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Research Article

Government Subsidy Decision-Making for Waste Tire Recycling under the Coexistence of the Retailer and the Internet Recycling Platform

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The low efficiency of the closed-loop supply chain in waste tire recycling has hindered the green development of China's automobile industry. Additionally, the government subsidy decision has a huge influence on green development. This study focuses on a closed-loop supply chain system that consists of five members, namely, manufacturer, retailer, Internet recycling platform, and government. It aims to investigate the effect of the government's subsidy mechanism on the decision-making process of recycling units, as well as to reveal the optimal strategies under different conditions. Under the coexistence of the retailer and the Internet recycling platform recycling programs implemented simultaneously by themselves, a two-stage Stackelberg game model is developed to explore the optimal government subsidy decision and the optimal pricing decision of manufacturer, retailer, and network platform in the closed-loop supply chain. At the same time, this paper investigates the effects of government subsidies on social welfare and the profits of supply chain members under different scenarios and then verifies the optimal government subsidy decision with MATLAB software through numerical examples and sensitivity analysis. The results show that the government subsidy coefficient is positively correlated with social welfare under four subsidy scenarios. To maximize the economic profit and social welfare of the members of the closed-loop supply chain, the government should appropriately select different subsidy objects within the range of different subsidy coefficients. When the subsidy coefficient $\gamma \in [0, 15]$ and the government chooses consumer as the subsidy object, the social welfare will be maximized when $\gamma > 15$ and the government chooses Internet recycling platform as the subsidy object. It is recommended that the government directly subsidizes the Internet recycling platform. However, in order to maintain the manufacturer's core position in the closed-loop supply chain, the subsidy coefficient for the Internet recycling platform should not exceed the critical value of 18. These results provide managerial insights for the government, manufacturer, and the third party to make decisions in the field of waste tire recycling. This paper presents the different subsidy conditions under which the government should appropriately select different subsidy objects. It also provides a theoretical and practical basis for improving the recycling efficiency of waste tires.

1. Introduction

At present, China's automobile industry is developing rapidly and the automobile market scale is expanding continuously. By the end of 2020, there were 281 million automobiles in China. With the increasing number of automobiles, the production of waste tires is increased rapidly by 8%–10% each year. In 2020, there were 20 million tons of waste tires produced in China. The increasing number of waste tires poses new challenges to the ecological and environmental strategy.

The rapid development of the resource recycling industry and Internet recycling platforms provides new opportunities for preventing "black pollution." Although the

Chinese government has successively promulgated the Code for the Selection of Commercial Tires, the Construction Specifications of Waste Tire Recycling System, the Recycling and Management Specification of Waste Tire, and the Industry Standard Conditions for Comprehensive Utilization of Waste Tires (2020 Edition) and started pilot work in certain regions, there is no real waste tire recycling system established in a standardized manner. Based on this, a large number of scholars have studied the pricing in the closed-loop supply chain (CLSC) and the decision problem of waste tires recycling under the government subsidy mode. The researchers gradually pay more attention to the guidance of the government subsidy mechanism on the closed-loop supply chain. The researches mainly focus on the recycling mode of waste tires, the selection decision of recycling channels in the closed-loop supply chain, the pricing decision of the closed-loop supply chain, and the influence of government reward and punishment mechanism on the closed-loop supply chain.

In the research about the recycling modes of waste tires, the scholars mainly focus on single recycling mode or mixed recycling mode, centered largely around the comparative analysis of three typical recycling modes including manufacturer recycling, retailer recycling, and third-party recycling. Shulman et al. analyzed the recycling mode selection of closed-loop supply chain under bilateral monopoly and found that there will be the highest return under manufacturer recycling mode [1]; Zhu built a model about waste tire recycling and reusing system and reclamation system based on system theory and circular economy theory [2]. Liang et al. proposed an integer model of multilevel reverse logistics network for optimizing waste tire's reverse logistics network, which solved the problems about initial collection point quantity, location, and product flow of waste tire's multilevel reverse logistics network [3]. Gong discussed the influence of different recycling modes and channel power structure on the optimal decision and performance of closed-loop supply chain [4]. Wang et al. investigated the relevant government departments and 10 representative enterprises implementing "Internet +" recycling in China. Through investigation, four typical "Internet +" recycling models were described [5]. Deng et al. designed the circular economy mode and evaluation indicator system of waste tire recycling in China [6].

Savaskan et al. first proposed the recycling channel problem of the closed-loop supply chain, established three modes of third-party recycling, manufacturer recycling, and retailer recycling, and built a Stackelberg game model [7]. Maiti and Giri also discussed the influence of recycling channel selection on the decision [8]. Das Roy and Sankar Sana investigated a multiechelon green supply chain system where a regular production process is integrated with a remanufacturing process. A random number of the collection returned items are defectives that are uniformly distributed in the collected lot [9]. Taleizadeh et al. built closed-loop supply chain decision models with single marketing channels and dual marketing channels, respectively, based on a dual-recycling channel structure composed of retailer and third party [10]. Gong et al. discussed the influence of different recycling modes and channel power structures on the optimal decisions of a closed-loop supply chain, and the results showed that the mixed recycling channel is optimal for the participants in the supply chain [11]. Taleizadeh et al. considered a two-level dual-channel green supply chain consisting of a retailer and a manufacturer with a separate sales channel for the manufacturer; they further recommend that manufacturers should invest in green technologies for their production [12]. Sana investigated a two-echelon supply chain; the optimal green quality and sales prices of the manufacturer and the retailer in both decentralized and centralize systems are considered, with price competition of two substitute products where the demand of the end customers depends on price and quality of the green product [13].

To improve the enthusiasm of participants in the closed-loop supply chain towards the recycling of waste tires, the government will introduce the corresponding reward and punishment mechanism and adopt a subsidy policy to promote remanufacturing generally. Heydari et al. considered a two-level reverse supply chain composed of a manufacturer and a retailer and analyzed the government's role in improving the coordinated supply chain development by providing different incentives (tax-free and subsidy) to supply chain participants [14]. Nielsen et al. compared the results of three government policies concerning the manufacturer Stackelberg (MS) and retailer Stackelberg (RS) [15]. Yan and Xie studied the influence of government subsidy on power battery manufacturer recycling. Based on whether there is government subsidy and according to the different subsidy objects [16], Wang et al. built three closed-loop supply chain models, respectively, characterized by government subsidy for manufacturer, government subsidy for retailer, and no government subsidies [17]. Huang et al. considered the pricing problem with regard to the two-way and dual-channel closed-loop supply chain of new energy vehicles under the four circumstances of government subsidy for consumers, government subsidy for OEM, government subsidy for retailer, and no government subsidy [18]. Zhou and Ran Gang considered the government subsidy and VAT refund policies and studied whether consumers' environmental awareness level will influence the implementation of government policies in a closed-loop supply chain [19].

Government subsidy policies play a vital role in the operation and green development of the closed-loop supply chain. In this regard, a large number of scholars have launched research. In contrast to previous research [20], our study focuses on the government subsidy decision-making under the coexistence of the retailer and the Internet recycling platform. Gorji et al. constructed a government-led Stackelberg game model and found that government subsidies have an impact on the equilibrium value of the decision variables of each center in the ELV supply chain and most significantly affect the profit of the recycling center [21]. Green development performance (GDP) and government rewards and penalties have a certain impact on the decision-making process of production and recycling units. The government's reward and punishment mechanism can effectively regulate the decision-making process of production and recycling units [22]. The government's reward and punishment subsidy policy have increased the product recycling rate and at the same time improved the product greening level, but the subsidy level needs to be adjusted according to the price of the recycled resources [23]. Third-party recyclers will change the optimal subsidy model according to the government's price subsidy level, while manufacturers always prefer the price subsidy model [24].

Barman et al. proposed a green supply chain model with a duopoly structure; in this study, the researchers focused on exploring the pricing strategy and greening strategy and comparing the optimal decisions in all the cases to maximize the overall profitability of the supply chain [25]. Sana constructed a newsvendor inventory model in light of green product marketing of corporate social responsible firms; green and nongreen marketing was analyzed including subsidy and tax implementation by government [26].

