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Research Article

Pricing Strategy and Carbon Emission Abatement under Cap-and-Trade Regulation Considering Social Learning

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In an uncertainty market, social learning plays a significant role in obtaining information to make better decisions. Under cap-and-trade regulation, this paper aims to investigate firms' pricing and carbon emission abatement issues considering the impact of social learning. This paper establishes a two-period model in a market consisting of a manufacturer and heterogeneous consumers. The manufacturer produces two alternatives (ordinary product and low-carbon product) and makes decisions on sales prices and carbon emission abatement levels. Consumers make decisions on whether and which product to buy. Consumers are not sure about their valuations of products and have the opportunity to discover their true valuation by social learning. The results show that the emission abatement level on ordinary product is affected by the pricing strategy for both types of products. However, the emission abatement level on low-carbon product is only affected by its own pricing strategy. It also shows that social learning lowers the emission abatement level on ordinary product, whereas it improves the emission abatement level on low-carbon product when charging a high price for low-carbon product. Moreover, the price of ordinary product in period 1 is no less than that in period 2. In contrast, the price of low-carbon product in period 2 is higher than that in period 1.

1. Introduction

In the complex social environment, consumers sometimes are not clear about their preferences and do not know which kind of product to choose. Under some conditions, they may know about their needs, but may have no opportunity to buy suitable products due to bad purchasing strategy [1]. An effective way to solve this problem is to gain more information through social learning. Consumers can actively learn from previous adopters via online mouth-to-mouth or offline social interaction [2]. Besides, the uncertainty existing among consumers also affects the firms' decisions on production and pricing, which may lead to mismatch between the supply and demand. To lower the impacts of uncertainty, firms can take some measures to induce consumers to learn about their valuation of products, preferences, or product quality [3]. For example, many electronic device producers set up showrooms to help potential purchasers learn more about their valuations and preferences [4].

Carbon emissions associated with economy development give rise to many issues, such as air pollution, global warming, and extreme weather, which threaten human beings [5]. Monforte and Ragusa [6] suggest that air pollution is closely related to human industrial activities and evaluate air pollution in the Mediterranean area by using the air quality index. The World Health Organization reports that about 600,000 deaths in Europe were caused by air pollution associated with greenhouse gases [7]. The sub-Saharan Africa is even worst affected by climate change [8]. Therefore, it is a worldwide concern to curb carbon emissions. Many developed countries signed the Kyoto Protocol and promised to reduce carbon emissions dramatically [9]. To achieve this goal, governments employ many ways among which, carbon cap-and-trade regulation is believed to be an effective way to control carbon emissions [10]. Under cap-and-trade regulation, enterprises can get certain number of emission allowances by grandfathering or by auction at the beginning of production horizon, the surplus or insufficient part can be traded in the carbon market [11]. However, it is not enough only to implement cap-and-trade regulation to curb carbon emissions. Many firms tend to seek cost-efficient methods to reduce carbon emissions in production processes to meet carbon emission limitation, such as adopting cleaner production equipment, designing pollution-abatement technologies, and so on [12, 13]. Another factor that drives firms to take costly measures to reduce carbon emission is that consumers with eco-friendly awareness are willing to pay a higher price for green products. A survey conducted by O'Connell [14] reports that approximately 17% of American consumers are willing to pay extra premium for eco-friendly products.

By combing the existing literature, we find that little attention has been paid to the impact of social learning on firms' operational decisions under carbon emission regulation. To fulfill this gap, this work attempts to investigate firms' production, pricing, and carbon emission reduction issues in the presence of social learning. To address the above questions, we establish a two-period supply chain model comprised of a manufacturer and two-segment consumers. The manufacturer produces two alternatives to meet consumers' preferences and makes decision on pricing in different periods. Under cap-and-trade regulation, the manufacturer also invests in abating carbon emissions to meet government regulation and consumers' environmental awareness. The consumers are divided into two segments: A-segment consumers who prefer to purchase ordinary products and B-segment consumers who tend to buy low-carbon products. In each period, consumers decide whether and which product to buy. The consumers know which type they belong to, but they are not sure about their own valuation of products; whereas consumers possibly discover their true valuations via social learning in the second period.

Several interesting findings are reached. It shows that the manufacturer has four different pricing strategies when producing two kinds of products. The manufacturer invests in different emission abatement levels on ordinary products under different pricing strategies, whereas the emission abatement level on low-carbon product is not affected by the pricing strategy of ordinary products. It also shows that the price of ordinary products in period 1 is no less than the price in period 2. In contrast with the pricing strategy of ordinary products, the price of low-carbon in period 1 is lower than that in period 2. In the presence of consumers' social learning behavior, the emission abatement level on ordinary products increases in the population of consumers who purchase in period 1 within A-segment consumer. For the low-carbon products, the emission abatement level increases in the proportion of consumers who buy products in period 1 only when the manufacturer charges a higher price for low-carbon products. The findings also suggest that social learning lowers the emission abatement level on ordinary products, but improves the emission abatement level on low-carbon products.

This work proceeds as below. Section 2 reviews the related literature on social learning and carbon cap-and-trade regulation. Section 3 describes the model in detail. Section 4 presents the manufacturer's optimal decisions on pricing and emission abatement considering the impact of social learning. In Section 5, we do some numerical experiments to illustrate how important factors affect the manufacturer's strategy and performance. In Section 6, some significant results are concluded.

2. Literature Review

Our work is closely related to two streams of literature: social learning and carbon cap-and-trade regulation. The literature on social learning starts from Banerjee [15] who points out that the potential buyers will adjust their purchasing decision after they obtain the information about products from the former buyers. Bergemann and Välimäki [16] suggest that consumers and firms actively learn the value of products from the previous adopters through various channels. Zhang [17] investigates the impact of observational learning on consumers' decision in American kidney market. Some researchers also study the cases of social learning on other aspects. For example, by establishing a two-period model comprising of one firm and two consumers, Bhalla [18] analyzes the scenario in which consumers learn about product quality. Swinney [19] shows that when consumers discover their preferences by social learning, the effect of quick-response practice is often weakened since consumers tend to adopt strategic behavior. Jing [3] points out that when the intensity of external spontaneous social learning is insufficient, seller can guide consumers to learn.

Besides the impacts of social learning on consumers, researchers are also interested in the impacts of social learning on firms. Candogan et al. [20] discuss the impact of spontaneous social learning on pricing within social network. Bose et al. [21] suggest that firms can adopt dynamic pricing strategy to control information inference conducted by future consumers from the previous buyers. Prasad et al. [22] explore the way to induce uninformed consumers to purchase in advance. Xiong and Chen [1] suggest that selling-induced learning can help consumers to find their true willingness to pay, which is helpful to optimize the firm's product line design. By establishing linear social learning model, Jing [3] studies the impact of social learning on pricing and consumers' purchasing decision. Hu et al. [2] analyze how social learning affects a firm's operational decision when producing alternatives by constructing an exponential social learning model. When a manufacturer sells two alternatives, social learning decides the operation of the manufacturer. By setting the proportion of updated belief and the prior belief, Papanastasiou and Savova [23] analyze the influence of social learning upon product quality on a firm's pricing strategy. Ifrach et al. [24] suggests that when strategic consumers exist in the market, social learning helps firms to make more profit. Considering the impact of social learning on pricing, Li et al. [25] shows that social learning can reduce a firm's production costs. The work aforementioned analyzes the impacts of social learning on consumers' purchasing decision, yet little attention has been paid to consumers' environmental awareness when purchasing. On the other hand, the researchers mentioned above show that social learning should be considered in manufacturers' pricing and production decisions, whereas they neglect the manufacturers' exterior production environment.

The literature on cap-and-trade regulation mainly focuses on production, pricing, and low-carbon product design. In production management, Benjaafar et al. [26] present three models to analyze how to curb carbon footprints under carbon cap-and-trade. Cao et al. [27] demonstrate the optimal production with carbon emission regulation and compare the effectiveness of different kinds of low-carbon subsidy policies. Under cap-and-trade regulation, Gong and Zhou [28] explore how a firm plans production in a multi-period horizon. The papers aforementioned study firms producing one single product. Some researchers also study the case in which a manufacturer provides different kinds of products. For example, García-Alvarado et al. [29] study a manufacturer's production decision considering the remanufacturing problem and show the impact of cap-and-trade scheme. Du et al. [30] discuss how a manufacturer makes decisions on producing low-carbon products and ordinary products under carbon cap-and-trade mechanism. Chen and Wang [31] suggest that multiproduction strategy on the low-carbon supply chain plays an important role in environmental protection and economic performance. In line with Du et al. [30] and Chen and Wang [31], we investigate a manufacturer's production decision on two types of products. Differently, we explore a condition with two periods. On the other hand, we assume that consumers in the market are heterogeneous on their valuation of products, and show the impact of social learning on production.

Apart from production management, researchers also pay attention to pricing problems under carbon emission regulation. Xu et al. [32] study how a manufacturer makes pricing decisions in a MTO model considering the carbon cap-and-trade mechanism. García-Alvarado et al. [29] discuss enterprises' pricing strategy by solving a Markov decision problem under different emission regulations. Cao and Yu [33] study a manufacturer's wholesale pricing strategy considering the impact of capital constraint. Qi et al. [34] analyze a manufacturer's wholesale pricing decision and retailers' retail pricing decision under cap-and-trade scheme. Different from the above work, we analyze a firm's dynamic pricing strategy in a two-period supply chain. As consumers have different willingness to pay and belong to different segments, four pricing strategies are explored in our model.

Pressed by the government's environment policies and consumers' eco-friendly awareness, many firms take costly measures to curb the impact of products on the environment, such as designing green products and using clean process equipment [12, 35]. Considering the competition among upstream firms and downstream firms, Liu et al. [36] analyze firms' optimal emission abatement decisions under different supply chain structure, and point out that the manufacturer who provides a higher emission abatement level makes more profit. Considering the impact of consumers' eco-friendly awareness on market demand, Jiang and Chen [37] analyze a firm's optimal production and pricing problems under carbon emission regulation. By comparing the cost and benefit of reducing carbon emissions, Wang et al. [38] investigate the impact of cap-and-trade mechanism, and show the condition under which a firm should invest in abating carbon emissions. Ouardighi et al. [39] examine how double marginalization effect influences firms' emission reduction decision. Zhu and He [40] analyze how the product types and competition styles affect the degree of product greenness. Considering consumers' low-carbon preference, Yang and Chen [41] show the impacts of different motivation schemes on a firm's investment decision upon carbon emission abatement. Similar to the work aforementioned, we also consider consumers' low-carbon preference and willingness to pay an extra premium for green products. The key difference between our work and theirs is that we assume that the consumers are strategic and heterogeneous. Consumers can purchase either in the initial period or in the second period, and they have the opportunity to find their true valuation through social learning. In addition, we discuss the situation under which a manufacturer produces alternative products and invests in reducing carbon emissions on both kinds of products to meet consumers' preferences.

3. Model Description

In the market, we consider a two-period model in which a monopolistic manufacturer sells products to two segments of consumers with heterogeneous valuation of products. For example, Hewlett–Packard produces different types of computers to meet consumers' requirement with different valuations and preferences. Consumers who prefer to buy ordinary products belong to A-segment with proportion ϕ, and those who prefer to buy low-carbon product belong to B-segment with proportion $1-\phi$. The B-segment consumers have higher valuation of products than those A-segment consumers, and they are willing to pay higher prices. The valuation of consumers within each segment takes two values: v_N or $v_L (v_L > v_N)$. The consumers only know which segment they belong to, but they are not sure about their valuation. The manufacturer cannot identify which segment each consumer belongs to. If some consumers buy products in period 1, the rest of the consumers have an opportunity to learn the key attributes of the products by online review or offline word-of-mouth. For example, when consumers plan to buy a computer, they would like to obtain some information about computers from their friends or via online product review. By doing so, they can identify their own preference over those attributes.

