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The Selection of Green Technology Innovations under Dual-Credit Policy

Ziyue Wang [1], Juan Zhang [1] and Huiju Zhao [2,*]

1 Business School, Hohai University, Nanjing 211100, China; zy.wang@hhu.edu.cn (Z.W.); hhuzhang@hhu.edu.cn (J.Z.)

2 Office of Informatization Construction Management, Nanjing University of Finance and Economics, Nanjing 210023, China

* Correspondence: 9120141031@nufe.edu.cn

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Abstract: In the pressure of excessive resource consumption and serious environmental pollution, government in China proposed a dual-credit policy to promote the production of green vehicles, such as energy-saving fuel vehicle (FV) and electric vehicle (EV). This study explores the firm's selection of green technology innovations (GTIs) under dual-credit policy, including the energy-saving technology for FV and the technology for producing EV. We found that the firm's technology capacity of improving the energy-saving level of FV plays an important role in affecting the firm's selections of GTIs. Specifically, when the technology capacity is moderate, the firm chooses both types of GTIs to produce both EV and energy-saving FV, otherwise he will choose one type only. Moreover, no matter which GTI is selected by the firm, its pricing and environmental efforts decisions keep the same. With the dual-credit policy, we found that it could encourage the production of the EV under certain conditions. Besides this, increasing the green credit of EV can align the economic and environmental interests while increasing standard energy consumption has conflicts in both interests. In particular, when the firm offers FV only or both EV and FV, increasing the price of credit has conflicting interests in economy and environment. However, when the firm offers EV only, increasing the price of credit could improve the firm's profit without hurting the environment.

Keywords: dual-credit policy; green innovation technology; product line design; energy-saving level

1. Introduction

With the rapid mass urbanization and economic development, many countries now face the problems of excessive resource consumption and serious environmental pollution, which arouse consumers' awareness to use greener products. To boost sales of green products, the government proposes a dual-credit policy for automobile industry in China. The dual-credit policy includes the corporate average fuel consumption credit (CAFC-credit) rules, which set targets for the average energy consumption rate for fuel vehicles, and the new energy vehicle credit (NEV-credit) rules, which stipulate credits by new energy vehicles and require certain NEV quotas [1].

In response to the dual-credit policy, many conventional vehicle firms decide to adopt the green technology innovation (GTI). There are two main methods for vehicle firms to make GTIs, including developing the energy-saving fuel vehicle (FV) and producing the pure electric vehicle (EV). The energy-saving FV is denoted as the vehicle involving new energies except petrol, such as electricity and hydrogen. For instance, the hybrid electric vehicle is a new energy-saving vehicle driven by both diesel engine and electric engine. The pure EV is driven by electricity only. Although the energy-saving FV is less environment-friendly than the pure EV, the pure EV shows lower convenience of use than the energy-saving FV, which limits the sales of EV. The low convenience of EV is attributed to that many EV firms are lack of mature technology capacities to increase the quality of EV and there are limited public service infrastructures supporting the operations of EV, such as limited charging stations. Based on the real practices in the automotive industry, vehicle firms could choose one or two GTIs to develop the green products. There are three product line strategies for vehicle firms, including offering the energy-saving FV only (Strategy F), offering the pure EV only (Strategy E), and offering them both (Strategy EF). Table 1 summarizes examples of the three product line designs in automotive industry.

Table 1. Examples on the three product line strategies in automotive industry.

Product Line	Business Case	Practices on Management
Strategy F	Citroen	At present, almost all manufacturers have started the electric transformation, but Citroen hasn't developed an independent electric platform. Citroen produces plug-in hybrid electric vehicles 'Aircross,' which will be kicked out of the EV models and re-classified as FV in the future. In 2020, Citroen launched a concept pure electric car 'Ami' with a mileage of just 70km.
Strategy E	NIO, WM Motor, Tesla	NIO only produces eS8, eS6, and eC6, which are all pure electric vehicles; WM provides three models of electric vehicles, which are EX5, EX6 Plus, and EX5-Z; Tesla's first electric car Roadster launched at 2008, and other model S, Model X came out these years.
Strategy EF	BMW, BYD, Toyota	In China, BMW provides both hybrid power vehicles 'i8' with a mileage of just 50km in electric model and pure electric 'i3' with a mileage of 340km; BYD produces electric vehicles such as E-series and S-series, and fuel vehicles such as F3 and Dynasty-series. Meanwhile, they try to improve greenhouse gas emission standard all the time.

Note: All information is from the respective firm's official website and the Chinese biggest automotive website www.autohome.com.cn until July 2020.

Different GTIs or product line designs of vehicle firms may take different effects on the firm and the environment, especially under the dual-credit system. Notice that if the firm decides to offer both FV and EV, the cannibalization between them will occur, which may influence the firm's GTI efforts and pricing decisions. Moreover, under the dual-credit system, the firms may be encouraged to adopt more environment-friendly GTI, which might pose fewer negative effects on the environment.

To help the firms to choose the appropriate GTI with and without dual-credit policy as well as provide suggestions for the government to set an appropriate dual-credit policy, this paper examines the following interesting questions: (1) How do the related factors influence the firm's selection of GTIs, pricing, and energy-saving efforts decisions when the dual-credit policy is not considered? (2) How does the dual-credit policy influence the firm's selection of GTIs, pricing, and energy-saving efforts? (3) How should government set a dual-credit policy to benefit the environment and the firm?

By utilizing an analytical framework based on the game-theoretical model, we obtain some interesting results. Firstly, the firm's technology capacity of increasing the energy-saving level of FV plays an important role in affecting the firm's selections of GTIs, namely offering EV only, energy-saving FV only, or both. Specifically, if the technology capacity is high, the firm would offer the FV with a high energy-saving level only; if the technology capacity is low, the firm would offer the pure EV only, which generates zero carbon emission. This is the most beneficial to the environment. Whereas, if the technology capacity is moderate, the firm could offer both EV and the FV with a moderate energy-saving level.

Secondly, no matter which GTI the firm chooses, its pricing decisions on each type of vehicle and environmental efforts on FV keep the same. In other words, the firm's pricing and energy-saving efforts decisions are independent of the firm's selection of GTIs.

Thirdly, the dual-credit policy could stimulate the firm to invest more in increasing the energy-saving rate of FV but encourage the production of EV only when the price of credit is small enough. Moreover, the retail price of EV is reduced under the dual-credit policy because the dual-credit policy makes it more profitable for the firm to produce EV. However, the retail price of FV decreases under the dual-credit policy only if the price of credit is large enough; otherwise, the firm will charge a higher price for FV under the dual-credit policy.

Finally, we summarize suggestions for the government to design an appropriate dual-credit policy from both economic and environmental aspects. Specifically, increasing the green credit of EV can align the economic and environmental interests of launching a dual-credit policy, while increasing standard energy consumption for per-unit of FV has conflicting interests in economy and environment. Especially, when the firm offers FV only (Strategy F) or both EV and FV (Strategy EF), increasing the price of credit also has conflicting interests in economy and environment. However, when the firm offers EV only, increasing the price of credit could improve the firm's profit without hurting the environment/increasing the carbon emissions.

The remainder of the paper is organized as follows. In Section 2, we review the related literature, followed by the introduction of model development in Section 3. Then, we solve and discuss the equilibrium result of the game in Section 4. Next in Section 5, we firstly give the sensitivity analysis and then give the numerical analysis with the consideration of dual-credit policy. Further in Section 6, we summarize our main results with a discussion. Finally, the conclusion and future research directions are given in Section 7.

2. Literature Review

This paper lies at two streams of literature: (1) dual-credit policy and (2) green technology innovation.

2.1. Dual-Credit Policy

After dual-credit policy was proposed by government in 2017, it attracted a lot of attention from all walks of life. However, to the best of our knowledge, a relatively small number of papers in the Operations Management literature focus on this topic. Among them, Cheng and Mu studied the production decision-making optimization problem of automobile manufacturers under dual-credit policy and established a game model of joint decisions between traditional and EV manufacturers [2]. Ou et al. investigated the impact of dual-credit policy on two types of electric vehicles (EVs), finding that dual credit is more conducive to battery EVs while CAFC credit alone is more conducive to plug-in EVs [3]. Li et al. attempted to investigate the impact of the dual-credit scheme on the penetration of new energy vehicles and the short-term strategy of the automotive industry [4].

Besides exploring the impact of a dual-credit policy on the EV development, Zhao et al. [5], Zhou et al. [1], and Lou et al. [6] illustrated how the dual-credit policy affects the environment. Specifically, Zhao et al. studied the impact of dual-credit policy on vehicle greenhouse gas emissions from the perspective of the life cycle [5]. Zhou et al. investigated the environment effects under dual-credit system by formulating three possible scenarios [1]. Lou et al. focused on the influence on improvements in fuel economy and production of FV, finding that the implementation of the dual-credit policy may not be able to reduce the production of high fuel consumption vehicles, which is harmful to environment [6].

Furthermore, there is literature comparing the dual-credit policy with other policies applied in the automotive industry [7–10]. According to the study of Li et al., compared with green-car subsidy, the dual-credit policy can significantly increase the number of new vehicles to two times as much as that of subsidy level [7]. Chen et al. studied the synergistic effect of dual-credit policy and government subsidy (including national subsidy and local subsidy) on the development of electric vehicle technology [8]. Zheng et al. built a dual-credit model considering R&D subsidy to explore how the price of positive credit and market size affect the R&D investment [9]. Li et al. examined the differences between subsidy scheme for constructing EV charging station and dual-credit scheme under a stylized production model by solving the production decision of FV and EV [10].

While most of these literatures examine the impact of dual-credit policy from the economic and environmental perspectives, few literatures explore the impact of dual-credit policy on the GTI [1] [8,9]. Of these literatures, Zhou et al. [1] is closest to our paper, which considers not only the dual-credit policy but also the GTI. However, they only considered one type of GTI, namely the energy-saving technology for FV, while our paper considers both the energy-saving technology and the pure electric-vehicle technology. Furthermore, we consider the consumer's low willingness-to-pay for EV because of its inconvenience of use.