In order to improve the incentive-based recycling policy, some scholars conducted a comprehensive economic analysis and Engineering Economic Analysis on the major tire manufacturers and recycling companies in Taiwan in the 1990s. The research found that improving the overall management efficiency needs to set different subsidies for waste tires at different stages [27]. With the goal of achieving optimal incentives, Wang et al. studied the optimal allocation strategy of government subsidies with multiple subsidy parties. The results show that when the recycling rate of electronic waste is low, the collector and retailer should be subsidized; otherwise the remanufacturing should be subsidized [28]. Then, Chen et al. studied the impact of the uncertain quantity of waste products and found that there is little essential difference between providing subsidies directly to manufacturers and consumers. Coordinating the supply chain requires government subsidies to achieve a higher target collection level [29]. Consider a manufacturer who sells a new product to consumers and examines the optimal recovery strategy and associated decisions by developing three models, further exploring the impacts of product quality and government subsidy on the optimal decisions [30]. Yu et al. established the logistics distribution functions for the passenger vehicles and commercial vehicles based on the service years of 220,000 ELVs from 2012 to 2016 in Shanghai and using a statistical model to predict and analyze the future trend of the number of the ELVs in China [31]. Using a Stackelberg game, the pricing mechanism of dual-channel power battery recycling models under different government subsidies is investigated [32].

As outlined so far, although more attention has been received and much research has been done for closed-loop supply chain and government subsidy mechanism, few pieces of literature focus on studying the government's optimal subsidy decision when retailer recycling and network platform recycling coexist in the closed-loop supply chain. Meanwhile, most of the existing research focuses on the high value-added product fields (such as the recycling of waste electronics and electrical appliances and NEV batteries) with regard to the recycling and reusing of renewable resources, while there are few researches on recycling and reusing of waste tires.

This study examines the effect of the government's subsidy mechanism by using four recycling modes of waste tires as well as to reveal the optimal strategies under different conditions. Stackelberg game model is developed to explore the government optimal subsidy decision and the optimal pricing decision of manufacturer, retailer, and network platform. The key contributions of this paper are threefold. Firstly, we build a closed-loop supply chain with regard to remanufacturing under the government subsidy and study the government subsidy decision problem when retailer recycling and network platform recycling coexist. Secondly, a dual-channel and two-stage supply chain model is established: Retailer and Internet recycling platforms are engaged in recycling waste tires together. Moreover, the Stackelberg master-slave game is played among manufacturers, retailers, and Internet recycling platforms. As a third point, based on the dual perspective of maximizing the enterprise's economic profit and government's social welfare, we study the government's best subsidy decision in this paper, hoping to provide a scientific decision basis for the government which intends to establish a subsidy system of waste tire recycling.

The remainder of the paper is organized as follows: The model descriptions and basic assumptions are presented in Section 2. Building and solving a closed-loop supply chain pricing decision model is presented in Section 3. Model comparison is conducted in Section 4. In Section 5, numerical examples and sensitivity analysis are presented. Section 6 shows the analysis results of gaps in current research and potential research opportunities for the future.

2. Model Descriptions and Basic Assumptions

2.1. Recycling Models Descriptions. In this paper, we take the CLSC composed of a (re)manufacturer (M), a retailer (R), and an Internet recycling platform (ET) as the research objects. The manufacturer (M) sells its tires through the retailer (R) in the positive channel, while the manufacturer (M) entrusts the retailer (R) and Internet recycling platform (ET) to recycle waste tires at the same time in the reverse channel. During recycling, the retailer and Internet recycling platform will pay a certain recycling price to the consumer, and the (re)manufacturer will pay a certain recycling transfer price to the retailer and Internet recycling platform. Meanwhile, in order to encourage the recycling and remanufacturing behaviors in the market, the government will provide the corresponding subsidies for different recycling participants to enhance the circulation utilization rate of resources. From this, we can see that there are four recycling models composed of (re)manufacturer M, retailer R, Internet recycling platform ET, and government G, based on different subsidy objects as shown in Figure 1.

2.2. Assumptions. The Stackelberg game is a typical sequential game in which a leading player can anticipate the response of the follower to their strategy. In this game

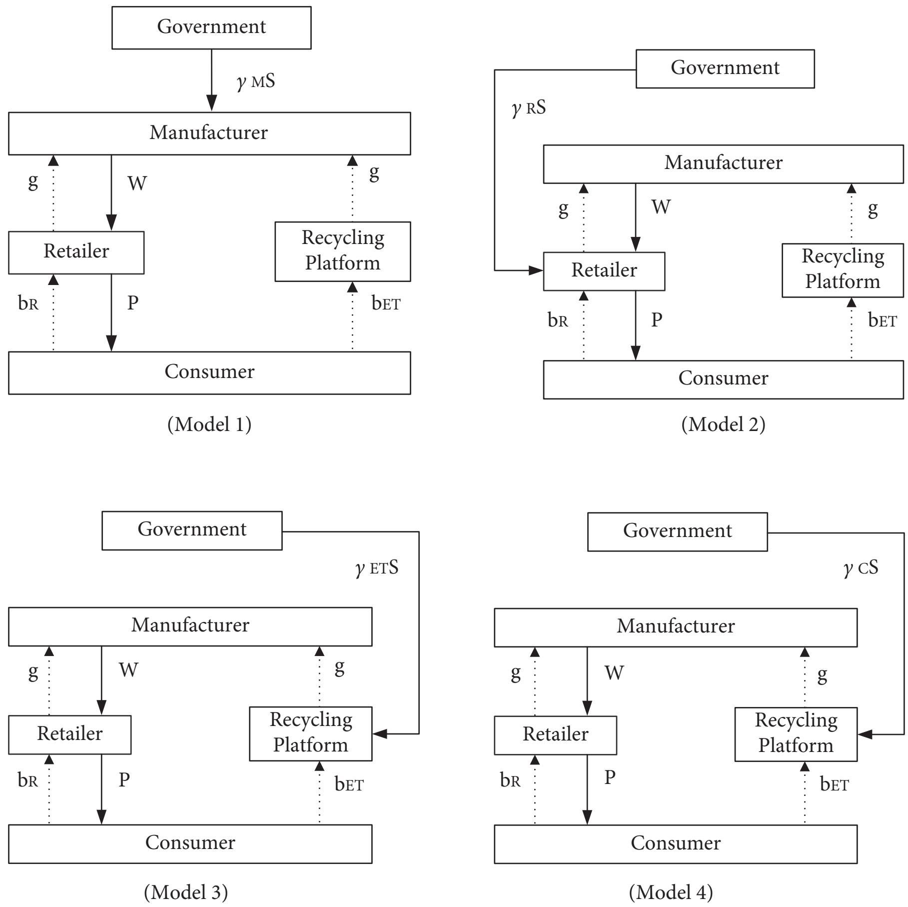

Figure 1: The structure of waste tire closed-loop supply chain model.

model, the player who makes the decision first is called the leader, while the next player makes the decision based on the leader's decision, which is called the follower. As stated before, in the proposed game model, the (re)manufacturer (M), the retailer (R), and the Internet recycling platform (ET) were reassumed as a single game player, respectively. This setting of a single player at each stage is not unrealistic from an economy of scale and stability, but it does not affect the main purpose of this paper, that is, to analyze the impacts of such government subsidies on the waste tire recycling supply chain in different game models. In this study, without changing the essence of the research, several assumptions and parameters are made as follows.

Assumption 1. All the recycled waste tires in the market can be used for remanufacturing, and one unit of waste tires can only remanufacture one unit of remanufactured tires. The market makes no distinction between the tires manufactured with new raw materials and tires remanufactured from the old ones; that is, they will be regarded as having the same quality and the same retail price.

Assumption 2. In the Stackelberg game, the manufacturer is the market leader, the retailer and Internet recycling platform are its followers, and all supply chain participants will make decisions to maximize their interests.

Assumption 3. The manufacturer is responsible for manufacturing new tires and remanufacturing tires. The unit price of production about the new tires is A_3, the unit price of production with regard to the remanufactured tires is c_r, and it is assumed that $\Delta = A_3 - c_r > 0$, with Δ indicating the cost saved through remanufacturing activity. The unit price of wholesale concerning the tires is W.

