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GOVERNMENTAL SUBSIDY POLICIES AND SUPPLY CHAIN DECISIONS WITH CARBON EMISSION LIMIT AND CONSUMER'S ENVIRONMENTAL AWARENESS

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Abstract. The carbon emission reduction has become an inevitable trend. Under the low-carbon environment, the government has been acting as an important role in the operation and management of supply chain. This paper considers four different governmental subsidy strategies, which includes none of members is subsidized (NS Scenario), only retailer is subsidized (RS Scenario), only manufacturer is subsidized (MS Scenario) and both members are subsidized (SS Scenario). A Stackelberg game model, which incorporates both governmental regulation and consumer's awareness of carbon emission, is developed to present the pricing and emission reduction behaviors for the supply chain members as well as the subsidy policies of government under different governmental subsidy strategies, and analyze the impact of relevant coefficients on the decisions and supply chain profits. It can be concluded that subsidizing to both members is more profitable for supply chain members and government in terms of environment protection and economic development. The results provide some managerial insights for the decision-makers and policy-makers to implement sustainability initiatives.

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1. Introduction

With the progress of industrial modernization, massive increase in harmful emissions leads to higher probability of natural disasters. As a typical example, carbon emission is believed to be the principal cause of global warming. Therefore, low-carbon supply chain has been a popular research topic in recent years. Under this background, carbon emission control drives firms to update and modernize technology, and transform their operations decisions. In fact, existing products are gradually replaced by low-carbon products. In UK, for example, a survey result in 2008 showed that over two-thirds people will give preference to purchase the products from the firms who take an active part in energy conservation and emission reduction [1], which results in a tendency that high-carbon products will be gradually replaced by the low-carbon products. In other words, low-carbonization drives firms to reconsider the operational and decision-making matters in their supply chain

Keywords. Supply chain management, subsidy policy, governmental regulation, consumer's awareness, carbon emission.

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management. Therefore, the product substitutability aroused by low carbonization is bound to affect the supply chain management significantly. But, as a strategy to spur firms to improve environmental performance, low carbonization has strong externality and public interest features, and cannot generate direct economic benefits to the firms [16,33]. Consequently, with fiscal policies, national governments often levy taxes or provide subsidy in line with different products energy consumption to drive firms in supply chain to realize products replacement and low carbonization when maximizing the profit. As a matter of fact, to encourage the development of new-energy automobile industry, various national governments have issued a series of preferential policies to stimulate firms to improve the technical level and market competitiveness [7,15].

The models will be developed to determine the optimal strategies of pricing and emission reduction for supply chain members and the optimal subsidy policy for government under different governmental subsidy modes. Then, we analyze the optimal decisions in different subsidy modes and the effects of relevant parameters on optimal decisions. The remainder of our paper is organized as follows: Section 2 gives the literature review of the emission-related theoretical and empirical researches. We provide the symbols and assumption of model in Section 3. In Section 4, we formulate the Stackelberg games in different scenarios. Section 5 gives a numerical example and make sensitivity analysis to show the application of the model. Finally, the conclusions and future research are given in Section 6.

2. Literature review

In this section, we review the literatures focusing on three issues related to emission reduction. The section firstly illustrates the related literature on the low-carbon supply chain. Secondly, the literature of consumer's environmental awareness in the supply chain is analyzed. Thirdly, the related literature on the impact of governmental policies on supply chain decisions is reviewed.

2.1. Low-carbon supply chain

The issue which incorporating the low-carbon supply chain into operational decisions has been recently studied by researchers [13,22,26]. In [37], Zhou *et al.* investigated the decision in a two-echelon supply chain with cooperative advertising and emission reduction cost sharing. In [23], Shaw *et al.* proposed a chance constrained based green supply chain network design model considering carbon emissions and carbon trading. In [29], Wang *et al.* focused on a Stackelberg game model for studying the issues of carbon emission reduction under different dominant powers. In [15], Li *et al.* illustrated the competition between supply chains, and investigated the equilibrium strategies in product sustainability. In [16], Liu et al. investigated the impact of products substitution and consumer's environmental awareness on supply chain members. In [9], Du *et al.* investigated the manufacturer's multi-product joint pricing and production decision problem considering consumer's environmental awareness with the cap-and-trade system.

2.2. Consumer's preference

Consumer's environmental awareness is an important factor influencing the decision of a low-carbon supply chain. Consumers will pay a premium for eco-friendly products in by 5%–25% [2,21]. In [5], Cai *et al.* found preference methods has been applied in the consumers' willingness to pay price premiums for environment friendly products. In [25], Skin *et al.* analyzed the relationship between price and service quality in mobile telecommunication, and demonstrate that consumer's preference is the factor considered in promoting competitiveness of price and service quality. In [36], Zhang *et al.* analyzed the impact of consumer's environmental awareness on coordination and demand within a two-echelon supply chain. In [34], Yakita *et al.* analyzed the welfare effects of R&D strategies of firms in symmetric equilibrium considering horizontal product differentiation, environmental awareness and environmental R&D spillovers in differentiated duopoly. In [14], Ji *et al.* focused on the emission reduction behaviors for supply chain members in the different channel and performed the sensitivity analysis of consumers' preference.

2.3. Governmental policies

The government plays a very important role in low-carbon supply chain with the implementation of different environmental policies [3,4,30]. In [11], Hammond *et al.* analyzed the role of government subsidies in the reverse supply chain management by applying Cournot game model under complete information. In [18], Mitra *et al.* developed the two-stage model involving the manufacturer and remanufacturer, then compared the optimal solutions under different subsidy modes in the closed-loop supply chain and analyzed the effect of government subsidy on the remanufacturing activities. In [17], Lu *et al.* proposed an optimization model of EPC's production decision-making with government subsidies, and obtained the optimal pricing and service performance levels. In [38], Zhu *et al.* presented the decision model to maximize the remanufacturer profit by considering consumer's environmental preference and governmental subsidy policy. In [35], Yu *et al.* developed an optimization model under oligopolistic competition considering green preferences and government subsidies, with the objective of profit maximization of the manufacturers. In [10], Hafezalkotob formulated the competitions of green and regular supply chains as a game theoretical model in the form of six scenarios based on government environmental protection policies, then analyzed the effects of government's policies on the players' optimal strategies. In [39], Wang *et al.* investigated the supply chain enterprise operations strategies and governmental carbon emission tax policy.

From the above mentioned literature, the low-carbon supply chain management and governmental subsidy are becoming important topics in the academic and practical research. Most of literature only regard the governmental subsidy as a parameter in model. However, in reality, there exist mutual relationship between governmental emission regulation and the decisions of supply chain members. Meanwhile, the supply chain decision is also affected by consumer's environmental awareness.