2.2. *Green Technology Innovation*

There are abundant researches investigating the GTI in operational-management area. Prior works studied the drivers of green technology innovation effort, including technological ability [11], financial ability [12,13], R&D subsidy [14,15], regulation [16–18], and market demand [19]. Besides, some researches were carried out from the perspective of different types of technology innovation. Gu et al. explored optimal production strategy under the battery recycling and a subsidy [20]. Li et al. investigated the efficiencies of a consumer subsidy and a dual-credit policy considering battery recycling rate [21]. Choi and Rhee emphasized the promoting effects of the recycling end-of-life battery for EV [22]. Greene et al. considered that fuel economy is influenced by cumulative mileage and daily use [23]. Huang et al. proposed that automakers can implement the fuel-saving technology without harmful vehicle operational characteristics [24].

As observed in the literature studying GTIs, most of them focus on one type of GTI, namely the energy-saving technology for FV [6,23,24] or the electric-vehicle technology [1,8,20–22,25]. On the other hand, our paper considers both of them while the firm could choose to adopt one or two types. In particular, when we consider the firm's selection of GTIs, the issue of product line design occurs. Few scholars add government policies into the firm's product line strategy. Among them, Zhang et al. designed a subsidy policy and concluded that firms could change their primary product design and develop both green and ordinary products to increasing firm's profits and improving environmental quality with such a subsidy policy [26]. Zheng et al. investigated the optimal production decisions of an auto manufacturer who produces both conventional vehicles and EVs under a subsidy policy, and derived conditions under which the manufacturer decides to offer EV [27]. Gao et al. focused on two types of green products with different green technologies and explored the manufacturer's and the retailer's decisions when government sets a product green standard and offers an environmental subsidy [28]. To the best of our knowledge, the study by Zhou et al. [1] is the only paper studying both GTIs and product line designs with the dual-credit policy. The difference between it and our paper has been stated elaborately in Section 2.1.

2.3. *Summary*

The positioning of this paper in the literature is summarized in Table 2. This literature analysis indicates that the contribution of our work includes three aspects. Firstly, although there is abundant literature studying GTIs in the operational-management area, there are none that consider the energy-saving technology and the pure electric-vehicle technology, simultaneously. We consider the issue of product line designs of the firm while they could choose to adopt one or two types of GTIs. Secondly, as most of these previous studies consider one type of vehicles, namely FV or EV, the consumer awareness on EV and FV cannot be distinguished clearly. In our paper, we distinguish EV and FV from not only their green levels but also the consumer's acceptance of them depending on their convenience of use. We show that the firm's decisions can be significantly influenced by taking the two aspects into account. Finally, few papers consider the firm's GTI decisions with the consideration of the dual-credit policy. Our paper examines how the dual-credit policy influences the firm's decisions and the environment. Our results provide suggestions for the government to set an environment-friendly dual-credit policy.

Table 2. Positioning of this paper in the literature.

Paper	GTI	GTI for FV	GTI for EV	Product Line Design	Dual-Credit Policy	Other Subsidies
Cheng and Mu [2]					√	
Ou et al. [3]					√	
Li et al. [4]					√	
Zhao et al. [5]					√	
Zhou et al. [1]	√		√	√	√	
Lou et al. [6]	√	√			√	
Li et al. [7]					√	√
Chen et al. [8]	√		√		√	√
Zheng et al. [9]	√				√	√
Li et al. [10]					√	√
Li et al. [11]	√					
Tan et al. [12]	√					
Aguilera-Caracuel and Ortiz-De-Mandojana [13]	√					√
Jung and Feng [14]	√					√
Wang et al. [15]	√					√
Jin et al. [16]	√					
Zheng et al. [17]	√					√
Liu et al. [19]	√					√
Gu et al. [20]	√		√			√
Li et al. [21]	√		√		√	√
Choi and Rhee [22]	√		√			
Greene et al. [23]	√	√				
Huang et al. [24]	√	√				
Zhang et al. [26]				√		√
Zheng et al. [27]				√		√
Gao et al. [28]	√			√		√
Our paper	√	√	√	√	√	

GTI, green technology innovation; FV, fuel vehicle; EV, electric vehicle.

3. Model Development

3.1. Model Description

This study considers a vehicle firm regulated by the dual-credit policy that needs to decide how to make the green technology innovation (GTI). The firm has three possible choices to make the GTI: producing the conventional fuel vehicle (FV) with an energy-saving level, producing both the FV and the electric vehicle (EV), or producing the EV only. Without loss of generality, we suppose that one unit of FV without GTI consumes the energy g, which is related to its gasoline consumption; one unit of EV consumes no gasoline because it is driven by electric energy. While the firm decides to make the GTI for FV, one unit of FV will consume the energy as $(1-x)g$, where $x(0 \le x \le 1)$ measures the energy-saving level of FV. Intuitively, the larger the value of x, the less energy consumption brought by FV. Following Niu et al. [29] and Yang and Chen [30], we can write the firm's GTI cost in Equation (1).

$$c(x) = \lambda(gx)^2 \tag{1}$$

where $\lambda > 0$ stands for the effect of an increase in the energy-saving level of FV on the development cost. Besides, this cost also reflects the interaction between the basic energy-consuming level (i.e., g) and the energy-saving level of FV. A higher g means that it is more difficult to increase the energy-saving level of the FV. A larger λ means a lower technology capacity for increasing the energy-saving level for the firm.

The dual-credit policy in China includes an energy credit and a green credit. The energy credit refers to the corporate average fuel consumption (CAFV) of FV and the green credit refers to the production of new energy vehicle (NEV). Denote g_f as the standard energy consumption per-unit of FV [1]; β_e as the green credit per-unit of EV, which is set by the government. Therefore, the firm producing the FV with the energy-saving level x could have the energy credit per-unit of FV as $-(g(1-x)-g_f)$. Intuitively, if the FV consumes more energy than the standard energy consumption, i.e., $g(1-x)-g_f > 0$, the energy credit of the firm could be negative. In addition, we assume that per-unit EV could always have a positive green credit β_e.

Defining D_f and D_e as the sales of FV and EV, respectively, we can write the accumulated credit (AC) of the firm, in Equation (2).

$$AC = -(g(1-x)-g_f)D_f + \beta_e D_e \tag{2}$$

If the energy credits are negative, they could be compensated by equal green credits. Note that the dual-credit policy declaims non-negative credits for the firm at the year end and the firm has to be punished if the AC is negative, such as stopping the production. Therefore, the firm will trade with other firms by paying the price of per-unit credit p_t. Instead, if the AC is positive, the firm could sell the AC at the per-unit price p_t. Therefore, we can write the accumulated credit value as

$$V_{AC} = -(g(1-x)-g_f)D_f p_t + \beta_e D_e p_t \tag{3}$$

3.2. Demand and Profit Function

According to research by Chiang et al. [31], Oersdemir et al. [32], and Luo et al. [33], we assume that consumers are heterogeneous and their reservation price (ν) is uniformly distributed over (0, 1) with in the market size from 0 to 1, with a density of 1. Consumers differ in their valuations of FV and EV from the two aspects: (1) the green level, and (2) the convenience of the vehicle. Note that although the firm could make GTIs for FV, the FV always generates positive carbon emissions corresponding to their energy consumption, while the EV generates zero carbon emission. Therefore, the EV is greener than the FV. Additionally, different from the literature indicating that consumers value the EV more than the FV, we consider that consumers will value the EV less than the FV because of its inconvenience. For example, the limited battery endurance of per-charging and few public service facilities such as charging stations reduce the consumer's willingness to use EV. Mentioned above, denoting the retail prices of FV and EV as p_f and p_e, respectively, we can describe the consumer's surplus values of purchasing FV and EV as

$$\begin{cases} u_f = v - p_f - \mu(1-x)g \\ u_e = \delta v - p_e, \end{cases} \tag{4}$$

where $\mu > 0$ reflects the degree to which consumers are sensitive to carbon emission. Furthermore, μ can also be considered as the social responsibility of consumers where a larger μ means a higher social responsibility. δ $(0 < \delta < 1)$ refers to the discount of the consumer's reservation price to EV because of its inconvenience of use.

If the firm offers only FV or EV, a consumer is willing to buy only if his/her net surplus is positive, that is $u_f > 0$ (i.e., $v \geq v_f \equiv p_f + \mu(1-x)g$) or $u_e > 0$ (i.e., $v \geq v_e \equiv p_e/\delta$). The sale of FV and EV should be $d_f = \int_{v_f}^1 dv = 1 - v_f$ and $d_e = \int_{v_e}^1 dv = 1 - v_e$, respectively. If the firm offers both EV and EV, the consumer prefers FV if $u_f > u_e$ (i.e., $v > \hat{v} \equiv (p_f - p_e + \mu(1-x)g)/(1-\delta)$), and otherwise he/she prefers EV.

Mentioned above, the firm has three product line strategies: offering FV only (Strategy F), offering EV only (Strategy E), and offering both EV and FV (Strategy EF). We use the superscript "E" (Strategy E), "F" (Strategy E), and "EF" (Strategy EF) to represent the firm's three product line strategies. We can write the sales of EV and FV under each strategy as (1) Strategy F: $D_f^F = 1 - v_f$, $D_e^F = 0$; (2) Strategy E: $D_f^E = 0$, $D_e^E = 1 - v_e$; and (3) Strategy EF: $D_f^{EF} = 1 - \hat{v}$, $D_e^{EF} = \hat{v} - v_e$.

For simplicity of analysis, we assume that the production cost, except the R&D cost, for the two types of vehicles is zero. Utilizing the superscript "B" and "D" to represent the case without and with the dual-credit policy, respectively, we can give the firm's profit with the dual-credit policy in the following.

$$\pi^{iD}(p_f, p_e, x) = (p_f - \lambda(gx)^2)D_f^i + p_e D_e^i + V_{AC} \; i = E, F, EF. \tag{5}$$

Letting $V_{AC} = 0$, we can easily get the firm's profit without the dual-credit policy, $\pi^{iB}(p_f, p_e, x)$. We use the total carbon emissions of the firm related to the total energy consumption to measure the environmental effects, CE where

$$CE = g(1-x)D_f \tag{6}$$

Note that we assume EV does not generate carbon emissions, thus the sale of EV does not take effects on CE. Accordingly, the larger CE, the less environment-friendly.