Assumption 4. The Internet recycling platform takes advantage of its online promotion and door-to-door pickup to recycle the waste tires. The recycling transfer price paid by the manufacturer to the Internet recycling platform or retailer is g, it is assumed that $g > b_R$ to ensure that it is profitable for the Internet recycling platform, and it is assumed that $\Delta > b_R$ to ensure that the manufacturer's remanufacturing activity is profitable.

Assumption 5. The consumer demand function in the positive channel is $Q = a - \partial P > 0$, with the demand being positive permanently. a is the total demand quantity in the market and ∂ is the sensitivity coefficient of consumers for the sale price. The recycling quantity functions for retailers and Internet recycling platforms in the reverse channel are $Q_R = k + \beta b_R - \theta b_{ET} Q_{ET} = k + \beta b_{ET} - \theta b_R$, respectively. k is the quantity of waste tires which are returned by the consumers without charge, β is the sensitivity coefficient for recycling price, θ is the sensitivity coefficient for cross price, and $\beta > \theta > 0$; that is, the influence of recycling price on recycling quantity in this channel is greater than that in the other channel. b_R is the recycling price paid by the retailer to the consumer and b_{ET} is the recycling transfer price paid by the Internet recycling platform to the consumer.

2.3. Descriptions for the Parameters and Symbols

β: The sensitivity coefficient of consumer for the sale price.

θ: The sensitivity coefficient for cross price, indicating the influence of price in this channel on recycling quantity in other channels, $\beta > \theta > 0$.

k: The quantity of waste tires which are returned by the consumers without charge.

∂: The sensitivity coefficient of consumer for sale price.

S: The highest price under government subsidy.

A_1: The unit cost of operation under recycling activity by the Internet recycling platform.

A_2: The unit cost of operation under sales activity by the retailer.

A_3: The unit cost of production with regard to the new tires.

c_r: The unit cost of production about the remanufactured tires.

Δ: The cost saved by the manufacturer in the remanufacturing activity, $\Delta = A_3 - c_r > 0$.

γ_j: The government's subsidy influence coefficient, j takes $MRET$ and C to indicate the influence of government subsidy on the manufacturer, retailer, Internet recycling platform, and consumer purchase, respectively.

a: The total demand quantity in the market.

P: The unit price of retail by the retailer.

W: The unit price of wholesale by the manufacturer;

g: The unit price of recycling transfer paid by the manufacturer to the Internet recycling platform or retailer.

b_R: The unit price of recycling paid by the retailer to the consumer.

b_{ET}: The unit price of recycling transfer paid by the Internet recycling platform to the consumer.

Π_j^i: j takes M, R, and ET to indicate the profits of manufacturer, retailer, and Internet recycling platform, respectively; i takes 1, 2, 3 and 4 to indicate Model 1, Model 2, Model 3, and Model 4.

SW: Social welfare.

3. Building and Solving of Closed-Loop Supply Chain Pricing Decision Model

The closed-loop supply chain pricing decision model is a three-level closed-loop supply chain system composed of manufacturer, retailer, and Internet recycling platform and other participants. The manufacturer is the leader in the entire closed-loop supply chain, who makes the pricing decision first. That is to say, under the four different subsidy policies, the manufacturer first determines the product's wholesale price W and pays the recycling transfer price g to the recycling parties (retailer and Internet recycling platform) in order to maximize the profit. The retailer determines the sale price P and recycling price b_R based on the wholesale price W and recycling transfer price g determined by the manufacturer. Meanwhile, the Internet recycling platform determines the optimal recycling price b_{ET}. There is a Nash equilibrium relationship between the two, and the optimal decision variables of all participants are obtained according to the backward induction method. The influence of government subsidy for manufacturer, retailer, Internet recycling platform, and consumer on each participant's pricing, profit distribution, and overall social welfare are studied, respectively. The function expression of social welfare is as follows:

$$SW = \Pi_R^1 + \Pi_{ET}^1 + \Pi_M^1 - S\left(Q_R^1 + Q_{ET}^1\right). \quad (1)$$

3.1. Model 1 with the Manufacturer as the Subsidy Object.

In this model, government subsidy for the manufacturer can stimulate the manufacturer's remanufacturing activities, equivalent to reducing the manufacturer's remanufacturing cost and increasing its profit. $\gamma_M S$ indicates the influence of government subsidy for manufacturers on remanufacturing. Under this model, the function expressions for the profits of manufacturer, retailer, and Internet recycling platform are as follows:

$$\begin{aligned}
\Pi_M^1 &= (W - A_3)Q + (\Delta + \gamma_M S - g)(Q_R + Q_{ET}),\\
\Pi_R^1 &= (P - W - A)_2 Q + (g - b_R)Q_R,\\
\Pi_{ET}^1 &= (g - b_{ET} - A_1)Q_{ET}.
\end{aligned} \quad (2)$$

According to the backward induction method, the retailer first solves the optimal value of sale price P, while the retailer and Internet recycling platform solves the optimal values of their respective recycling prices b_R and b_{ET}. Finally, the manufacturer solves the optimal values of its wholesale price W and recycling transfer price g.

The partial derivatives of P and b_R in the retailer profit expression (3) as well as b_{ET} in the Internet recycling platform profit expression (4) are found. With $\partial\Pi_R^1/\partial P = 0$ the P related expression including W is solved:

$$P = \frac{a + W\alpha + \alpha A_2}{2\alpha}. \quad (3)$$

There is a Nash equilibrium between the retailer and Internet recycling platform. The b_R and b_{ET} related expressions including g are solved simultaneously with $\{\partial\Pi_R^1/\partial b_R = 0, \partial\Pi_{ET}^1/\partial b_{ET} = 0\}$, as follows:

$$\begin{aligned} b_{ET} &= -\frac{(k - g\beta)(2\beta + \theta) + 2\beta^2 A_1}{4\beta^2 - \theta^2}, \\ b_R &= -\frac{(k - g\beta)(2\beta + \theta) + \beta\theta A_1}{4\beta^2 - \theta^2}. \end{aligned} \tag{4}$$

The expressions (5)–(7) are introduced into the manufacturer profit function (1.1) of Model 1. To maximize self-interest, the partial derivatives of the wholesale price W and recycling price g are found, respectively. That is, $\partial\Pi_M^1/\partial b_g = 0$ and $\partial\Pi_M^1/\partial b_W = 0$ are found, respectively. In Model 1, the optimal equilibrium solutions of W and g can be calculated as

$$\begin{aligned} W^1 &= \frac{a - \alpha A_2 + \alpha A_3}{2\alpha}, \\ g^1 &= \frac{-2(k + \Delta(-\beta + \theta)) + (\beta - \theta)(A_1 + 2S\gamma_M)}{4(\beta - \theta)}. \end{aligned} \tag{5}$$

The expression (8) is introduced into expression (1.4) to obtain the optimal equilibrium solution of the retail price in Model 1:

$$P^1 = \frac{3a + \alpha(A_2 + A_3)}{4\alpha}. \tag{6}$$

The expression (9) is introduced into expressions (6) and (7) to obtain the optimal equilibrium solutions of recycling prices by the retailer and Internet recycling platform in Model 1:

$$b_R^1 = -\frac{\beta\theta A_1 + (2\beta + \theta)\left(k - (\beta\Delta/2) + (k\beta/(2\beta - 2\theta)) - t(1/4)n\beta q\left(A_1 + 2S\gamma_M\right)\right)}{4\beta^2 - \theta^2}, \tag{7}$$

$$b_{ET}^1 = -\frac{2\beta^2 A_1 + (2\beta + \theta)\left(k - (\beta\Delta/2) + (k\beta/(2\beta - 2\theta)) - t(1/4)n\beta q\left(A_1 + 2S\gamma_M\right)\right)}{4\beta^2 - \theta^2}. \tag{8}$$

