$			
(0, 0)	+	+	Unstable point
(0, 1)	–	±	Saddle point
(1, 0)	–	±	Saddle point
(1, 1)	+	–	ESS

According to the local stability results in Table 3, we obtain the following proposition, which demonstrates the ESS of auto manufacturers under different strategies.

Proposition 2.

- (1) If $(e^2k_2 - 3\lambda)/e \leq \theta < ek_1$, $(x, y) = (0, 0)$ is ESS;
- (2) If $ek_1 \leq \theta < ek_2$, $(x, y) = (1, 0)$ is ESS;
- (3) If $ek_2 \leq \theta \leq (e^2k_1 + 3\lambda)/e$, $(x, y) = (1, 1)$ is ESS;
- (4) $(x, y) = (0, 1)$ or (x_0, y_0) would not be ESS in any case.

Proposition 2 shows the local stability of the equilibrium point of the system and the corresponding conditions. As can be seen, the two auto manufacturers are unlikely to produce EVs simultaneously when consumers only have a small or moderate preference for the environment. As a result of the long-term repeated game, both M1 and M2 are inclined to use the FV strategy if consumer environmental preference is sufficiently low. However, both will adopt the EV strategy if the environmental preference is sufficiently high. This is because when consumer environmental preference is sufficiently low, auto manufacturers cannot attract enough consumers by offering EVs to cover the costs of additional R&D. This phenomenon is not uncommon in developing countries where consumers tend to be less aware of environmental benefits and are more sensitive to the price of a vehicle itself. Conversely, when consumers place a high priority on carbon reduction, both M1 and M2 have the incentive to offer EVs. Note that when consumers have a moderate environmental preference, only the stronger M1 will select the EV strategy, while the weaker M2 may prefer to adopt the FV strategy to avoid direct competition with the stronger M1. In this case, M1 will produce EVs due to its cost advantage after practicing long-term imitating

and learning behaviours. Meanwhile, M2 chooses the opposite strategy to survive. From Proposition 2, it can be concluded that consumers' environmental preferences influence auto manufacturers' evolutionary equilibrium. This result also explains why the share of EVs is higher in developed countries than that in underdeveloped countries. For example, in 2022, the EV market share is 25% in Germany, while EVs account for only 1.3% of the Indian auto market.

Next, we show the evolution path and gain more managerial insights through numerical studies. According to the announcement of the Production Enterprises and Product of Road Motor Vehicle released in February 2018 by the Chinese government, a total of 218 auto manufacturers, including 59 EV manufacturers, complied with national regulations and technical requirements (Ji et al., 2019). Thus, we let the initial values of x and y be 0.27. Taking BYD NEV (new energy vehicle) E6 and FV M6 as examples, the production costs of EVs and FVs are 0.25 and 0.0554 million yuan, respectively (Fan and Dong, 2018). It is assumed that the cost factors of EVs are $k_1 = 0.2$ and $k_2 = 0.4$. For the other parameters, we set $\lambda = 3$, $e = 5$, and $\theta = \{0.5, 1.5, 2.5\}$ for low, moderate, and high consumer environmental preferences, respectively. In addition, we set t in $[0, 20]$. The evolution paths are shown in Fig. 1, which reveals that as consumer environmental preference θ increases, the dynamic system will evolve from ESS (0, 0) to ESS (1, 0) to ESS (1, 1).

For low consumer environmental preferences, as shown in Fig. 1(a), strategy *FF* is the steady equilibrium strategy of the system. Although we assume that the two types of auto manufacturers only have cost differences in EVs and not in FVs, the final stable strategy of M2 will evolve to FVs faster than that of M1. In Fig. 1(b), it will evolve into a local stability point (1, 0) under moderate consumer environmental preferences. In this case, M1 and M2 choose different production strategies. Figure 1(c) shows that higher consumer environmental preference causes the final stable strategy to evolve to strategy *EE*. Due to the production cost advantage, we find that the final stable strategy of M1 will evolve to EVs at a faster rate. These findings suggest that cultivating consumer environmental awareness is an important means to motivate auto manufacturers to produce EVs to reduce air pollution.

