Incentive Model of Carbon Emission Trading for Online Shopping Supply Chains Based on O2O Mode

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Abstract. To address the problem of low-carbon operation enthusiasm of online shopping supply chains based on O2O mode, first, the carbon emission model of supply chain members is constructed by the adjusting cost and production functions, and the corresponding incentive model is constructed according to the carbon emission trading system. Second, the incentive model is solved and analyzed based on the optimal emission reduction cost and the optimal carbon emission incentive. Finally, optimal control theory is used to analyze the dynamic optimization of the model. The result shows that with the improvement of anastomosis in online and offline operations, the emission reduction cost is reduced. Supply chain members need to reduce carbon emissions only when their business scale is more than a certain amount. The cost of emission reduction for supply chain members is a concave function of the cost for its operation equipment or the correct emission price.

Keywords. Online to offline, Online shopping supply chain, Low carbon, Incentive.

1. Introduction

Online shopping market capacity continues to increase with the development of the Internet. China’s online shopping scale reached 6 trillion in 2019, and the annual penetration of total retail sales for social consumer goods exceeded 10%. Although online shopping brings convenience and low cost, its development is affected by its limitations. For example, some of express services only provide the convenience of pickup, and they have no other service such as product maintenance, repair, and recovery. A new business model, namely, the online to offline (O2O) model, has been developed in this context. Consumers can choose online businesses and visit their stores to feel the authenticity of their products and services, then decide whether to buy the products based on the model. Therefore, the O2O model has good prospects for development because it combines the convenience of online ordering and payment with the offline experience. However, online shopping results in low- and high-carbon effects. For example, online shopping produces considerable amounts of packaging material that are not recycled completely. At present, two types of incentives are in place to reduce carbon emissions. The first type, namely, government incentives, includes carbon emission quota incentives and carbon tax incentives. The second type, namely, market incentives, mainly refers to carbon emission trading incentives. Since the 1980s, developed countries have used government and market incentives to deal with environmental problems. However, in implementation, the government incentive cost is high and the efficiency is low, resulting in an inability to generate lasting incentives for enterprises’ emission reduction behavior. In recent years, an increasing number of countries have
focused on carbon emission trading, which is an effective market incentive to internalize external environmental effects. In this context, for the O2O model and carbon emission trading mechanism, an urgent problem is the development of a low-carbon incentive model for online shopping supply chains.

The O2O model was first proposed by Alex Rampell (2011), the founder of TrialPay, a US payment company. Rampell believed that the focus of the O2O model is to guide online users to offline stores to consume effectively [1]. Wu and Bai (2015) used the concave function model to minimize supply chain operating costs, including carbon emission cost, logistics cost, and fixed cost of distribution centers as regards the network design problem of low-carbon supply chain based on online shopping. Then, they proposed a Lagrangian heuristic algorithm based on the model [2]. Soleille (2006) emphasized the importance of carbon emission trading cost, market behavior, and government legislation. He also believed that the trading costs should be appropriate, market behavior should reduce the price fluctuations and maintain the balance of supply and demand, and the government should enact legislation to ensure the successful implementation of carbon emission trading system [3]. Floros and Vlachou (2005) studied the effect of carbon taxes on CO2 emissions, finding that the direct or indirect cost for carbon emissions could be reduced by the imposition of carbon taxes on enterprises [4]. Caro et al. (2011) confirmed that the supply chain members would strive to reduce carbon emissions if the upper limit of the emission reduction in the supply chain is set based on a quantitative model [5]. Mayor and Tol (2007) found that not every tax system for carbon emissions can produce good results [6]. Dobos (2005) thought that carbon emissions could be described by the function of production rate as an independent variable and that the optimal production and inventory policy would be brought after the carbon emission trading was introduced [7]. Agatz, et al. (2008) used the methods of revenue management to encourage customers to choose the same delivery time as their neighbors and reduce transportation distance to reduce carbon emissions by designing appropriate pricing mechanisms [8]. Wu et al. (2014) used the convex function to describe the total cost of the supply chain by considering the carbon emissions for the supplier’s supplying process. On this basis, an incentive model for low-carbon supply chains was proposed based on online shops and their suppliers. The model was compared and analyzed from the perspective of carbon taxes and carbon excess penalties based on the supply chain’s cooperative operation [9].