The results of equations (6)–(8) are the optimal pricing strategies of all participants in the closed-loop supply chain in Model 1. The optimal profits of manufacturer, retailer, and Internet recycling platform can be obtained by introducing the results into the profit function:

$$\begin{aligned} \Pi_M^1 &= \frac{4k^2\alpha\beta + 8k\alpha\beta\Delta(\beta - \theta) + \left(4\alpha\beta\Delta^2(\beta - \theta) + a^2(2\beta - \theta)\right)(\beta - \theta) + \alpha(\beta - \theta)\beta(\beta - \theta)A_1^2}{8\alpha(\beta - \theta)(2\beta - \theta)} \\ &\quad + \frac{(2\beta - \theta)\left(A_2 + A_3\right)\left(-2a + \alpha\left(A_2 + A_3\right)\right) + 8S\beta(k + \Delta(\beta - \theta))\gamma_M + 4S^2\beta(\beta - \theta)\gamma_M^2}{8\alpha(\beta - \theta)(2\beta - \theta)}, \\ \Pi_R^1 &= \frac{1}{16}\left(\frac{\left(a - \alpha\left(A_2 + A_3\right)\right)^2}{\alpha} + \frac{1}{\left(-4\beta^2 + \theta^2\right)^2}\beta\left(\left(2\beta^2 + 3\beta\theta - \theta^2\right)A_1 + 2(2\beta + \theta)\left(k + \beta\Delta - \Delta\theta + S(\beta - \theta)\gamma_M\right)\right)^2\right), \\ \Pi_{ET}^1 &= \frac{\left(\beta\left(\left(6\beta^2 + \beta\theta - 3\theta^2\right)A_1 - 2(2\beta + \theta)\left(k + \beta\Delta - \Delta\theta + S(\beta - \theta)\gamma_M\right)\right)^2\right)}{\left(16\left(-4\beta^2 + \theta^2\right)^2\right)}. \end{aligned} \tag{9}$$

The relevant pricing decision variables are introduced into Q_{ET} and Q_R to obtain

$$\begin{aligned} Q_{ET}^1 &= \frac{1}{16\beta^2 - 4\theta^2}\beta\left(-\left(6\beta^2 + \beta\theta - 3\theta^2\right)A_1 + 2(2\beta + \theta)\left(k + \beta\Delta - \Delta\theta + S(\beta - \theta)\gamma_M\right)\right), \\ Q_R^1 &= \frac{1}{16\beta^2 - 4\theta^2}\beta\left(\left(2\beta^2 + 3\beta\theta - \theta^2\right)A_1 + 2(2\beta + \theta)\left(k + \beta\Delta - \Delta\theta + S(\beta - \theta)\gamma_M\right)\right). \end{aligned} \tag{10}$$

The expressions (9) and (10) are introduced into the function of social welfare to obtain

$$SW^1 = \Pi_M^1 + \Pi_R^1 + \Pi_{ET}^1 - \frac{S\beta((-\beta+\theta)A_1 + 2(k+\beta\Delta - \Delta\theta + S(\beta-\theta)\gamma_M))}{4\beta - 2\theta}. \quad (11)$$

3.2. Model 2 with the Retailer as the Subsidy Object. The government subsidy for retailer can reduce the operating cost of the retailer's sales activities to encourage the retailer to open up sales channels. $\gamma_R S$ indicates the cost reduction brought by the subsidy for the retailer. Under this model, the function expressions for the profits of manufacturer, retailer, and Internet recycling platform are defined as

$$\begin{aligned}
\Pi_M^2 &= (W - A_3)Q + (\Delta - g)(Q_R + Q_{ET}),\\
\Pi_R^2 &= (P - W - A_2 + \gamma_R S)Q + (g - b_R)Q_R,\\
\Pi_{ET}^2 &= (g - b_{ET} - A_1)Q_{ET}.
\end{aligned} \quad (12)$$

With similar solving process in Model 1 under Section 3.1, the equilibrium solutions in Model 2 are presented as

$$\begin{aligned}
P^2 &= \frac{3a + \alpha(A_2 + A_3 - S\gamma_R)}{4\alpha},\\
b_{ET}^2 &= -\frac{2\beta^2 A_1 + (2\beta+\theta)(k - 1/4\beta(2(\Delta + k/-\beta+\theta) + A_1))}{4\beta^2 - \theta^2},\\
b_R^2 &= -\frac{\beta\theta A_1 + (2\beta+\theta)(k - 1/4\beta(2(\Delta + k/-\beta+\theta) + A_1))}{4\beta^2 - \theta^2},\\
W^2 &= \frac{a + \alpha(-A_2 + A_3 + S\gamma_R)}{2\alpha},\\
g^2 &= 1/4\beta(2(\Delta + k/-\beta+\theta) + A_1).
\end{aligned} \quad (13)$$

The expressions (13) are introduced into expressions (12) to obtain the optimal profits of manufacturer, retailer, and Internet recycling platform:

$$\begin{aligned}
\Pi_M^2 &= \frac{1}{8}\left(\frac{\beta(2(k+\Delta(\beta-\theta)) + (-\beta+\theta)A_1)^2}{2\beta^2 - 3\beta\theta + \theta^2} + \frac{(a - \alpha A_2 - \alpha A_3 + S\alpha\gamma_R)^2}{\alpha}\right),\\
\Pi_R^2 &= \frac{1}{16}\left(\frac{\beta\left(2(k+\Delta(\beta-\theta))(2\beta+\theta) + \left(2\beta^2 + 3\beta\theta - \theta^2\right)A_1\right)^2}{\left(-4\beta^2 + \theta^2\right)^2} + \frac{(a - \alpha A_2 - \alpha A_3 + S\alpha\gamma_R)^2}{\alpha}\right),\\
\Pi_{ET}^2 &= \frac{\beta\left(-2(k+\Delta(\beta-\theta))(2\beta+\theta) + \left(6\beta^2 + \beta\theta - 3\theta^2\right)A_1\right)^2}{16\left(-4\beta^2 + \theta^2\right)^2}.
\end{aligned} \quad (14)$$

The relevant equilibrium solutions in Model 2 are introduced into Q_{ET} and Q_R to obtain

$$Q_{ET}^2 = \frac{\beta\left(2(k+\Delta(\beta-\theta))(2\beta+\theta)-\left(6\beta^2+\beta\theta-3\theta^2\right)A_1\right)}{16\beta^2-4\theta^2},$$
$$Q_R^2 = \frac{\beta\left(2(k+\Delta(\beta-\theta))(2\beta+\theta)+\left(2\beta^2+3\beta\theta-\theta^2\right)A_1\right)}{16\beta^2-4\theta^2}. \tag{15}$$

The expressions (14) and (15) are introduced into the function of social welfare (0) to obtain

$$SW^2 = \Pi_M^2 + \Pi_R^2 + \Pi_{ET}^2 - \frac{S\beta(2(k+\Delta(\beta-\theta))+(-\beta+\theta)A_1)}{4\beta-2\theta}. \tag{16}$$

3.3. Model 3 with the Internet Recycling Platform as the Subsidy Object. The government subsidy for the Internet recycling platform can reduce the operating cost of its recycling activities. $\gamma_{ET}S$ indicates the cost reduction. Under this model, the function expressions for the profits of manufacturer, retailer, and Internet recycling platform are expressed as

$$\begin{aligned}\Pi_M^3 &= (W-A_3)Q+(\Delta-g)(Q_R+Q_{ET}),\\ \Pi_R^3 &= (P-W-A_2)Q+(g-b_R)Q_R,\\ \Pi_{ET}^3 &= (g-b_{ET}-A_1+\gamma_{ET}S)Q_{ET}.\end{aligned} \tag{17}$$

With a similar solving process in Model 1 under Section 3.1, the equilibrium solutions of all participants in Model 3 are as follows:

$$\begin{aligned}P^3 &= \frac{3a+\alpha(A_2+A_3)}{4\alpha},\\ b_{ET}^3 &= \frac{2(2\beta+\theta)(\beta\Delta(\beta-\theta)+k(-3\beta+2\theta))}{4(\beta-\theta)\left(4\beta^2-\theta^2\right)} + \frac{\beta\left(6\beta^2-7\beta\theta+\theta^2\right)(-A_1+S\gamma_{ET})}{4(\beta-\theta)\left(4\beta^2-\theta^2\right)},\\ b_R^3 &= \frac{2(2\beta+\theta)(\beta\Delta(\beta-\theta)+k(-3\beta+2\theta))+\beta(2\beta-3\theta)(\beta-\theta)(A_1-S\gamma_{ET})}{4(\beta-\theta)\left(4\beta^2-\theta^2\right)},\\ W^3 &= \frac{a-\alpha A_2+\alpha A_3}{2\alpha},\\ g^3 &= \frac{-2(k+\Delta(-\beta+\theta))+(\beta-\theta)(A_1-S\gamma_{ET})}{4(\beta-\theta)}.\end{aligned} \tag{18}$$