We assume that a type-v_i consumer's willingness to pay is v_i, $(i = N, L)$. Denote α_N the proportion of type-v_N within A-segment consumers, and α_L the proportion of type-v_L consumers within B-segment. Assuming $0 < \alpha_L < \alpha_N < 1$ to ensure that B-segment consumers' valuation is higher than A-segment, then, $\overline{v}_N = \alpha_N v_N + (1-\alpha_N) v_L$, $\overline{v}_L = \alpha_L v_N + (1-\alpha_L) v_L$, and $\overline{v}_N < \overline{v}_L$. Each consumer demands at most one unit item over the two periods. In addition, consumers are willing to pay an extra price for the eco-friendly products. Thus, if a consumer knows his valuation of product for sure, the valuation for product-i is $(1+\tau_i)v_i, \forall i = N, L$ in period j, $j = 1, 2$, where τ_i represents the carbon emission abatement level on product-i decided by the manufacturer; otherwise, the consumer's valuation for product-i is $(1+\tau_i)\overline{v}_i$.

To satisfy consumers' preferences, the manufacturer produces two alternative products: an ordinary product (called "product-N") and a low-carbon product (called "product-L"). Under carbon cap-and-trade regulation, the manufacturer invests in carbon emission abatement, with the carbon emission abatement level τ_N on ordinary products and τ_L on low-carbon products, respectively. The unit cost of product is $c_0 + (1/2)\lambda\tau_i^2 (i = N, L)$, where c_0 is the fixed marginal cost of product and $(1/2)\lambda\tau_i^2$ is per unit cost raised from carbon emission reduction. Parameter λ represents the carbon emission abatement coefficient and a large value implies that the manufacturer is not efficient in abating carbon emissions. The quadratic function of emission abatement cost indicates the diminishing effects to carbon emission reduction [36, 40]. Assuming the initial carbon emissions per unit product are e_0, the carbon emissions per unit item are $(1-\tau)e_0$ after investing in carbon emission abatement.

Denote θ_N and $\theta_L(0 \le \theta_N \le 1, 0 \le \theta_L \le 1)$ as the proportions of consumers who buy products in period 1 within A-segment and B-segment, respectively. A higher $\theta_N(\theta_L)$ represents that more consumers prefer to buy products early; otherwise, they like to postpone consumption. In the initial period, consumers know little information about their valuation; whereas a consumer who does not purchase in period 1 has an opportunity to discover their true valuation via social learning. Let s denote the social learning intensity that represents the probability that a consumer is able to identify his true valuation by period 2. Thus, among A-segment consumers,$s(1-\theta_N)\phi\alpha_N$ type-υ_N consumers and $s(1-\theta_N)(1-\alpha_N)\phi$ type-υ_L consumers are able to find their true valuation. For B-segment consumers, $s\alpha_L(1-\theta_L)(1-\phi)$ consumers know valuation υ_N consumers and $s(1-\alpha_L)(1-\theta_L)(1-\phi)$consumers know their valuation υ_L for sure.

Assuming that the manufacturer and the consumers are risk-neutral, the manufacturer aims to maximize their profit and the consumers try to maximize their expected utility. The manufacturer launches two kinds of products at the initial period and announces their prices p_{ij} at the beginning of each period. Under the pressure of government regulation and consumers' eco-friendly awareness, the manufacturer also invests in reducing carbon emissions under cap-and-trade mechanism. After observing the price, each consumer determines whether and which kind of products to buy in that period. If a consumer does not purchase any product in period 1, he stays in the market and decides whether to buy in period 2, with the probability s that he knows his true valuation for sure. The uninformed consumers' purchasing decision is based on expected valuation. In period 2, the informed consumers decide whether to purchase on the basis of their true valuation.

4. Model Analysis

In this section, given that consumers possibly discover their true valuation via social learning, we try to derive the manufacturer's optimal carbon emission reduction decision and the pricing strategy. We start our analysis from the second period based on the rational expectation theory.

To induce the customers to buy products, there exist the following individual rationality (abbreviated as "IR") constraints,

$$\text{IR-1}: \ \upsilon_i(1+\tau_i) - p_{i2} \ge 0, \tag{1}$$

$$\text{IR-2}: \ \overline{\upsilon}_i(1+\tau_i) - p_{i2} \ge 0. \tag{2}$$

IR-1 guarantees that the informed customers gain nonnegative utility. For those who are not sure about their valuation in period 2, their null payoff when buying products gives rise to constraint IR-2. In addition, the optimal product line design should be able to induce consumers to reveal their true valuation of products, thereby leading to the incentive compatibility (abbreviated as "IC") constraintsas below:

$$\begin{aligned} \text{IC-NL}: \ & \upsilon_N(1+\tau_N) - p_{N2} \ge \upsilon_N(1+\tau_L) - p_{L2}, \\ & \overline{\upsilon}_N(1+\tau_N) - p_{N2} \ge \overline{\upsilon}_N(1+\tau_L) - p_{L2}, \end{aligned} \tag{3}$$

$$\begin{aligned} \text{IC-LN}: \ & \upsilon_L(1+\tau_L) - p_{L2} \ge \upsilon_L(1+\tau_N) - p_{N2}, \\ & \overline{\upsilon}_L(1+\tau_L) - p_{L2} \ge \overline{\upsilon}_L(1+\tau_N) - p_{N2}. \end{aligned} \tag{4}$$

IC-NL indicates that an informed type-υ_N consumer is better off by choosing the product that can reveal his true valuation type and an uninformed A-segment consumer is better off to choose product-N. IC-LN indicates that an informed type-υ_L consumer or an uninformed B-segment consumer is better off by choosing the product-L. From IR constraints, we know that the manufacturer can either decide the price p_{i2} at $\upsilon_i(1+\tau_i)$ or $\overline{\upsilon}_i(1+\tau_i)$. By choosing a higher price, the marginal profit per unit product is enhanced but the sales volume is reduced, whereas by choosing a lower price, the manufacturer can induce more consumers to purchase products. When designing two product lines, the manufacturer has four different pricing strategies: high prices for both kinds of products (H–H pricing strategy), high price for product-N and low-price for product-L (H–L pricing strategy), low price for product-N and high price for product-L (L–H pricing strategy), and low prices for both types of products (L–L pricing strategy). We use the superscript T to denote the pricing strategy, and T can be HH, HL, LH, and LL.

4.1. H–H Pricing Strategy. The prices decided by the manufacturer should ensure that consumers who purchase items have a null payoff. Thus, IR constraints are written as.

$$\text{IR-N}: \ \overline{\upsilon}_N(1+\tau_N) - p_{N2} \ge 0, \tag{5}$$

$$\text{IR-L}: \ \upsilon_L(1+\tau_L) - p_{L2} \ge 0. \tag{6}$$

The IC constraints are written as

$$\text{IC-NL}: \ \overline{\upsilon}_N(1+\tau_N) - p_{N2} \ge \overline{\upsilon}_N(1+\tau_L) - p_{L2}, \tag{7}$$

$$\text{IC-LN}: \ \upsilon_L(1+\tau_L) - p_{L2} \ge \upsilon_L(1+\tau_N) - p_{N2}. \tag{8}$$

By analyzing the constraints, we can get that p_{N2} and p_{L2} satisfy

$$p_{N2} = \overline{\upsilon}_N(1+\tau_N), p_{L2} = \upsilon_L(1+\tau_L) - \upsilon_L(1+\tau_N) + \overline{\upsilon}_N(1+\tau_N). \tag{9}$$

In period 1, to induce the consumers to buy items early, price p_{i1} must ensure that the utility that a consumer obtains in period 1 is not less than the expected utility he can get when discovering his true valuation type in period 2. In period 1, an uninformed consumer's net utility is $u_{i1} = \overline{\upsilon}_i(1+\tau_i) - p_{i1}$ when choosing product-i. Under the H–H pricing strategy, the net utility of an uninformed A-segment in period 1 is zero, and the net utility of informed type-υ_L in period 1 equals to $s(1-\alpha_L)[\upsilon_L(1+\tau_L) - p_{L2}]$. As a result, there exists

$$\overline{\upsilon}_N(1+\tau_N) - p_{N1} = 0, \tag{10}$$

$$\bar{v}_L(1+\tau_L) - p_{L1} = s(1-\alpha_L)[v_L(1+\tau_L) - p_{L2}]. \quad (11)$$

When the manufacturer chooses H–H pricing strategy, the informed type-v_N consumers cannot buy any products in that period. Besides, the uninformed consumers within B-segment are not able to buy product-L and turn to buy product-N to get the utility $\bar{v}_L(1+\tau_N) - p_{N2}$. In this scenario, the population of consumers within A-segment buy product-N in period 1 is $\theta_N\phi$. Therefore, the manufacturer's expected profit gained by selling type-N product within A-segment consumers is given by

$$\pi_{N1}^{HH} = p_{N1}\theta_N\phi - \left[c_0 + \frac{1}{2}\lambda\tau_N^2 + p_e e_0(1-\tau_N)\right]\theta_N\phi. \quad (12)$$

In Equation (12), p_e represents the carbon trading price. In period 2, given social learning intensity s, the sales volumes of product-N and product-L are $(1-\theta_N)(1-s)\phi$ and $s(1-\theta_N)(1-\alpha_N)\phi$, respectively. Thus, the expected profit of the manufacturer gained from selling product-N is

$$\begin{aligned}\pi_{N2}^{HH} =& \left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right](1-\theta_N)(1-s)\phi \\ &+ \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]s(1-\alpha_N)(1-\theta_N)\phi.\end{aligned} \quad (13)$$

The total expected profit gained by selling products to A-segment consumer is

$$\pi_N^{HH} = \pi_{N1}^{HH} + \pi_{N2}^{HH}. \quad (14)$$

For the B-segment consumers, the population who buy product-N in period 1 is $\theta_L(1-\phi)$. In period 2, $s(1-\alpha_L)(1-\theta_L)(1-\phi)$ consumers buy product-L and $(1-s)(1-\theta_L)(1-\phi)$ consumers who cannot learn their valuation buy product-N. Thus, the manufacturer's expected profit gained from B-segment consumers in period 1 is given by

$$\pi_{L1}^{HH} = \left[p_{L1} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]\theta_L(1-\phi). \quad (15)$$

The expected profit of the manufacturer gained from B-segment consumers in period 2 is expressed as

$$\begin{aligned}\pi_{L2}^{HH} =& \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]s(1-\alpha_L)(1-\theta_L)(1-\phi) \\ &+ \left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right](1-s)(1-\theta_L)(1-\phi).\end{aligned} \quad (16)$$

The total expected profit gained from B-segment is

$$\pi_L^{HH} = \pi_{L1}^{HH} + \pi_{L2}^{HH}. \quad (17)$$

Under H–H pricing strategy, given the initial carbon emission allocation G, the expected profit of the manufacturer is

$$\Pi^{HH} = \pi_N^{HH} + \pi_L^{HH} + p_e G. \quad (18)$$

The next proposition fully describes the manufacturer's optimal carbon emission reduction levels and the optimal prices in this scenario.

Proposition 1. *Under H–H pricing strategy, the optimal carbon emission reduction level on product-N is* $\tau_N^{HH*} = ((\bar{v}_N + p_e e_0)/\lambda) - (s(v_L - \bar{v}_N)[(1-\alpha_N)(1-\theta_N)\phi + (1-\alpha_L)(1-\phi)] /\lambda[\theta_N\phi + (1-\theta_N)(1-s)\phi + (1-s)(1-\theta_L)(1-\phi)])$ *and the reduction level on product-L is* $\tau_L^{HH*} = ((v_L + p_e e)_0/\lambda) - (v_L - \bar{v}_L)\theta_L(1-\phi)/\lambda[\theta_L(1-\phi) + s(1-\alpha_N)(1-\theta_N)\phi + s(1-\alpha_L)(1-\theta_L)(1-\phi)]$. *The optimal prices are* $p_{N1}^{HH*} = \bar{v}_N(1+\tau_N^{HH*})$, $p_{L1}^{HH*} = \bar{v}_L(1+\tau_L^{HH*}) - s(1-\alpha_L)(v_L - \bar{v}_N)(1+\tau_N^{HH*})$, $p_{N2}^{HH*} = \bar{v}_N(1+\tau_N^{HH*})$, *and* $p_{L2}^{HH*} = v_L(1+\tau_L^{HH*}) - v_L(1+\tau_N^{HH*}) + \bar{v}_N(1+\tau_N^{HH*})$.