The process is as follows: Firstly, the firm determines the optimal GTI selection/product line strategy, i.e., Strategy E, F, or EF. Secondly, with respect to product line strategy, the firm decides the GTI on FV. Finally, the firm sets the retail prices for EV, FV, or both. With and without the dual-credit policy, we can solve the firm's equilibrium solutions by using backward induction method.

4. Equilibrium

In the following, we first examine the benchmark without dual-credit policy. Then, we examine the equilibrium results under dual-credit policy. By further comparing these results, we provide insights into how the dual-credit policy affects a firm's production decision about EV and FV, the pricing decision, and consumers' purchase decision. We use the superscript "*" to represent the equilibrium outcomes.

4.1. Decision Without a Dual-Credit Policy

When the dual-credit policy is not considered, we can compare the firm's profits under the three product line strategies and get the equilibrium solutions for the firm. The complete derivation is shown as proof of Proposition 1 in Appendix A.

Proposition 1. *In the absence of a dual-credit policy, the firm's equilibrium decisions are determined as*

(i) if $\lambda \le \lambda_l^B$, the firm only considers offering the FV with $x^{B*} = \mu/(2g\lambda)$ and charges the price as $p_f^{B*} = (1-\mu g)/2 + 3\mu^2/(8\lambda)$,

(ii) if $\lambda_l^B < \lambda < \lambda_h^B$, the firm decides to offer two types of vehicles with $x^{B*} = \mu/(2g\lambda)$. The equilibrium retail prices for the EV and FV are $p_e^{B*} = \delta/2$ and $p_f^{B*} = (1-\mu g)/2 + 3\mu^2/(8\lambda)$, respectively,

(iii) if $\lambda \ge \lambda_h^B$, the firm chooses to offer the EV only and charges the retail price as $p_e^{B*} = \delta/2$, where $\lambda_l^B = \mu/(4g)$ and $\lambda_h^B = \mu^2/(4g\mu - 4(1-\delta))$.

Proposition 1 shows that the firm's technology capacity of improving the energy-saving level of FV plays a key role in influencing the firm's product line strategies. The firm's production decisions follow two thresholds, namely a lower bound (i.e., λ_l^B) and a higher bound (i.e., λ_h^B) for the firm's technology capacity. It shows that when the firm's technology capacity is high enough, it prefers to offer an energy-saving FV only; when the firm's technology capacity is low enough, it will choose to offer EV only. Interestingly, when the firm's technology capacity is moderate, the firm will produce both FV and EV.

Based on the results in Proposition 1, we further get the following sensitivity analysis.

Corollary 1. *Analyzing the effects of the parameters on the equilibrium energy-saving level of FV and prices for FV and EV leads to the following results (the proof of Corollary 1 can be seen in Appendix A):*

(i) $\partial x^{B*}/\partial\mu > 0$, $\partial x^{B*}/\partial g > 0$, $\partial x^{B*}/\partial\lambda < 0$;

(ii) $\partial p_f^{B*}/\partial g < 0$, $\partial p_f^{B*}/\partial\lambda < 0$, $\partial^2 p_f^{B*}/\partial\mu^2 > 0$, $\partial p_e^{B*}/\partial\delta > 0$.

Corollary 1 (i) shows that, if consumers become more sensitive to the social responsibility (i.e., as μ increases), it is optimal for the firm to pay more attention to increase the energy-saving level of FV. Moreover, as the basic carbon emission of one unit of FV increases (i.e., as g increases), the firm should invest more to improve the energy-saving level of FV. Similarly, a lower technology capacity of the firm in improving the energy-saving level also reduces the firm's incentive to increase its environmental effort. Finally, a larger price of credit can encourage the firm to increase the energy-saving level of FV.

Corollary 1 (ii) demonstrates the impact of related factors on the equilibrium prices. For the FV: firstly, with a higher capacity to improve the energy-saving level of FV (i.e., the cost factor λ is smaller), the firm prefers to charge a higher price for the FV (i.e., $\partial p_f^{B*}/\partial\lambda < 0$). Usually, a higher technology capacity means a lower production cost for per-unit of the FV. The intuition is that the firm should charge a lower price for the FV. However, Corollary 1 (i) shows that, as the firm's technology capacity increases, the firm is willing to make more environmental effort (i.e., $\partial x^{B*}/\partial\lambda < 0$), which increases the cost for improving the energy-saving level of FV.

Secondly, when consumers are more sensitive to the environmental protection, i.e., μ is larger, the price for FV decreases firstly and then increases (i.e., $\partial^2 p_f^{B*}/\partial\mu^2 > 0$). This is counterintuitive. As Corollary 1 (i) indicates, the firm would improve the FV's energy-saving level as μ increases, which enables the firm to raise the price for EV. However, consumers paid more concern to environmental protection, leading consumers to valuate less on the FV. Hence, with a low value of μ, the energy-saving level of FV would be still at a low level; that is, the carbon emission of FV is large, and an increase in the consumer's social responsibility would have a strong negative effect on the consumer's valuation on FV. In this setting, the firm would charge a lower price for FV. Hence, if μ is large, the carbon emission of FV is small, owing to its large energy-saving level, so a larger consumer's social responsibility would have a weaker negative effect on the consumer's valuation on FV. The firm would charge a higher price for FV, owing to its high energy-saving level. For the EV, $\partial p_e^{B*}/\partial\delta > 0$ shows that the firm will charge a higher price for EVs as the consumer values the inconvenience of EV less.

4.2. Decision with a Dual-Credit Policy

Similar to that without a dual-credit policy, we can compare the firm's profits under the three product line strategies with the dual-credit policy and get the equilibrium solutions for the firm (which are shown in Proposition 2). More detailed process can be seen as proof of Proposition 2 in Appendix A.

Proposition 2. *In the absence of a dual-credit program, the firm's equilibrium decisions are determined as*

(i) if $\lambda \le \lambda_l^D$*, the firm only considers offering the FV only with* $x^{D*} = (\mu + p_t)/(2g\lambda)$ *and charges the price as* $p_f^{D*} = (1 - \mu g + g p_t - g_f p_t)/2 + (\mu + p_t)(3\mu - p_t)/(8\lambda)$,

(ii) if $\lambda_l^D < \lambda < \lambda_h^D$*, the firm decides to offer two types of vehicles with* $x^{D*} = (\mu + p_t)/(2g\lambda)$*. The equilibrium retail prices for the EV and FV are* $p_e^{D*} = (\delta - p_t\beta_e)/2$ *and* $p_f^{D*} = (1 - \mu g + g p_t - g_f p_t)/2 + (\mu + p_t)(3\mu - p_t)/(8\lambda)$, respectively,

(iii) if $\lambda \ge \lambda_h^D$*, the firm chooses to offer the EV only and charges the retail price as* $p_e^{D*} = (\delta - p_t\beta_e)/2$*, where*

$$\lambda_l^D = \frac{(\mu + p_t)^2}{(4(g\mu + g p_t - g_f p_t) + 4\beta_e p_t/\delta)}$$

and

$$\lambda_h^D = \frac{(\mu + p_t)^2}{(4(g\mu + g p_t - g_f p_t) + 4\beta_e p_t - 4(1-\delta))}.$$

Proposition 2 shows that the firm's product line strategy with a dual-credit policy is similar to that without the dual-credit policy, which follows two bounds. However, comparing Propositions 1 and 2, we can obtain the following results in Corollaries 2 and 3.

Corollary 2. *The comparison between the lower bound and higher bound with and without the dual-credit policy shows that both* $\lambda_l^D < \lambda_l^B$ and $\lambda_h^D < \lambda_h^B$ hold only if the condition $p_t < \mu(\beta_e - \delta g - \delta g_f)/(\delta g)$ *is satisfied. The proof of Corollary 2 can be found in Appendix A.*

Corollary 2 shows that the dual-credit policy makes it more possible for the firm to produce EV only if the credit price in a dual-credit policy is small enough. To be specific, when the condition $p_t < \mu(\beta_e - \delta g - \delta g_f)/(\delta g)$ holds, if $\lambda \in (\lambda_l^D, \lambda_l^B)$, the firm offers FV only in the absence of a dual-credit policy but offers both EV and FV under the dual-credit policy. Meanwhile, if $\lambda \in (\lambda_h^D, \lambda_h^B)$, the firm offers both FV and EV in the absence of the dual-credit policy but offers EV only under the dual-credit policy, which implies that the EV could dominate the market and completely replace the FV because of the dual-credit policy. Instead, when the credit price is large enough, satisfying $p_t \geq \mu(\beta_e - \delta g - \delta g_f)/(\delta g)$, the firm will invest a lot in increasing the energy-saving level of FV. Thus, the firm prefers producing FV because it generates a high-positive energy credit that benefits the firm. Mentioned above, only setting the appropriate parameters in the dual-credit policy could encourage the production of EV.

Corollary 3. *The comparison between the energy-saving level of FV and the prices of FV and EV with and without the dual-credit policy shows* $x^{D*} > x^{B*}$; $p_e^{D*} < p_e^{B*}$; $p_f^{D*} > p_f^{B*}$ if $0 < p_t < 4\lambda(g - g_f) + 2\mu$ *holds, and vice versa. Detailed proof of Corollary 3 is in Appendix A.*

Corollary 3 shows that the dual-credit policy can stimulate the firm to invest more in the technology innovation of FV, namely, increasing the energy-saving level of FV (shown in Figure 1a). Moreover, the retail price of EV is reduced under the dual-credit policy because the dual-credit policy makes it more profitable for the firm to produce EV (shown in Figure 1b). However, for the FV, the retail price decreases under the dual-credit policy only if the credit value is large enough; otherwise, the firm will set a higher price for FV under a dual-credit policy compared to that without the dual-credit policy (shown in Figure 1c). This is because a low price of credit means a low energy-saving level of FV; the production of FV is costlier with a dual-credit policy than that without a dual-credit policy since the firm has to deal with the negative credit by the production of FV. However, if the credit value is large enough, i.e., $p_t > 4\lambda(g - g_f) + 2\mu$, the firm will increase the energy-saving level of FV to a high level, which makes the per-unit production of FV create a positive credit. Therefore, the firm will reduce the price of FV because of the profitability of positive credits under a dual-credit policy.