The expressions (18) are introduced into expressions (17) to obtain the optimal profits of manufacturer, retailer, and Internet recycling platform:

$$\begin{aligned}\Pi_M^3 &= \frac{4k^2\alpha\beta+8k\alpha\beta\Delta(\beta-\theta)+\left(4\alpha\beta\Delta^2(\beta-\theta)+a^2(2\beta-\theta)\right)(\beta-\theta)}{8\alpha(\beta-\theta)(2\beta-\theta)}\\ &\quad+\frac{4S\beta(k+\Delta(\beta-\theta))\gamma_{ET}+S^2\beta(\beta-\theta)\gamma_{ET}^2-2\beta A_1(2(k+\beta\Delta-\Delta\theta)+S(\beta-\theta)\gamma_{ET})}{8\alpha(\beta-\theta)(2\beta-\theta)},\\ \Pi_R^3 &= \frac{1}{16}\left(\frac{(a-\alpha(A_2+A_3))^2}{\alpha}+\frac{\beta\left(2(k+\Delta(\beta-\theta))(2\beta+\theta)+\left(2\beta^2+3\beta\theta-\theta^2\right)(A_1-S\gamma_{ET})\right)^2}{\left(-4\beta^2+\theta^2\right)^2}\right),\\ \Pi_{ET}^3 &= \frac{\beta\left(-2(k+\Delta(\beta-\theta))(2\beta+\theta)+\left(6\beta^2+\beta\theta-3\theta^2\right)(A_1-S\gamma_{ET})\right)^2}{16\left(-4\beta^2+\theta^2\right)^2}.\end{aligned} \tag{19}$$

The relevant equilibrium solutions in Model 3 are introduced into Q_{ET} and Q_R to obtain

$$Q_{ET}^3 = \frac{\beta\left(2\,(2\beta+\theta)\,(k+\beta\Delta-\Delta\theta)-\left(6\beta^2+\beta\theta-3\theta^2\right)A_1+S\left(6\beta^2+\beta\theta-3\theta^2\right)\gamma_{ET}\right)}{16\beta^2-4\theta^2},$$
$$Q_R^3 = \frac{\beta\left(2\,(k+\Delta\,(\beta-\theta))\,(2\beta+\theta)+\left(2\beta^2+3\beta\theta-\theta^2\right)(A_1-S\gamma_{ET})\right)}{16\beta^2-4\theta^2},$$
$$Q_R^3 = \frac{\beta\left(2\,(k+\Delta\,(\beta-\theta))\,(2\beta+\theta)+\left(2\beta^2+3\beta\theta-\theta^2\right)(A_1-S\gamma_{ET})\right)}{16\beta^2-4\theta^2}. \tag{20}$$

The expressions (19) and (20) are introduced into the function of social welfare to obtain

$$SW^3 = \Pi_M^3+\Pi_R^3+\Pi_{ET}^3-\frac{S\beta\,(2\,(k+\Delta\,(\beta-\theta))-(\beta-\theta)\,(A_1-S\gamma_{ET}))}{4\beta-2\theta}. \tag{21}$$

3.4. Model 4 with the Consumer as the Subsidy Object. To simplify the calculation, it is assumed that the government subsidy for consumer will affect the consumer's desire to buy new tires and then affect the total market demand. $\gamma_C S$ indicates the increased market demand. Under this model, the function expressions for the profits of manufacturer, retailer, and Internet recycling platform can be characterized by

$$\Pi_M^4 = (W-A_3)\,(Q+\gamma_C S)+(\Delta-g)\,(Q_R+Q_{ET}),$$
$$\Pi_R^4 = (P-W-A_2)\,(Q+\gamma_C S)+(g-b_R)Q_R,$$
$$\Pi_{ET}^3 = (g-b_{ET}-A_1)Q_{ET}. \tag{22}$$

With a similar solving process in Model 1 under Section 3.1, the equilibrium solutions of all participants in Model 4 are as follows:

$$P^4 = \frac{3a+\alpha A_2+\alpha A_3+3S\gamma_C}{4\alpha},$$
$$b_{ET}^4 = -\frac{2\beta^2A_1+(2\beta+\theta)\,(k-1/4\beta\,(2\,(\Delta+k/-\beta+\theta)+A_1))}{4\beta^2-\theta^2},$$
$$b_R^4 = -\frac{\beta\theta A_1+(2\beta+\theta)\,(k-1/4\beta\,(2\,(\Delta+k/-\beta+\theta)+A_1))}{4\beta^2-\theta^2},$$
$$W^4 = \frac{a-\alpha A_2+\alpha A_3+S\gamma_C}{2\alpha},$$
$$g^4 = \left(\frac{1}{4}\beta\left(2\left(\Delta+\frac{k}{-\beta+\theta}\right)+A_1\right)\right). \tag{23}$$

The expressions (23) are introduced into expressions (22) to obtain the optimal profits of manufacturer, retailer, and Internet recycling platform

$$\Pi_M^4 = \frac{1}{8}\left(\frac{\beta\left(2\left(k+\Delta(\beta-\theta)\right)+(-\beta+\theta)A_1\right)^2}{2\beta^2-3\beta\theta+\theta^2}+\frac{\left(a-\alpha\left(A_2+A_3\right)+S\gamma_C\right)^2}{\alpha}\right),$$

$$\Pi_R^4 = \frac{1}{16}\left(\frac{\beta\left(2\left(k+\Delta(\beta-\theta)\right)(2\beta+\theta)+\left(2\beta^2+3\beta\theta-\theta^2\right)A_1\right)^2}{\left(-4\beta^2+\theta^2\right)^2}+\frac{\left(a-\alpha\left(A_2+A_3\right)+S\gamma_C\right)^2}{\alpha}\right), \quad (24)$$

$$\Pi_{ET}^3 = \frac{\beta\left(-2\left(k+\Delta(\beta-\theta)\right)(2\beta+\theta)+\left(6\beta^2+\beta\theta-3\theta^2\right)A_1\right)^2}{16\left(-4\beta^2+\theta^2\right)^2}.$$

The relevant equilibrium solutions in Model 4 are introduced into Q_{ET} and Q_R to obtain

$$Q_{ET}^4 = \frac{\beta\left(2\left(k+\Delta(\beta-\theta)\right)(2\beta+\theta)-\left(6\beta^2+\beta\theta-3\theta^2\right)A_1\right)}{16\beta^2-4\theta^2},$$

$$Q_R^4 = \frac{\beta\left(2\left(k+\Delta(\beta-\theta)\right)(2\beta+\theta)+\left(2\beta^2+3\beta\theta-\theta^2\right)A_1\right)}{16\beta^2-4\theta^2}. \quad (25)$$

The expressions (24) and (25) are introduced into the function of social welfare to obtain

$$SW^4 = \Pi_M^4+\Pi_R^4+\Pi_{ET}^4-\frac{S\beta\left(2\left(k+\Delta(\beta-\theta)\right)+(-\beta+\theta)A_1\right)}{4\beta-2\theta}. \quad (26)$$

4. Model Comparison

4.1. Comparison of the Optimal Equilibrium Solutions of Various Indicators in the Sales Channel

4.1.1. Comparison of Wholesale Price

Proposition 1. *if* $(\gamma_R/\gamma_C)>(1/\alpha)$, *then,* $W^2>W^4>W^1=W^3$; *if* $(\gamma_R/\gamma_C)<(1/\alpha)$ *then* $W^4>W^2>W^1=W^3$,

$$W^1=W^3,\ W^2-W^3=\frac{S\gamma_R}{2}>0,$$
$$W^4-W^3=\frac{S\gamma_C}{2\alpha}>0;. \quad (27)$$

Proof

$$W^2-W^4=\frac{-S\gamma_C+S\alpha\gamma_R}{2\alpha},$$
$$\text{if } \frac{\gamma_R}{\gamma_C}>\frac{1}{\alpha}, \text{ then } W^2-W^4>0, \quad (28)$$
$$\text{if } \frac{\gamma_R}{\gamma_C}<\frac{1}{\alpha}, \text{ then } W^2-W^4<0.$$

Conclusion. In case of the government subsidy for manufacturer or Internet recycling platform, the product's wholesale price remains unchanged; in case of the government subsidy for retailer or consumer, the product's wholesale price is higher than that in case of the government subsidy for other participants, but the product's wholesale price under the government subsidy for retailer and consumer is relevant to α coefficient. The specific influence will be further discussed in the analysis of examples.