In summary, research on the O2O model is mainly focused on its concept and connotation, and analysis of its practical applications needs to be improved. Research on low carbon incentives in supply chains is mainly focused on carbon emission limits, carbon taxes, or carbon emission trading independently. Incentives considering carbon emission trading based on the O2O model are rare. Considering the above analysis, as regards the problem of low carbon operation enthusiasm in online shopping supply chains based on the O2O model, first, the carbon emission model of supply chain members is constructed by the adjusting cost function and production function. The corresponding incentive model is constructed according to the carbon emission trading system. Second, the incentive model is solved and analyzed based on the optimal emission reduction cost and the optimal carbon emission incentive. Finally, optimal control theory is used to analyze the dynamic optimization of the model.

2. Construction of Incentive Model
The incentive for carbon emission trading means that the total carbon emissions of the national or regional is set by the government according to the requirements of environmental protection, which is freely allocated to the relevant enterprises, and the carbon emissions obtained by the enterprise is its initial emission rights. If the initial emission rights are not equal to the enterprise’s actual carbon emissions, its shortage or surplus can be traded in the carbon emission trading market. The latest research shows that carbon emission trading under the control of carbon emission intensity has high adaptability and is suitable for developing countries such as China to participate in global carbon emission trading. Carbon emission intensity is a way to control greenhouse gas emissions, which was successfully done in such developed countries as the UK, Germany, and France, which have voluntary emission reduction agreements. They believe that the company will be responsible for purchasing
carbon emission amounts in the market if its carbon emissions exceed the target. Many types of allocation modes are used for the enterprise’s initial carbon emission rights, and the mode considering the enterprise’s historical emissions and contributions to society can be fair and efficient. Therefore, the model in this paper is based on this mode.

2.1. Carbon Emission Model of the Supply Chain’s Enterprises

The member enterprises of the online shopping supply chain include suppliers, online shops, and express delivery businesses. Assuming that the value for the enterprises’ operating equipment is $V$ and the price of their product or service is 1 per unit, the gross profit of member companies (Eberly and Wang, 2009) is

$$P(V) = RV^d$$  \hspace{2cm} (1)

$R$ is the output rate per unit equipment, which is constant. $d < 1$, which means that the member enterprises’ marginal revenue decreases with their operation size.

The net income of the member enterprise, namely, $I$, is

$$I = P(V) - A(Q,V)$$  \hspace{2cm} (2)

$P(V)$ is the operating equipment’s gross income and $Q$ is its purchasing cost. $A(Q,V)$ is its adjustment cost, which includes its purchasing and late maintenance costs. The adjustment cost function is

$$A(Q,V) = a(i)V$$  \hspace{2cm} (3)

$i = Q/V$, which is the ratio of the member enterprises’ daily operating expenses to their equipment value. $a(i)$ is

$$a(i) = i + \frac{s}{2}i^2$$  \hspace{2cm} (4)

$s$ is the strength coefficient of adjustment cost, and $s > 0$. Moreover, the market liquidity of member companies' products or services is decreasing with $s$ increasing continuously.

The following formula can be concluded from (3) and (4)

$$A(Q,V) = Q + \frac{sQ^2}{2V}$$  \hspace{2cm} (5)

The change in the value of operating equipment is caused by depreciation and loss of production, so,

$$\dot{V} = Q - \delta V$$  \hspace{2cm} (6)

$\delta$ is the depreciation rate of equipment.

$c$ is the cost of carbon emission reduction for member enterprises, whose carbon emission is

$$E = S(c)P(V)/f_{oc}$$  \hspace{2cm} (7)

$f_{oc}$ is the degree of coincidence between online and offline operations for the online shopping supply chain. $S(c)$ is the carbon emission intensity for the member enterprises, which means the ratio of carbon emission to its output. The increase in investment for emissions reduction will reduce the intensity of pollution emissions. $S'(c) < 0$, $S'(c) > 0$, $c \geq 0$. $S(c)$ is

$$S(c) = S(0)e^{-\omega c}$$  \hspace{2cm} (8)
is constant, \( S(0) \) is the carbon emission intensity when the member enterprises operate with no carbon emissions reduction.