Corollary 4. *With a dual-credit policy, analyzing the effects of parameters on the equilibrium energy-saving level of FV and prices leads to the following results (the proof of Corollary 4 can be found in Appendix A):*

$$\partial x^{D*}/\partial p_t > 0,\ \partial p_e^{D*}/\partial p_t < 0,\ \partial^2 p_f^{D*}/\partial p_t^2 < 0,\ \partial p_e^{D*}/\partial \beta_e < 0,\ \partial p_f^{D*}/\partial \lambda \ = \ (\mu + p_t)(p_t - 3\mu)/(8\lambda^2).$$

Corollary 4 indicates that with the dual-credit policy, a higher price of credit always encourages the firm to produce a higher energy-saving level FV (shown in Figure 1a). Moreover, as the price of credit increases, the firm will charge a lower price for EV (shown in Figure 1b). This is because per unit of EV can create a positive credit which reduces the cost for EV. Similarly, as the positive credit of producing a unit of EV increases, the firm will charge a decreasing price for EV. However, the retail price of FV increases in p_t firstly, and then decreases in it (shown in Figure 1c). This is because a low price of credit will lead to a low energy-saving level for FV so that per-unit sale of FV will generate a negative credit which increases the cost of producing FV. If the price of credit is in a high level under which the firm offers a high energy-saving level for FV, the FV could generate the positive credit. In this case, the firm could charge a decreasing price for FV as the price of credit increases, which is similar to the retail price of EV.

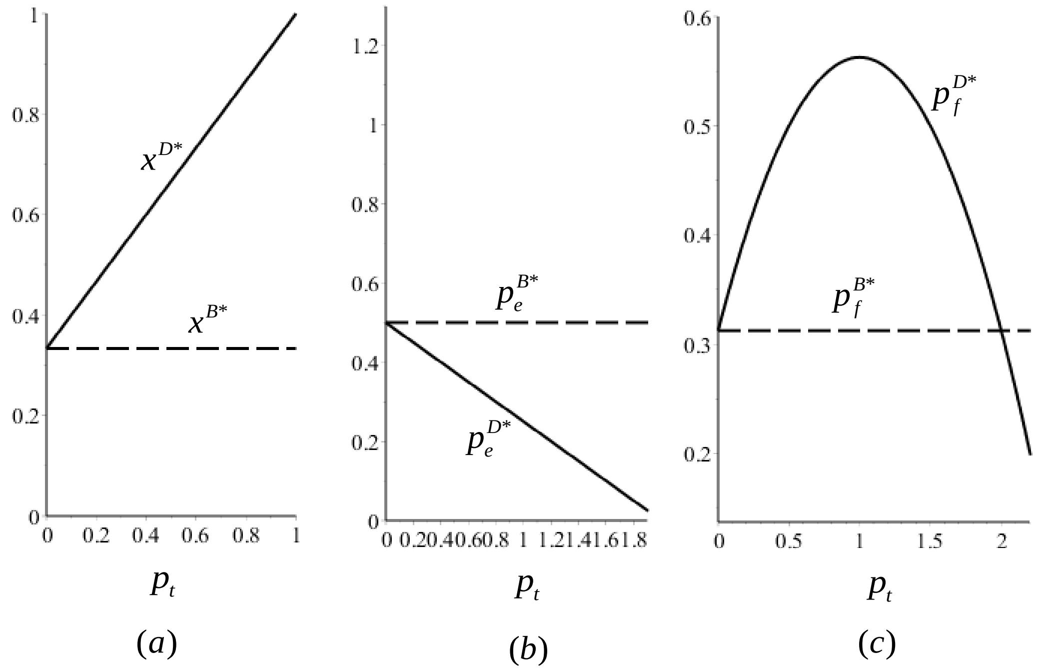

Figure 1. The impact of the price of credit on the equilibrium solutions. Note: (**a**) shows the impact of the price of credit on energy-saving level of FV with and without dual-credit policy; (**b**) shows the impact of that on the retail price of EV with and without dual-credit policy; (**c**) shows the impact of that on the retail price of EV with and without dual-credit policy.

Different from the case without a dual-credit policy, we further find that if the price of credit is large enough (i.e., $p_t > 3\mu$), $\partial p_f^{D*}/\partial\lambda > 0$ will hold. Although a larger technology capacity of the firm (i.e., a low λ) could lead to a higher energy-saving level for FV, a large enough price of credit can compensate the cost of improving the energy-saving level, thus the firm could charge a lower price for FV.

5. Analysis

The policy maker proposes a dual-credit policy for stimulating the sales of EV so as to reduce the total carbon emission of vehicles. However, as mentioned above, the dual-credit policy influences the firm's decisions significantly, which might have some unexpected impacts. In this section, we focus on analyzing the effect of the dual-credit policy on the sales of vehicles, the firm's profit, and the environment.

5.1. Sensitivity Analysis

Proposition 3. *Under the dual-credit policy, the impacts of g_f, β_e, and p_t on the firm's profit can be solved. Table 3 shows related results and the detailed solution procedure is in the proof of Proposition 3 in Appendix A.*

Table 3. The impacts of dual-credit policy on the firm's profit.

Factors \ Strategy	Offering FV only	Offering both FV and EV	Offering EV only
g_f	$\partial\pi^{FD*}/\partial g_f > 0$	$\partial\pi^{EFD*}/\partial g_f > 0$	-
β_e	-	$\partial\pi^{EFD*}/\partial\beta_e > 0$	$\partial\pi^{ED*}/\partial\beta_e > 0$
p_t	$\partial\pi^{FD*}/\partial p_t > 0$ if $g(1-x^{D*}) - g_f < 0$	$\partial\pi^{EFD*}/\partial p_t > 0$ if $-\beta_e/\delta < g(1-x^{D*}) - g_f < -\beta_e$	$\partial\pi^{ED*}/\partial p_t > 0$

Proposition 3 explores the effects of a dual-credit policy on the firm's profit. $\partial\pi^{FD*}/\partial g_f > 0$ and $\partial\pi^{EFD*}/\partial g_f > 0$ imply that a higher standard energy consumption per-unit is more profitable for the firm. This is because a higher stand energy consumption per-unit means a lower negative or a higher positive energy credit associated with per-unit sale of FV, which benefits the firm. Similarly, a higher positive green credit can always lead to a higher profit of the firm (i.e., $\partial\pi^{EFD*}/\partial\beta_e > 0$ and $\partial\pi^{ED*}/\partial\beta_e > 0$). Therefore, a higher standard energy consumption per-unit and a higher positive green credit per-unit can be complementary in improving the firm's profit.

Proposition 3 also illustrates the effect of the price of credit (i.e., p_t) on the firm's profit. Intuitively, if the firm produces EV only, the firm could get more benefits from selling a unit of EV as the price of credit increases. Therefore, the firm's profit increases in the price of credit. When the firm offers both EV and FV, increasing the price of credit could benefit the firm if the energy credit of FV is negative and its absolute value is moderate. Under this condition, it is easily proven that the sale of FV decreases in p_t and the sale of EV increases in p_t. This is due to the fact that producing EV is profitable for the firm from not only the profit margin of per-unit sale of EV but also the green credit value. Obviously, as p_t increases, the profitability of EV increases. Therefore, when the condition (i.e., $-\beta_e/\delta < g(1-x^{EFD*}) - g_f < -\beta_e$) holds, which ensures that the gain of the increased sales of EV overweighs the loss of the decreased sales of FV, the firm's profit will increase in the price of credit. Additionally, when the firm offers FV only and the energy credit of FV is positive, which implies the energy-saving level of FV is large enough, increasing the price of credit can improve the firm's profit.

Proposition 4. *Under the dual-credit policy, the impacts of* g_f, β_e, and p_t *on environment can be solved. Table 4 shows the related results and the detailed solution procedure is in the proof of Proposition 4 in Appendix A.*

Table 4. The impacts of dual-credit policy on environment.

Factors \ Strategy	Offering FV only	Offering both FV and EV	Offering EV only
g_f	$\partial CE^{FD*}/\partial g_f > 0$	$\partial CE^{EFD*}/\partial g_f > 0$	-
β_e	-	$\partial CE^{EFD*}/\partial\beta_e < 0$	-
p_t	$\partial CE^{FD*}/\partial p_t < 0$ if $g(1-x^{D*}) - g_f > 0$	$\partial CE^{EFD*}/\partial p_t < 0$ if $g(1-x^{D*}) - g_f + \beta_e > 0$	-

From the perspective of environmental protection, Proposition 4 shows that as the standard energy consumption increases, the carbon emissions increase (i.e., $\partial CE^{FD*}/\partial g_f > 0$ and $\partial CE^{EFD*}/\partial g_f > 0$). However, as the green credit corresponding to per-unit of EV increases, which encourages the firm to produce EV, the carbon emissions will be reduced.

Proposition 4 also indicates the effect of the price of credit on the environment. To be specific, if the firm adopts Strategy EF to offer both EV and FV, increasing the price of credit will reduce the carbon emissions when the sum of the green credit per-unit of EV and the energy credit per-unit of FV under Strategy EF is positive. When this condition is satisfied, we can easily see that the sales of the FV are decreasing in p_t. Moreover, the energy-saving level of FV is increasing in p_t. Therefore, it is obvious that the carbon emissions are decreasing in p_t. However, because no EVs are produced under Strategy F, the carbon emissions are decreasing in p_t if the energy credit of FV is positive.

Combing Propositions 3 and 4 shows that increasing the green credit of EV can align the economic and environmental interests of launching a dual-credit policy while increasing the standard energy consumption for per-unit of FV has conflicting interests in economy and environment. Especially, when the firm offers FV only (Strategy F) or both EV and FV (Strategy EF), increasing the price of credit also has conflicting interests in economy and environment. However, when the firm offers EV only, increasing the price of credit could improve the firm's profit without hurting the environment/increasing the carbon emissions.