4.1.2. Comparison of Retail Prices

Proposition 2. $P^4>P^1=P^3>P^2$.

Proof

$$P^1=P^3,$$
$$P^4-P^1=\frac{3S\gamma_C}{4\alpha}>0, \quad (29)$$
$$P^1-P^2=\frac{S\gamma_R}{4}>0.$$

Conclusion: In case of the government subsidy for consumers, it has the highest retail price of product; in case of the government subsidy for retailer, it has the lowest retail price of product; in case of the government subsidy for manufacturer or Internet recycling platform, the retail price of product remains unchanged. Therefore, considering the consumer market, in case of the government subsidy for retailer, it is conducive to promoting consumer desire, driving market demand, and expanding the tire recycling market, to achieve economic and environmental benefits. □

4.2. Comparison of the Optimal Equilibrium Solutions of Various Indicators in Recycling Channel

4.2.1. Comparison about Recycling Prices by Retailer

Proposition 3

$$\begin{aligned}
&\text{if } \frac{\beta}{\theta} > \frac{3}{2}, \text{ then } b_R^1 > b_R^2 = b_R^4 > b_R^3;\\
&\text{if } \frac{\beta}{\theta} \left\langle \frac{3}{2}, \text{ and } \frac{\gamma_M}{\gamma_{ET}} \right\rangle \frac{3\theta - 2\beta}{2(2\beta + \theta)}, \text{ then } b_R^1 > b_R^3 > b_R^2 = b_R^4;\\
&\text{if } \frac{\beta}{\theta} < \frac{3}{2}, \text{ and } \frac{\gamma_M}{\gamma_{ET}} < \frac{3\theta - 2\beta}{2(2\beta + \theta)}, \text{ then } b_R^3 > b_R^1 > b_R^2 = b_R^4;
\end{aligned} \tag{30}$$

Proof

$$\begin{aligned}
&b_R^1 - b_R^2 = \frac{S\beta\gamma_M}{2(2\beta - \theta)} > 0, b_R^4 = b_R^2,\\
&b_R^1 - b_R^3 = \frac{S\beta\left((2\beta - 3\theta)\gamma_{ET} + 2(2\beta - \theta)\gamma_M\right)}{4(2\beta - \theta)(2\beta - \theta)},\\
&\quad \text{if } \frac{\gamma_M}{\gamma_{ET}} > \frac{3\theta - 2\beta}{2(2\beta - \theta)}, \text{ then } b_R^1 - b_R^3 > 0;\\
&\quad \text{if } \frac{\gamma_M}{\gamma_{ET}} < \frac{3\theta - 2\beta}{2(2\beta - \theta)}, \text{ then } b_R^1 - b_R^3 < 0;\\
&b_R^2 - b_R^3 = \frac{S\beta(2\beta - 3\theta)\gamma_{ET}}{4(2\beta - \theta)(2\beta - \theta)},\\
&\quad \text{if } \frac{\beta}{\theta} > \frac{3}{2}, \text{ then } b_R^2 - b_R^3 > 0, \text{ if } \frac{\beta}{\theta} < \frac{3}{2}, \text{ then } b_R^2 - b_R^3 < 0.
\end{aligned} \tag{31}$$

Conclusion. If $\beta/\theta < 3/2$, in case of the government subsidy for retailer or consumer, it has no influence on the retailer's recycling price of waste tires; in case of the government subsidy for manufacturer or Internet recycling platform, it will increase the retailer's recycling price, but the relationship between the two is relevant to $\gamma_M\backslash\gamma_{ET}\beta\backslash\theta$ coefficient which will be further discussed in the analysis of examples. If $\beta/\theta < 3/2$, in case of the government subsidy for manufacturer, it has the highest recycling price of waste product by the retailer; in case of the government subsidy for retailer or consumer, it does not influence the retailer's recycling price of waste product. □

4.2.2. Comparison about Recycling Prices by Internet Recycling Platform

Proposition 4

$$\begin{aligned}
&\text{if } \frac{\gamma_M}{\gamma_{ET}} > \frac{6\beta - \theta}{2(2\beta + \theta)},\\
&\text{then } b_{ET}^3 > b_{ET}^1 > b_{ET}^2 = b_{ET}^4;\\
&\text{if } \frac{\gamma_M}{\gamma_{ET}} < \frac{6\beta - \theta}{2(2\beta + \theta)},\\
&\text{then } b_R^1 > b_R^3 > b_R^2 = b_R^4;
\end{aligned} \tag{32}$$

Proof

$$\begin{aligned}
&b_{ET}^1 - b_{ET}^2 = \frac{S\beta\gamma_M}{2(2\beta - \theta)} > 0, b_{ET}^4 = b_R^2,\\
&b_{ET}^1 - b_{ET}^3 = \frac{S\beta\left(\theta - 6\beta)\gamma_{ET} + 2(2\beta - \theta)\gamma_M\right)}{4(2\beta - \theta)(2\beta - \theta)},\\
&\quad \text{if } \frac{\gamma_M}{\gamma_{ET}} > \frac{6\beta - \theta}{2(2\beta - \theta)}, \text{ then } b_{ET}^1 - b_{ET}^3 > 0;\\
&\quad \text{if } \frac{\gamma_M}{\gamma_{ET}} < \frac{6\beta - \theta}{2(2\beta - \theta)}, \text{ then } b_R^1 - b_R^3 < 0;\\
&b_{ET}^2 - b_{ET}^3 = \frac{S\beta(\theta - 6\beta)\gamma_{ET}}{4(2\beta - \theta)(2\beta + \theta)} < 0;
\end{aligned} \tag{33}$$

Conclusion. In case of the government subsidy for Internet recycling platform or manufacturer, it has the highest recycling price of waste tire by the Internet recycling platform, but the relationship between the two is relevant to β, θ coefficients which will be further discussed in the analysis of examples; in case of the government subsidy for retailer or consumer, the recycling price remains unchanged by the Internet recycling platform and it has the lowest recycling price by the Internet recycling platform at this moment. □

4.2.3. Comparison about Recycling Transfer Prices

Proposition 5

$$g^1 > g^2 = g^4 > g^3. \tag{34}$$

Proof

$$\begin{aligned}
&g^2 = g^4;\\
&g^1 - g^3 = \frac{S\left(\gamma_{ET} + 2\gamma_M\right)}{4} > 0;\\
&g^2 - g^3 = \frac{S\gamma_{ET}}{4} > 0;\\
&g^1 - g^2 = \frac{S\gamma_M}{4} > 0;
\end{aligned} \tag{35}$$

Conclusion. In case of the government subsidy for manufacturer, it has the highest recycling transfer price of waste tire by the manufacturer; in case of the government subsidy for Internet recycling platform, it has the lowest recycling transfer price by the manufacturer; in case of the government subsidy for retailer or consumer, the manufacturer's recycling transfer price remains unchanged.

In Models 1, 2, 3, and 4, the comparison on the optimal profits of manufacturer, retailer, and Internet recycling platform as well as social welfare depends on

$\alpha\backslash\beta\backslash\theta\backslash\gamma_j k\backslash A_j\backslash S$ and other parameters which will be further discussed in the analysis of examples. □

5. Numerical Examples and Sensitivity Analysis

5.1. Numerical Examples. In the analysis of Section 4, the relevant conclusion is obtained through the analytical analysis of the optimal decisions. In order to prove the correctness and validity of the conclusion in Section 4, this section will verify the model conclusion according to the definitions of model parameters and the assumptions of relationships between parameters.