To explore the cost difference between two auto manufacturers in the production of EVs, with the previous parameter settings, we additionally set $\theta = 1.6$ and $k_1 = 0.2$. To ensure $(e^2k_2 - 3\lambda)/e \leq \theta \leq (e^2k_1 + 3\lambda)/e$ and $e^2k_1 + 3\lambda \geq e^2k_2$, we set $k_2 = 0.25, 0.35, 0.45, 0.55$, respectively. The results are shown in Fig. 2.

As shown in Fig. 2, when the other variables do not change, ESS is from (1, 1) to (1, 0) as k_2 increases. Given the specific consumer environmental preference ($\theta = 1.6$), when the cost difference is sufficiently small, M1 and M2 will choose the same production strategy (producing EVs)

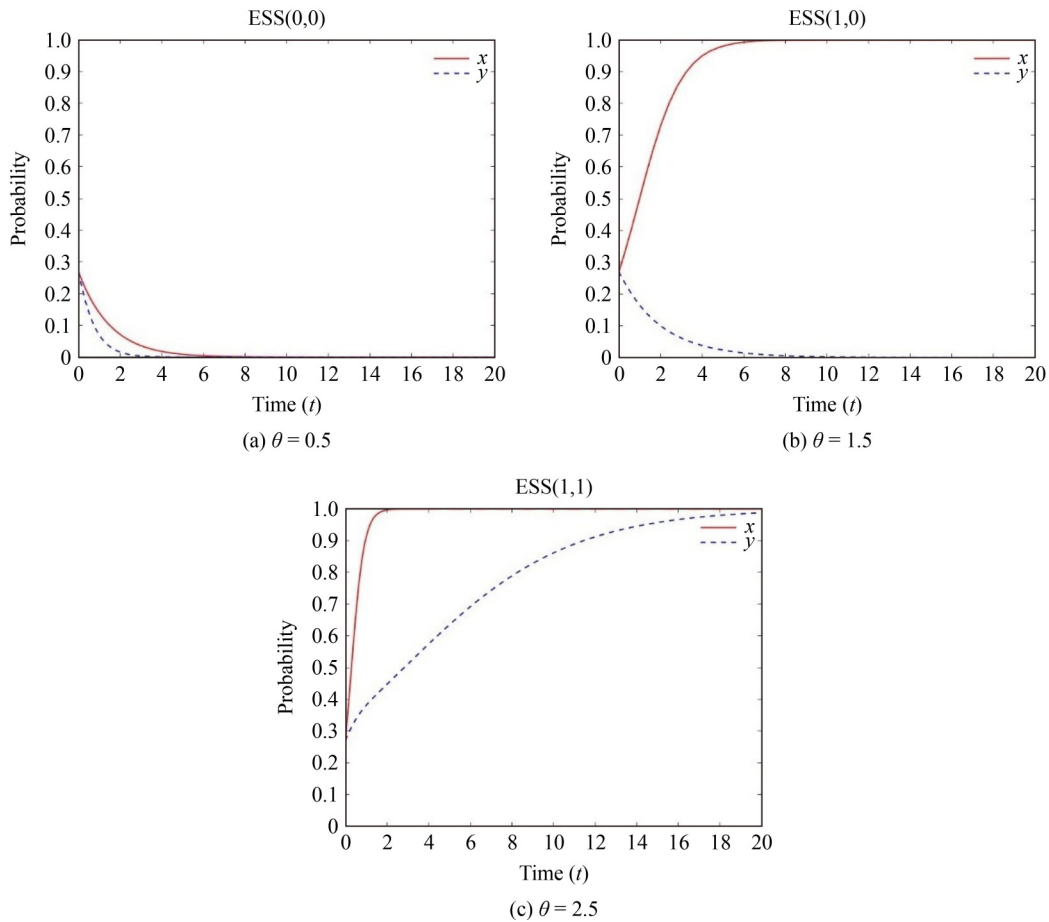


Fig. 1 Evolutionary diagram of the auto manufacturers.