3. Model description and assumptions

In this paper, we consider the supply chain consisting of one-single manufacturer and one-single retailer. Meanwhile, the three stage Stackelberg game models, in which the government are the leader of supply chain members, and manufacturer and retailer are respectively the leader and follower within a supply chain, has been developed. To formulate the model, the following assumptions are introduced:

Assumption 3.1. *The demand of products is the function of the retail price and the reduction rate of carbon emission. The demand is a decreasing function of the product's retail price p and increasing function of the emission reduction rate e. This assumption is consistent with related literature [12,20]. Without loss of generality, the demand function can be defined by*

$$Q = a - p + \gamma\left(e - e_0\right), \tag{3.1}$$

where a implies the demand curve intercept and represents the market potential size, γ implies the consumer's sensitiveness and preference on the reduction rate of carbon emission, e_0 implies the carbon emission limits regulated by government.

Assumption 3.2. *The cost for carbon emission reduction $C(e)$ is seen as the investment of the manufacturer to reduce carbon emission, and doesn't affect supply chain members' marginal cost. The emission reduction can be considered as technical innovation when production level is obsolete. In order to model the emission reduction cost, we suppose the cost is convex and increasing in the emission reduction rate, which satisfies $e \geq 0$, $C(e) \geq 0$, $C'(e) > 0$ and $C''(e) > 0$. The form of quadratic function to indicate the emission reduction cost is similar to existing literature such as above literature [27–29]. So the cost of carbon emission reduction is given by*

$$C(e) = \frac{k}{2}e^2, \tag{3.2}$$

where k is the cost effectiveness of reduction rate. In other word, the smaller the value of k is, the more effectiveness of the emission reduction. And the cost $C(e)$ is assumed to be a one-time investment, so the value of k is set to be significant large.

Assumption 3.3. *Based on the literature about the governmental policies [6,24], we assume s_1 and s_2 represent the subsidy provided by government to retailer and manufacturer respectively. The social welfare function includes producer surplus, consumer surplus, governmental budget and environmental benefits. It can be represented by*

$$\mathrm{SW} = \mathrm{PS} + \mathrm{CS} - \mathrm{GE} + \mathrm{EB}. \tag{3.3}$$

Based on the welfare economic, PS *is defined as the profits of supply chain members, and* $\mathrm{PS} = \pi_m + \pi_r$*.* CS *represents the retail price that customers would be willing to pay, and* $\mathrm{CS} = Q^2/2$*.* GE *indicates the governmental expenditure and is given by* $\mathrm{GE}^R = s_1 \cdot Q$ *and* $\mathrm{GE}^M = s_2 \cdot ke^2/2$*.* EB *shows the benefit arising from emission reduction, and* $\mathrm{EB} = \delta Q \cdot e$*, where δ stands for the environmental effectiveness of emission reduction.*

Assumption 3.4. *In addition, to ensure the profit functions of the manufacturer and retailer are jointly concave and have the optimal decisions, we assume the parameters satisfy the conditions $4k-\gamma^2 > 0$ and $\gamma e_0 < a-p+\gamma e$.*

Assumption 3.5. *To guarantee the positive margin of members' profits to sell a product, we assume the condition $p > w$ in which implies that there is a loss if the products are not sold [19]. The marginal operation costs of manufacturer and retailer are c_m and c_r. As c_r is toosmall relative to c_m, we can assume c_r is negligible for the sake of constructing the model and the cost of manufacturer is equal to c [12].*

4. Strategies in non-cooperative game

For the different government subsidies, the models to maximize social welfare and supply chain members' profits are developed under four scenarios: none of members is subsidized (NS Scenario), only retailer is subsidized (Scenario RS), only manufacturer is subsidized (Scenario MS) and both members are subsidized (Scenario SS). The equilibrium solutions are derived to compare the relative effects of various governmental subsidy modes. The problem can be considered as a Stackelberg game problem between the government and supply chain members.

4.1. Case 1: None of members is subsidized (NS scenario)

In this case, we firstly study the decisions of the manufacturer and retailer for NS scenario in which the manufacturer determines the wholesale price and emission reduction rate based on the response of the retailer, then the retailer decides the retail price to maximize the profit. Based on the above process, we can obtain the profits of supply chain members as follows:

$$\pi_m = (w-c)\left[a-p+\gamma\left(e-e_0\right)\right] - \frac{k}{2}e^2 \tag{4.1}$$

$$\pi_r = (p-w)\left[a-p+\gamma\left(e-e_0\right)\right]. \tag{4.2}$$

Proposition 4.1. *For the case of* NS *mode, given the governmental emission limit and consumer's environmental awareness, the optimal decisions of supply chain members are $\left(w^{\mathrm{NS}}, e^{\mathrm{NS}}, p^{\mathrm{NS}}\right)$, the market demand is Q^{NS} and the profit for supply chain is π_{sc}^{NS}.*

Proof. In fact, the decisions between members are a two-stage Stackelberg game with complete information, and we obtain the solutions of pricing and emission reduction rate by backward induction. From equation (4.2), we get the second-order partial derivatives of π_r with respect to p as $\partial^2\pi_r/\partial p^2 < 0$, so the retailer's profit function should be a strictly concave in the retail price. Thus, equating the first-order condition to zero, we get $p\left(w,e\right) = \left[a+w+\gamma\left(e-e_0\right)\right]/2$. Substituting the value of p into the manufacturer's profit, we can obtain the second-order partial derivatives of π_m with respect to w and e that the determinant is $k - \gamma^2/4$. From assumptions, Hessian matrix is the negative definite and jointly concave in the wholesale price and reduction rate. Equation the first-order condition to zero, we obtain $w^{\mathrm{NS}} = \left[2k\left(a+c-\gamma e_0\right) - c\gamma^2\right]/\left(4k-\gamma^2\right)$, $e^{\mathrm{NS}} = \gamma\left(a-c-\gamma e_0\right)/\left(4k-\gamma^2\right)$. Substituting the values of w^{NS} and e^{NS} into p, we get $p^{\mathrm{NS}} = \left[k\left(3a+c-3\gamma e_0\right) - c\gamma^2\right]/\left(4k-\gamma^2\right)$. Here, the market demand is $Q^{\mathrm{NS}} = k\left(a-c-\gamma e_0\right)/\left(4k-\gamma^2\right)$, and the members' profits are $\pi_m^{\mathrm{NS}} = k\left(a-c-\gamma e_0\right)^2/2\left(4k-\gamma^2\right)$ and $\pi_r^{\mathrm{NS}} = k^2\left(a-c-\gamma e_0\right)^2/\left(4k-\gamma^2\right)^2$. □

Lemma 4.2. *For the case of* NS*, the retail price will decrease and reduction rate will increase with the increase of governmental emission limit.*

Proof. It is straightforward from the partial derivatives of p^{NS} and e^{NS} with respect to e_0. □

Lemma 4.3. *For the case of* NS *mode, when* $0 < \gamma < 2\sqrt{k}$ *and* $e_0 > (a-c)^2/4k$ *or* $0 < \gamma < \left(a-c-\sqrt{\Delta_1}\right)/e_0$ *and* $e_0 < (a-c)^2/4k$*, the retail price will decrease with consumer's environmental awareness; and when* $\left(a-c-\sqrt{\Delta_1}\right)/e_0 < \gamma < 2\sqrt{k}$ *and* $e_0 < (a-c)^2/4k$*, the retail price will increase with consumer's environmental awareness , where* $\Delta_1 = 4\left[(a-c)^2 - 4ke_0\right]$.