The specific data is assumed as follows:

$$\begin{aligned} a &= 1000,\\ \alpha &= 1,\\ k &= 20,\\ \beta &= 6,\\ \theta &= 2,\\ A_3 &= 60,\\ C_r &= 15,\\ A_1 &= 12,\\ A_2 &= 6,\\ S &= 25,\\ \gamma_M &= 2,\\ \gamma_R &= 1,\\ \gamma_C &= 1.8,\\ \gamma_{ET} &= 1.6. \end{aligned} \tag{36}$$

In this paper, we use Mathematica 9.0 simulation software to conduct the analysis of examples in the automobile tire industry. Based on the above parameter settings, the various decision parameters and optimal profits can be obtained as shown in Table 1.

5.2. Sensitivity Analysis. As the main purpose of this paper is to discuss how the government chooses subsidy objects to maximize social welfare and the profits of various participants, this section will discuss the influence of important parameters on social welfare and the profits of various participants.

5.2.1. The Influence of Government Subsidy Coefficient γ on Social Welfare under 4 Subsidy Modes. According to Figure 2, when the government chooses different subsidy objects, the influences of government subsidy coefficient on social welfare are similar. It can be found that when the government subsidy coefficient increases, the social welfare under the four subsidy modes will all be improved in varying degrees. When $\gamma \in [0, 15]$, SWC > SWET > SWM > SWR, indicating that it is conducive to improve the social welfare when the government chooses consumer as the subsidy object within this subsidy coefficient range; when $\gamma \in [15, 42]$, SWET > SWC > SWM > SWR, indicating that the government should subsidize the Internet recycling platform to maximize the social welfare within this subsidy coefficient range; when $\gamma > 42$, SWET > SWM > SWC > SWR, indicating that the government should still subsidize the Internet recycling platform to maximize the social welfare within this subsidy coefficient range. However, we can see that the social profit obtained under the subsidy mode for manufacturer is second only to that under the subsidy mode for Internet recycling platform, indicating that the government can subsidize the manufacturer when the Internet recycling platform is not chosen as the subsidy object due to certain reasons.

In conclusion, no matter how the subsidy coefficient changes, the social welfare under the subsidy model for the retailer is significantly lower than those under the other three subsidy modes. Therefore, it is recommended that the government does not choose retailers as the subsidy object. When the subsidy coefficient $\gamma \in [0, 15]$, it is recommended that the government chooses consumer as the subsidy object to maximize the social welfare; when the subsidy coefficient $\gamma > 15$, it is recommended that the government chooses Internet recycling platform as the subsidy object to maximize the social welfare.

5.2.2. The Influence of Government Subsidy Coefficient γ on the Profits of Various Participants under 4 Subsidy Modes

(1) Profit Comparison for Different Supply Chain Participants in Case of One Certain Subsidy Object. According to Figures 3 and 4, we can see that the profit of the Internet recycling platform does not change with the government subsidy coefficient, indicating that it has no influence on the profit of the Internet recycling platform when the government chooses retailer and consumer as the subsidy objects. According to Figure 5, it shows that the profit growth of the Internet recycling platform is not significantly affected when the government chooses manufacturer as the subsidy object. Therefore, when the government chooses the Internet recycling platform as the subsidy object, it can expand the recycling scale of the Internet recycling platform and increase consumers' online recycling willingness.

According to Figure 6, we can see that the profits of manufacturer, retailer, and Internet recycling platform increase with the subsidy coefficient, but the influence degrees are relatively different. The influence on the profit of Internet recycling platform is the most significant, followed by that of retailer and at last that of manufacturer. When $\gamma \in [0, 18]$, $\prod_M > \prod_R > \prod_{ET}$, and when $\gamma > 18$, $\prod_{\mathrm{ET}} > \prod_R > \prod_{\mathrm{M}}$, indicating that the profits of Internet recycling platform and retailer will be higher than that of manufacturer when the government subsidy coefficient for Internet recycling platform is higher than a certain value, which is not conducive to maintain the manufacturer's leading role in the supply chain. Therefore, in order to maintain the manufacturer's central role in the supply chain of waste tire recycling, the government subsidy coefficient for the Internet recycling platform shall not be over the critical value 18.

Table 1: Numerical simulation results and comparison of models based on four different subsidy objects.

Variable name	Subsidy object manufacturer M	Subsidy object retailer R	Subsidy object Internet recycling platform ET	Subsidy object consumer C	Result comparison
P	766.5	760.3	766.5	789	C > M = ET > R
W	527	539.5	527	549.5	C > R > M = ET
g	48	23	13	23	M > R = C > ET
b_R	25.8	10.8	8.2	10.8	M > R = C > ET
b_{ET}	20.6	5.6	20.2	5.6	M > ET > R = C
Q_{ET}	92.2	32.2	124.8	32.2	ET > M > R = C
Q_R	133.4	73.4	28.8	73.4	M > R = C > ET
Π_M	119647.7	117283	113960	122128	M > R > C > ET
Π_R	57486.9	58377.29	54660.5	60799.8	C > R > M > ET
Π_{ET}	1417.7	173.1	2595.84	173.1	ET > M > R = C
S_W	172912.3	56083.5	167376	180461	C > M > ET > R

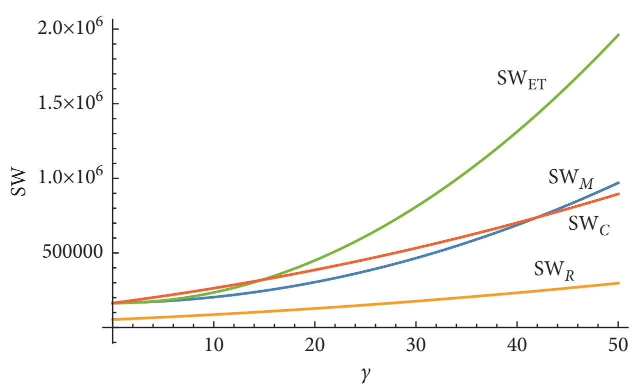

Figure 2: The Influence of γ on the social welfare of participants in closed-loop supply chain.

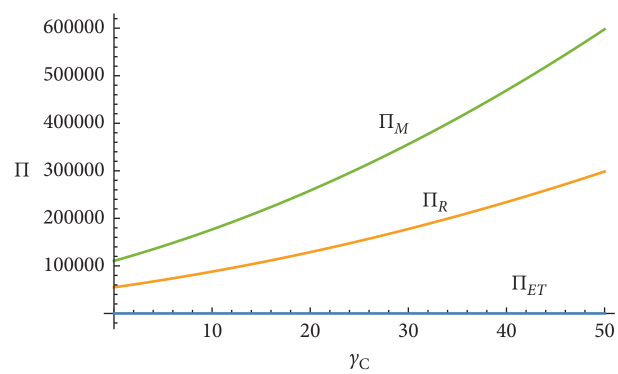

Figure 4: The influence of γ_C on the profits of various participants in CLSC when the consumer is subsidized.

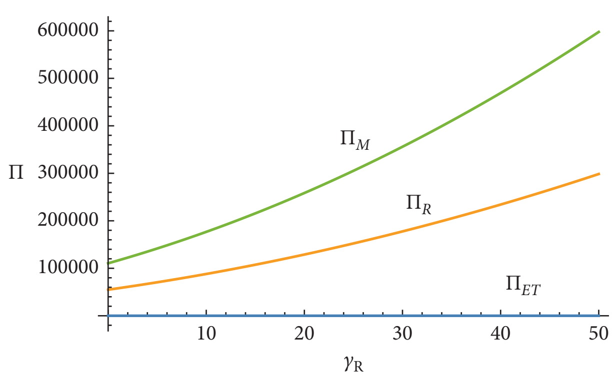

Figure 3: The influence of γ_R on the profits of various participants in closed-loop supply chain when the retailer is subsidized.

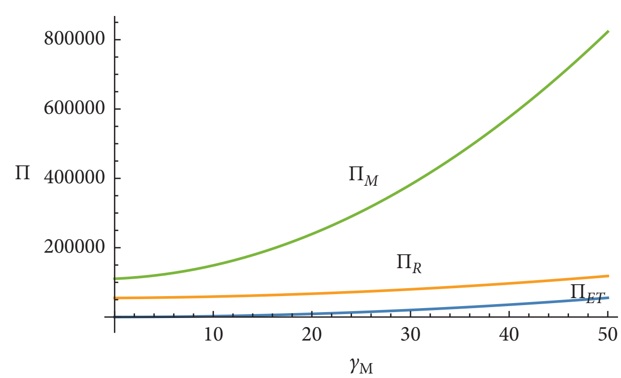

Figure 5: The influence of γ_M on the profits of various participants in CLSC when the manufacturer is subsidized.