2.2. Incentive Model
Assuming that \( S \) is the national carbon emission intensity and \( Y \) is the gross national product, \( SY \) is total carbon emissions. \( SY \) is allocated to the enterprise in the proportion of \( P \) according to the grandfather principle; the remainder of \( SY \) is allocated to the enterprise according to its output value. The historical carbon emissions for the country or the enterprise is \( E_n \) and \( E_{nj} \) respectively, the output of the enterprise is \( Y_j \), so the quota for the initial carbon emission allocated to the enterprise \( j \) is

\[
D_j = \frac{E_{nj}}{E_n} pSY + \frac{Y_j}{Y} (1 - p)SY = \overline{D} + (1 - p)SY,
\]

\( \overline{D} = \frac{E_{nj}}{E_n} pSY \), \( \overline{D} \) is a fixed value, which has nothing to do with the enterprise’s output.

Assuming that \((1 - p)S = w \), \((1 - \xi)\psi = \omega \), so the enterprise’s initial emission rights are

\[
D(V) = \overline{D} + wY(V) = \overline{D} + wRV^d
\]

The price for carbon emission is set to a fixed value, namely, \( \nu \), for convenient analysis, and \( E \) is the enterprise’s carbon emissions, so the purchasing cost for the emission right is \( \nu(E - D(V)) \).

Therefore, the objective function of the enterprise’s profit maximization is

\[
\text{Max} \int_{Q_0} \xi e^{-c} [Y(V_0) - A(Q, V_0) - c] - \nu(E - D(V))] dt
\]

\[s.t. \quad \dot{V} = Q - \partial V, \]
\[V(0) = V_0, \quad c \geq 0\]

3. Model Solution and Analysis

3.1. Solution Based on Optimal Costs for Carbon Emission Reduction
In this part, the member company of the online shopping supply chain has equipment which is the value of \( V \), and the optimal cost for carbon emission reduction, namely, \( c \), is analyzed as follows:

\[
\text{Min} \left[ c + \nu(E - D(V)) \right]
\]

\[s.t. \quad c \geq 0\]

The above formula’s derivation based on (1), (8), and (10) is

\[
c = \frac{1}{\mu} \ln \left[ \frac{\nu S(0) RV^d}{f_{\nu}^{\text{cov}}} \right]
\]

Assuming \( c = 0 \), its equipment’s value, namely, \( V_* \), is \( d \sqrt{\frac{f_{\nu}^{\text{cov}}}{\nu S(0) R}} \) when the supply chain member has no investment in the carbon emission reduction.

Therefore, the supply chain member’s optimal investment for the carbon emission reduction is
\[ c(V) = \begin{cases} 0 & \text{when } V < V_* \\ \frac{1}{u} \ln(vuS(0)RV^\alpha / f_d^\infty) & \text{when } V \geq V_* \end{cases} \] (14)

Thus, the following formula can be drawn when \( V \geq V_* \):

\[ \frac{\partial c}{\partial V} = \frac{d}{uV} > 0, \quad \frac{\partial^2 c}{\partial V^2} < -\frac{d}{uV^2} < 0, \quad \frac{\partial c}{\partial u} = \frac{1}{uv}, \quad \frac{\partial^2 c}{\partial u^2} = -\frac{1}{uv^2} < 0. \]

Our conclusions are as follows.

Incentive conclusion 1: The online shopping supply chain needs to invest in carbon emission reduction only when its sales reach a certain size according to the carbon emission trading system. Moreover, the investment is reduced with the increase in operating equipment in the first half, and the investment is added in the second half. At the same time, the member’s enthusiasm for carbon emission reduction is strengthened with an increase in emission price. The investment is reduced with the increase in the price in the first half, and the investment is added in the second half. On the other hand, the cost of emission reduction is reduced with the improvement of Anastomosis of online and offline operations.

3.2. Solution Based on the Optimal Carbon Emission Incentive

In this part, the optimal incentive problem of the supply chain member company considers the optimal emission reduction cost, namely, \( c(V) \), is analyzed as follows.