Proposition 1 demonstrates that the manufacturer's carbon emission abatement decision highly depends on the social learning intensity s, the proportion of each valuation type α_i, the population of consumers that buy products in period 1, and the proportion of B-segment consumers in the market ϕ. Specifically, the carbon emission abatement level of product-N decreases in s, θ_L, c, and increases in α_L and θ_N. With a higher social learning intensity, the possibility that consumers are able to discover their valuation v_N is enhanced. Under H–H strategy, the manufacturer gives up the type-v_N consumers in period 2. As a result, he does not have motivation to invest more funds in abating carbon emissions on product-N. A large θ_L means that more consumers are willing to purchase product-L, thereby leading to more investment in product-L to meet consumers' demand. In this case, the manufacturer has to cut off the investment in product-N, which leads to a lower τ_N^{HH*}. A similar thing happens when ϕ is relatively large.

For the carbon emission abatement level of product-L τ_L^{HH*}, it increases in the social learning intensity s, but decreases in α_L, α_N, θ_L, and θ_N. With a higher social learning intensity, more B-segment consumers will know their valuation type-v_L for sure. Under a higher pricing strategy, the manufacturer can gain more profit from type-v_L consumers, and therefore they are willing to invest in a higher emission abatement level. The parameter $\alpha_L(\alpha_N)$ stands for the population of type-v_N consumers. Given a larger $\alpha_L(\alpha_N)$, more type-v_N consumers will discover their low willingness to pay, which drives down the manufacturer's motivation of reducing carbon emissions on product-L. When θ_L and θ_N are relatively large, it means that more consumers buy product in period 1, which leads to less consumers buying items in period 2. In this case, the cost of investing in a higher emission abatement level exceeds the benefit of charging a higher price. As a result, the manufacturer tends to lower the carbon emission abatement level of product-L.

Interestingly, we find that τ_L^{HH*} increases in ϕ when $\phi < (1/2)$, whereas it decreases in ϕ when $\phi \geq (1/2)$.When $\phi < (1/2)$, the population of B-segment consumer is larger than that of A-segment consumer, which means that more consumers are willing to purchase product-L. Thus, the manufacturer has incentive to invest more in product-L and charges a higher price to make more profit. In addition, the carbon emission abatement levels increase in the carbon trading price and decrease in the investment coefficient of carbon emission abatement. Because, when the carbon trading price is relatively high, the manufacturer can earn more profit from the carbon trading market by selling more carbon emission permits. Thus, the manufacturer tends to invest in higher emission abatement levels. A large λ means that the manufacturer is not efficient in reducing carbon emission. As a result, the manufacturer would like to lower carbon emission abatement levels to save costs.

Under H–H pricing strategy, the prices of product-N are the same over the entire horizon and are independent of the carbon emission abatement level of product-L. This is because the uninformed A-segment consumers do not have the opportunity to buy product-L. However, the prices of product-L decrease in the carbon emission abatement level. The intuition behind this result is that the uninformed B-segment consumers turn to purchase product-N when the price of product-L is very high in period 2. Therefore, the manufacturer has to consider the consumers' reaction within B-segment when deciding the price of product-L.

4.2. H–L Pricing Strategy. In this subsection, we are going to analyze the scenario in which the manufacturer charges a higher price for product-N and a lower price for product-L in period 2. In this case, the IR constraints are given by

$$\text{IR-N}: \ \bar{v}_N(1+\tau_N) - p_{N2} \geq 0, \tag{19}$$

$$\text{IR-L}: \ \bar{v}_L(1+\tau_L) - p_{L2} \geq 0. \tag{20}$$

Under H–L pricing strategy, the consumers who know their true valuation v_N for sure in period 2 are not able to buy any kinds of products. Thus, the IC constraints are written as

$$\text{IC-NL}: \ \bar{v}_N(1+\tau_N) - p_{N2} \geq \bar{v}_N(1+\tau_L) - p_{L2}, \tag{21}$$

$$\text{IC-LN}: \ \bar{v}_L(1+\tau_L) - p_{L2} \geq \bar{v}_L(1+\tau_N) - p_{N2}. \tag{22}$$

Based on the rational expectation theory, the prices in period 1 should satisfy the following equations.

$$\begin{aligned} &\bar{v}_N(1+\tau_N) - p_{N1} = 0, \\ &\bar{v}_L(1+\tau_L) - p_{L1} = s(1-\alpha_L)[v_L(1+\tau_L) - p_{L2}]. \end{aligned} \tag{23}$$

When conducting H–L pricing strategy, the informed type-v_N consumers cannot buy any product and the uninformed B-segment consumers turn to buy product-N. In this scenario, the profit gained from A-segment consumers in period 1 is given by

$$\pi_{N1}^{HL} = p_{N1}\theta_N\phi - \left[c_0 + \frac{1}{2}\lambda\tau_N^2 + p_e e_0(1-\tau_N)\right]\theta_N\phi. \tag{24}$$

The profit obtained from A-segment consumers in period 2 is

$$\begin{aligned} \pi_{N2}^{HL} = &\left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right](1-\theta_N)(1-s)\phi \\ &+ \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]s(1-\alpha_N)(1-\theta_N)\phi. \end{aligned} \tag{25}$$

Then, the total profit gain from A-segment consumers is

$$\pi_N^{HL} = \pi_{N1}^{HL} + \pi_{N2}^{HL}. \tag{26}$$

The profit obtained from B-segment consumers in period 1 is

$$\pi_{L1}^{HL} = \left[p_{L1} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]\theta_L(1-\phi). \tag{27}$$

The profit obtained from B-segment consumers in period 2 is

$$\begin{aligned} \pi_{L2}^{HL} = &\left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right] \\ &\cdot \left[s(1-\alpha_L)(1-\theta_L) + (1-s)(1-\theta_L)\right](1-\phi). \end{aligned} \tag{28}$$

Then, the total profit gain from B-segment consumers is

$$\pi_L^{HL} = \pi_{L1}^{HL} + \pi_{L2}^{HL}. \tag{29}$$

The total expected profit of the manufacturer under H–L pricing strategy is

$$\Pi^{HL} = \pi_N^{HL} + \pi_L^{HL} + p_e G. \tag{30}$$

It can be proved that Π^{HL} is concave in τ_N and τ_L. Therefore, we can get the following proposition that presents the manufacturer's optimal decisions under H–L pricing strategy.

Proposition 2. *Under H–L pricing strategy, the optimal carbon emission abatement levels are* $\tau_N^{HL*} = ((\bar{v}_N + p_e e_0)/\lambda) - (\bar{v}_L - \bar{v}_N[s(1-\alpha_N)(1-\theta_N)\phi + s(1-\alpha_L)(1-\phi) + (1-s)(1-\theta_L)(1-\phi)]/\lambda[\theta_N\phi + (1-\theta_N)(1-s)\phi]$ *and* $\tau_L^{HL*} = ((\bar{v}_L + p_e e_0)/\lambda) - (v_L - \bar{v}_L s(1-\alpha_L)\theta_L(1-\phi)/\lambda[\theta_L(1-\phi) + s(1-\alpha_N)(1-\theta_N)\phi + (1-s\alpha_L)(1-\theta_L)(1-\phi)]$. *The optimal prices are* $p_{N1}^{HL*} = \bar{v}_N(1+\tau_N^{HL*})$, $p_{L1}^{HL*} = \bar{v}_L(1+\tau_L^{HL*}) - s(1-\alpha_L)[(v_L - \bar{v}_L)(1+\tau_L^{HL*}) + (\bar{v}_L - \bar{v}_N)(1+\tau_N^{HL*})]$, $p_{N2}^{HL*} = \bar{v}_N(1+\tau_N^{HL*})$, *and* $p_{L2}^{HL*} = \bar{v}_L(1+\tau_L^{HL*}) - \bar{v}_L(1+\tau_N^{HL*}) + \bar{v}_N(1+\tau_N^{HL*})$.

Proposition 2 demonstrates the manufacturer's optimal decisions under H–L pricing strategy. Different from H–H pricing strategy, we find that the correlation between τ_N^{HL*} and s is uncertain. On the other hand, τ_N^{HL*} decreases in α_N when α_N is relatively small and increases in α_N when α_N is relatively large. Note the manufacturer charges a higher price for product-N which has a positive relationship with τ_N^{HL*}. When α_N is relatively small, less A-segment consumers purchase in period 1. Besides, the informed type-v_N consumers cannot buy any product in period 2. Facing a small sales volume, the manufacturer has no incentive to offer a higher emission abatement level of product-N. Contrary to our intuition, τ_L^{HL*} decreases in the social learning intensity s. Due to charging a low price for product-L, both the uninformed and the informed B-segment consumers can buy product-L. In this scenario, investing in a higher emission abatement level does not bring much profit for the manufacturer. In contrary, it costs the manufacturer too much in abating carbon emissions. So it is the best for the manufacturer to lower the emission abatement level of product-L.

4.3. L–H Pricing Strategy. Under L–H pricing strategy, the manufacturer charges a lower price for product-N and a higher price for product-L. In this scenario, the IR constraints that guarantee consumers' participation in period 2 are as below:

$$\text{IR-N}: \ v_N(1+\tau_N) - p_{N2} \geq 0, \tag{31}$$

$$\text{IR-L}: \ v_L(1+\tau_L) - p_{L2} \geq 0. \tag{32}$$

The IC constraints that ensure the consumers to reveal their valuation type are

$$\text{IC-NL}: \ v_1(1+\tau_N) - p_{N2} \geq v_1(1+\tau_L) - p_{L2}, \quad (33)$$

$$\text{IC-LN}: \ v_2(1+\tau_L) - p_{L2} \geq v_2(1+\tau_N) - p_{N2}. \quad (34)$$

Thus, the prices in period 2 are $p_{N2} = v_N(1+\tau_N)$, $p_{L2} = v_L(1+\tau_L) - v_L(1+\tau_N) + v_N(1+\tau_N)$.

To ensure consumers to buy product in period 1, there exist

$$\bar{v}_N(1+\tau_N) - p_{N1} = v_1(1+\tau_N) - p_{N2}, \quad (35)$$

$$\bar{v}_L(1+\tau_L) - p_{L1} = s(1-\alpha_L)[v_L(1+\tau_L) - p_{L2}]. \quad (36)$$

By substituting p_{N2} and p_{L2} into Equations (35) and (36), we can get the prices in period 1

$$\begin{aligned} p_{N1} &= \bar{v}_N(1+\tau_N), \\ p_{L1} &= \bar{v}_L(1+\tau_L) - s(1-\alpha_L)(v_L - v_N)(1+\tau_N). \end{aligned} \quad (37)$$

Under L–H pricing strategy, in period 2, both the informed type-v_N consumers and the uninformed consumers choose to buy product-N, and the informed type-v_L consumers choose to buy product-L. As a result, the expected profit obtained from A-segment consumers in period 1 is given by

$$\pi_{N1}^{LH} = p_{N1}\theta_N\phi - \left[c_0 + \frac{1}{2}\lambda\tau_N^2 + p_e e_0(1-\tau_N)\right]\theta_N\phi. \quad (38)$$

The expected profit gained from A-segment consumers in period 2 is

$$\begin{aligned} \pi_{N2}^{LH} = &\left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right] \\ &\cdot [s\alpha_N(1-\theta_N)\phi + (1-\theta_N)(1-s)\phi] \\ &+ \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]s(1-\alpha_N)(1-\theta_N)\phi. \end{aligned} \quad (39)$$

In a similar way, we can get

$$\pi_{L1}^{LH} = \left[p_{L1} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]\theta_L(1-\phi), \quad (40)$$

$$\begin{aligned} \pi_{L2}^{LH} = &\left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]s(1-\alpha_L)(1-\theta_L)(1-\phi) \\ &+ \left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right] \\ &\cdot [s\alpha_L(1-\theta_L) + (1-\theta_L)(1-s)](1-\phi). \end{aligned} \quad (41)$$

Thus, the total expected profit under L–H pricing strategy is

$$\Pi^{LH} = \pi_{N1}^{LH} + \pi_{N2}^{LH} + \pi_{L1}^{LH} + \pi_{L2}^{LH} + p_e G. \quad (42)$$

The next proposition demonstrates the manufacturer's optimal carbon emission abatement strategy and the optimal pricing decision under L–H pricing strategy.