5.2. Numerical Analysis

Different from the effects of parameters g_f and β_e on the firm's profit and environment, the effect of p_t is complicated. Especially, if the conditions in Propositions 3 and 4 are not satisfied, the effects of p_t on the firm's profit and environment are uncertain. This section is aimed to further study the impacts of the price of credit on the firm's profit and environment following numerical analysis. Table 5 provides a view of comparisons between cases with and without a dual-credit policy from both economic and environmental perspectives.

Table 5. Comparison with and without the dual-credit policy.

Strategy / Type	Offering FV only	Offering both FV and EV	Offering EV only
Profits	π^{FB*} v.s π^{FD*} (Figure 2)	π^{EFB*} v.s π^{EFD*} (Figure 3)	π^{EB*} v.s π^{ED*} (Figure 4)
Carbon emissions	CE^{FB*} v.s CE^{FD*} (Figure 5)	CE^{EFB*} v.s CE^{EFD*} (Figure 6)	-

Note: Strategy F, offering FV only; Strategy EF, offering both EV and FV; Strategy E, offering EV only.

Giving the parameters values such as $\beta_e = 0.5$, $\delta = 0.1$, $g_f = 2.9$, $g = 3$, $\mu = 0.1$, and $\lambda = 0.8$, we can depict the firm's profit with the changing of p_t under Strategies F, EF, and E in Figures 2–4, respectively. With the dual-credit policy, we see that the firm's profit is increasing in p_t under Strategies E and EF. However, under Strategy F, the firm's profit decreases as p_t firstly and then increases as p_t. This is because a small p_t leads to a small energy-saving level for FV, which incurs a negative energy credit for producing FV. Accordingly, the firm has to pay more for deleting the negative credits as the price of credit increases. Instead, if p_t is in a high level leading to a high energy-saving level for FV, per-unit FV could generate a positive energy credit, which is more profitable for the firm as p_t increases.

Furthermore, we find an interesting result by comparing the firm's profits with and without the dual-credit policy. As shown in Figure 2, the firm might get a lower profit with a dual-credit policy compared to that without a dual-credit policy. This case occurs when the price of credit is in a low level where the firm has to pay more R&D costs for the increasing energy-saving level of FV as well as undertaking more loss of profit caused by the negative energy credit under a dual-credit policy, compared to a no-policy case.

Following the same date structure, we can depict the carbon emissions of all vehicles under Strategy F and EF (where the carbon emission is zero under Strategy E) in Figures 5 and 6, respectively. They show similar characteristics under the two strategies as p_t increases, namely, decreasing firstly and then increasing in p_t when the dual-credit policy is offered. This result is due to, when p_t is in a low level, the firm's energy credit is negative, under which the firm has to pay more costs of deleting the negative credits as p_t increases. It is intuitive that as the cost of credit increases, the retail price of FV increases and the sale of FV is reduced. In all, an increasing p_t could reduce the carbon emissions of FV when p_t is in a low level. Instead, as p_t increases to be a high level, the firm's energy credit changes to be positive, the sales of FV will increase largely as p_t increases, which eventually increases the carbon emissions. Accordingly, the carbon emissions could be more under the dual-credit policy compared to that without the dual-credit policy when p_t is large. This result is counterintuitive, while one may expect that the dual-credit policy is always environment-friendly.

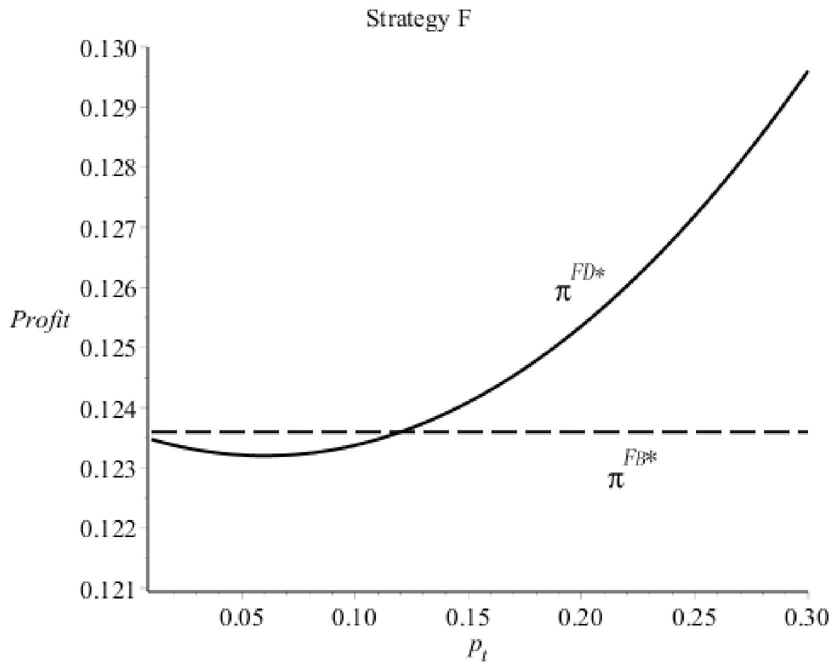

Figure 2. The firm's profit under Strategy F ("*" refers to the optimal outcomes).

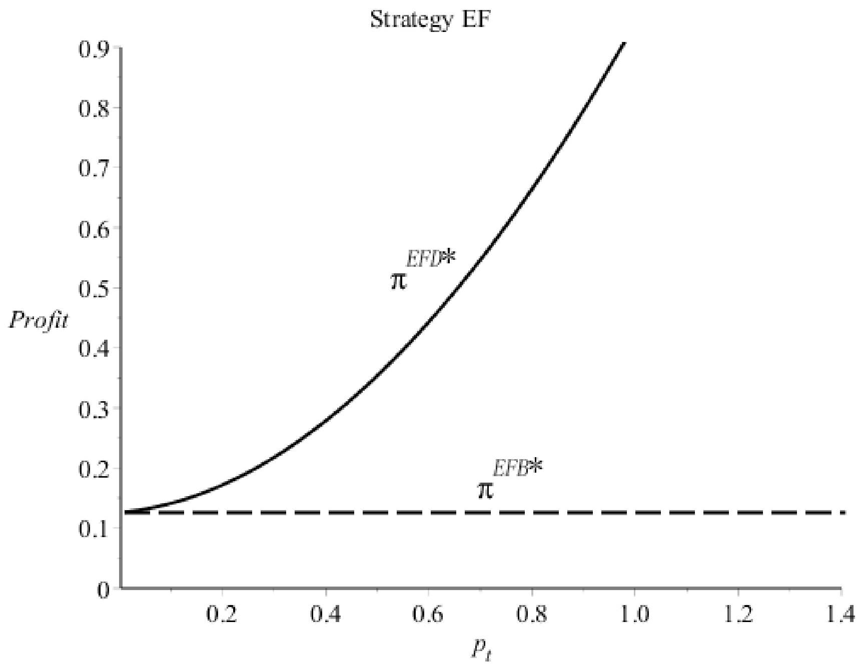

Figure 3. The firm's profit under Strategy EF ("*" refers to the optimal outcomes).

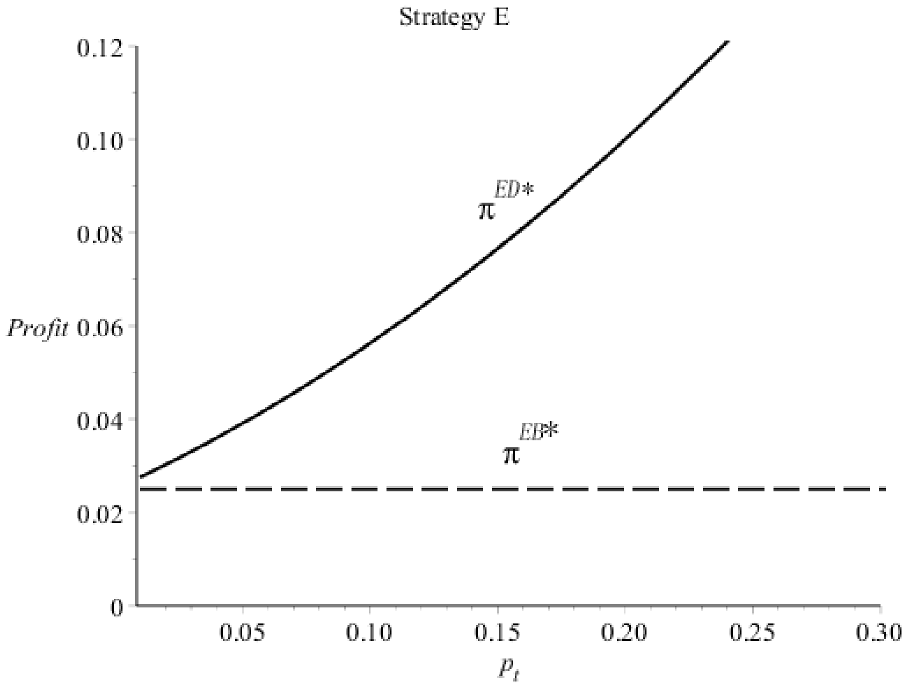

Figure 4. The firm's profit under Strategy E ("*" refers to the optimal outcomes).