Proof. From Proposition 4.1, we can obtain the partial derivative of p^{NS} with respect to γ as $\partial p^{\mathrm{NS}}/\partial\gamma = -3k\left[e_0\gamma^2 - 2\gamma(a-c) + 4e_0k\right]/\left(4k-\gamma^2\right)^2$. To facilitate the discussion, we assume $\aleph_1(\gamma) = -e_0\gamma^2 + 2\gamma(a-c) - 4bk$. Obviously, $\aleph_1(\gamma)$ draws a quadratic function pointing downward, in which its criterion is $\Delta_1 = 4\left[(a-c)^2 - 4ke_0\right]$. When $e_0 > (a-c)^2/4k$, we can find that there is no intersection point on the curve of $\aleph_1(\gamma)$ and abscissa. Only when the condition $\Delta_1 > 0$ is satisfied, $\aleph_1(\gamma) < 0$ will be multiplicated, and existing $\partial p^{\mathrm{NS}}/\partial\gamma < 0$. So two intersection points are $\gamma_1 = \left(a-c-\sqrt{\Delta_1}\right)/e_0$ and $\gamma_2 = \left(a+c-\sqrt{\Delta_1}\right)/e_0$ between the curve of $\aleph_1(\gamma)$ and abscissa. Based on assumption, we have the satisfactory point $\gamma_1 = \left(a-c-\sqrt{\Delta_1}\right)/e_0$. In a word, the retail price will decrease in consumer's environmental awareness when $0 < \gamma < \left(a-c-\sqrt{\Delta_1}\right)/e_0$; and increase with consumer's environmental awareness when $\left(a-c-\sqrt{\Delta_1}\right)/e_0 < \gamma < 2\sqrt{k}$. □

Lemma 4.4. *For the case of* NS*, when* $\frac{\left(2ke_0-\sqrt{\Delta_2}\right)}{(a-c)} < \gamma < 2\sqrt{k}$ *and* $e_0 > (a-c)/2\sqrt{k}$*, the carbon emission reduction rate will decrease with consumer's environmental awareness; and when* $0 < \gamma < \left(2ke_0-\sqrt{\Delta_2}\right)/(a-c)$ *and* $e_0 > (a-c)/2\sqrt{k}$ *or* $0 < \gamma < 2\sqrt{k}$ *and* $e_0 < (a-c)/2\sqrt{k}$*, the reduction rate will increase with consumer's environmental awareness, where* $\Delta_2 = 4\left[(a-c)^2 - 4ke_0\right]$.

Proof. From Proposition 4.1, we can obtain the partial derivative of e^{NS} with respect to γ as $\partial e^{\mathrm{NS}}/\partial\gamma = \left[\left(\gamma^2+4bk\right)(a-c) - 8k\gamma e_0\right]/\left(4k-\gamma^2\right)^2$. To facilitate the discussion, we assume that $\aleph_2(\gamma) = (a-c)\gamma^2 - 8k\gamma e_0 + 4k(a-c)$. Obviously, $\aleph_2(\gamma)$ draws a quadratic function pointing upward, in which its criterion is $\Delta_2 = 16k\left[4ke_0^2 - (a-c)^2\right]$. When $e_0 < (a-c)/2\sqrt{k}$, we can find that there is no intersection point on the curve of $\aleph_2(\gamma)$ and abscissa. Only when the condition $\Delta_2 > 0$ is satisfied, $\aleph_2(\gamma) < 0$ will be multiplicated, and existing $\partial e^{\mathrm{NS}}/\partial\gamma > 0$. So we obtain that two intersection points are $\gamma_3 = \left(2ke_0-\sqrt{\Delta_2}\right)/(a-c)$ and $\gamma_4 = \left(2ke_0+\sqrt{\Delta_2}\right)/(a-c)$ between the curve of $\aleph_2(\gamma)$ and abscissa. Based on assumption, we have the satisfactory point $\gamma_3 = \left(2ke_0-\sqrt{\Delta_2}\right)/(a-c)$. In other word, the reduction rate will increase as consumer's environmental awareness increases when $0 < \gamma < \left(2ke_0-\sqrt{\Delta_2}\right)/(a-c)$; and the reduction rate will decrease as consumer's environmental awareness increases when $\left(2ke_0-\sqrt{\Delta_2}\right)/(a-c) < \gamma < 2\sqrt{k}$. □

From the above results, if the governmental emission limit is above a threshold, the retail price will decrease with consumer's environmental awareness increasing; conversely if governmental emission limit is smaller than the threshold, the retail price will increase with consumer's environmental awareness increasing. This indicates that as consumer's environmental awareness increases, consumers' purchase intention will gradually increase and retailer can appropriately increase the price. Meanwhile, if the governmental emission limit is relatively small, consumer's environmental awareness can promote the manufacturer to improve the emission reduction rate; but if governmental emission limit is relatively great, and when consumer's environmental awareness is less than the threshold, the manufacturer don't improve the emission reduction rate. The reason is that with the increasing of governmental emission limit, the emission reduction cost cannot neutralize the profit from demand increasing, resulting in the manufacturer's lacks of motivation in reducing carbon emission.

4.2. Case 2: Only retailer is subsidized (RS Scenario)

In this scenario, only low-carbon subsidy is provided to retailer in supply chain. Therein, the subsidy s_1 can be seen as a financial intervention to marketing behavior, and the supply chain supply chain members' profits is no longer affected by the subsidy on manufacturer s_2. Based on the above, we can obtain supply chain members' profits as following

$$\pi_m = (w-c)\left[a-p+\gamma\left(e-e_0\right)\right]-\frac{k}{2}e^2 \tag{4.3}$$

$$\pi_r = (p-w+s_1)\left[a-p+\gamma\left(e-e_0\right)\right]. \tag{4.4}$$

Proposition 4.5. *For the case of* RS*, given the governmental emission limit and consumer's environmental awareness, the optimal decisions for members are* $\left(w^{\mathrm{RS}}, e^{\mathrm{RS}}, p^{\mathrm{RS}}\right)$*, the market demand is* Q^{RS}*, and the profit for supply chain is* π_{sc}^{RS}*.*

Proof. It is similar to the proof of Proposition 4.1, therefore, the process of proof is omitted.