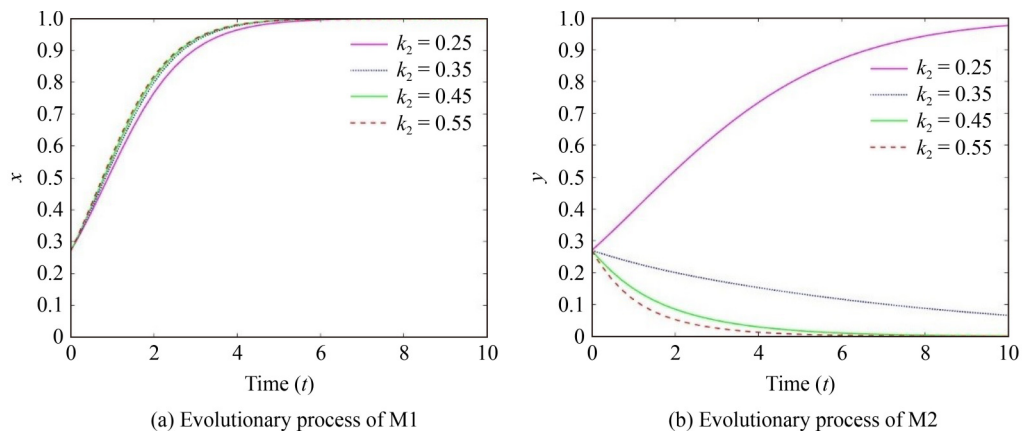


Fig. 2 The effects of production cost coefficient on the evolution equilibrium.

in the long term. However, as the cost difference increases, the final stable strategies of M1 and M2 will evolve into different strategies. In particular, as shown in Fig. 2(a), with the increase of k_2 , the competitive advantage of M1 is more significant, and it will evolve to strategy EV at a faster speed. For M2, the final stable strategy will evolve from EV to FV, as shown in Fig. 2(b). Furthermore, M2 with a higher production cost will more easily

reach a stable state (strategy FV). The above findings reveal that the production cost factors for EVs have significant impacts on the evolutionary equilibrium and that differences in production cost can lead auto manufacturers to choose different stable strategies in the long term. This finding is partly supported by the fact that BYD is among the first to choose to produce EVs in China due to its leading advantages in R&D and cost.

6 Evolutionary analysis with government subsidy

From the above discussions, when consumer environmental preference is low or moderate, it is challenging to motivate two auto manufacturers to produce EVs simultaneously due to market competition. This, however, will impede the further development of EVs. Therefore, governments must launch subsidy programs for EVs to promote their production and reduce environmental pollution. According to the different subsidy objects, we further discuss the impacts of the two types of government subsidy programs (subsidy to manufacturers or consumers) on the production strategy of auto manufacturers.

6.1 Subsidy auto manufacturers

Under the manufacturer subsidy, the government provides a subsidy s_m to the auto manufacturer for an EV (Srivastava et al., 2022). In other words, the auto manufacturer receives the total subsidy $s_m D_i^{j*}$ when producing EVs. The payoff matrix of M1 and M2 with manufacturer subsidy is shown in Table 4.

From Table 4, the replicator dynamics equations with manufacturer subsidies are expressed by Eqs. (9) and (10), respectively.

$$F(x)_{s_m} = x(1-x)[y(\pi_1^{EE*} + s_m D_1^{EE*} - \pi_1^{FE*}) + (1-y)(\pi_1^{EF*} + s_m D_1^{EF*} - \pi_1^{FF*})], \quad (9)$$

$$F(y)_{s_m} = y(1-y)[x(\pi_2^{EE*} + s_m D_2^{EE*} - \pi_2^{EF*}) + (1-x)(\pi_2^{FE*} + s_m D_2^{FE*} - \pi_2^{FF*})]. \quad (10)$$

Just like the case without subsidy, by calculating $\det(J_{s_m})$ and $\text{tr}(J_{s_m})$, we obtain the ESS of auto manufacturers with manufacturer subsidies, which is shown in the following proposition.

Proposition 3.