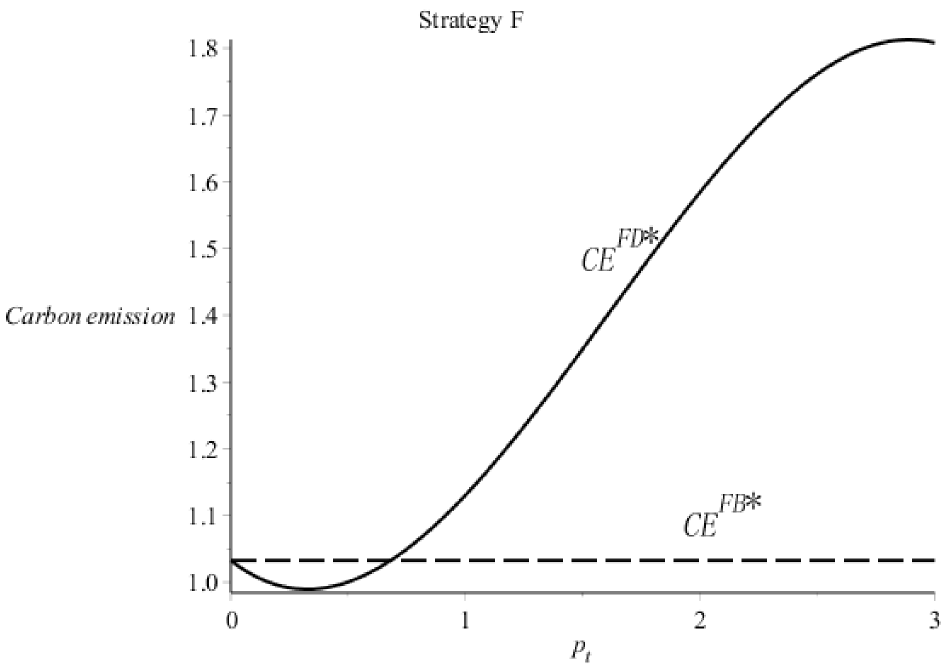

Figure 5. The carbon emissions under Strategy F ("*" refers to the optimal outcomes).

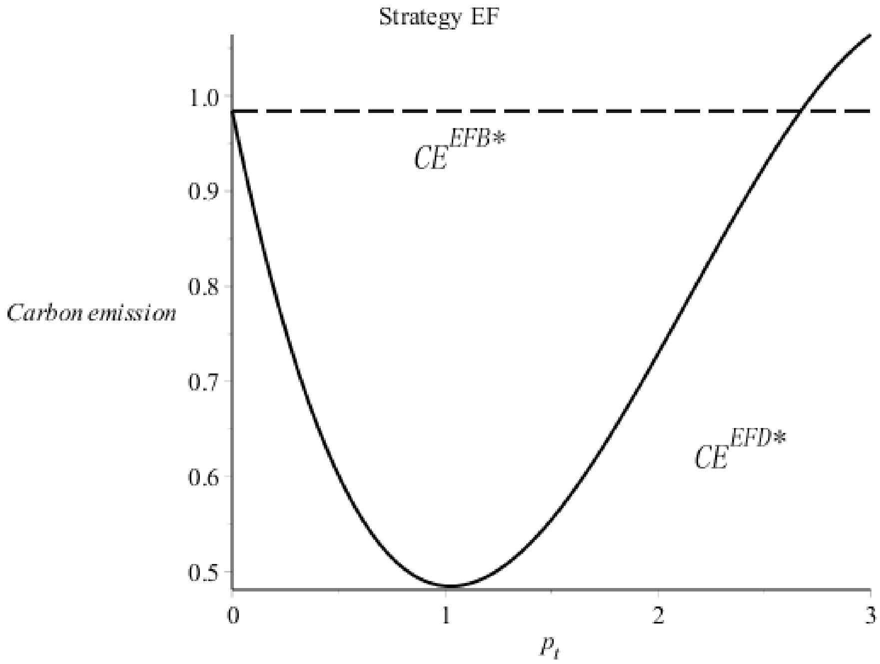

Figure 6. The carbon emissions under Strategy EF ("*" refers to the optimal outcomes).

In summary, by comparing the cases with and without the dual-credit policy, we find that a dual-credit policy might not only hurt the firm's profit but also hurt the environment/increase the carbon emissions. In particular, the price of credit shows complicated impacts on the profit and the environment. For example, when the firm offers energy-saving FV only, the dual-credit policy could reduce the firm's profit and the total carbon emissions if the price of credit is in a low level, and vice versa. Therefore, the government should be more careful in designing the dual-credit policy, especially in setting the price of credit.

6. Discussion

This section provides a discussion of the main results. We show our main findings by answering our research questions mentioned above.

(1) How do the related factors influence the firm's selection of GTIs, pricing, and energy-saving efforts decisions when the dual-credit policy is not considered?

The firm's selection of GTIs: The firm's technology capacity of increasing the energy-saving level of FV plays an important role in affecting the firm's selections of GTIs, namely offering the EV only, the energy-saving FV only, or both. Specifically, if the technology capacity is high, the firm would offer the FV with a high energy-saving level only; if the technology capacity is low, the firm would offer the pure EV only which generates zero carbon emission. This is the most beneficial to environment. Whereas, if the technology capacity is moderate, the firm could offer both EV and FV with a moderate energy-saving level. Similar results were also obtained by Zhou et al. [1] while they analyzed thresholds from the perspective of marginal production cost, different from that of technology capacity in our paper.

Pricing and energy-saving efforts: No matter which GTIs the firm chooses, its pricing decisions on each type of vehicles and the environmental efforts of FV keep the same. In other words, the firm's pricing and environmental efforts decisions are independent of its selection of GTIs. Besides this, with a higher capacity to improve the energy-saving level of FV, the firm prefers to charge a higher price for FV and make more environmental efforts on increasing the energy-saving level of FV. Finally, when the consumer's social responsibility is larger, the price for FV decreases firstly and then increases, while the price for EV keeps the same. Meanwhile, the firm would invest more in increasing the energy-saving level of FV.

(2) How does the dual-credit policy influence the firm's selection of GTIs, pricing, and energy-saving efforts?

The dual-credit policy could always stimulate the firm to invest more in increasing the energy-saving rate of FV but only encourage the firm to produce EV when the price of credit is small enough. Besides this, the retail price of EV is reduced under the dual-credit policy because the dual-credit policy makes it more profitable for the firm to produce EV. However, the retail price of FV decreases under the dual-credit policy only if the price of credit is large enough; otherwise, the firm will set a higher price for FV under the dual-credit policy compared to that without the dual-credit policy. What's more, different from the case without the dual-credit policy, although a larger technology capacity of the firm (i.e., a low λ) could lead to a higher energy-saving level for FV, a large enough price of credit can compensate the cost of improving the energy-saving level, thus the firm could charge a lower price for FV.

(3) How should the government set a dual-credit policy to benefit the environment and the firm?

We find that under a dual-credit policy, increasing the standard energy consumption per-unit and the positive green credit per-unit can be complementary in improving the firm's profit. Additionally, while an increasing standard energy consumption could increase the total carbon emissions, an increasing green credit corresponding to per-unit of EV would reduce the total carbon emissions which benefits the environment. Therefore, an increasing green credit of EV can align the economic and environmental interests of the dual-credit policy, but an increasing standard energy consumption per-unit of FV has a conflict between economic and environmental interests.

Especially, the price of credit shows the complicated effects on the firm's profit and environment. Specifically, we see that a dual-credit policy could hurt the firm's profit when the price of credit satisfies certain conditions. As one may expect that the dual-credit policy is always environment-friendly, our results show that the dual-credit policy could hurt the environment. For example, when the firm offers energy-saving FV only, the dual-credit policy could reduce the firm's profit and the total carbon emissions if the price of credit is in a low level, and vice versa. Therefore, the government should be more careful in designing the dual-credit policy, especially in setting the price of credit.

Here, we summarize suggestions for government to design an appropriate dual-credit policy. Specifically, increasing the green credit of EV can align the economic and environmental interests of launching the dual-credit policy, while increasing standard energy consumption for per-unit of FV has conflicting interests in economy and environment. When the firm offers FV only (Strategy F) or both EV and FV (Strategy EF), increasing the price of credit also has conflicting interests in economy and environment. However, when the firm offers EV only, increasing the price of credit could improve the firm's profit without hurting the environment/increasing the carbon emissions. Lou et al. [6] also found that dual-credit policy may be harmful to the environment on account of numbers of high fuel consumption vehicles. In their model, however, a large number of fuel vehicles and a small number of electric vehicles produced by automakers are supposed, and the selection of EV and FV is not considered.

7. Conclusions

An increasing number of consumers purchase the pure EV due to its lower prices and high energy-saving level. However, some consumers still choose to buy traditional FV or hybrid FV, which start up by assistant electricity to save energy consumption while driving normally by fuel to keep long-distance mileage. Dual-credit policy starts from the perspective of firms, aiming at promoting the mass production of EV and the upgrade from traditional vehicles to more environmentally vehicles such as hybrid power and pure EV, finally achieving the goal of green economy. Under the guidance of the dual-credit policy, how will firms respond to the production and product line strategy of FV and EV? Further, how efficient is the dual-credit policy for environmental protection?

This study considers a firm's two types of green technology innovations—energy-saving technology for FV and technology for producing EV—and focuses on studying the influence of dual-credit policy on the firm's selection of GTIs, profit, and environment, based on a non-competitive supply chain which considers reservation value of consumers. We solve the firm's equilibrium pricing and GTI decisions under Strategy F, E, and EF without and with dual-credit policy, respectively. We discuss how a firm chooses GTIs and explore how the policy influences the firm's profit and environment via analytical and numerical analysis. Our results provide suggestions for government about how to design a dual-credit policy.

Our research can be further extended in several directions. First, we do not consider the environmental quality of EV. Actually, though the percentage of greenhouse gas emissions by electric-driving vehicles is much smaller than that by fuel-driving vehicles, the battery life of EV is an indirect indicator of the environmental quality. Second, we do not consider the competition in the supply chain. In future research, it may be interesting to explore how firms respond to price, product line, green technology innovation, etc., in a market with two competing firms under a dual-credit policy. Third, it is more meaningful to investigate the difference in efficiencies between the dual-credit policy and other policy such as the consumer subsidy policy. Finally, it could be interesting to investigate the dual-credit policy on the environment following an empirical study, regarding issues such as quantifying the effectiveness of policy based on the real production data and exploring more factors influencing the effect of policy.

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Appendix A

Proof of Proposition 1. The firm has three product line strategies without dual-credit policy: (a) Strategy F: producing FV only; (b) Strategy E: producing EV only; (c) Strategy EF: offering both of FV and EV. We derive the firm's equilibrium decisions under each strategy and then compare the firm's profits under the three strategies, to get the optimal strategy for the firm.

