

PRICING STRATEGIES FOR END-OF-LIFE VEHICLE REGARDING REWARD-PENALTY MECHANISM AND CUSTOMERS' ENVIRONMENTAL AWARENESS

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Abstract. Governments are paying more attention to end-of-life vehicle (ELV) recycling since it is closely related to the circular economy and sustainability development. Considering the reward-penalty-mechanism (RPM) and customers' environmental awareness (CEA), this study discusses the optimal recycling price, collection effort level of the ELVs, dismantling level of available parts and RPM intensity in a two-echelon supply chain consisting of a take back center (TBC), a dismantling center (DC) and the government. First, two models, Stackelberg and Collusion behaviour models, are constructed by using of game theory and the optimal decisions are obtained. Furthermore, optimal solutions are compared and some propositions are proposed. Finally, a numerical example is illustrated to study the effects of some parameters including CEA fluctuation, sale price of the scrapped parts and carbon emission savings. The results show that CEA fluctuation is always positive for collection efforts and recycling quantity. A higher CEA fluctuation alleviates the regulatory pressures and helps the government reduce regulation costs. A higher sale price of the scrapped parts helps the TBC achieve higher recycling scales. Carbon-emission-savings and CEA are key points in deciding the intensity and form of RPM. The optimal decisions are more sensitive to the change of parameters under the Collusion behaviour model. Based on the findings, the government should take measures to enhance the level of CEA and provide enterprises policy support to enhance the efficiency and effectiveness of ELV recycling. DCs should invest in dismantling technology and achieve breakthroughs. TBCs should take measures to appeal to more consumers to participate in ELV recycling. It is better for TBCs and DCs to cooperate to achieve an overall win-win situation.

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1. INTRODUCTION

In the face of growing environmental problems and increasingly scarce resources, the circular economy has become a new growth point for global sustainable development. The development of a circular economy can effectively improve the recycling efficiency of materials and products and reduce greenhouse gas emissions in all links of the industrial chain. Many green practices are implemented in production and consumption, such

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as the “three Rs” approach: reduce, reuse and recycle. In automobile field, end-of-vehicle (ELV) recycling is the main approach. ELV recycling has two advantages. One is to remove all the toxic fluids to avoid water and soil pollution; the other is to extract reusable components and reuse them in manufacturing and maintenance. Some countries and organizations have put forward specific policies and initiative to stimulate ELV recycling. For example, the Europe Union’s ELV Directive 2000/53/EC encourages manufacturers design their vehicles with the reusable and recycling parts. The World Economic Forum has proposed the circular car initiative, emphasizing the importance of car full lifecycle management involving ELV recycling and material reuse². To better develop the circular economy, China made major amendments to the Administrative Measures for the Recycling of ELVs in 2019 to allow the remanufacturing of five assembly parts of used vehicles. ELV recycling is an important component of the circular economy of the automotive industry, which achieve not only good economic benefits, but also obvious environmental and social benefits.

As car ownership increases, the number of ELVs is also increasing. ELVs generate approximately 7–8 million tons of waste each year in the EU. More than 12 million vehicles are currently scrapped and recycled each year in the U.S. When ELVs are not adequately managed, they can cause environmental problems [15, 39, 42]. Many enterprises engaged in ELV recycling. Almost 3500 firms with different sizes in the UK run authorized treatment facilities. From the perspective of market value, the recyclable resources produced by ELV recycling are considerable. An ELV can be disassemble into approximately 1.5 tons of scrap steel³. Every year, car recycling in North America produces enough steel to produce 13 million new vehicles and saves about 85 million barrels of oil. Professional ELV recycling and disposal can not only reduce harm to the environment, but also rationally reuse the available and remanufactured material and auto parts to maximize the utility of resources to alleviate resource shortages in the long term [47, 49, 55]. Therefore, ELV recycling and reusing is an important issue that must be addressed.

Although ELV recycling is essential to the circular economy, the recycling rate of ELVs is low. For example, in China, the number of cars reached 302 million in 2021, a year-on-year increase of 7.5%. China has stepped into the peak period of car scrapping [25]. However, the amount of scrapped and dismantled automobiles in China is less than 1% of the amount of ownership, far lower than the average of 7% in developed countries. In 2021, the theoretical number of vehicles scrapped should have been 8.527 million, while the actual number of regular vehicles recycled and dismantled was only 2.493 million, and the recycling rate was as low as 29.2%, as shown in Figure 1. One reason for the low recycling rate is that the formal channel of scrapping procedures of automobiles are more complicated than informal channel, including prechecking, professional dismantling, and reasonable classification, which result in high costs and low recycling prices. Furthermore, the price of an ELV in informal channels is more than 10 times that in formal channels. Therefore, car owners prefer to trade scrapped cars in the informal market to obtain higher profits, which results in a low rate of ELV recycling. Take back centers (TBCs) of ELVs must implement some measures to encourage car owners to scrap their cars through formal channels, thereby driving up the recycling rate. Therefore, balancing the optimal recycling price, collection efforts of the ELVs and costs is an important issue for TBCs.