Proposition 3. *Under L–H pricing strategy, the optimal emission abatement levels are* $\tau_N^{LH*} = ((v_N + p_e e_0)/\lambda) + (v_L - v_N) s[(1-\alpha_N)\theta_N\phi - (1-\alpha_N)(1-\theta_N)\phi - (1-\alpha_L)(1-\phi)]/\lambda[\theta_N\phi + (1-\theta_N)(1-s+s\alpha_N)\phi + (1-s+s\alpha_L)(1-\theta_L)(1-\phi)]$ *and* $\tau_L^{LH*} = ((v_L + p_e e_0)/\lambda) - (v_L - \bar{v}_L)\theta_L(1-\phi)/\lambda[\theta_L(1-\phi) + s(1-\alpha_N)(1-\theta_N)\phi + s(1-\alpha_L)(1-\theta_L)(1-\phi)]$. *The optimal prices are* $p_{N1}^{LH*} = \bar{v}_N(1+\tau_N^{LH*})$, $p_{L1}^{LH*} = \bar{v}_L(1+\tau_L^{LH*}) - s(1-\alpha_L)(v_L - v_N)(1+\tau_N^{LH*})$, $p_{N2}^{LH*} = v_N(1+\tau_N^{LH*})$, *and* $p_{L2}^{LH*} = v_L(1+\tau_L^{LH*}) - v_L(1+\tau_N^{LH*}) + v_N(1+\tau_N^{LH*})$.

From Proposition 3, we find that the relationship between τ_N^{LH*} and θ_L is affected by social learning intensity. When $s \leq (1-\alpha_N)\theta_N\phi/((1-\alpha_N)(1-\theta_N)\phi + (1-\alpha_L)(1-\phi)$, τ_N^{LH*} increases in θ_L; whereas when $s > (1-\alpha_N)\theta_N\phi/((1-\alpha_N)(1-\theta_N)\phi + (1-\alpha_L)(1-\phi))$, τ_N^{LH*} decreases in θ_L. With relatively small social learning intensity, the population of uninformed consumers within B-segment increases. When charging a higher price for product-L, the uninformed consumers within B-segment are not able to buy product-L. However, the preference of product-L is stronger than product-N for those consumers. In this case, if more consumers buy products in period 1, the manufacturer has to invest in a higher emission abatement level of product-N to induce the uninformed B-segment consumers to buy product-N. In a similar way, the scenario in which s is relatively large can be analyzed. Different from Propositions 1 and 2, the price of product-N in period 2 is lower than the price in period 1. As we know, the condition that ensures the uniformed consumers to buy in period 1 is that an uninformed consumer's net utility in period 1equals to an informed consumer's utility in period 2. Thus, when charging a lower price for product-N in period 2, the manufacturer can charge a higher price in period 1.

4.4. L–L Pricing Strategy. In this scenario, the manufacturer charges lower prices of both kinds of products. Then, the IR constraints that ensure consumers to buy products in period 2 are changed into

$$\text{IR-N}: \ v_N(1+\tau_N) - p_{N2} \geq 0, \quad (43)$$

$$\text{IR-L}: \ \bar{v}_L(1+\tau_L) - p_{L2} \geq 0. \quad (44)$$

The IC constraints that induce the consumers to reveal their true valuation are

$$\text{IC-NL}: \ v_N(1+\tau_N) - p_{N2} \geq v_N(1+\tau_L) - p_{L2}, \quad (45)$$

$$\text{IC-LN}: \ \bar{v}_L(1+\tau_L) - p_{L2} \geq \bar{v}_L(1+\tau_N) - p_{N2}. \quad (46)$$

Based on the rational expectation theory, the conditions that ensure consumers to buy products in period 1 are as below.

$$\bar{v}_N(1+\tau_N) - p_{N1} = v_N(1+\tau_N) - p_{N2}, \quad (47)$$

$$\bar{v}_L(1+\tau_L) - p_{L1} = s(1-\alpha_L)[v_L(1+\tau_L) - p_{L2}]. \quad (48)$$

Then, we can get $p_{N2} = v_N(1+\tau_N)$, $p_{L2} = \bar{v}_L(1+\tau_L) - \bar{v}_L(1+\tau_N) + v_N(1+\tau_N)$, $p_{N1} = \bar{v}_N(1+\tau_N)$, $p_{L1} = \bar{v}_L(1+\tau_L) - s(1-\alpha_L)[(v_L - \bar{v}_L)(1+\tau_L) + (\bar{v}_L - v_1)(1+\tau_N)]$.

Under L–L pricing strategy, the A-segment consumers choose to buy product-N, and the informed type-v_L consumers are able to buy product-L. Thus, the expected profit gained from A-segment consumers is

$$\begin{aligned}\pi_N^{LL} =& p_{N1}\theta_N\phi - \left[c_0 + \frac{1}{2}\lambda\tau_N^2 + p_e e_0\left(1-\tau_N\right)\right]\theta_N\phi \\ &+ \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0\left(1-\tau_L\right)\right]s\left(1-\alpha_N\right)\left(1-\theta_N\right)\phi \\ &+ \left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0\left(1-\tau_N\right)\right] \\ &\cdot \left[s\alpha_N\left(1-\theta_N\right)\phi + \left(1-\theta_N\right)(1-s)\phi\right]. \end{aligned} \tag{49}$$

For B-segment consumers, all consumers are able to buy product-L. Thus, the expected profit gained from B-segment consumers is expressed as

$$\begin{aligned}\pi_L^{LL} =& \left[p_{L1} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0\left(1-\tau_L\right)\right]\theta_L(1-\phi) \\ &+ \left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0\left(1-\tau_N\right)\right]s\alpha_L\left(1-\theta_L\right)(1-\phi) \\ &+ \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0\left(1-\tau_L\right)\right] \\ &\cdot \left[s\left(1-\alpha_L\right)\left(1-\theta_L\right) + (1-s)\left(1-\theta_L\right)\right](1-\phi). \end{aligned} \tag{50}$$

The total expected profit of the manufacturer is

$$\Pi^{LL} = \pi_N^{LL} + \pi_L^{LL} + p_e G. \tag{51}$$

The next proposition that demonstrates the manufacturer's optimal decisions under L–L pricing strategy is shown below.

Proposition 4. *When charging lower prices of products, the emission abatement levels are* $\tau_N^{LL*} = \left(\left(v_N + p_e e_0\right)/\lambda\right) - \left(v_L - v_N\right)\left(1-\alpha_L\right)\left[s\left(1-\alpha_N\right)\left(1-\theta_N\right)\phi + s\left(1-\alpha_L\right)(1-\phi) + (1-s)\left(1-\theta_L\right)\right]/\lambda\left[\theta_N\phi + \left(1-\theta_N\right)\left(1-s+s\alpha_N\right)\phi + s\alpha_L\left(1-\theta_L\right)(1-\phi)\right]$ *and* $\tau_L^{LL*} = \left(\left(\bar{v}_L + p_e e_0\right)/\lambda\right) - \left(v_L - \bar{v}_L\right)s\left(1-\alpha_L\right)\theta_L(1-\phi)/\lambda\left[\theta_L(1-\phi) + s\left(1-\alpha_N\right)\left(1-\theta_N\right)\phi + \left(1-s\alpha_L\right)\left(1-\theta_L\right)(1-\phi)\right]$. *The optimal prices are* $p_{N1}^{LL*} = \bar{v}_N\left(1+\tau_N^{LL*}\right)$, $p_{L1}^{LL*} = \bar{v}_L\left(1+\tau_L^{LL*}\right) - s\left(1-\alpha_L\right)\left[\left(v_L - \bar{v}_L\right)\left(1+\tau_L^{LL*}\right) + \left(\bar{v}_L - v_N\right)\left(1+\tau_N^{LL*}\right)\right]$, $p_{N2}^{LL*} = v_N\left(1+\tau_N^{LL*}\right)$, *and* $p_{L2}^{LL*} = \bar{v}_L\left(1+\tau_L^{LL*}\right) - \bar{v}_L\left(1+\tau_L^{LL*}\right) + v_N\left(1+\tau_N^{LL*}\right)$.

Proposition 4 shows the manufacturer's optimal decisions when charging low prices for both kinds of products. Compared to the manufacturer's strategies in different scenarios, we find that when choosing the same pricing strategy upon product-L, the carbon emission abatement levels of product-L remain the same. The carbon emission abatement level of product-N is affected by the pricing strategy of product-L. When choosing the same pricing strategy of product-L, the population of consumers who buy product-L is fixed. As long as the emission abatement level meets the consumers' requirement, the manufacturer tends to keep the same level. However, the pricing strategy of product-L affects the sales volume of product-N. Thus, the optimal emission abatement levels of product-N change with different pricing strategies of product-L.

4.5. Without Social Learning. In this scenario, the consumers do not have an opportunity to learn about their true valuation, and they make purchasing decision based on the expected utility. The manufacturer's pricing strategy is static and charges a sole price for one kind of product. In this case, IR constraints and IC constraints are written as

$$\bar{v}_N\left(1+\tau_N\right) - p_N \geq 0,\ \bar{v}_L\left(1+\tau_L\right) - p_L \geq 0. \tag{52}$$

$$\begin{aligned}\bar{v}_N\left(1+\tau_N\right) - p_N &\geq \bar{v}_N\left(1+\tau_L\right) - p_L, \\ \bar{v}_L\left(1+\tau_L\right) - p_L &\geq \bar{v}_L\left(1+\tau_N\right) - p_N. \end{aligned} \tag{53}$$

Then, we can get the price of product-N $p_N = \bar{v}_N\left(1+\tau_N\right)$ and the price of product-L $p_L = \bar{v}_L\left(1+\tau_L\right) - \bar{v}_L\left(1+\tau_N\right) + \bar{v}_N\left(1+\tau_N\right)$.

Without social learning, all A-segment consumers choose to buy product-N and B-segment consumers choose to buy product-L. Thus, the manufacturer's expected profit is given by

$$\begin{aligned}\Pi =& \phi\left[p_N - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0\left(1-\tau_N\right)\right] \\ &+ (1-\phi)\left[p_L - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0\left(1-\tau_L\right)\right] + p_e G. \end{aligned} \tag{54}$$

Proposition 5. *Without social learning, the optimal carbon emission abatement levels are* $\tau_N^* = \left(\bar{v}_N + p_e e_0\right)/\lambda$ *and* $\tau_L^* = \left(\bar{v}_L + p_e e_0\right)/\lambda$. *The optimal prices of product-N and product-L are* $p_N^* = \bar{v}_N\left(1+\tau_N^*\right)$ *and* $p_L^* = \bar{v}_L\left(1+\tau_L^*\right) - \bar{v}_L\left(1+\tau_N^*\right) + \bar{v}_N\left(1+\tau_N^*\right)$.

Proposition 5 shows that the carbon emission abatement levels increase in the consumers' valuation. When consumers' valuation of products is high, the manufacturer can make more profit by charging a higher price. Under this situation, the manufacturer is promoted to invest in a higher emission abatement level. Similar to other propositions in Section 4, the price of product-N is independent of the emission abatement level of product-L, and the price of product-L highly depends on emission abatement strategy of product-N.

Compared with the scenarios in which consumers have the opportunity to discover their true valuation via social learning, we can get the following corollary.

Corollary 6. *Social learning reduces the carbon emission abatement of product-N. Social learning improves the emission abatement level of product-L under high pricing strategy but reduces the emission abatement level under low pricing strategy.*

Without social learning, the manufacturer decides the emission abatement level based on consumers' mean valuation. When having no access to discover their true valuation, the informed type-v_N consumers may not buy any product. As a result, the manufacturer has no incentive to improve the emission abatement level of product-N with the sales volume decreasing. A similar thing happens when charging a lower price for product-L. When conducting a higher pricing strategy of product-L, the manufacturer has to enhance the emission abatement level to induce the informed type-v_L consumers to purchase in period 2. Therefore, we can conclude that social learning improves the emission abatement level of product-L.