With manufacturer subsidies,

(1) when $(e^2 k_2 - 3\lambda)/e \leq \theta < e k_1$, if $s_m < \bar{s}_{m1}$, $(x, y) = (0, 0)$ is ESS; if $\bar{s}_{m1} \leq s_m < \bar{s}_{m2}$, $(x, y) = (1, 0)$ is ESS; if $s_m \geq \bar{s}_{m2}$, $(x, y) = (1, 1)$ is ESS;

(2) when $e k_1 \leq \theta < e k_2$, if $s_m \geq \bar{s}_{m2}$, $(x, y) = (1, 1)$ is ESS, where $\bar{s}_{m1} = -N/D_1^{EF*}$, $\bar{s}_{m2} = -P/D_2^{EE*}$.

Proposition 3 reveals that manufacturer subsidies for auto manufacturers may affect their production strategy

in some way. Specifically, in Proposition 3(1), if the manufacturer subsidy is sufficiently small, it can only affect the production strategy of manufacturers in the short term. However, for the long term, M1 and M2 will continue to adopt the FV strategy, and the government subsidy will eventually be invalidated. If the manufacturer subsidy is moderate, the system evolution tends to point (1, 0), that is, M1 tends to produce EVs, while M2 is more likely to produce FVs. This suggests that government subsidies are effective in this case for the stronger auto manufacturer, but not for the weaker manufacturer. Therefore, when the government’s funding is limited, it should pay greater attention to the auto manufacturers with high R&D levels and prioritize them in providing financial subsidies. If the manufacturer subsidy is high, the system evolution tends to point (1, 1), which means that both M1 and M2 tend to choose the EV strategy in the presence of sufficient subsidy funds. In this case, the government subsidy policy is indeed effective in promoting the EV market. According to Proposition 3(2), when consumers have a moderate preference for carbon emission, the government should only encourage the weaker M2 to adopt the EV strategy. In such a case, the government’s optimal manufacturer subsidy is $-P/D_2^{EE*}$, which compensates for the EV production cost of the weaker M2.

Consequently, the government should develop various subsidizing programs based on the circumstances. In other words, when consumers are less environmentally conscious, the government’s reasonable policy should encourage auto manufacturers with cost advantages to produce EVs. In contrast, when consumers have a moderate environmental preference, the government should focus on subsidizing auto manufacturers with cost disadvantages to motivate them to choose the EV strategy.

6.2 Subsidy consumers

Another direct means for the government to subsidize the EV industry is to provide subsidies to consumers who purchase EVs (Gu et al., 2017). Here, we use s_c to denote the subsidies offered to consumers. Under a consumer subsidy scheme, government subsidies have a direct impact on consumer purchase utility. Taking the FE case as an example, the utility of purchasing an FV from M1 and an EV from M2 are $u_1^{FE} = v - p_1^{FE} - \lambda x^{FE}$ and $u_2^{FE} = v + \theta e - p_2^{FE} - \lambda(1 - x^{FE}) + s_c$, respectively. The solving processes are similar to those in the case without

Table 4 Payoff matrix of M1 and M2 with manufacturer subsidies

M1	M2	
	EV strategy	FV strategy
EV strategy	$(\pi_1^{EE*} + s_m D_1^{EE*}, \pi_2^{EE*} + s_m D_2^{EE*})$	$(\pi_1^{EF*} + s_m D_1^{EF*}, \pi_2^{EF*} + s_m D_2^{EF*})$
FV strategy	$(\pi_1^{FE*} + s_m D_1^{FE*}, \pi_2^{FE*} + s_m D_2^{FE*})$	$(\pi_1^{FF*}, \pi_2^{FF*})$

government subsidies; thus, they are omitted here for brevity. Table 5 summarizes the payoff matrix for M1 and M2 with consumer subsidies.