Consumer environmental awareness (CEA) is a critical factor in ELV recycling. On the one hand, CEA has a positive effect on recycling [10, 16, 22, 66], which can push TBC to autonomously participate in the environmental market [22]. Meanwhile, CEA affects consumers’ cognition and behaviour related to ELV recycling and decisions, so the ELV recycling rate is affected by CEA [21, 60]. A TBC, such as a car maker’s own recycling channel and a third-party recycling channel, directly communicates with the consumer and plays a foundational role in ELVs supply. The TBC’s recycling efforts, such as advertising, general education and recycling services, can improve CEA, which in turn increases recycling rates through formal channels. As mentioned above, a higher recycling price is more attractive to consumers; therefore, it is important to improve CEA. On the other hand, CEA promotes the dismantle center (DC) performance. DC masters the core technology of ELV recycling and is responsible for the precheck and professional dismantling services. To maximize profits, DC invests in dismantling

²<https://www.weforum.org/projects/the-cDcular-cars-initiative>

³<http://finance.sina.com.cn/money/future/roll/2023-03-14/doc-imykvqxx5202569.shtml>

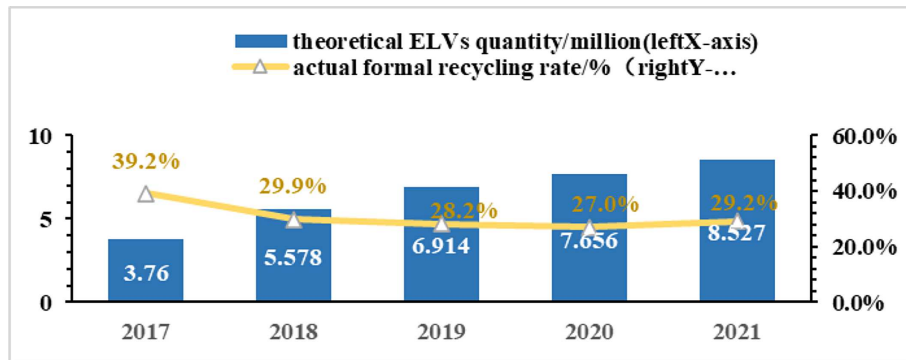


FIGURE 1. The theoretical ELV quantity in 2021 (million).

technology to improve the quality of recycled parts to stimulate sales. CEA can effectively amplify the positive effects of investment. The higher the CEA, the more acceptable dismantled parts are to consumers. Therefore, the collection efforts of TBC can influence CEA and further influence the recycling quantity. Meanwhile, CEA influences DC's investment result and performance. Hence, CEA is an important factor in recycling and green practice in automobile industry and it is necessary to consider CEA in ELV recycling. Therefore, under the influence of CEA, how to decide the optimal collection efforts of TBCs, the dismantling level of the available parts of DCs, and the balance of their profits and costs are important factor to consider.

The government plays an important role in promoting and regulating ELV recycling initiatives [14]. Many countries have taken measures to increase the level of use of ELV resources. These measures are part of efforts to promote the circular economy and reduce waste. The United States has adopted a subsidy policy, which can be as high as 4,000 US dollars/vehicle. The EU has adopted a deposit system and market access permission to regulate and standardize the ELV recycling industry [45]. Japan has established an ELV recycling law that stipulates the responsibilities of car manufacturers and consumers are required to pay car recycling fees when purchasing new cars [63]. Some literature combines the reward and penalty together and considers the reward-penalty-mechanism (RPM) [6, 8, 52]. RPM involves providing rewards or incentives for compliance with desired policies and imposing penalties for noncompliance. RPM is effective in guiding recycling activities [50]. Selecting the most appropriate regulation form is a crucial decision for the government. The RPM enables the government to adjust rewards and penalties based on the evolving needs and goals of ELV policy regulations. Therefore, this paper focuses on the RPM. Most studies set RPM to be fixed. However, as the recycling rate of recyclable products changes, it is more reasonable to set it as an endogenous variable. Therefore, it is important to study when the government implements rewards or penalties and their intensity.