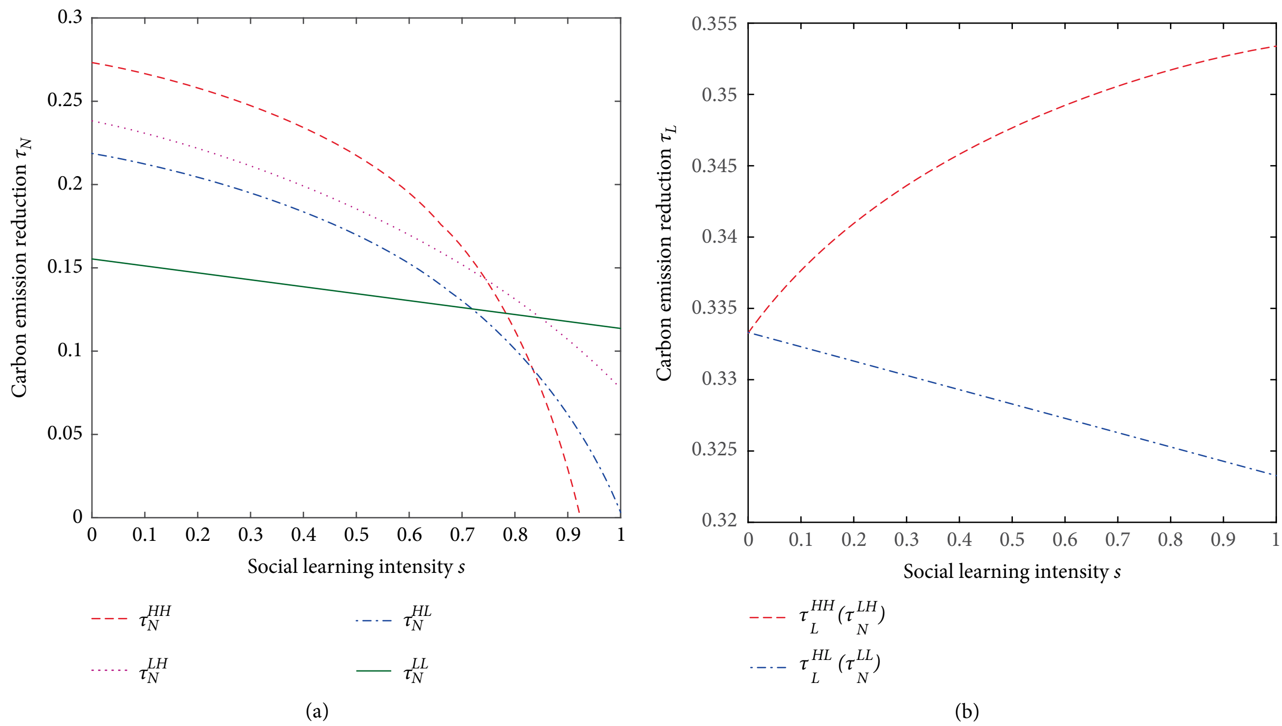


FIGURE 1: (a) Relationship between τ_N and s, (b) relationship between τ_L and s.

5. Numerical Experiments

In this section, we are going to examine the impacts of some key factors, such s, θ_i, α_i, and ϕ on the manufacturer's optimal strategies and their profit. Setting $p_e = 0.5$, $G = 4$, $s = 0.6$, $\theta_L = 0.4$, $\theta_N = 0.6$, $\alpha_N = 0.7$, $\alpha_L = 0.4$, and $\phi = 0.6$. Note that when analyzing the relationship between some parameter and the manufacturer's decision, we assume this parameter is variable.

The first set of numerical experiments illustrates the impacts of social learning intensity on the emission abatement levels, the optimal prices, and the expected profit of the manufacturer.

Figure 1 depicts the impact of social learning on the emission abatement levels. From Figure 1, we can see that the carbon emission abatement levels of product-N decrease in the social learning intensity regardless of adopting which kind of pricing strategies. This is because more and more consumers are able to know their valuation of products for sure. The informed type-v_L consumers choose to buy product-L and the informed type-v_N consumers give up purchasing. Thus, the manufacturer lacks emission reduction motivation and tends to lower the emission abatement level to save costs. Figure 1(a) also shows that the emission abatement levels of product-N are different under different pricing strategies, which indicates that the manufacturer's emission reduction decision of product-N is affected by the pricing strategy of product-L. Moreover, we can also see that the high pricing strategy improves the emission abatement level of product-N when the social learning intensity is less than a certain value. This is because the effect of charging a higher price is stronger than the effect of true valuation discovery in this scenario. Whereas when the learning intensity is much strong, more informed type-v_N consumers give up buying if the manufacturer charges a higher price. In this case, a lower pricing strategy helps improve emission abatement level.

Figure 1(b) shows the relationship between the emission abatement level of product-L and social learning intensity s. We can see that the emission abatement level of product-L is closely related to its own pricing strategy and is not affected by the pricing strategy of product-N. The reason behind this result is that the pricing strategy of product-N does not affect the sales volume of product-L. Figure 1(b) also shows that social learning intensity improves the emission abatement under higher pricing strategy due to the increased willingness to pay for the informed type-v_L consumers. However, with low pricing strategy, the emission abatement level of product-L decreases because the uninformed consumers tend to buy product-N.

Figure 2 presents how social learning intensity affects the expected profit of the manufacturer. It shows that social learning hurts the manufacturer. Given $\phi = 0.7$, the proportion of A-segment consumer is larger than that of B-segment consumer. In this case, the informed type-v_N consumers either buy products at a lower price or give up purchasing. The profit that gained from type-v_N consumers decreases with social learning intensity increasing. Figure 2 also shows that the manufacturer makes more profit under H–H pricing strategy when $s < s_1$; the L–L pricing strategy brings more profit for the manufacturer when $s > s_2$. Only when $s_1 < s < s_2$, the H–L pricing strategy is weakly better than the H–H pricing strategy. The results indicate that the net pricing strategy dominates under most conditions, which provides guidelines for the manufacturer to choose the specific pricing strategy.

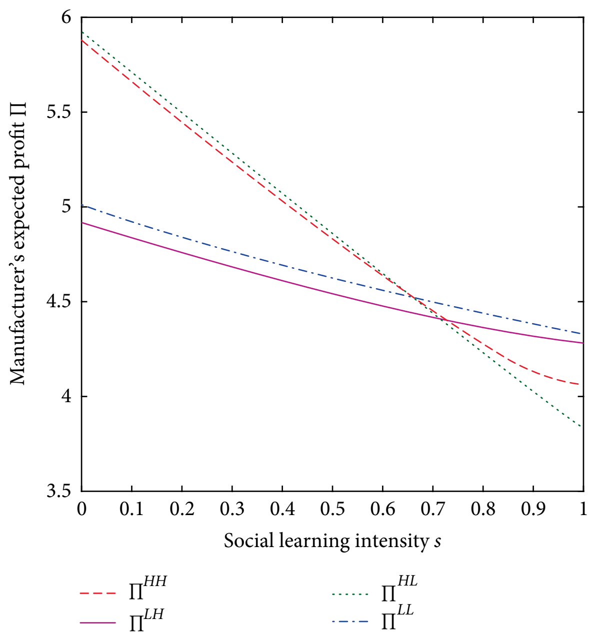


Figure 2: Impacts s of on Π.

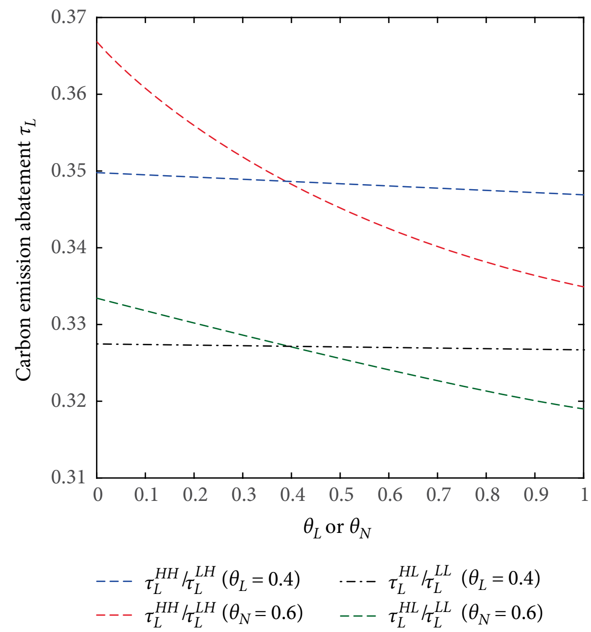


Figure 3: Relationship between τ_L and θ_i.

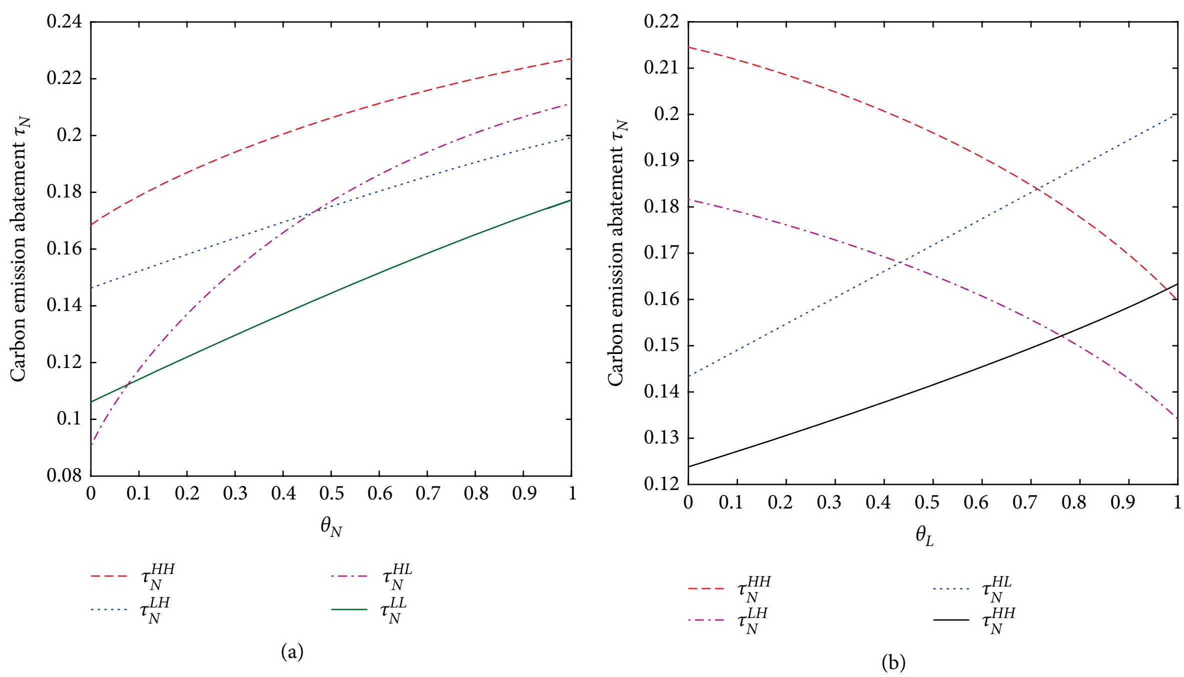
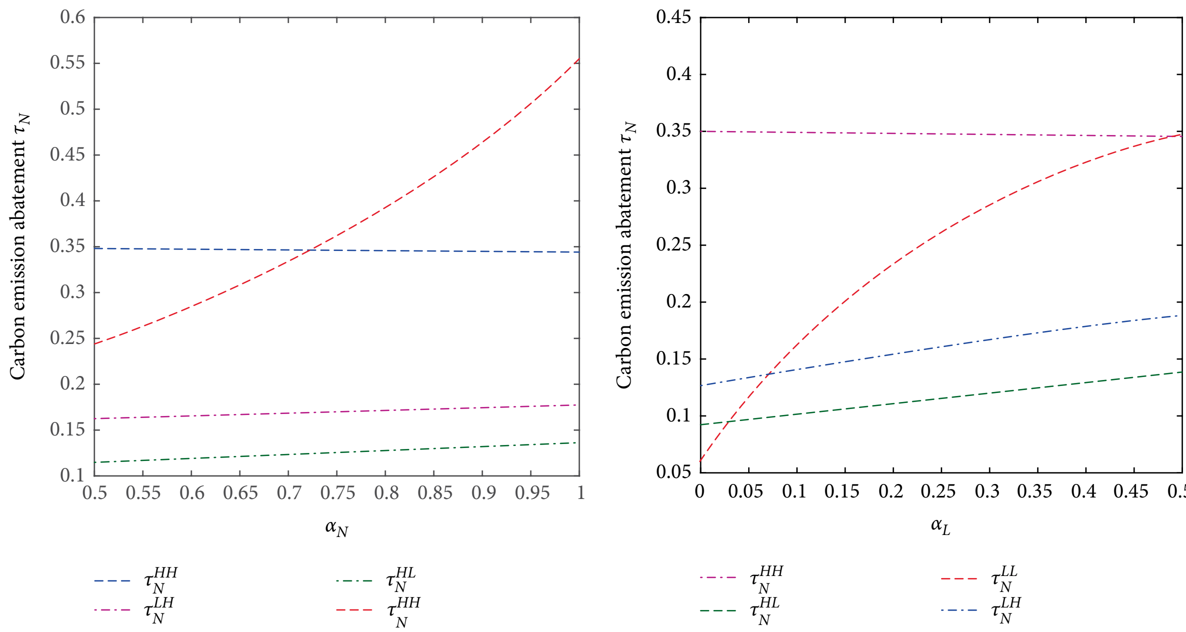