Table 5 Payoff matrix of M1 and M2 with consumer subsidies

M1	M2	
	EV strategy	FV strategy
EV strategy	$(\pi_1^{EE*}, \pi_2^{EE*})$	$(\pi_1^{EF*} + I, \pi_2^{EF*} + J)$
FV strategy	$(\pi_1^{FE*} + G, \pi_2^{FE*} + H)$	$(\pi_1^{FF*}, \pi_2^{FF*})$

In Table 5, $G = \frac{s_c^2 - 2(e^2k_2 + 3\lambda - e\theta)s_c}{18\lambda}$, $H = \frac{2(3\lambda - e^2k_2 + e\theta)s_c + s_c^2}{18\lambda}$, $I = \frac{2(3\lambda - e^2k_1 + e\theta)s_c + s_c^2}{18\lambda}$, and $J = \frac{s_c^2 - 2(3\lambda + e^2k_1 - e\theta)s_c}{18\lambda}$. To ensure positive equilibrium decisions and profits under a consumer subsidy scheme, the government subsidies should satisfy $s_c < e^2k_1 + 3\lambda - e\theta$.

From Table 5, the replicator dynamics equations with the consumer subsidies are given by:

$$F(x)_{s_c} = x(1-x)[y(\pi_1^{EE*} - \pi_1^{FE*} - G) + (1-y)(\pi_1^{EF*} + I - \pi_1^{FF*})], \tag{11}$$

$$F(y)_{s_c} = y(1-y)[x(\pi_2^{EE*} - \pi_2^{EF*} - J) + (1-x)(\pi_2^{FE*} + H - \pi_2^{FF*})]. \tag{12}$$

Similar to the case without subsidies, by calculating $\det(\mathbf{J}_{s_c})$ and $\text{tr}(\mathbf{J}_{s_c})$, we have the ESS of auto manufacturers with consumer subsidies, which is shown in the following proposition.

Proposition 4.

With consumer subsidies,

- (1) when $(e^2k_2 - 3\lambda)/e \leq \theta < ek_1$, if $s_c < \bar{s}_{c1}$, $(x, y) = (0, 0)$ is ESS; if $\bar{s}_{c1} \leq s_c < \bar{s}_{c2}$, $(x, y) = (1, 0)$ is ESS; if $s_c \geq \bar{s}_{c2}$, $(x, y) = (1, 1)$ is ESS;
- (2) when $ek_1 \leq \theta < ek_2$, if $s_c \geq \bar{s}_{c2}$, $(x, y) = (1, 1)$ is ESS, where $\bar{s}_{c1} = e^2k_1 - e\theta$, $\bar{s}_{c2} = e^2k_2 - e\theta$.

Similar to the case with manufacturer subsidies, Proposition 4 demonstrates that consumer subsidies can also affect auto manufacturers' production strategies to a certain extent. Differently, consumer subsidies support the EV industry from the demand side. By directly subsidizing consumers, it can reduce the actual cost of purchasing EVs for consumers, thus promoting the demand for EVs, and subsequently affecting the production strategy of auto manufacturers. Intuitively, relatively fewer consumer subsidies cannot encourage enough consumers to choose EVs. Thus, consumer subsidies do not have the desired effect in this circumstance. On the contrary, auto manufacturers will only be incentivized to produce EVs if the consumer subsidies are substantial. Specifically, when consumer environmental preference is

low, moderate consumer subsidies can encourage M1 to select the EV strategy. Larger consumer subsidies dramatically increase the utility of purchasing EVs for consumers. In this situation, the EV strategy is always dominant over the FV strategy for any auto manufacturer. Even though M2 is at a cost disadvantage, the greater subsidies enable it to charge a higher sales price to cover production costs.

We have evaluated separately the effects of manufacturer and consumer subsidies on the production strategies of auto manufacturers. The purpose of the government subsidy scheme is to promote the EV industry better. To this end, we further analyze which subsidy policy is superior by comparing the minimum total subsidy costs under two types of subsidy programs. Note that when both auto manufacturers choose to produce EV, the demands of M1 and M2 are the same under different subsidy programs. Therefore, we only need to compare the minimum unit subsidy costs (i.e., \bar{s}_{m2} and \bar{s}_{c2}).

Proposition 5.

If $\theta < \bar{\theta}$, $\bar{s}_{m2} > \bar{s}_{c2}$; otherwise, $\bar{s}_{m2} \leq \bar{s}_{c2}$, where $\bar{\theta} = 2ek_2 - ek_1 - 3\lambda/e$.