Based on the above analysis and considering the RPM and CEA, the major aim of this study is to investigate the following problems: (1) TBC and DC are responsible for the collection and dismantling of ELVs, respectively, so what are the optimal collection efforts of the TBC and dismantling level of the available parts of the DC? (2) To increase consumers' willingness to recycle through formal channels, what is the optimal recycling price of ELVs? (3) Government RPM will affect the efficiency of ELV recycling. When should the government implement reward (penalty) mechanism and what should be the intensity of RPM? (4) How do CEA, the price of scrapped parts and the efficiency of collection and dismantling efforts affect the equilibrium results?

In practice, DCs are usually the qualified comprehensive companies that can be regarded as the leader; TBCs are either some small third-party collectors which can be regarded as the followers, or the subsidiaries of DCs. And TBCs and DCs can be considered to have cooperative behaviour at this time. So to answer the above questions, we use Stackelberg and Collusion behaviour to describe the decision behaviour of TBC and DC. Our contributions and key findings are as follows. First, we consider government regulation and CEA simultaneously. Government intervention is considered as an endogenous variable that depends on the market situation. The

results show that the RPM intensity weakens as CEA increases until withdraws; RPM relates not only to recycling quantity, but also the economic value of carbon emission reduction and downstream product competition, which provides suggestions on what factors governments should consider when adopting RPM policy. Second, we consider two behaviour models, Stackelberg and Collusion. The results indicates that Collusion behaviour significantly increases the recycling efforts of TBC and contributes to doubling ELV recycling quantity. Finally, some practice and investment recommendations are obtained *via* comparison and analysis of the equilibrium results. The TBC should pay more attention to improving CEA and the DC should adopt different investment levels under different stages. The government should help to improve the cooperation environment and provide more favour investment policy for ELV recycling.

The remainder of this paper is organized as follows. The related literature is reviewed in Section 2. Section 3 presents problem descriptions, notations and assumptions. Furthermore, two models are constructed, the optimal solutions are derived, and the optimal results are compared under the two behaviour models. In Section 4, numerical studies are conducted to obtain more results and management implications. Finally, conclusions and directions for future research are presented in Section 5.

2. LITERATURE REVIEW

2.1. ELVs

ELV recycling, as one of the most important components of the circular economy, has recently attracted increasing attention. ELV recycling and dismantling save resources and reduce energy consumption and carbon emissions. Therefore, an increasing number of papers have focused on ELV recycling. Some studies have focused on the feasibility and design of ELV reverse recycling networks [12, 17, 38, 64] and some scholars have analysed the feasibility of ELV recycling. Bellmann and Khare [1] analysed the feasibility of the ELV recycling in terms of technology and finance and proposed that the carmaker or the importer is responsible for life-cycle management. Gerrard and Kandlikar [13] presented a valuation framework for ELVs directive in Europe and proposed that the design of reuse and remanufacturing was the key point of the next step. By presenting a comparison of the Japanese and Chinese ELV recycling laws and the handling process, Zhao and Chen [63] reported constructive comments in terms of legislation, consumer education and technology. Shankar *et al.* [43] provided managerial insights into the optimal quantities of mass flow by formulating a mixed-integer mathematical program model for ELV recycling.

Some studies have focused on ELV recycling operation management. To meet the recovery and reuse rate of ELVs required by EU directives, Farel *et al.* [11] constructed a system dynamic model with cost-benefit-analysis and found that benefits increases and costs saving can be achieved by the recycling network under certain scenarios. Gorji *et al.* [15] investigated the optimal price decisions of the TBC and the inspection center and the optimal repair level of the repair center under three scenarios. Mohan and Amit [36] investigated the pricing competition between formal dismantlers and homogeneous informal dismantlers. Zhou *et al.* [65] researched the recycling pricing and remanufacture quality improvement decisions of ELVs considering the heterogeneous quality of recycled ELVs. As a subsection of ELV recycling, the recycling of electric vehicle batteries has drawn the interest of researchers. Tang *et al.* [48] constructed six recycling models with different competition relationships among manufacturer, retailer and third-party to meet the minimum recycling rate.

Increasing numbers of studies have investigated ELV recycling, but they have mainly focused on the recycling network design and operation management of ELVs, with some researchers have considered government subsidies or CEA factors. However, few studies have focused on government RPM and CEA simultaneously. Following Gorji *et al.* [15] that mainly considered government subsidies, we examine a ELVs reverse supply chain taking RPM related to carbon emission reduction and CEA fluctuation into consideration.