Figure 4: (a) Impact of θ_N on τ_N, (b) impact of θ_N on τ_N.

The second set of numerical experiments examines the impact of θ_i on the manufacturer's decisions and the expected profit. Figure 3 shows that τ_L decreases in θ_L and θ_N. With more consumers buying products in period 1, the effect of social learning is weaker in period 2. On the other hand, the sales volume decreases due to the higher price of product-L in period 2. In this case, the manufacturer cannot make much profit in period 2. As a result, the manufacturer would like to decrease the investment in reducing carbon emissions of product-L. The result implies that the emission abatement level of product-L is affected by the population of consumers who buy product in period 1. Compared with the affection of A-segment consumers, the impact of B-segment consumers is much stronger. Thus, the manufacturer's decision in abating carbon emissions of product-L still highly depends on the population of B-segment consumers.

Figure 4(a) shows the impact of θ_N on the emission abatement level of product-N. It can be seen that the emission abatement levels of product-N in different scenarios increase in θ_N. As we know, social learning lowers consumers' willingness



(a)

(b)

Figure 5: (a) Impact of α_N on τ_N, (b) impact of α_L on τ_N.

to pay for product-N in period 2. Thus, the manufacturer can make more profit if more consumers buy products in period 1, which also improves the manufacturer's motivation to reduce carbon emissions. In addition, the emission abatement level of product-N under H–H pricing strategy is higher than those in other cases due to the increased population who turn to buy product-N in period 2. Figure 4(b) shows that the emission abatement levels of product-N increase in θ_L when charging a higher price for product-L, but decrease in θ_L when charging a lower price for product-N.

The third set of numerical examples demonstrates the impacts of α_i on the emission abatement levels and the expected profit of the manufacturer. Figure 5 shows that the emission abatement level under H–H pricing strategy is higher than those under other pricing strategies, and it weakly decreases in α_L. The result indicates that the pricing strategy plays an important role in reducing carbon emissions. It can also be seen that the emission abatement levels in other scenarios increase in α_L, especially under L–L pricing strategy. When the manufacturer charges lower prices for both types of products, more consumers tend to buy product-N with α_L increasing. So the manufacturer can make more profit from consumers who buy product-N, which drives up the emission abatement level of product-N.

Similar to the impacts of α_L, the emission abatement level of product-N decreases in α_N under H–H pricing strategy, but increases in α_N under other situations, as shown in Figure 5(b). From Figure 5(b), we can also see that the emission abatement level τ_N under H–H pricing strategy is the highest when $\alpha_N < \overline{\alpha}_N$. The emission abatement level τ_N under L–L pricing strategy is the highest when $\alpha_N > \overline{\alpha}_N$. When α_N is relatively large, more type-υ_N consumers purchase product-N when the manufacturer charges a lower price. In this case, the manufacturer makes more profit due to the enlarged sales volume,

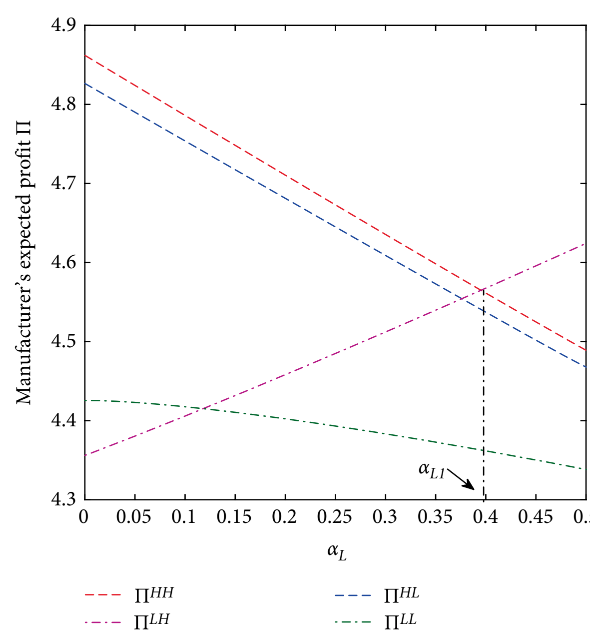
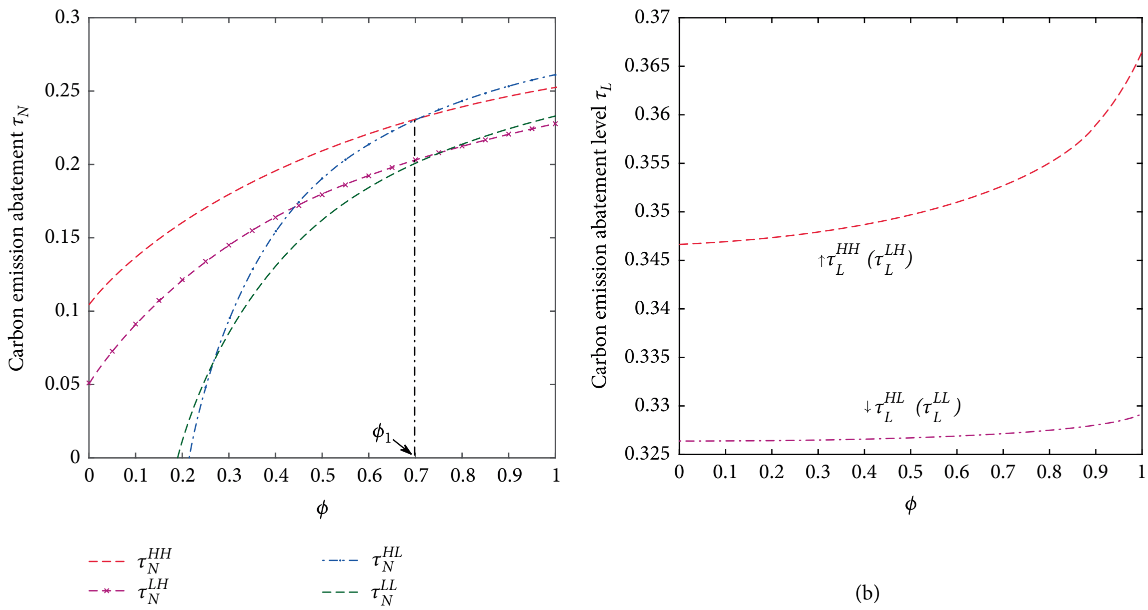


Figure 6: Relationship α_L and Π.

which improves the manufacturer's capability to invest more capital in reducing emissions of product-N.

Figure 6 shows that the manufacturer's expected profit decreases in α_L in other scenarios but L–H scenario. A larger α_L means that more consumers are type-υ_N and they tend to buy product-N; H–H and H–L pricing strategies prevent type-υ_N consumers to buy product-N, which reduces the manufacturer's expected profit gained from selling product-N. Although type-υ_N consumers face lower price under L–L pricing strategy, the lower price for product-L also induces



(a)

Figure 7: (a) Impact of ϕ on τ_N, (b) impact of ϕ on τ_L.

consumers to buy product-L. In the scenario that type-υ_N consumers account for a large proportion in the market, the manufacturer makes less profit with α_L increasing. However,the L–H pricing strategy drives consumers to buy more product-N. As a result, the manufacturer's expected profit increases in α_L in a market dominated by type-υ_N consumers. Moreover, when $\alpha_L < \alpha_{L1}$, H–H pricing strategy brings more for the manufacturer. When $\alpha_L \geq \alpha_{L1}$, L–H pricing strategy is better than any other strategies. The managerial insight from this result is that the manufacturer should set a higher price for product-L when simultaneously offering ordinary products and low-carbon products.

Figure 7(a) shows that the emission abatement levels of product-N increase in regardless of which kind of pricing strategy chosen by the manufacturer. With a larger ϕ, more consumers belong to A-segment. As reducing carbon emissions induces consumers to pay a higher price for eco-friendly products, the manufacturer can make more profit by investing in carbon emission abatement. Thus, the emission abatement level of product-N increases in ϕ. When charging a higher price for product-L, the manufacturer invests in abating carbon emissions on product-N only when it is larger than a certain value, as shown in Figure 7(a). When ϕ is relatively small, the effect of social learning on sales of product-N is weak, the benefit of abating carbon emissions of product-N is much small. On the other hand, the lower price induces more consumers to buy product-L. As a result, the manufacturer does not invest in abating carbon emissions on product-N. Moreover, the emission abatement level τ_N under L–L pricing strategy is higher than those in any other scenarios when $\phi > \phi_1$, which is caused by the increased sales volume of product-N. Figure 7(b) shows that the emission abatement level τ_L weakly increases in ϕ. It implies that the population of B-segment consumers does not play a role in abating carbon emissions.

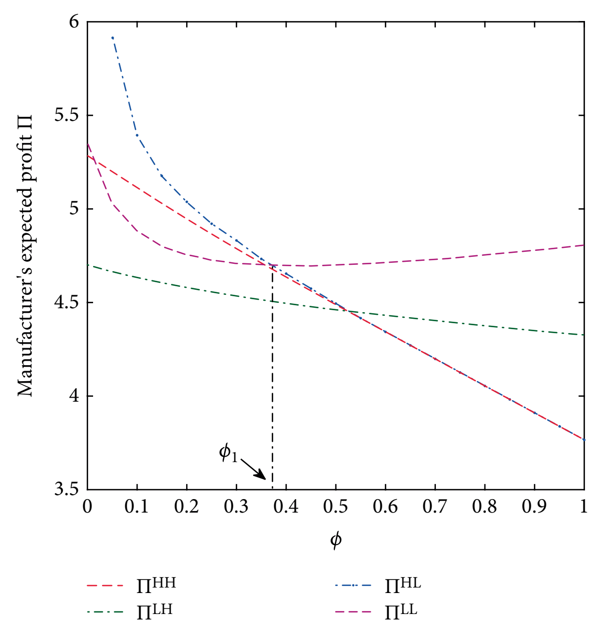


Figure 8: Impact of ϕ on Π.

Figure 8 depicts the impact of ϕ on the manufacturer's expected profit. It shows that the expected profit of the manufacturer decreases in ϕ under H–H, H–L, and L–H pricing strategy. It implies that as long as a higher price exits, the consumers' purchasing capability is driven down, especially when a large part of consumers' true valuation is υ_N. Under L–L pricing strategy, the manufacturer's expected profit decreases in ϕ when $\phi < \phi_3$, but weakly increases in ϕ when $\phi > \phi_3$. The reason behind this result is that more type-υ_N consumers discover their true valuation via social learning when ϕ is relatively large. Under L–L pricing strategy, all consumers make buying decision and the manufacturer earns more profit with the sales volume increasing.