From the government's standpoint, subsidy funds are limited; thus, it is vital to investigate how to use fewer funds to achieve the goal of promoting the EV industry. Proposition 5 demonstrates that when the system evolves toward the point (1, 1), the advantages and drawbacks of the two types of government subsidy programs for auto manufacturers and consumers depend on customers' environmental preferences. Specifically, when environmental preference is relatively small, the manufacturer subsidy is larger than the consumer subsidy; otherwise, the former is less.

The results reveal that consumers' environmental preferences have a direct impact on the choice of government subsidy scheme. When such preference is relatively low, EVs are unattractive to consumers and uncompetitive in the market because of the higher price. Notably, subsidizing consumers can significantly increase consumers' utility and demand for purchasing EVs, while subsidizing manufacturers only increases manufacturers' economic incentives to produce EVs without promoting consumer demand. Thus, it can take less money to subsidize consumers than to subsidize manufacturers to encourage auto manufacturers to select the EV strategy. In this context, the government would be better off implementing consumer subsidies. On the contrary, if consumers in the market already have a relatively high level of environmental awareness, which indicates that the EV market has great potential, the effect of consumer subsidies will be considerably diminished. In such a situation, the government should employ manufacturer subsidies rather than consumer subsidies. This finding suggests that the government might select a less costly and more efficient subsidy policy according to consumers' environmental preferences. Different from Li et al. (2019), who

concluded that manufacturer subsidies have a better effect on EV diffusion than consumer subsidy, we find that the type of subsidy that is more cost-effective ultimately depends on consumers' environmental preferences.

Notably, the threshold $\bar{\theta}$ has a significant impact on the government's choice of subsidy policy. We can easily find that the threshold $\bar{\theta}$ decreases with k_1 , whereas it increases with k_2 . A greater k_1 (or smaller k_2) leads to a smaller threshold $\bar{\theta}$. Thus, according to Proposition 5, the government is more likely to implement consumer subsidies. This finding further suggests that it would be more effective for the government to adopt consumer subsidies when there is a substantial difference in the production costs of EVs among auto manufacturers.

7 Conclusions and managerial implications

The development of EVs has attracted the attention of governments and automakers worldwide as the world seeks a viable option to reduce carbon emissions. This study explores the pricing competition between two asymmetrical auto manufacturers who choose to produce either EVs or FVs. Considering consumers' preferences, we derive the consumer demands in different competitive settings. Based on these demand functions, we then develop a one-shot duopoly game and an evolutionary game to analyze the production strategies of auto manufacturers and investigate the effectiveness of two types of government subsidy policies. The main conclusions and managerial insights are as follows.

First, the auto manufacturer that first adopts the EV strategy may gain an advantage by occupying a monopolistic position if consumer environmental preference is sufficiently strong.

Second, when producing EVs simultaneously, environmental preference may adversely affect the two auto manufacturers. Moreover, when consumer environmental preference is moderate, competition will significantly affect the decisions of both auto manufacturers. Specifically, the auto manufacturer with a cost advantage chooses EVs and the one with a cost disadvantage adopts FVs in the long run. When consumer environmental preference is sufficiently low, producing EVs is not a priority for any auto manufacturer.

Third, by conducting numerical experiments, we find that the production cost of EVs also impacts the final stable strategy of auto manufacturers. The more significant the difference in production costs is, the more inclined auto manufacturers will be to choose different production strategies. These findings provide some production-related insights for auto manufacturers. Specifically, they can decide when to adopt the EV strategy according to the environmental awareness level of consumers in the market and the comparison of production costs between

themselves and competitors.

Forth, both manufacturer and consumer subsidies can be effective only if the amounts of subsidies reach a certain threshold. Additionally, we identify the conditions under which one type of government subsidy is considered more cost-effective than the other.

In addition, this paper also has two valuable managerial insights for government regulators who are responsible for promoting EV adoption. 1) It is important for the government to actively cultivate consumer awareness of environmental protection. In addition to EVs, this conclusion is also applicable to other similar environmentally friendly industries (e.g., solar equipment, organic food, and sustainable clothing). 2) Government subsidies for EVs can be tailor-made in accordance with the degree of environmental awareness among consumers in the market. Specifically, in developed countries (where consumers place a high value on environmental protection), governments should choose to subsidize manufacturers, whereas in developing countries (where consumers place a low value on environmental protection), consumer subsidy is more cost-effective.