The Hamilton function of a supply chain member company is

\[ H = P(V) - A(Q, V) - c(V) - \nu(E - D(V)) + \lambda(Q - \delta V) \] (15)

The following formula is obtained according to \( \frac{\partial H}{\partial Q} \):

\[ \lambda = \frac{\partial A(Q, V)}{\partial Q} = 1 + s \cdot i \] (16)

The Euler equation is

\[ \dot{\lambda} = r\lambda - \frac{\partial H}{\partial V} = r\lambda - \frac{\partial P(V)}{\partial V} + \frac{\partial A(Q, V)}{\partial V} + \frac{\partial c(V)}{\partial V} + \frac{\partial [\nu(E - D(V))]}{\partial V} + \lambda \dot{\delta} \] (17)

\[ \frac{\partial c}{\partial V} = \frac{d}{uV} \text{ when } V > V_* \text{ and} \]

\[ \frac{\partial [\nu(E - D(V))]}{\partial V} = -vwRdV^{d-1} / f_d^\infty \] (18)

\[ \frac{\partial [c(V) + \nu(E - D(V))]}{\partial V} = \frac{d}{uV} - vwRdV^{d-1} / f_d^\infty \] (19)

So \( \frac{\partial [c(V) + \nu(E - D(V))]}{\partial V} < 0 \) when \( V > d \sqrt[1/d-1]{f_d^\infty / vuwR} \).

Therefore, the emission reduction cost for the supply chain member enterprise adds with the increase of its operation scale. The purchase cost for carbon emission rights in the carbon emission trading market is also decreased, and its total for the carbon emission is decreased if \( V > d \sqrt[1/d-1]{f_d^\infty / vuwR} \).
Formula (17) is simplified as
\[
\dot{\lambda} = (r + \delta)\lambda - RdV^{-1} f_d^{oo} - \frac{s}{2} i^2 + \frac{d}{uV} - vwRdV^{-1} f_d^{oo}
\]
(20)
The time in formula (17) is derived as
\[
\dot{\lambda} = \frac{\partial \lambda}{\partial t} = \frac{\partial}{\partial t} \left[ \frac{1 + s \cdot Q}{V} \right] = \frac{s}{V} \dot{Q} - \frac{sQ}{V^2} \dot{V} = \frac{s}{V} \dot{Q} - s \cdot i^2 + is\delta
\]
(21)
The following formula is obtained when \( V > V_s \) according to (20) and (21).
\[
\dot{Q} = \frac{V}{s} \left[ r + \delta - RdV^{-1} f_d^{oo} + rs\frac{Q}{V} + \frac{s}{2} \left( \frac{Q}{V} \right)^2 + \frac{d}{uV} - vwRdV^{-1} f_d^{oo} \right]
\]
(22)
\( c(V) = 0 \) when \( V < V_s \). Similarly, we can conclude
\[
\frac{\partial [v(E - D(V))] }{\partial V} = vRdV^{-1} (S(0) - w) / f_d^{oo}
\]
(23)
So
\[
\dot{Q} = \frac{V}{s} \left[ r + \delta - RdV^{-1} f_d^{oo} + rs\frac{Q}{V} + \frac{s}{2} \left( \frac{Q}{V} \right)^2 + vRdV^{-1} (S(0) - w) / f_d^{oo} \right]
\]
(24)
Based on the above analysis, we can conclude the following.
Incentive conclusion 2: In the current carbon emission trading system, the emission reduction cost for the supply chain member enterprise is increased with the increase in its operation scale. However, the purchase cost for carbon emission rights in the carbon emission trading market is decreased, and its total for carbon emissions is decreased when \( V > \text{Max} \left\{ \frac{f_d^{oo}}{vuwS(0)R}, \frac{f_d^{oo}}{vwR} \right\} \).