6. Conclusion

Under cap-and-trade regulation, this paper investigates the manufacturer's product line design and the pricing strategy considering the impact of social learning. Because of consumers' eco-friendly awareness and idiosyncratic valuations of different kinds of products, the manufacturer offers different products with different emission abatement levels. The results show that the emission abatement levels on product-N are different when the manufacturer chooses different pricing strategies. Whereas when following the same pricing strategy for product-L, the emission abatement level on product-L remains the same, regardless of the choice of pricing strategy for product-N. The findings also show that social learning drives down the emission abatement level of product-N; however, it drives up the emission abatement level on product-L when making a higher price for product-L, but drives down the emission abatement level when charging a lower price for product-L. In addition, the emission abatement level of product-N increases in the proportion of consumers who purchase in period 1 within A-segment consumer.The emission abatement level of product-L increases in the population of consumers who buy products in period 1 when charging a higher price for product-L, but it decreases when charging a lower price for product-L. In summary, the conclusions of this paper provide valuable managerial insights for manufacturers to design product lines and to choose different pricing strategies in practice.

Appendix

A. Proof of Proposition 1

The proof started from the second period based on the rational expectation theory. Under H–H pricing strategy, the uninformed A-segment consumers are able to buy product-N, and the informed B-segment consumers are able to buy product-L. Thus, the individual rationality constraints are written as

$$\text{IR-N}: \ \overline{v}_N(1+\tau_N)-p_{N2}\geq 0, \quad (A.1)$$

$$\text{IR-L}: \ v_L(1+\tau_L)-p_{L2}\geq 0. \quad (A.2)$$

To induce the A-segment consumers to buy product-N and B-segment consumers to buy product-L, the incentive compatibility constraints are given by

$$\text{IC-NL}: \ \overline{v}_N(1+\tau_N)-p_{N2}\geq \overline{v}_N(1+\tau_L)-p_{L2}, \quad (A.3)$$

$$\text{IC-LN}: \ v_L(1+\tau_L)-p_{L2}\geq v_L(1+\tau_N)-p_{N2}. \quad (A.4)$$

Thus, we can get the prices in period 2

$$p_{N2}=\overline{v}_N(1+\tau_N), \quad (A.5)$$

$$p_{L2}=v_L(1+\tau_L)-v_L(1+\tau_N)+\overline{v}_N(1+\tau_N). \quad (A.6)$$

In period 1, when buying product-i ($i=N, L$) the net utility of an uninformed consumer is $u_{i1}=\overline{v}_i(1+\tau_i)-p_{i1}$. To ensure uninformed consumers to buy products in period 1, there exists $u_{i1}=u_{i2}$. As $u_{N1}=0$, $u_{N2}=s(1-\alpha_L)[v_L(1+\tau_L)-p_{L2}]$, then, we get

$$\overline{v}_N(1+\tau_N)-p_{N1}=0, \quad (A.7)$$

$$\overline{v}_L(1+\tau_L)-p_{L1}=s(1-\alpha_L)[v_L(1+\tau_L)-p_{L2}]. \quad (A.8)$$

Thus, the prices in period 1 are written as

$$\begin{aligned}p_{N1}&=\overline{v}_N(1+\tau_N),\\ p_{L1}&=\overline{v}_L(1+\tau_L)-s(1-\alpha_L)(v_L-\overline{v}_N)(1+\tau_N).\end{aligned} \quad (A.9)$$

In period 1, the population of A-segment consumers who product-N is $\theta_N\phi$. In period 2, the population among A-segment consumers who buy product-N is $(1-\theta_N)(1-s)\phi$, and the population who buy product-L is $s(1-\theta_N)(1-\alpha_N)\phi$. Thus, the manufacturer's expected profit gained from A-segment consumers is

$$\begin{aligned}\pi_N^{HH}=&p_{N1}\theta_N\phi-\left[c_0+\frac{1}{2}\lambda\tau_N^2+p_e e_0(1-\tau_N)\right]\theta_N\phi\\ &+\left[p_{N2}-c_0-\frac{1}{2}\lambda\tau_N^2-p_e e_0(1-\tau_N)\right](1-\theta_N)(1-s)\phi\\ &+\left[p_{L2}-c_0-\frac{1}{2}\lambda\tau_L^2-p_e e_0(1-\tau_L)\right]s(1-\alpha_N)(1-\theta_N)\phi.\end{aligned} \quad (A.10)$$

Similarly, we can get the manufacturer's expected profit gained from B-segment consumers,

$$\begin{aligned}\pi_L^{HH}=&\left[p_{L1}-c_0-\frac{1}{2}\lambda\tau_L^2-p_e e_0(1-\tau_L)\right]\theta_L(1-\phi)\\ &+\left[p_{L2}-c_0-\frac{1}{2}\lambda\tau_L^2-p_e e_0(1-\tau_L)\right]s(1-\alpha_L)(1-\theta_L)(1-\phi)\\ &+\left[p_{N2}-c_0-\frac{1}{2}\lambda\tau_N^2-p_e e_0(1-\tau_N)\right](1-s)(1-\theta_L)(1-\phi).\end{aligned} \quad (A.11)$$

Considering the initial carbon emission cap G, the manufacturer's expected profit is.

$$\Pi^{HH}=\pi_N^{HH}+\pi_L^{HH}+p_e G. \quad (A.12)$$

Taking the second derivatives, we get

$$\frac{\partial^2\Pi^{HH}}{\partial(\tau_N)^2}=-\lambda(1-s)[1-\theta_N(1-\phi)]-\lambda s\theta_N\phi, \quad (A.13)$$

$$\begin{aligned}\frac{\partial^2\Pi^{HH}}{\partial(\tau_L)^2}=&-s\lambda(1-\alpha_L)(1-\theta_L)(1-\phi)\\ &-\theta_L\lambda(1-\phi)-s\lambda\phi(1-\alpha_N)(1-\theta_N),\end{aligned} \quad (A.14)$$

$$\frac{\partial^2\Pi^{HH}}{\partial\tau_L\tau_N}=0. \quad (A.15)$$

Denote $W_{HH}=-\lambda(1-s)[1-\theta_N(1-\phi)]-\lambda s\theta_N\phi$ and $Q_{HH}=-s\lambda(1-\alpha_L)(1-\theta_L)(1-\phi)-\theta_L\lambda(1-\phi)-s\lambda\phi(1-\alpha_N)(1-\theta_N)$. The Hessian matrix of $\Pi^{HH}(\tau_L,\tau_N)$ is

$$H(\tau_L, \tau_N) = \begin{bmatrix} W_{HH} & 0 \\ 0 & Q_{HH} \end{bmatrix}. \quad \text{(A.16)}$$

Then, $\det[H(\tau_L, \tau_N)] = W_{HH}Q_{HH} > 0$. Hence, by solving $\left(\partial\Pi^{HH}/\partial\tau_N\right) = 0$ and $\left(\partial\Pi^{HH}/\partial\tau_L\right) = 0$, we get

$$\tau_N^{HH*} = \frac{\bar{v}_N + p_e e_0}{\lambda} - \frac{s(v_L - \bar{v}_N)[(1-\alpha_N)(1-\theta_N)\phi + (1-\alpha_L)(1-\phi)]}{\lambda[\theta_N\phi + (1-\theta_N)(1-s)\phi + (1-s)(1-\theta_L)(1-\phi)]}, \quad \text{(A.17)}$$

$$\tau_L^{HH*} = \frac{v_L + p_e e_0}{\lambda} - \frac{(v_L - \bar{v}_L)\theta_L(1-\phi)}{\lambda[\theta_L(1-\phi) + s(1-\alpha_N)(1-\theta_N)\phi + s(1-\alpha_L)(1-\theta_L)(1-\phi)]}. \quad \text{(A.18)}$$

Substituting τ_N^{HH*} and τ_L^{HH*} into $p_{N1}, p_{L1}, p_{N2}, p_{L2}$, we get $p_{N1}^{HH*} = \bar{v}_N\left(1+\tau_N^{HH*}\right)$, $p_{L1}^{HH*} = \bar{v}_L\left(1+\tau_L^{HH*}\right) - s(1-\alpha_L)(v_L - \bar{v}_N)\left(1+\tau_N^{HH*}\right)$, $p_{N2}^{HH*} = \bar{v}_N\left(1+\tau_N^{HH*}\right)$, and $p_{L2}^{HH*} = v_L\left(1+\tau_L^{HH*}\right) - v_L\left(1+\tau_N^{HH*}\right) + \bar{v}_N\left(1+\tau_N^{HH*}\right)$.

B. Proof of Proposition 2

Under H–L pricing strategy, the uninformed A-segment consumers are able to buy product-N, and both the informed and uninformed B-segment consumers are able to buy product-L. Thus, the individual rationality constraints are written as

$$\text{IR-N}: \ \bar{v}_N(1+\tau_N) - p_{N2} \geq 0, \quad \text{(B.1)}$$

$$\text{IR-L}: \ \bar{v}_L(1+\tau_L) - p_{L2} \geq 0. \quad \text{(B.2)}$$

The IC constraints are written as

$$\text{IC-NL}: \ \bar{v}_N(1+\tau_N) - p_{N2} \geq \bar{v}_N(1+\tau_L) - p_{L2}, \quad \text{(B.3)}$$

$$\text{IC-LN}: \ \bar{v}_L(1+\tau_L) - p_{L2} \geq \bar{v}_L(1+\tau_N) - p_{N2}. \quad \text{(B.4)}$$

Then, we can get

$$\begin{aligned} p_{N2} &= \bar{v}_N(1+\tau_N), \\ p_{L2} &= \bar{v}_L(1+\tau_L) - \bar{v}_L(1+\tau_N) + \bar{v}_N(1+\tau_N). \end{aligned} \quad \text{(B.5)}$$

The prices in period 1 should satisfy

$$\begin{aligned} \bar{v}_N(1+\tau_N) - p_{N1} &= 0, \\ \bar{v}_L(1+\tau_L) - p_{L1} &= s(1-\alpha_L)[v_L(1+\tau_L) - p_{L2}]. \end{aligned} \quad \text{(B.6)}$$

Then, we can get

$$\begin{aligned} p_{N1} &= \bar{v}_N(1+\tau_N), \\ p_{L1} &= \bar{v}_L(1+\tau_L) - s(1-\alpha_L)[v_L(1+\tau_L) - p_{L2}]. \end{aligned} \quad \text{(B.7)}$$

Among A-segment consumers, the population of who buys product-N in period 2 is $(1-\theta_N)(1-s)\phi$, and the population who buys product-L is $s(1-\alpha_N)(1-\theta_N)\phi$. Thus, the total profit gained from A-segment consumers in two periods is

$$\begin{aligned} \pi_N^{HL} = {} & p_{N1}\theta_N\phi - \left[c_0 + \frac{1}{2}\lambda\tau_N^2 + p_e e_0(1-\tau_N)\right]\theta_N\phi \\ & + \left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right](1-\theta_N)(1-s)\phi \\ & + \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]s(1-\alpha_N)(1-\theta_N)\phi. \end{aligned} \quad \text{(B.8)}$$

In a similar way, we can get the profit obtained from B-segment consumers

$$\begin{aligned} \pi_L^{HL} = {} & \left[p_{L1} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]\theta_L(1-\phi) \\ & + \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right] \\ & \cdot [s(1-\alpha_L)(1-\theta_L) + (1-s)(1-\theta_L)](1-\phi). \end{aligned} \quad \text{(B.9)}$$

The total expected profit of the manufacturer under H–L pricing strategy is

$$\Pi^{HL} = \pi_N^{HL} + \pi_L^{HL} + p_e G. \quad \text{(B.10)}$$

By taking the second derivatives of Π^{HL}, there exists.