In the case of RS, the optimal governmental subsidy can be obtained as $s_1^{\mathrm{RS}} = \left(a-c-\gamma e_0\right)\left(3k+2\gamma\delta\right)/\left[k-\gamma\left(\gamma+2\delta\right)\right]$. The other decisions are $p^{\mathrm{RS}} = \left[c\left(k-\gamma^2\right)-2\gamma\delta\left(a-\gamma e_0\right)\right]/\left[k-\gamma\left(\gamma+2\delta\right)\right]$, $w^{\mathrm{RS}} = \left[k\left(2a-c-2\gamma e_0\right)-c\gamma\left(\gamma+2\delta\right)\right]/\left[k-\gamma\left(\gamma+2\delta\right)\right]$ and $e^{\mathrm{RS}} = \gamma\left(a-c-\gamma e_0\right)/\left[k-\gamma\left(\gamma+2\delta\right)\right]$. So the profits of manufacturer and retailer are $\pi_m^{\mathrm{RS}} = k\left(4k-\gamma^2\right)\left(a-c-\gamma e_0\right)^2/2\left[k-\gamma\left(\gamma+2\delta\right)\right]^2$ and $\pi_r^{\mathrm{RS}} = \left[k\left(a-c-\gamma e_0\right)\right]^2/\left[k-\gamma\left(\gamma+2\delta\right)\right]^2$ respectively. □

Lemma 4.6. *For the case of* RS*, when* $0 < \gamma < \left[\sqrt{\Delta_4}-2k\left(3a-3c-2\delta e_0\right)\right]/e_0$*, the optimal subsidy* s_1 *on retailer will decrease with consumer's environmental awareness increasing; when* $\left[\sqrt{\Delta_4}-2k\left(3a-3c-2\delta e_0\right)\right]/e_0 < \gamma < \sqrt{k+\delta^2}-\delta$*, the optimal subsidy* s_1 *on retailer will increase with consumer's environmental awareness increasing,* $\Delta_3 = 4k^2\left(3a-3c-2\delta e_0\right)^2 - k\left[3ke_0-2\delta\left(a-c+2\delta e_0\right)\right]\left[3ke_0-8\delta\left(a-c\right)\right]$*.*

Proof. From Proposition 4.5, we can obtain the partial derivative of s_1^{NS} with respect to γ as $\partial s_1^{\mathrm{RS}}/\partial\gamma = \left[\left(3\gamma+4\delta\right)\left(2a-2c-\gamma e_0\right)+\gamma^2\delta\left(a-c+2\delta e_0\right)-k^2 e_0\right]/\left[k-\gamma\left(\gamma+2\delta\right)\right]^2$. To simplify the discussion, we assume that $\aleph_3(\gamma) = \left[2\delta\left(a-c+\delta e_0\right)-3ke_0\right]\gamma^2 + 2k\gamma\left[3\left(a-c\right)-2\delta\right] + k\left[3ke_0-2\left(a-c\right)\left(3\gamma+\delta\right)\right]$. Obviously, $\aleph_3(\gamma)$ draws a quadratic function pointing downward, in which criterion $\Delta_3 = 4k^2\left(3a-3c-2\delta e_0\right)^2 + k\left[3ke_0-2\delta\left(a-c+2\delta e_0\right)\right]\left[8\delta\left(a-c\right)-3ke_0\right] > 0$. We can find two intersection points are $\gamma_5 = -\left[\sqrt{\Delta_4}+2k\left(3a-3c-2\delta e_0\right)\right]/e_0$ and $\gamma_6 = \left[\sqrt{\Delta_4}-2k\left(3a-3c-2\delta e_0\right)\right]/e_0$ between the curve of $\aleph_3(\gamma)$ and abscissa. Based on assumption, we have the satisfactory point $\gamma_6 = \left[\sqrt{\Delta_4}-2k\left(3a-3c-2\delta e_0\right)\right]/e_0$. In other word, the price will decrease with consumer's environmental awareness increasing when $0 < \gamma < \left[\sqrt{\Delta_4}-2k\left(3a-3c-2\delta e_0\right)\right]/e_0$; and increase with consumer's environmental awareness increasing when $\left[\sqrt{\Delta_4}-2k\left(3a-3c-2\delta e_0\right)\right]/e_0 < \gamma < \sqrt{k+\delta^2}-\delta$. □

4.3. Case 3: Only manufacturer is subsidized (MS Scenario)

In this scenario, only low-carbon subsidy is provided to the manufacturer in supply chain. Therein, the subsidy s_2 can be seen as a financial intervention to reduction behavior, and the supply chain members' profits is no longer affected by the subsidy on retailer s_1. Based on the above, we can obtain the manufacturer's and retailer's profits as following

$$\pi_m = (w-c)\left[a-p+\gamma\left(e-e_0\right)\right] - \frac{k}{2}\left(1-s_2\right)e^2 \tag{4.5}$$

$$\pi_r = (p-w)\left[a-p+\gamma\left(e-e_0\right)\right]. \tag{4.6}$$

Proposition 4.7. *For the case of* MS*, given the governmental emission limit and consumer's environmental awareness, the optimal decisions for supply chain members are* $\left(w^{\mathrm{MS}}, e^{\mathrm{MS}}, p^{\mathrm{MS}}\right)$*, the market demand is* Q^{MS}*, and the profit for supply chain is* π_{sc}^{MS}*.*

Proof. The proof is similar to the proof of Proposition 4.1, therefore it is omitted.

In the case of MS, the optimal governmental subsidy can be obtained as $s_2^{\mathrm{MS}} = \left[3k(\gamma+\delta)+\delta\left(k+\gamma^2\right)\right]/k\left(7\gamma+4\delta\right)$. Retailer's retail price and manufacturer's wholesale price are obtained as $p^{\mathrm{MS}} = \left[\left(4k-\gamma\delta\right)\left(3a+c-3\gamma e_0\right)-c\gamma\left(7\gamma+4\delta\right)\right]/\left[16k-\gamma\left(7\gamma+8\ \delta\right)\right]$, $w^{\mathrm{RS}} = \left[k\left(2a-c-2\gamma e_0\right)-c\gamma\left(\gamma+2\delta\right)\right]/\left[16k-\gamma\left(7\gamma+8\delta\right)\right]$, respectively. The optimal emission reduction rate is $e^{\mathrm{MS}} = \left(7\gamma+4\delta\right)\left(a-c-\gamma e_0\right)/\left[16k-\gamma\left(7\gamma+8\delta\right)\right]$. Thus the manufacturer's and retailer's profits are $\pi_m^{\mathrm{MS}} = \left(4k-\gamma\delta\right)\left(a-c-\gamma e_0\right)^2/2\left[16k-\gamma\left(7\gamma+8\delta\right)\right]$ and $\pi_r^{\mathrm{MS}} = \left(4k-\gamma\delta\right)^2\left(a-c-\gamma e_0\right)^2/\left[16k-\gamma\left(7\gamma+8\delta\right)\right]^2$ respectively. □