(2) Profit Comparison for the Same Supply Chain Participant in Case of Different Subsidy Objects. From the manufacturer's perspective, it can be seen from Figure 7 that the maximum profit will be obtained with regard to the manufacturer when $\gamma \in [0, 25]$ and the government chooses retailer or consumer as the subsidy object; the maximum profit is obtained about the manufacturer when $\gamma > 25$ and the government directly chooses manufacturer as the subsidy object. From the retailer's perspective, it can be seen from Figure 8 that the maximum profit will be obtained concerning the retailer when $\gamma \in [0, 17]$ and the government chooses retailer or consumer as the subsidy object; the maximum profit will be obtained about the retailer when $\gamma > 17$ and the government chooses Internet recycling platform as the subsidy object. From the Internet recycling platform's perspective, it can be seen from Figure 9 that, regardless of the government subsidy coefficient, the maximum profit can be obtained about the Internet recycling platform only when the government chooses the Internet recycling platform as the subsidy object. When the

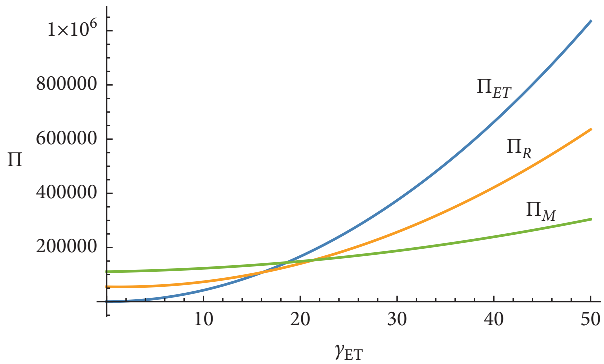

Figure 6: The influence of γ_{ET} on the profits of various participants in CLSC when the Internet recycling platform is subsidized.

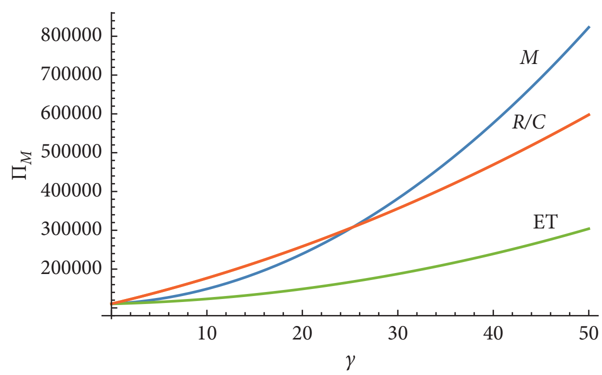

Figure 7: The influence of γ on the profit of manufacturer in case of different subsidy objects.

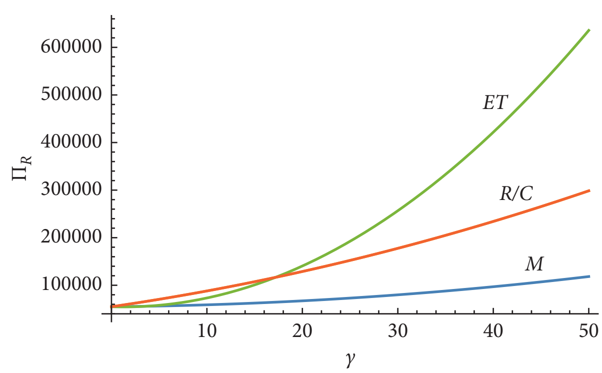

Figure 8: The influence of γ on the profit of retailer in case of different subsidy objects.

government chooses retailer or consumer as the subsidy object, the Internet recycling platform's profit will not be affected.

Therefore, based on the above conclusions, we can clearly know whether it is beneficial to our maximum profit when the government chooses different subsidy objects in different subsidy coefficient ranges. At the same time, it can also provide a reference for the government. If the government introduces relevant subsidy policies to regulate the

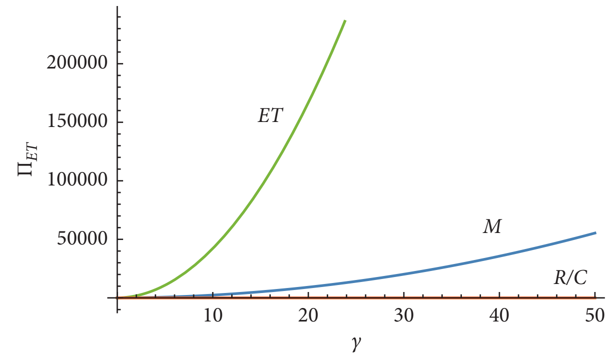

Figure 9: The influence of γ on the profit of Internet recycling platform in case of different subsidy objects.

tire recycling market, it should select the appropriate subsidy object within the subsidy coefficient range to maximize the target object's profit and social welfare.

6. Conclusion and Prospect

In this paper, we discuss the problem of government's optimal subsidy decision when retailer recycling and network platform recycling coexist, build a mixed recycling system of waste tires, establish and solve the optimal functions of various decision variables under four modes based on the dual perspectives of maximizing the enterprise's economic profit and government's social welfare, and analyze the influence of government subsidy coefficient on the economic benefits and social effects of closed-loop supply chain participants through adopting the theoretical analysis and numerical simulation methods. The optimal pricing strategies were proposed for manufacturers, retailers, and recyclers. By comparing different pricing decisions and numerical examples, the results show the following: (1) The government formulates subsidies for the manufacturer or Internet recycling platform, the product's wholesale price remains unchanged, and it has the highest recycling price of waste product by the retailer, while for the subsidies for retailer or consumer, the product's wholesale price is higher than that of other participants. The product's wholesale price under the government subsidy for retailer and consumer is relevant to coefficient α. (2) The government formulates subsidies for the consumer, it has the highest retail price of product; in case of the government subsidy for retailer, it has the lowest retail price of product. (3) When the target of government subsidies is retailer or consumer, it does not influence the retailer's recycling price of waste tires; in case of the government subsidy for manufacturer or Internet recycling platform, it will increase the retailer's recycling price. (4) The government formulates subsidies for Internet recycling platforms or manufacturers, and it has the highest recycling price of waste tire by the Internet recycling platform, but the relationship between them is related to the coefficients of β and θ.

Under the four subsidy modes, the government subsidy coefficient is positively correlated with social welfare. The social welfare will be maximized when $\gamma \in [0, 15]$ and the government chooses consumer as the subsidy object; the social welfare will be maximized when $\gamma > 15$ and the government chooses Internet recycling platform as the subsidy object. Government agencies often prescribe subsidized policies that directly target specific consumers to stimulate the market demand for waste tire recycling. We construct different pricing models corresponding to different targets of subsidies based on the game theory and analyze their differences. When the government chooses retailers and consumers as the subsidy objects, the subsidy coefficient change will have no influence on the profit of the Internet recycling platform. When the government chooses the Internet recycling platform as the subsidy object, the profits of supply chain participants increase with the increase of subsidy coefficient. If the subsidy object is the manufacturer, then the growth profit of Internet recycling platform is not significant. These pricing models provide policy suggestions for achieving optimal operating conditions in the closed-loop supply chain. To fully play the role of the Internet recycling platform, it is recommended that the government directly subsidizes the Internet recycling platform. However, in order to maintain the manufacturer's core position in the closed-loop supply chain, the subsidy coefficient for the Internet recycling platform should not exceed the critical value 18. In addition, the government should select different subsidy objects appropriately within different subsidy coefficient ranges to maximize the profits of participants in a closed-loop supply chain.

Despite the significant results yielded in the present study, it also posits some shortcomings that should be considered in future research. First, it is assumed that both the product demand function and waste tire recycling function are linear in the research, and it should be required to consider the uncertainty of the product demand function or the waste tire recycling function in future research. Secondly, the market makes no distinction between the tires manufactured with new raw materials and tires remanufactured from the old ones; that is, they will be regarded as having the same quality and the same retail price. We should deeply explore the effect of the different retail price in the future. Thirdly, consumer behaviors and different preferences should be considered in the construction of the optimization function.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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