$$\frac{\partial^2\Pi^{HL}}{\partial(\tau_N)^2} = -\lambda[1 - s(1-\theta_N)], \quad \text{(B.11)}$$

$$\frac{\partial^2\Pi^{HL}}{\partial(\tau_L)^2} = -\lambda[1 + s\alpha_L(1-\theta_L)](1-\phi) - s\lambda\phi(1-\alpha_N)(1-\theta_N), \quad \text{(B.12)}$$

$$\frac{\partial^2\Pi^{HL}}{\partial\tau_L\tau_N} = 0. \quad \text{(B.13)}$$

Denote $W_{HL} = -\lambda[1 - s(1-\theta_N)]$ and $Q_{HL} = -\lambda[1 + s\alpha_L(1-\theta_L)](1-\phi) - s\lambda\phi(1-\alpha_N)(1-\theta_N)$. The Hessian matrix of $\Pi^{HL}(\tau_L, \tau_N)$ is.

$$H(\tau_L, \tau_N) = \begin{bmatrix} W_{HL} & 0 \\ 0 & Q_{HL} \end{bmatrix}. \quad \text{(B.14)}$$

Then, $\det[H(\tau_L, \tau_N)] = W_{HL}Q_{HL} > 0$. Hence, by solving $\left(\partial\Pi^{HL}/\partial\tau_N\right) = 0$ and $\left(\partial\Pi^{HL}/\partial\tau_L\right) = 0$, we get

$$\tau_N^{HL*} = \frac{\overline{v}_N + p_e e_0}{\lambda} - \frac{(\overline{v}_L - \overline{v}_N)[s(1-\alpha_N)(1-\theta_N)\phi + s(1-\alpha_L)(1-\phi) + (1-s)(1-\theta_L)(1-\phi)]}{\lambda[\theta_N\phi + (1-\theta_N)(1-s)\phi]}, \tag{B.15}$$

$$\tau_L^{HL*} = \frac{\overline{v}_L + p_e e_0}{\lambda} - \frac{(v_L - \overline{v}_L)s(1-\alpha_L)\theta_L(1-\phi)}{\lambda[\theta_L(1-\phi) + s(1-\alpha_N)(1-\theta_N)\phi + (1-s\alpha_L)(1-\theta_L)(1-\phi)]}. \tag{B.16}$$

Then, we can get the optimal prices decided by the manufacturer $p_{N1}^{HL*} = \overline{v}_N(1+\tau_N^{HL*})$, $p_{L1}^{HL*} = \overline{v}_L(1+\tau_L^{HL*}) - s(1-\alpha_L)[(v_L - \overline{v}_L)(1+\tau_L^{HL*}) + (\overline{v}_L - \overline{v}_N)(1+\tau_N^{HL*})]$, $p_{N2}^{HL*} = \overline{v}_N(1+\tau_N^{HL*})$, and $p_{L2}^{HL*} = \overline{v}_L(1+\tau_L^{HL*}) - \overline{v}_L(1+\tau_N^{HL*}) + \overline{v}_N(1+\tau_N^{HL*})$.

C. Proof of Proposition 3

Under L–H pricing strategy, the IR constraints and IC constraints are expressed as

$$\text{IR-N}: \ v_N(1+\tau_N) - p_{N2} \geq 0, \tag{C.1}$$

$$\text{IR-L}: \ v_L(1+\tau_L) - p_{L2} \geq 0, \tag{C.2}$$

$$\text{IC-NL}: \ v_1(1+\tau_N) - p_{N2} \geq v_1(1+\tau_L) - p_{L2}, \tag{C.3}$$

$$\text{IC-LN}: \ v_2(1+\tau_L) - p_{L2} \geq v_2(1+\tau_N) - p_{N2}. \tag{C.4}$$

Thus, we can get the prices in period 2

$$p_{N2} = v_1(1+\tau_N),\ p_{L2} = v_2(1+\tau_L) - v_2(1+\tau_N) + v_1(1+\tau_N). \tag{C.5}$$

Based on the rational expectations theory, the prices in period 1 satisfy

$$\overline{v}_N(1+\tau_N) - p_{N1} = v_1(1+\tau_N) - p_{N2}, \tag{C.6}$$

$$\overline{v}_L(1+\tau_L) - p_{L1} = s(1-\alpha_L)[v_2(1+\tau_L) - p_{L2}] \tag{C.7}$$

Thus, $p_{N1} = \overline{v}_N(1+\tau_N)$, $p_{L1} = \overline{v}_L(1+\tau_L) - s(1-\alpha_L)(v_2 - v_1)(1+\tau_N)$.

Among A-segment consumers, the population who buy product-N in period 1 is $\theta_N\phi$, and the population is $s\alpha_N(1-\theta_N)\phi + (1-\theta_N)(1-s)\phi$ in period 2. The population who buys product-L is $s(1-\alpha_N)(1-\theta_N)\phi$. As a result, the manufacturer's expected profit gained from A-segment consumers is

$$\begin{aligned}\pi_N^{LH} =& p_{N1}\theta_N\phi - \left[c_0 + \frac{1}{2}\lambda\tau_N^2 + p_e e_0(1-\tau_N)\right]\theta_N\phi \\ &+ \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]s(1-\alpha_N)(1-\theta_N)\phi \\ &+ \left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right] \\ &\cdot [s\alpha_N(1-\theta_N)\phi + (1-\theta_N)(1-s)\phi].\end{aligned} \tag{C.8}$$

Similarly, we can get

$$\begin{aligned}\pi_L^{LH} =& \left[p_{L1} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right]\theta_L(1-\phi) \\ &+ \left[p_{L2} - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right] \\ &\cdot s(1-\alpha_L)(1-\theta_L)(1-\phi) \\ &+ \left[p_{N2} - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right] \\ &\cdot [s\alpha_L(1-\theta_L) + (1-\theta_L)(1-s)](1-\phi).\end{aligned} \tag{C.9}$$

By taking the second derivatives of Π^{LH}, there exists

$$\begin{aligned}\frac{\partial^2\Pi^{LH}}{\partial(\tau_N)^2} =& -\lambda[1 - s(1-\alpha_L)](1-\theta_L)(1-\phi) \\ &- \lambda[1 - s(1-\alpha_N)](1-\theta_N)(1-\phi),\end{aligned} \tag{C.10}$$

$$\begin{aligned}\frac{\partial^2\Pi^{LH}}{\partial(\tau_L)^2} =& -\lambda s(1-\alpha_L)(1-\theta_L)(1-\phi) \\ &- \lambda\theta_L(1-\phi) - s\lambda\phi(1-\alpha_N)(1-\theta_N),\end{aligned} \tag{C.11}$$

$$\frac{\partial^2\Pi^{LH}}{\partial\tau_L\tau_N} = 0. \tag{C.12}$$

Denote $W_{LH} = -\lambda[1 - s(1-\alpha_L)](1-\theta_L)(1-\phi) - \lambda[1 - s(1-\alpha_N)](1-\theta_N)(1-\phi)$ and $Q_{LH} = -\lambda s(1-\alpha_L)(1-\theta_L)(1-\phi) - \lambda\theta_L(1-\phi) - s\lambda\phi(1-\alpha_N)(1-\theta_N)$.

The Hessian matrix of $\Pi^{LH}(\tau_L, \tau_N)$ is

$$H(\tau_L, \tau_N) = \begin{bmatrix} W_{LH} & 0 \\ 0 & Q_{LH} \end{bmatrix}. \tag{C.13}$$

Then, $\det[H(\tau_L, \tau_N)] = W_{LH}Q_{LH} > 0$. Hence, by solving $(\partial\Pi^{LH}/\partial\tau_N) = 0$ and $(\partial\Pi^{LH}/\partial\tau_L) = 0$, we get

$$\tau_N^{LH*} = \frac{v_N + p_e e_0}{\lambda} + \frac{(v_L - v_N)s[(1-\alpha_N)\theta_N\phi - (1-\alpha_N)(1-\theta_N)\phi - (1-\alpha_L)(1-\phi)]}{\lambda[\theta_N\phi + (1-\theta_N)(1-s+s\alpha_N)\phi + (1-s+s\alpha_L)(1-\theta_L)(1-\phi)]}, \tag{C.14}$$

$$\tau_L^{LH*} = \frac{v_L + p_e e_0}{\lambda} - \frac{(v_L - \overline{v}_L)\theta_L(1-\phi)}{\lambda[\theta_L(1-\phi) + s(1-\alpha_N)(1-\theta_N)\phi + s(1-\alpha_L)(1-\theta_L)(1-\phi)]}. \tag{C.15}$$

Substituting τ_N^{LH*} and τ_L^{LH*} into $p_{N1}, p_{L1}, p_{N2}, p_{L2}$, we get $p_{N1}^{LH*} = \overline{v}_N\left(1+\tau_N^{LH*}\right)$, $p_{L1}^{LH*} = \overline{v}_L\left(1+\tau_L^{LH*}\right) - s(1-\alpha_L)(v_L - v_N)\left(1+\tau_N^{LH*}\right)$, $p_{N2}^{LH*} = v_N\left(1+\tau_N^{LH*}\right)$, and $p_{L2}^{LH*} = v_L\left(1+\tau_L^{LH*}\right) - v_L\left(1+\tau_N^{LH*}\right) + v_N\left(1+\tau_N^{LH*}\right)$.

D. Proof of Proposition 4

The proof is similar to that of Proposition 3.

E. Proof of Proposition 5

Without social learning, the manufacturer's pricing strategy is static. The IR constraints and IC constraints are given by

$$\text{IR-N}: \ \overline{v}_N(1+\tau_N) - p_N \ge 0, \tag{E.1}$$

$$\text{IR-L}: \ \overline{v}_L(1+\tau_L) - p_L \ge 0, \tag{E.2}$$

$$\text{IC-NL}: \ \overline{v}_N(1+\tau_N) - p_N \ge \overline{v}_N(1+\tau_L) - p_L, \tag{E.3}$$

$$\text{IC-LN}: \ \overline{v}_L(1+\tau_L) - p_L \ge \overline{v}_L(1+\tau_N) - p_N. \tag{E.4}$$

Then, we can get $p_N = \overline{v}_N(1+\tau_N)$ and $p_L = \overline{v}_L(1+\tau_L) - \overline{v}_L(1+\tau_N) + \overline{v}_N(1+\tau_N)$.Thus, the manufacturer's expected profit is

$$\begin{aligned}\Pi = &\phi\left[p_N - c_0 - \frac{1}{2}\lambda\tau_N^2 - p_e e_0(1-\tau_N)\right] \\ &+ (1-\phi)\left[p_L - c_0 - \frac{1}{2}\lambda\tau_L^2 - p_e e_0(1-\tau_L)\right] + p_e G.\end{aligned} \tag{E.5}$$

By taking the second derivatives of $\prod$, there exists

$$\frac{\partial^2\Pi}{\partial(\tau_N)^2} = -\lambda\phi, \tag{E.6}$$

$$\frac{\partial^2\Pi}{\partial(\tau_L)^2} = -\lambda(1-\phi), \tag{E.7}$$

$$\frac{\partial^2\Pi}{\partial\tau_L\tau_N} = 0, \tag{E.8}$$

$$H(\tau_L, \tau_N) = \begin{bmatrix} -\lambda\phi & 0 \\ 0 & -\lambda(1-\phi) \end{bmatrix}. \tag{E.9}$$

Then, $\det[H(\tau_L, \tau_N)] = \lambda^2\phi(1-\phi) > 0$. Hence, by solving $(\partial\Pi/\partial\tau_N) = 0$ and $(\partial\Pi/\partial\tau_L) = 0$, we get $\tau_N^* = ((\overline{v}_N + p_e e_0)/\lambda)$ and $\tau_L^* = ((\overline{v}_L + p_e e_0)/\lambda)$. Hence, $p_N^* = \overline{v}_N(1+\tau_N^*)$ and $p_L^* = \overline{v}_L(1+\tau_L^*) - \overline{v}_L(1+\tau_N^*) + \overline{v}_N(1+\tau_N^*)$.

Data Availability

In this paper, we do not use any data. To avoid ambiguity and misperception, we omit the data availability statement in the revised manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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