(a) Strategy F: producing FV only.

The firm's profit function can be written as

$$\pi^{FB}\left(p_f, x\right) = (p_f - \lambda (gx)^2)(1 - v_f) \tag{A1}$$

where $v_f = p_f + \mu(1-x)g$.

As the firm firstly decides the energy-saving level of FV and then the price, by using backward induction method, we firstly solve $\partial\pi^{FB}/\partial p_f = 0$ to get the best response of FV's price. Due to $\partial^2\pi^{FB}/\partial p_f^2 < 0$, i.e., $\pi^{FB}(p_f, x)$ is concave in p_f, we get the first order condition $\partial\pi^{FB}/\partial p_f = 0$ and get $p_f^{FB}(x) = (\lambda g^2 x^2 + 1 - g\mu(1-x))/2$. Substituting $p_f^{FB}(x)$ into $\pi^{FB}\left(p_f, x\right)$, we can solve $\partial\pi^{FB}/\partial x = 0$ and $\partial^2\pi^{FB}/\partial x^2 < 0$, then get $x^{B*} = \mu/2g\lambda$. Taking $x^{B*} = \mu/2g\lambda$ into $p_f^{FB}(x)$, we can get the firm's optimal price of FV, namely $p_f^{B*} = (1-\mu g)/2 + 3\mu^2/(8\lambda)$. Then, we get the firm's optimal profits in strategy F, which are denoted as π^{FB*} and $\pi^{FB*} = \left(1/2 + \mu^2/(8\lambda) - g\mu/2\right)^2$.

We assume a positive sale of FV, thus $0 < v_f < 1$ should be satisfied. While $x^{B*} = \mu/2g\lambda$ and $p_f^{B*} = (1-\mu g)/2 + 3\mu^2/(8\lambda)$, we can solve $0 < v_f < 1$ to get $\mu^2/(4g\mu+4) < \lambda < \mu^2/(4g\mu-4)$. For simplicity of analysis, we assume that $\mu^2/(4g\mu+4) < \lambda < \mu^2/(4g\mu-4)$ always hold so that there are always positive price and sales of FV.

(b) Strategy E: producing EV only.

The firm's profit function can be written as

$$\pi^{EB}(p_e) = p_e(1 - v_e) \quad \text{(A2)}$$

where $v_e = p_e/\delta$.

Solving $\partial\pi^{EB}/\partial p_e = 0$ and $\partial^2\pi^{EB}/\partial p_e^2 < 0$, we can get the best response of the firm for EV, namely $p_e^{B*} = \delta/2$. Taking $p_e^{B*} = \delta/2$ into $\pi^{EB}(p_e)$, we can get the firm's optimal profits in Strategy E, which are denoted as π^{EB*} and $\pi^{EB*} = \delta/4$.

Note that we assume a positive sale of EV, thus $0 < v_e < 1$ should be satisfied. While $p_e^{B*} = \delta/2$, we can find that $0 < v_e < 1$ can always be satisfied.

(c) Strategy EF: offering both of FV and EV.

The firm's profit function can be written as

$$\pi^{EFB}\left(p_f, p_e, x\right) = (p_f - \lambda(gx)^2)(1 - \hat{v}) + p_e(\hat{v} - v_e) \quad \text{(A3)}$$

where $\hat{v} = (p_f - p_e + g\mu(1 - x))/(1 - \delta)$, $v_e = p_e/\delta$.

To prove the concavity of $\pi^{EFB}\left(p_f, p_e, x\right)$ in $\left(p_f, p_e\right)$, we write the Hessian Matrix of $\pi^{EFB}\left(p_f, p_e, x\right)$ in $\left(p_f, p_e\right)$ as

$$H(\pi^{EFB}) = \begin{vmatrix} \frac{\partial^2\pi^{EF}}{\partial p_f^2} & \frac{\partial^2\pi^{EF}}{\partial p_f p_e} \\ \frac{\partial^2\pi^{EF}}{\partial p_e p_f} & \frac{\partial^2\pi^{EF}}{\partial p_e^2} \end{vmatrix} \equiv \begin{vmatrix} \frac{2}{\delta-1} & \frac{2}{1-\delta} \\ \frac{2}{1-\delta} & \frac{2}{\delta(\delta-1)} \end{vmatrix} \quad \text{(A4)}$$

Because $0 < \delta < 1$,$H(\pi^{EFB})$ is negative definite in $\left(p_f, p_e\right)$ and the condition for concavity of the firm's profit function holds, then we solve $\partial\pi^{EFB}/\partial p_f = 0$ and $\partial\pi^{EFB}/\partial p_e = 0$ simultaneously to get the best response of firm's prices for FV and EV, namely

$$p_f^{EFB}(x) = (1 + \lambda g^2 x^2)/2 - g\mu(1 - x)/2 \quad \text{(A5)}$$

and

$$p_e^{EFB}(x) = \delta/2 \quad \text{(A6)}$$

Substituting $p_f^{EFB}(x)$ and $p_e^{EFB}(x)$ into (A.2), we can solve $\partial\pi^{EFB}/\partial x = 0$ and $\partial^2\pi^{EFB}/\partial x^2 < 0$ to get the firm's optimal energy-saving level for FV, namely $x^{B*} = \mu/2g\lambda$.

Taking $x^{B*} = \mu/2g\lambda$ into $p_f^{EFB}(x)$ and $p_e^{EFB}(x)$, to get $p_f^{EFB*} = (1 - \mu g)/2 + 3\mu^2/(8\lambda)$ and $p_e^{EFB*} = \delta/2$. Then, we can get the firm's optimal profits in strategy EF, which are denoted as π^{EFB*}. We ignore the expression here.

Note that there are sufficient conditions for the firm to offer both of FV and EV, that are $0 < v_e < v_f$ and $0 < \hat{v} < 1$, otherwise the firm will only produce FV or EV. Substituting p_f^{EFB*}, p_e^{EFB*} and x^{B*} into the two conditions, we get $\mu/4g < \lambda < \mu^2/(4g\mu + 4\delta - 4)$.

Next, we can find the optimal production line decisions for the firm by comparing firm's optimal profits under Strategy F, Strategy E, and Strategy EF, namely π^{FB*}, π^{EB*}, and π^{EFB*}.

Firstly, suppose that the condition $\mu/4g < \lambda < \mu^2/(4g\mu + 4\delta - 4)$ holds, namely, it is possible for the firm to offer both types of vehicles, because we find that

$\pi^{EFB*} - \pi^{FB*} = \delta\mu^2(4g\lambda - \mu)^2/(64\lambda^2(1 - \delta)) > 0$,

$\pi^{EFB*} - \pi^{EB*} = (4g\lambda\mu + 4\delta\lambda - \mu^2 - 4\lambda)^2/(64\lambda^2(1 - \delta)) > 0$.

Therefore, as long as the condition $\mu^2/4g < \lambda < \mu^2/(4g\mu + 4\delta - 4)$ holds, the firm prefers to offer both FV and EV rather than produce FV or EV only.

Secondly, suppose that $\lambda \notin (\mu/4g, \mu^2/(4g\mu + 4\delta - 4))$, namely, the firm does not offer both types of vehicles. Remind that we have assumed the conditions $\mu^2/(4g\mu + 4) < \lambda < \mu^2/(4g\mu - 4)$, now we compare the π^{FB*} and π^{EB*} when the conditions $\mu^2/(4g\mu + 4\delta - 4) \le \lambda < \mu^2/(4g\mu - 4)$ satisfied.

$\pi^{FB*} - \pi^{EB*} = T/64\lambda^2$.

We find that $\partial T(\lambda)/\partial\lambda$ is monotonous. Denoting $\partial T(\lambda)/\partial\lambda$ as $h(\lambda)$, we can get $h(\lambda = \mu^2/(4g\mu + 4\delta - 4)) < 0$ and $h(\lambda = \mu^2/(4g\mu - 4)) < 0$. Thus, the term $\partial T(\lambda)/\partial\lambda < 0$ always holds when conditions $\mu^2/(4g\mu + 4\delta - 4) \le \lambda < \mu^2/(4g\mu - 4)$ are satisfied, which means T is monotone decreasing. Because of $T(\lambda = \mu^2/(4g\mu + 4\delta - 4)) < 0$ and $T(\lambda = \mu^2/(4g\mu - 4)) < 0$, we can get $T < 0$ when conditions $\mu^2/(4g\mu + 4\delta - 4) \le \lambda < \mu^2/(4g\mu - 4)$ are satisfied, i.e., $\pi^F < \pi^E$. So, when the conditions $\mu^2/(4g\mu + 4\delta - 4) \le \lambda < \mu^2/(4g\mu - 4)$ are satisfied, the firm prefers to produce EV only.

Thirdly, we compare the π^{FB*} and π^{EB*} when the conditions $\mu^2/(4g\mu + 4) < \lambda \le \mu/4g$ satisfied. Similar to the derivation above, because of $h(\lambda = \mu^2/(4g\mu + 4)) < 0$ and $h(\lambda = \mu/4\text{g}) < 0$, we deduce that $\partial T(\lambda)/\partial\lambda < 0$, i.e., T is decreasing. Then we can get $T(\lambda = \mu^2/(4g\mu + 4)) > 0$ and $T(\lambda = \mu/4\text{g}) > 0$, therefore when conditions $\mu^2/(4g\mu + 4) < \lambda \le \mu/4g$ are satisfied, there is $T > 0$, i.e., $\pi^F > \pi^E$. At this time, the firm prefers to produce FV only.