Lemma 4.8. *For the case of* MS*, when* $\left(\sqrt{\Delta_4}-4\delta\right)/7 < \gamma < 2\left(\sqrt{7k+49\delta^2}-4\delta\right)/7$*, the optimal subsidy on manufacturer will decrease with consumer's environmental awareness increasing; and when* $0<\gamma<\left(\sqrt{\Delta_4}-4\delta\right)/7$*, the optimal subsidy on manufacturer will increase with consumer's environmental awareness increasing, where* $\Delta_4 = 64\left(\delta^2+7k\right)$*.*

Proof. From Proposition 4.7, we can obtain the partial derivative of s_2^{NS} with respect to γ as $\partial s_2^{\mathrm{MS}}/\partial\gamma = \delta\left[\gamma\left(7\gamma+8\delta\right)-16k\right]/k\left(7\gamma+4\delta\right)^2$. To facilitate the discussion, we let $\aleph_4(\gamma) = 7\gamma^2+8\gamma\delta-16k$. Obviously, $\aleph_4(\gamma)$ draws a quadratic function pointing upward, in which its criterion is $\Delta_4 = 64\left(\delta^2+7k\right) > 0$. We can find that two intersection points are $\gamma_7 = -\left(\sqrt{\Delta_4}+4\delta\right)/7$ and $\gamma_8 = \left(\sqrt{\Delta_4}-4\delta\right)/7$ between the curve of $\aleph_4(\gamma)$ and abscissa. Based on assumption, we have the satisfactory point $\gamma_8 = \left(\sqrt{\Delta_4}-4\delta\right)/7$. In other word, the price will decrease as consumer's environmental awareness increases when $0<\gamma<\left(\sqrt{\Delta_4}-4\delta\right)/7$; increase as consumer's environmental awareness increases when $\left(\sqrt{\Delta_4}-4\delta\right)/7<\gamma<2\left(\sqrt{7k+49\delta^2}-4\delta\right)/7$. □

4.4. Case 4: Both members are subsidized (SS Scenario)

This scenario is to investigate equilibrium solution of the low-carbon supply chain when the government provides subsidies to the retailer s_1 and manufacturer s_2. Similar to the above scenarios, we infer that the supply chain members may intend to maximize their profits. The profit functions of manufacturer and retailer are respectively formulated as

$$\pi_m = (w-c)\left[a-p+\gamma\left(e-e_0\right)\right] - \frac{k}{2}\left(1-s_2\right)e^2 \tag{4.7}$$

$$\pi_r = (p-c+s_1)\left[a-p+\gamma\left(e-e_0\right)\right]. \tag{4.8}$$

Proposition 4.9. *For the case of* SS*, given the governmental emission limit and consumer's environmental awareness, the optimal decisions for supply chain members are* $\left(w^{\mathrm{SS}}, e^{\mathrm{SS}}, p^{\mathrm{SS}}\right)$*, the market demand is* Q^{MS}*, and the profit for supply chain is* π_{sc}^{SS}*.*

Proof. Given the subsidy s_1 and s_2, the decisions can be obtained $p(s_1,s_2) = [k(1-s_2)(3a+c-3\gamma e_0-s_1)-\gamma^2(c-s_1)]/[4k(1-s_2)-\gamma^2]$, $w(s_1,s_2) = [2k(1-s_2)(a+c-\gamma e_0+s_1)-c\gamma^2]/\left[4k\left(1-s_2\right)-\gamma^2\right]$ and $e\left(s_1,s_2\right) = \gamma\left(a-c-\gamma e_0+s_1\right)/\left[4k\left(1-s_2\right)-\gamma^2\right]$. So, we get the market demand is $Q\left(s_1,s_2\right) = k\left(1-s_2\right)\left(a-c-\gamma e_0+s_1\right)/\left[4k\left(1-s_2\right)-\gamma^2\right]$, the profits are respectively $\pi_m(s_1,s_2) = k(1-s_2)(a-c-\gamma e_0+s_1)^2/2\left[4k(1-s_2)-\gamma^2\right]$ and $\pi_r(s_1,s_2) = \left[k(1-s_2)(a-c-\gamma e_0+s_1)\right]^2/\left[4k(1-s_2)-\gamma^2\right]^2$. Furthermore, the optimal subsidies s_1 and s_2 are provided. We obtain the optimal subsidies $s_1^{\mathrm{SS}} = (a-c-\gamma e_0)\left[3k+\delta(\gamma+\delta)\right]/\left[k-(\gamma+\delta)^2\right]$ and $s_2^{\mathrm{SS}} = \frac{\delta}{(\gamma+\delta)}$. Similarly, the other decisions are obtained as $p^{\mathrm{SS}} = \{ck-(\gamma+\delta)\left[\delta(a-\gamma e_0)+c\gamma\right]\}/\left[k-(\gamma+\delta)^2\right]$, $w^{\mathrm{SS}} = \left[k(2a-c-2\gamma e_0)-c(\gamma+\delta)^2\right]$ and $e^{\mathrm{SS}} = (\gamma+\delta)(a-c-\gamma e_0)/\left[k-(\gamma+\delta)^2\right]$. So the manufacturer's and retailer's profits are respectively $\pi_m^{\mathrm{SS}} = k\left[4k-\gamma(\gamma+\delta)\right](a-c-\gamma e_0)^2/2\left[k-(\gamma+\delta)^2\right]^2$ and $\pi_r^{\mathrm{SS}} = \left[k(a-c-\gamma e_0)\right]^2/\left[k-(\gamma+\delta)^2\right]^2$. □

Lemma 4.10. *For the case of* SS, *(i) No matter how consumer's environmental awareness changes, the optimal subsidy to retailer will decrease with consumer's environmental awareness increasing; (ii) If the* $0 < \gamma < \left[(a-c)\left(3k+\delta^2\right)+\delta e_0\left(\delta^2-k\right)+\sqrt{\Delta_5}\right]/\left[3ke_0-\delta(a-c+\delta e_0)\right]$, *the optimal subsidy on all members will increase with consumer's environmental awareness increasing; when* $\left[(a-c)\left(3k+\delta^2\right)+\delta e_0\left(\delta^2-k\right)+\sqrt{\Delta_5}\right]/\left[3ke_0-\delta(a-c+\delta e_0)\right] < \gamma < \sqrt{k}-\delta$, *the optimal subsidy on all members will decrease with consumer's environmental awareness increasing.*