Several limitations to our model deserve further investigation. First, this paper only considered the case wherein auto manufacturers produce either EVs or FVs. However, firms may produce both EVs and FVs simultaneously, which is worth considering in future studies. Second, it would be more interesting to study the optimal decisions on product prices and government subsidies based on real-world operational data from the empirical perspective.

Competing Interests The authors declare that they have no competing interests.

References

- Bahrami S, Amini M H (2018). A decentralized trading algorithm for an electricity market with generation uncertainty. *Applied Energy*, 218: 520–532
- Bian J, Zhang G, Zhou G (2020). Manufacturer vs. consumer subsidy with green technology investment and environmental concern. *European Journal of Operational Research*, 287(3): 832–843
- Bunsen T, Cazzola P, Gorner M, Paoli L, Scheffer S, Schuitmaker R, Tattini J, Teter J (2018). *Global EV Outlook 2018: Towards cross-modal electrification*. Online Report by International Energy Agency
- Chemama J, Cohen M C, Lobel R, Perakis G (2019). Consumer subsidies with a strategic supplier: Commitment vs. flexibility. *Management Science*, 65(2): 681–713
- Egbue O, Long S (2012). Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy Policy*, 48: 717–729
- Fan R, Dong L (2018). The dynamic analysis and simulation of government subsidy strategies in low-carbon diffusion considering