3.3. Analysis of the Distribution Characteristics of Steady-State for the Incentive Model
In this part, the distribution characteristics of steady-state and the condition of its solution for the incentive model will be analyzed.
When \( V < V_s \), \( V \) in the formula (24) is partially derived as
\[
\left. \frac{\partial Q}{\partial V} \right|_{V=0} = \frac{Rd(d-1)\nu^2}{s(rV + Q)f_d^{oo}} (1 - vS(0) + vw) + \frac{Q}{V}
\]
(25)
So \( \frac{\partial Q}{\partial V} \bigg|_{V=0} < 0 \) only when \( V < \frac{1}{s(0) - w} \left[ 1 + \frac{sQ(rV + Q)f_d^{oo}}{Rd(d-1)v^2} \right] \), Vise versa.
Therefore, the price for the carbon emission rights \( V \) is related to the slope of the curve \( \dot{Q} = 0 \) on the phase plane of \( Q - V \).
Similarly, the price for the carbon emission rights \( V \) is related to the slope of the curve \( \dot{Q} = 0 \) when \( V > V_s \).
The Jacobi matrix of the incentive model is
\[
J(V^\delta, Q^\delta) = \begin{pmatrix}
\frac{\partial V}{\partial V} & \frac{\partial V}{\partial Q} \\
\frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial Q}
\end{pmatrix} \bigg|_{V^0 = 0} = \begin{pmatrix}
-r & 1 \\
1 & 0
\end{pmatrix}
\]

The follow formulas are obtained from (26) when \( V < V_* \)
\[
\left. \frac{\partial V}{\partial Q} \right|_{V^0 = 0, Q^0 = 0} = V \left[ rs + sQ \right] \bigg/ V^2 = r + \frac{Q}{V} = r + \delta
\]

\[
\det J(V^\delta, Q^\delta) = \frac{\text{Rd}(1-d)V^{d-1}}{Sf^\omega} \left[ V(S(0) - w) - 1 \right].
\]

Therefore, \( \det J(V^\delta, Q^\delta) < 0 \) when \( V(S(0) - w) < 1 \)

Similarly, the following formulas are obtained from (26) when \( K > K_* \)
\[
\left. \frac{\partial V}{\partial Q} \right|_{V^0 = 0, Q^0 = 0} = V \left[ rs + sQ \right] \bigg/ V^2 = r + \delta
\]

\[
\det J(V^\delta, Q^\delta) = -\frac{d}{sV} \left[ R(1 + vw)(1 - d)V^d / f^\omega - 1 \right].
\]

Therefore, \( \det J(V^\delta, Q^\delta) < 0 \) when \( V > d \left( \frac{f^\omega}{uR(1 + vw)(1 - d)} \right) \).

Based on the above analysis, our conclusions are as follows.

Incentive conclusion 3: The steady-state solution of the incentive model, namely, \((V^\delta, Q^\delta)\) is a saddle point when \( V < V_* = \frac{d}{vwS(0)R} \) and \( V(S(0) - w) < 1 \). The equilibrium point of the incentive model is the saddle point only if it meets \( V > d \left( \frac{f^\omega}{uR(1 + vw)(1 - d)} \right) \) at the same time, and the model has no steady-state solution if it does not meet the above conditions.

4. Conclusions

An analysis framework for an incentive model for carbon emission trading is first proposed, and optimal control theory is used to analyze the dynamic optimization of carbon emission trading incentives. Then, the adjustment cost and production functions are used to analyze the behavior of suppliers facing the incentive of carbon emission trading. On this basis, an incentive model based on carbon emission trading is proposed. The model is solved and its incentive mechanism is analyzed. The result shows that supply chain member enterprises need to invest in carbon emission reduction only when their operation scales reach a certain size according to the carbon emission trading system.
The investment is a concave function of its investment for the operating equipment and of the enterprise’s price for carbon emission rights. By contrast, the cost of emission reduction for the member enterprise reduces with the increase in O2O integration. The operating equipment’s purchasing cost for member enterprises, especially, for express companies, decreases with the increase in O2O integration. Although member enterprises have different sizes and businesses, they can benefit from the carbon emission trading market. Among the enterprises, suppliers and express delivery business benefit the most because of the high value of their equipment, namely, production equipment and transportation and storage facilities and equipment. By contrast, online shops have less valuable equipment, which is mainly IT equipment.

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