Proof. From Proposition 4.9, we can obtain the partial derivatives of s_1^{SS} and s_2^{SS} with respect to γ as $\partial s_1^{\mathrm{SS}}/\partial\gamma = -\delta/(\gamma+\delta)^2$ and $\partial s_1^{\mathrm{SS}}/\partial\gamma = -\{\gamma^2[3ke_0-\delta(a-c+\delta e_0)]-2\gamma[(a-c)(3k+\delta^2)+\delta e_0(\delta^2-k)]+k[3ke_0-\delta(7a-7c+2\delta e_0)]\}/[k-(\gamma+\Delta)^2]^2$. According to the assumption, we can easily prove $\partial s_1^{\mathrm{SS}}/\partial\gamma < 0$, namely the optimal subsidy on retailer will decrease with consumer's environmental awareness increasing. Further, to facilitate the discussion, we let $\aleph_5(\gamma) = \left[\delta(a-c+\delta e_0)-3ke_0\right]\gamma^2 + 2\left[(a-c)\left(3k+\delta^2\right)+e_0\left(\delta^2-k\right)\right]\gamma + k\left[\left(3k-2\delta^2\right)-7(a-c)\right]$. Obviously, $\aleph_5(\gamma)$ draws a quadratic function pointing downward, in which $\Delta_5 = 4\left[(a-c)\left(3k+\delta^2\right)+e_0\left(\delta^2-k\right)\right]^2 - \left[ke_0\left(3k+5\delta^2\right)-\delta\left(7k+\delta^2\right)(a-c+\delta e_0)\right]^2 > 0$. Then, we can obtain two intersection points are respectively $\gamma_9 = \left[(a-c)\left(3k+\delta^2\right)+\delta e_0\left(\delta^2-k\right)+\sqrt{\Delta_5}\right]/\left[3ke_0-\delta(a-c+\delta e_0)\right]$ and $\gamma_{10} = \left[(a-c)\left(3k+\delta^2\right)+\delta e_0\left(\delta^2-k\right)-\sqrt{\Delta_5}\right]/\left[3ke_0-\delta(a-c+\delta e_0)\right]$ between the curve and abscissa. Based on assumption, we have the satisfactory point $\gamma_9 = \left[(a-c)\left(3k+\delta^2\right)+\delta e_0\left(\delta^2-k\right)+\sqrt{\Delta_5}\right]/\left[3ke_0-\delta(a-c+\delta e_0)\right)$. In other word, the price will increase as consumer's environmental awareness increases when $0 < \gamma < \left[(a-c)\left(3k+\delta^2\right)+\delta e_0\left(\delta^2-k\right)+\sqrt{\Delta_5}\right]/\left[3ke_0-\delta(a-c+\delta e_0)\right]$; and decrease as consumer's environmental awareness increases when $\left[(a-c)\left(3k+\delta^2\right)+\delta e_0\left(\delta^2-k\right)+\sqrt{\Delta_5}\right]/\left[3ke_0-\delta(a-c+\delta e_0)\right] < \gamma < \sqrt{k}-\delta$. □

5. Numerical analysis

In this section, we further present the numerical examples to verify the obtained propositions and lemmas in different models and analyze the impacts of governmental emission limits and consumer's environmental awareness on the optimal decisions of supply chain members and the government. The data adopted in numerical analysis are collected from one company in China which intends to introduce special energy-saving cars into the market [8,31,39]. Numerical simulations are conducted based on the following parameters: (1) market size parameters: $a = 20$, $\gamma = 0.5$; (2) environmental function parameters: $\delta = 0.25$, $e_0 = 0.5$; (3) cost function parameters: $c = 3$, $k = 20$.

5.1. The impact of consumer's environmental awareness

Figure 1 describes the curves of the optimal emission reduction rate in different scenario with the change of consumer's environmental awareness. Obviously, it demonstrates consumer's environmental awareness can effectively motivate the manufacturer to increase the emission reduction rate. The higher the consumer's environmental awareness is, the higher the emission reduction rate is. Meanwhile, the emission reduction rate in

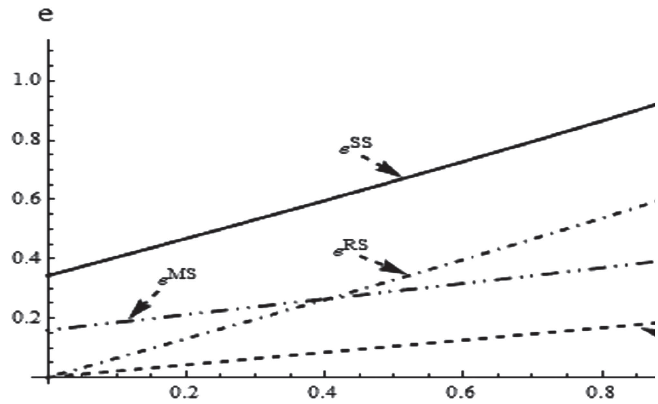

FIGURE 1. The impact of consumer's environmental awareness on the emission reduction rate.

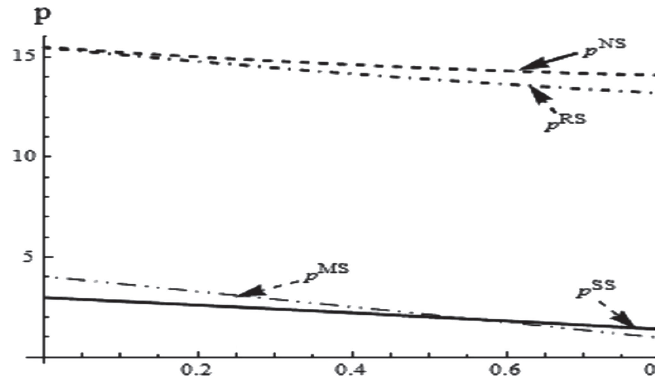

FIGURE 2. The impact of consumers' environmental awareness on the retail price.

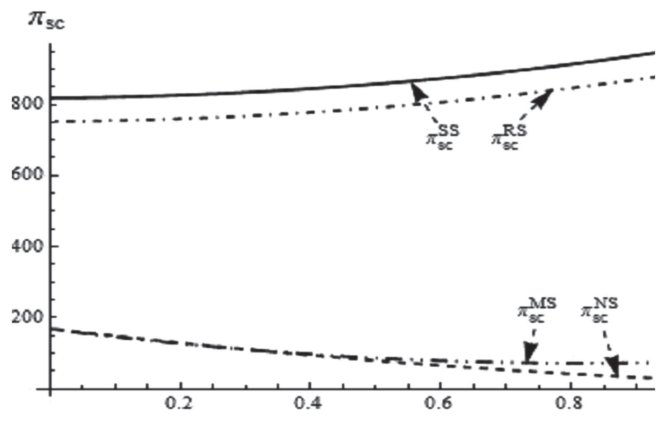

FIGURE 3. The impact of consumer's environmental awareness on the supply chain profit.

the scenario SS is higher than those in other scenarios. And the emission reduction rate has a much steeper falling in the scenario MS than that in scenario RS when $0 < \gamma < 0.401$, and the emission reduction rate is improved in scenario RS when $0.401 < \gamma < 1$. It can be concluded that the additional income from the increase

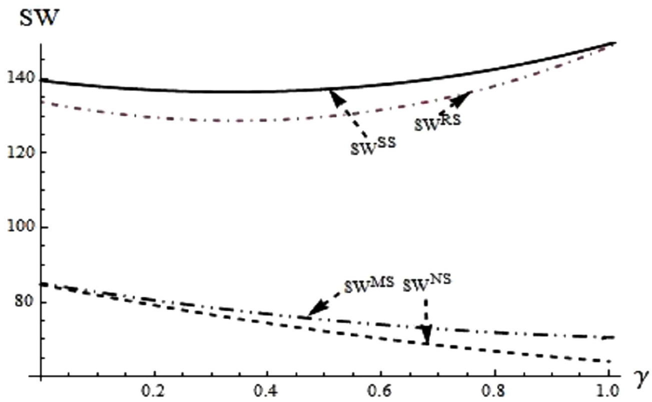

FIGURE 4. The impact of consumer's environmental awareness on the social welfare.