- the behavior of heterogeneous agents. *Energy Policy*, 117: 252–262
- Fan Z P, Cao Y, Huang C Y, Li Y (2020). Pricing strategies of domestic and imported electric vehicle manufacturers and the design of government subsidy and tariff policies. *Transportation Research Part E: Logistics and Transportation Review*, 143: 102093
- Friedman D (1991). Evolutionary games in economics. *Econometrica*, 59(3): 637–666
- Gao Y, Leng M (2021). Incentivizing the adoption of electric vehicles under subsidy schemes: A duopoly analysis. *Operations Research Letters*, 49(4): 473–476
- Gao Y, Leng M, Zhang Y, Liang L (2022). Incentivizing the adoption of electric vehicles in city logistics: Pricing, driving range, and usage decisions under time window policies. *International Journal of Production Economics*, 245: 108406
- Gu H, Liu Z, Qing Q (2017). Optimal electric vehicle production strategy under subsidy and battery recycling. *Energy Policy*, 109: 579–589
- Gu X, Ieromonachou P, Zhou L (2019). Subsidising an electric vehicle supply chain with imperfect information. *International Journal of Production Economics*, 211: 82–97
- Han Z, Hu B, Dawande M (2022). Curbing emissions: Environmental regulations and product offerings across markets. *Manufacturing & Service Operations Management*, 24(6): 3236–3251
- Hausfather Z (2019). Factcheck: How electric vehicles help to tackle climate change. Online Article from Carbon Brief
- Huang J, Leng M, Liang L, Liu J (2013). Promoting electric automobiles: Supply chain analysis under a government's subsidy incentive scheme. *IIE Transactions*, 45(8): 826–844
- Ji S, Zhao D, Luo R (2019). Evolutionary game analysis on local governments and manufacturers' behavioral strategies: Impact of phasing out subsidies for new energy vehicles. *Energy*, 189: 116064
- Kieckhäfer K, Volling T, Spengler T S (2014). A hybrid simulation approach for estimating the market share evolution of electric vehicles. *Transportation Science*, 48(4): 651–670
- Li J, Jiao J, Tang Y (2019). An evolutionary analysis on the effect of government policies on electric vehicle diffusion in complex network. *Energy Policy*, 129: 1–12
- Lim M K, Mak H Y, Rong Y (2015). Toward mass adoption of electric vehicles: Impact of the range and resale anxieties. *Manufacturing & Service Operations Management*, 17(1): 101–119
- Liu C, Huang W, Yang C (2017). The evolutionary dynamics of China's electric vehicle industry: Taxes vs. subsidies. *Computers & Industrial Engineering*, 113: 103–122
- Luo C, Leng M, Huang J, Liang L (2014). Supply chain analysis under a price-discount incentive scheme for electric vehicles. *European Journal of Operational Research*, 235(1): 329–333
- Ma G, Lim M K, Mak H Y, Wan Z (2019). Promoting clean technology adoption: To subsidize products or service infrastructure? *Service Science*, 11(2): 75–95
- Ma J, Hou Y, Wang Z, Yang W (2021). Pricing strategy and coordination of automobile manufacturers based on government intervention and carbon emission reduction. *Energy Policy*, 148: 111919
- Narassimhan E, Johnson C (2018). The role of demand-side incentives and charging infrastructure on plug-in electric vehicle adoption: Analysis of US states. *Environmental Research Letters*, 13(7): 074032
- Raz G, Ovchinnikov A (2015). Coordinating pricing and supply of public interest goods using government rebates and subsidies. *IEEE Transactions on Engineering Management*, 62(1): 65–79
- Rietmann N, Hügler B, Lieven T (2020). Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO₂ emissions. *Journal of Cleaner Production*, 261: 121038
- Safarzadeh S, Rasti-Barzoki M (2019). A game theoretic approach for assessing residential energy-efficiency program considering rebound, consumer behavior, and government policies. *Applied Energy*, 233: 44–61
- Shao L, Yang J, Zhang M (2017). Subsidy scheme or price discount scheme? Mass adoption of electric vehicles under different market structures. *European Journal of Operational Research*, 262(3): 1181–1195
- Srivastava A, Kumar R R, Chakraborty A, Mateen A, Narayanamurthy G (2022). Design and selection of government policies for electric vehicles adoption: A global perspective. *Transportation Research Part E: Logistics and Transportation Review*, 161: 102726
- Taylor T A, Xiao W (2019). Donor product-subsidies to increase consumption: Implications of consumer awareness and profit-maximizing intermediaries. *Production and Operations Management*, 28(7): 1757–1772
- Xiao T, Chen G (2009). Wholesale pricing and evolutionarily stable strategies of retailers with imperfectly observable objective. *European Journal of Operational Research*, 196(3): 1190–1201
- Ye F, Cai Z, Chen Y, Li Y, Hou G (2021). Subsidize farmers or bioenergy producer? The design of a government subsidy program for a bioenergy supply chain. *Naval Research Logistics*, 68(8): 1082–1097
- Yu J J, Tang C S, Li M K, Shen Z J M (2022). Coordinating installation of electric vehicle charging stations between governments and automakers. *Production and Operations Management*, 31(2): 681–696
- Yu J J, Tang C S, Shen Z J M (2018). Improving consumer welfare and manufacturer profit via government subsidy programs: Subsidizing consumers or manufacturers? *Manufacturing & Service Operations Management*, 20(4): 752–766
- Yu Y, Zhou D, Zha D, Wang Q, Zhu Q (2021). Optimal production and pricing strategies in auto supply chain when dual credit policy is substituted for subsidy policy. *Energy*, 226: 120369
- Zarazua de Rubens G, Noel L, Sovacool B K (2018). Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale. *Nature Energy*, 3(6): 501–507
- Zhang J, Huang J (2021). Vehicle product-line strategy under government subsidy programs for electric/hybrid vehicles. *Transportation Research Part E: Logistics and Transportation Review*, 146: 102221
- Zhang X (2014). Reference-dependent electric vehicle production strategy considering subsidies and consumer trade-offs. *Energy Policy*, 67: 422–430
- Zhu M, Liu Z, Li J, Zhu S X (2020). Electric vehicle battery capacity allocation and recycling with downstream competition. *European Journal of Operational Research*, 283(1): 365–379
- Zhu X, Ren M, Wu G, Pei J, Pardalos P M (2019). Promoting new energy vehicles consumption: The effect of implementing carbon regulation on automobile industry in China. *Computers & Industrial Engineering*, 135: 211–226