To conclude the discussions above, for the assumed conditions that $\mu^2/(4g\mu + 4) < \lambda < \mu^2/(4g\mu - 4)$, if $\lambda \le \mu/4g$, the firm only considers offering the FV; if $\mu/4g < \lambda < \mu^2/(4g\mu + 4\delta - 4)$, the firm decides to offer two types of vehicles; and if $\mu^2/(4g\mu + 4\delta - 4) \le \lambda < \mu^2/(4g\mu - 4)$, the firm chooses to offer the EV only. Denoting $\mu/4g$ and $\mu^2/(4g\mu + 4\delta - 4)$ as λ_l^B and λ_h^B, respectively. □

Proof of Corollary 1. According to proof of Proposition 1, $\partial x^{B*}/\partial\mu = 1/(2g\lambda) > 0$, $\partial x^{B*}/\partial g = -\mu/(2g^2\lambda) < 0$, $\partial x^{B*}/\partial\lambda = -\mu/(2g\lambda^2) < 0$, $\partial p_e^{B*}/\partial\mu = 0$, $\partial p_e^{B*}/\partial\delta = 1/2 > 0$, $\partial p_f^{B*}/\partial g = -\mu/2 < 0$, $\partial p_f^{B*}/\partial\lambda = -3\mu^2/8\lambda^2 < 0$, $\partial^2 p_f^{B*}/\partial\mu^2 = 3/4\lambda > 0$. □

Proof of Proposition 2. When the government issues the dual-credit system, there are three possible production line strategies for the firm that is similar to that proof of proposition 1, namely, Strategy F, E, and EF. Different from the case without dual-credit system (as in Proposition 1), the firm's profit function in Strategy F, E, and EF are as follows:

$$\pi^{FD}(p_f, x) = (p_f - \lambda(gx)^2)(1 - v_f) + p_t(g_f - g(1 - x))(1 - v_f) \tag{A7}$$

$$\pi^{ED}(p_f, x) = p_e(1 - v_e) + p_t\beta_e d_e \tag{A8}$$

$$\pi^{EFD}(p_f, x) = (p_f - \lambda(gx)^2)(1 - \hat{v}) + p_e(\hat{v} - v_e) + p_t(g_f - g(1 - x))(1 - \hat{v}) + p_t\beta_e(\hat{v} - v_e) \tag{A9}$$

where $v_f = p_f + \mu(1 - x)g$, $\hat{v} = (p_f - p_e + g\mu(1 - x))/(1 - \delta)$, $v_e = p_e/\delta$.

The process of proof is similar to that in the proof of Proposition 1. Thus, we ignore it here. □

Proof of Corollary 2. Solving $\lambda_l^D - \lambda_l^B$ and $\lambda_h^D - \lambda_h^B$, we can get

$$\lambda_l^D - \lambda_l^B = \frac{p_t(\delta g\mu + \delta g p_t + \delta\mu g_f - \mu\beta_e)}{4g(\delta g\mu + \delta g p_t - \delta g_f p_t + \beta_e p_t)},$$

and

$$\lambda_h^D - \lambda_h^B = \frac{p_t(g\mu^2 + g\mu p_t - \mu^2\beta_e + \mu^2 g_f + 2\delta\mu + \delta p_t - 2\mu - p_t)}{4(g\mu + \delta - 1)(g\mu + g p_t - g_f p_t + \beta_e p_t + \delta - 1)}.$$

Solving $\lambda_l^D - \lambda_l^B < 0$ and $\lambda_h^D - \lambda_h^B < 0$, we can get $p_t < \mu(\beta_e - \delta g - \delta g_f)/(\delta g)$ and $p_t < -\mu(g\mu - \mu\beta_e + \mu g_f + 2\delta - 2)/(\mu g + \delta - 1)$, respectively.

Due to $\mu(\beta_e - \delta g - \delta g_f)/(\delta g) < -\mu(g\mu - \mu\beta_e + \mu g_f + 2\delta - 2)/(\mu g + \delta - 1)$, thus both $\lambda_l^D - \lambda_l^B < 0$ and $\lambda_h^D - \lambda_h^B < 0$ hold if $p_t < \mu(\beta_e - \delta g - \delta g_f)/(\delta g)$ is satisfied. □

Proof of Corollary 3. According to the Proposition 1 and Proposition 2, we can find that $x^{D*} - x^{B*} = p_t/(2g\lambda) > 0$ (i.e., $x^{D*} > x^{B*}$), $p_e^{D*} - p_e^{B*} = -p_t\beta_e/2 < 0$ (i.e., $p_e^{D*} - p_e^{B*} < 0$); and $p_f^{D*} -$

$p_f^{B*} = p_t(4\lambda(g-g_f)+2\mu-p_t)/8\lambda$. If $0 < p_t < 4\lambda(g-g_f)+2\mu$ holds, then $p_f^{D*}-p_f^{B*} > 0$ satisfied, i.e., $p_f^{D*} > p_f^{B*}$. □

Proof of Corollary 4. According to the Proposition 2, we can get $\partial x^{D*}/\partial p_t = 1/(2g\lambda) > 0$,$\partial p_e^{D*}/\partial p_t = -\beta_e/(2g\lambda) < 0$, $\partial^2 p_f^{D*}/\partial p_t^2 = -1/4\lambda < 0$, $\partial p_e^{D*}/\partial \beta_e = -p_t/(2g\lambda) < 0$, $\partial p_f^{D*}/\partial \lambda = (\mu+p_t)(p_t-3\mu)/(8\lambda^2)$. □

Proof of Proposition 3. According to the proof of Proposition 2, we can get that

$$\begin{aligned}
\partial\pi^{FD*}/\partial g_f &= -p_t((4g\mu+4gp_t-4g_fp_t-4)\lambda-(\mu+p_t)^2)/(8\lambda),\\
\partial\pi^{EFD*}/\partial g_f &= p_t(4\lambda(g\mu+gp_t+\beta_ep_t-g_fp_t+\delta-1)-(\mu+p_t)^2)/8\lambda(\delta-1),\\
\partial\pi^{EFD*}/\partial \beta_e &= -p_t((\delta g\mu+\delta gp_t-\delta g_fp_t+\beta_ep_t)4\lambda-\delta(\mu+p_t)^2)/8\lambda(\delta-1)\delta,\\
\partial\pi^{ED*}/\partial \beta_e &= p_t(\beta_ep_t+\delta)/2\delta > 0.
\end{aligned}$$

In Strategy F, to prompt $v_f < 1$, the condition $\lambda < (\mu+p_t)^2/(4g\mu+4gp_t-4g_fp_t-4)$ should be satisfied, leading to $\partial\pi^{FD*}/\partial g_f > 0$. In Strategy EF, when $\lambda_l^D < \lambda < \lambda_h^D$ is satisfied, the firm gets the optimal profit π^{EFD*}. Furthermore, $\partial\pi^{EFD*}/\partial g_f > 0$ can be deduced by the condition $\lambda < \lambda_h^D$ and $\partial\pi^{EFD*}/\partial\beta_e > 0$ can be deduced by the condition $\lambda_l^D < \lambda$.

We can write π^{EFD*} as

$$\pi^{EFD*} = (p_f^{D*}-\lambda(gx^{D*})^2-p_t(g(1-x^{D*})-g_f))D_f^{D*}+(p_e^{D*}+p_t\beta_e)D_e^{D*}$$

where x^{D*}, p_f^{D*}, p_e^{D*}, D_f^{D*} and D_e^{D*} are given by Proposition 2.

Letting $X = p_f^{D*}-\lambda(gx^{D*})^2-p_t(g(1-x^{D*})-g_f$ and $Y = p_e^{D*}+p_t\beta_e$, we can solve $\partial X/\partial p_t > 0$, $\partial Y/\partial p_t > 0$, $\partial D_f^{D*}/\partial p_t > 0$ and $\partial D_e^{D*}/\partial p_t > 0$ simultaneously to get $-\beta_e/\delta < g(1-x^{D*})-g_f < -\beta_e$ where $x^{D*} = (\mu+p_t)/(2g\lambda)$. Obviously, if $\partial X/\partial p_t > 0$, $\partial Y/\partial p_t > 0$, $\partial D_f^{D*}/\partial p_t > 0$ and $\partial D_e^{D*}/\partial p_t > 0$ hold, $\partial\pi^{EFD*}/\partial p_t > 0$ holds.

Similarly, we can easily prove that if $g(1-x^{D*})-g_f > 0$ holds, $\partial\pi^{FD*}/\partial p_t > 0$ will occur. In addition, $\partial\pi^{ED*}/\partial p_t > 0$ always holds. □

Proof of Proposition 4. Taking x^{D*}, p_f^{D*}, and p_e^{D*} into Equation (6) to get CE^{FD*} and CE^{EFD*}, take the derivative of them as follows:

$$\begin{aligned}
\partial CE^{FD*}/\partial g_f &= (2g\lambda-\mu-p_t)/(4\lambda),\\
\partial CE^{EFD*}/\partial g_f &= (2g\lambda-\mu-p_t)p_t/4\lambda(1-\delta),\\
\partial CE^{EFD*}/\partial \beta_e &= (2g\lambda-\mu-p_t)p_t/4\lambda(\delta-1).
\end{aligned}$$

With the assumption $2g\lambda-\mu-p_t > 0$, which ensure $x^{D*} \le 1$, we can easily prove that $\partial CE^{FD*}/\partial g_f > 0$, $\partial CE^{EFD*}/\partial g_f > 0$, $\partial CE^{EFD*}/\partial\beta_e < 0$.

Under the dual-credit policy, we can write CE^{EFD*} and CE^{FD*} as

$$CE^{EFD*} = (2g\lambda-\mu-p_t)A/(16\lambda^2(1-\delta))$$

and

$$CE^{FD*} = (2g\lambda-\mu-p_t)B/(16\lambda^2),\ \text{respectively}$$

where $A = -(4g\lambda\mu+4g\lambda p_t+4\lambda\beta_ep_t-4\lambda g_fp_t+4\delta\lambda-4\lambda-(\mu+p_t)^2)$ and $B = -(4g\lambda\mu+4g\lambda p_t-4\lambda g_fp_t-4\lambda-(\mu+p_t)^2)$.

We can easily prove that if $\partial A/\partial p_t < 0$ ($\partial B/\partial p_t < 0$) then $\partial CE^{EFD*}/\partial p_t < 0$ ($\partial CE^{FD*}/\partial p_t < 0$). Solving $\partial A/\partial p_t < 0$ and $\partial B/\partial p_t < 0$, we can get $\beta_e+g(1-x^{D*})-g_f > 0$ and $g(1-x^{D*})-g_f > 0$, respectively. □

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