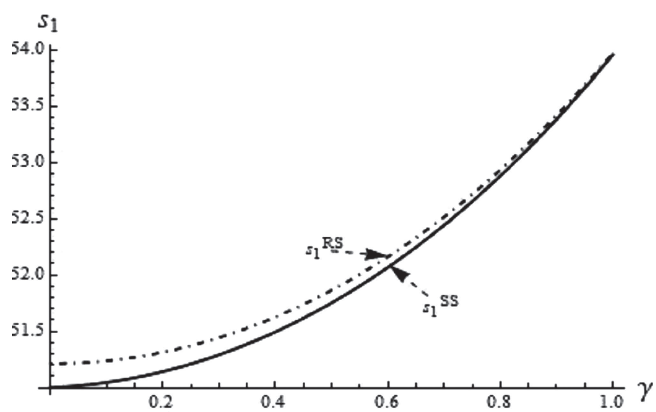

FIGURE 5. The impact of consumer's environmental awareness on the optimal subsidy to retailer.

of consumer's environmental awareness is high enough to offset the emission reduction cost, so the manufacturer can always benefit from the implementation of carbon emission reduction.

Figure 2 illustrates the curves of optimal prices in different scenarios with the change of consumer's environmental awareness. It demonstrates that consumer's environmental awareness can effectively encourage the retailer to reduce price. With consumer's environmental awareness increasing, the difference of retail price between NS scenario and RS scenario is increasingly evident. However, we show that when consumer's environmental awareness is relatively small ($\gamma < 0.56$), the retail price under MS scenario will be higher than that under SS scenario.

Figure 3 depicts the curves of optimal profit in the supply chain with the change of consumer's environmental awareness. Clearly, it can be shown that consumer's environmental awareness is positive interrelated to the supply chain profit in the RS scenario and SS scenario, and negative interrelated to the supply chain profit in the NS scenario and MS scenario. It also shows that the supply chain profit is the highest in the SS scenario followed by the scenario of RS. However, the supply chain profit in the NS scenario is lower than the other scenarios followed by the MS scenario. Interestingly, the supply chain profit in RS scenario is higher than that in MS scenario. This indicates that the loss of efficiency in RS scenario is mitigated because the retailer is closer to the market than manufacturer and has more ability to influence the underlying demand. The results indicate the reason why there is a difference among the supply chain profits in different scenarios with the change of consumer's environmental awareness.

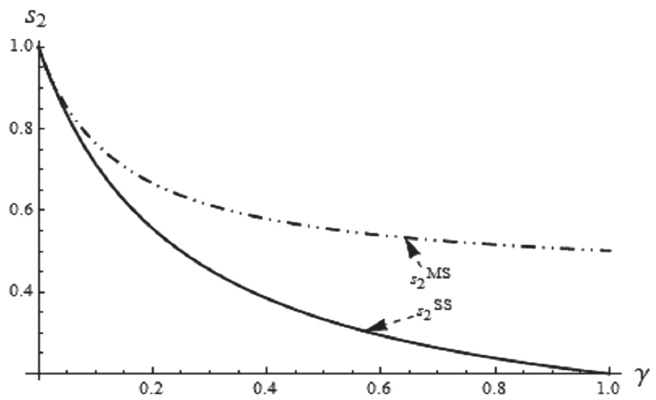

FIGURE 6. The impact of consumer's environmental awareness on the optimal subsidy to manufacturer.

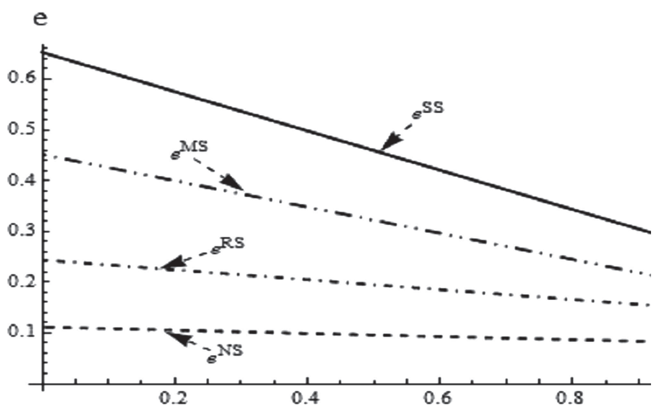

FIGURE 7. The impact of the governmental emission limit on the reduction rate.

The effect of consumer's environmental awareness on social welfare is shown in Figure 4. As shown in Figure 4, social welfares decrease with consumer's environmental awareness increasing in the NS and MS scenarios. There are U-shape relationship between consumer's environmental awareness and social welfare in RS and SS scenarios. For the government, the subsidy behavior should be helpful to develop high-tech industries and not to subsidize marketing activities, especially under the low-carbon environment. Since subsidy to the marketing activity only makes consumer surplus greatly improved, it is detrimental to implement the policy of carbon emission reduction and improve the production efficiency. The governmental subsidy should be diversified to motivate the supply chain members to reduce emission and improve profit.

Finally, to illustrate the optimal subsidies to supply chain members at various consumer's environmental awareness with the different scenarios, numerical simulations results are shown in Figures 5 and 6. The curves indicate the optimal subsidy decreases as consumer's environmental awareness increases in the RS scenario or in the SS scenario, while the curves of optimal subsidy decrease gradually both in the NS scenario and the MS scenario. Consequently, when these conditions are known, choosing the SS scenario may be a reasonable subsidy strategy for government. Also, we find that the governmental subsidy in the SS scenario could increase supply chain members' profits, promote demand, and improve social welfare.

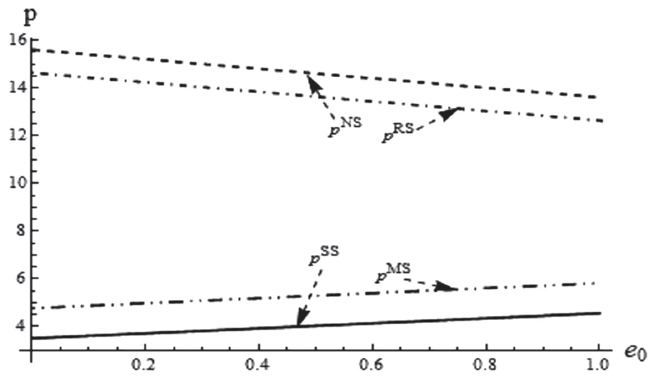

FIGURE 8. The impact of the governmental emission limit on the retail price.

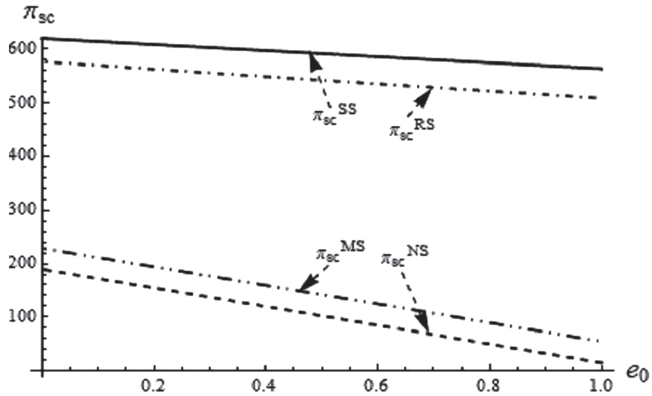

FIGURE 9. The impact of the governmental emission limit on supply chain profit.

5.2. The impact of governmental emission limits

In this section, we investigate the effects of the change of governmental emission limit. Under different values of emission limits, we examine the impacts on optimal subsidy for government and decisions for supply chain members. Figure 7 shows the relationship between the governmental emission limit and emission reduction rate in different scenarios and demonstrates that the higher governmental emission limit makes the emission reduction rate lower. Intuitively, we find that governmental subsidy can effectively increase the emission reduction rate compare for NS scenario. In addition, the curves also shows that the emission reduction rate is the highest in SS scenario followed by the MS scenario, and that in NS scenario is lower than the above scenarios followed by RS scenario.

Then, Figure 8 demonstrates that the retail prices in NS and RS scenarios are all positively associated with the governmental emission limit. By contrast, the governmental emission limit is in negative correlation to the retail price in MS and SS scenarios. From the relationship, we know that as governmental emission limit increases, the gap among the different scenarios in retail price is reduced. It is suggested that the government should take intelligently advantage of fiscal policies. Further, the effect of governmental emission limit on profit and social welfare are shown in Figures 9 and 10. We can find that the change trends of supply chain profits and social welfare are the same as governmental emission limit changes. As the curves shown, the profit and social welfare decrease with governmental emission limit increasing in various scenarios.

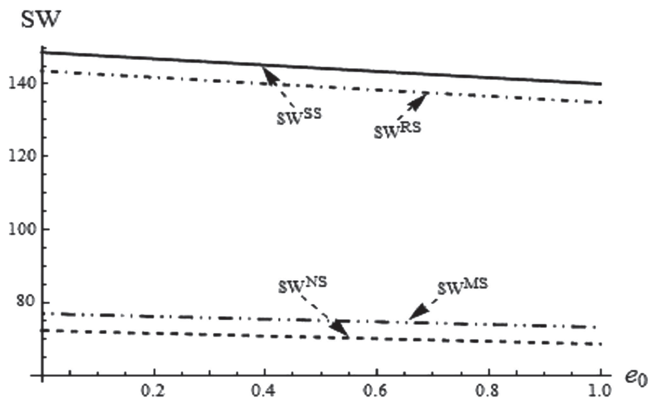

FIGURE 10. The impact of the governmental emission limit on the social welfare.

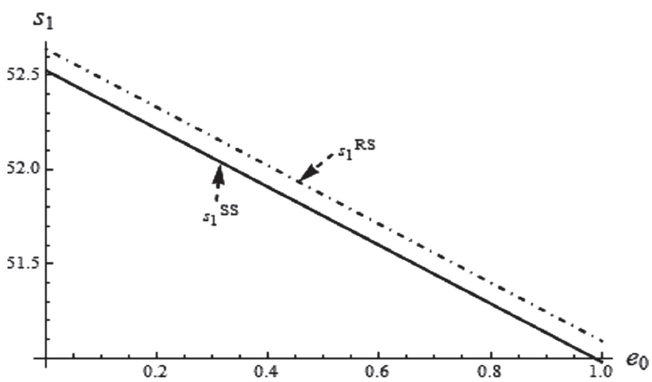

FIGURE 11. The impact of the governmental limit on the optimal subsidy to the retailer.

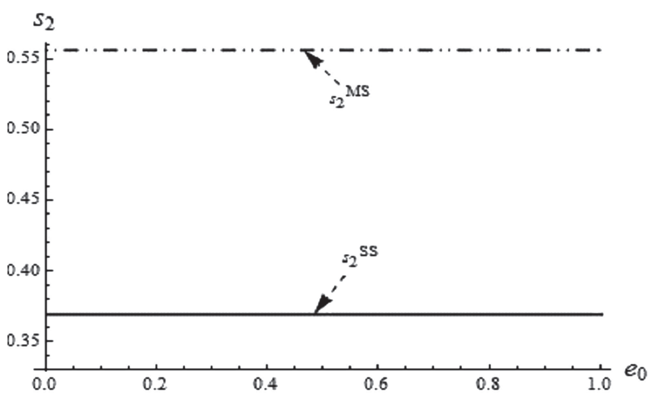

FIGURE 12. The impact of the governmental limit on the optimal subsidy to the manufacturer.

The relationship between the governmental subsidy and carbon emission limit in supply chain are shown as Figures 11 and 12, and respectively depict the curves of optimal subsidy to the retailer and manufacturer with the change of governmental emission limit. Figure 11 implies that the implementation of governmental emission limit is unfavorable to the increasing of optimal subsidy in RS and SS scenarios in. Similarly, governmental subsidy to the manufacturer is irrelevant to governmental emission limit (as shown in Fig. 12). For the government, an important question is how to balance the objectives of environmental, economic and expenditure to maximize the social welfare. Obviously, SS scenario is profitable for improving the above performances synthetically.

6. Conclusions

This paper develops the models to investigate the decisions of governmental subsidy and the decisions of pricing and emission reduction for supply chain members under the low-carbon environment. Our main contribution is to introduce governmental emission limit and consumer's environmental awareness in supply chain. Different subsidy strategies are taken into account, including NS scenario, RS scenario, MS scenario and SS scenario. And we present the following three main results: Firstly, consumer's environmental awareness and governmental emission limit are the most important factors influencing decisions of the government and supply chain members. Secondly, the optimal subsidies in the RS and SS are proportional to consumer's environmental awareness, but inversely proportional to the governmental emission limit. Thirdly, the governmental subsidy could increase supply chain member's profits and promote demand by relieving the cost burden of manufacturer's emission reduction and retailer's marketing

It is necessary for government to use financial intervention and for supply chain members to raise consumer's environmental awareness, which can be regarded as the activity to guide customers to purchase the low-carbon products. Thus, such behavior can promote economic development and social progress.

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