2.2. Government intervention in supply chain

To achieve sustainability and a green economy, many studies have considered government intervention, such as government subsidies, taxes, the combinations of reward and penalty and other forms [36, 48]. Some researchers have investigated the effect of government intervention on channel choice, pricing strategy and recycling rate. Wang *et al.* [50] proposed that the RPM depended on the minimum rate set by the government and the realistic recycling rate achieved by the collector. Liu *et al.* [31] found that government subsidies promoted the development of formal channels but facing the competition from informal channels, higher subsidies are not always effective. Zhang *et al.* [61] suggested that it is better to use the penalty and subsidy together on illegal and formal collectors. Based on a practical case of Beijing electrical vehicle power battery recycling, Tang *et al.* [48] found that a reasonable minimum recycling rate is necessary to make the RPM perform well; otherwise, it may cause benefit losses. Chen and Ulya [3] studied the different results of government RPM between the minimum recycling rate and the intensity with different collectors. Three cooperation scenarios were constructed by Gorji *et al.* [15] to study the effect of government subsidies. They found that the subsidy had the most advantages with respect to the TBC but had no effect on the repair center's profits.

Some papers shed light on recycling timing from the dynamic multiperiod recycling perspective. Jung and Feng [23] considered a two-period model of green technology investment under uncertainty and suggested that it was social welfare not government costs that should be the criterion for subsidy design. Zaman and Zaccour [58] investigated a two-period recycling model of ELVs based on the usage-year of the car and found that the government had to plan for intertemporal subsidies. Mitra and Webster [35] studied the effect of government subsidies on the interaction of the manufacturer and remanufacturer under two-period. The results showed that subsidies contributed to remanufacturing design and increased the recycling rate. Wang *et al.* [53] studied the RPM by constructing a two-period closed-loop supply chain and found that RPM can reduce the selling price and raise the collection rate.

The above studies emphasized the importance of government intervention on remanufacturing and recycling. The results showed that government intervention always facilitates the development of the reverse supply chain. However, they assumed that the government intervention is an exogenous variable and that the intervention form is fixed as a subsidy or tax, so government intervention takes only one form and does not reward or punish companies according to the actual situation. In this study, government RPM is considered and is set as an endogenous variable. The RPM depends on the market situation rather than being set them in advance, which is more in line with practice and provides us a clear understanding of the key factors influencing government policy-making.

2.3. CEA

CEA has important meaning in the enterprise operation, especially for products design and pricing strategies. Many results have shown that CEA can have a positive effect on green product design. Christmann and Taylor [7] proposed that manufacturers face increasing pressures from higher CEA. Liu *et al.* [30] found that increasing CEA always benefited superior product stakeholders compared to the inferior product stakeholders. Hong and Guo [19] investigated cooperation contracts considering CEA. Du *et al.* [9] found that channel profits and carbon emissions always increased in CEA. Yu *et al.* [56] found that CEA can incentivize a manufacturer to produce more green products with higher green levels even though the efforts may not lead to increasing profits.

Some researchers have focused on consumer differentiation, where consumers were divided into those with CEA and those without CEA. Hong *et al.* [18] investigated the green product pricing strategy with nongreen product preference under different CEA levels and proposed that a differential pricing strategy should be adopted. Rodriguez-Ibeas [41] found that the effects of CEA depended on the degree of differentiation and cost to achieve it between green products and normal products. Meng *et al.* [34] found that the greater the proportion of green consumers, the better it was for social welfare, consumer surplus and economic contribution. Hong *et al.* [20] proposed that CEA always played a positive role in the design of green products regardless of preference.

TABLE 1. Related literature for this study.

Literature	Players	ELV recycling	Government intervention		CEA
			RPM	Subsidy or tax	
Gorji <i>et al.</i> [15]	G, IC, RC and TBC	✓		✓	
Tang <i>et al.</i> [48]	a M, a R and/or a TPC	✓	✓ (exogenous)		
Wang <i>et al.</i> [52]	a formal dismantler		✓ (exogenous)		
Wang <i>et al.</i> [50]	and few informal dismantlers		✓ (exogenous)		
	a M and a collector		✓ (exogenous)		
Zhang <i>et al.</i> [61]	G, legal collector	✓	✓ (exogenous)		
	and illegal collector				
Chen and Ulya [3]	a M, one R and/or a TPC		✓ (exogenous)		✓
Zaman and Zaccour [58]	G and consumer	✓		✓	
Wang <i>et al.</i> [53]	a M and a collector		✓ (exogenous)		
Zhou <i>et al.</i> [65]	a M, a R or/and a TPC	✓			
Hong <i>et al.</i> [20]	a M and a R			✓	✓
This study	G, a TBC and a DC	✓	✓ (endogenous)	×	✓

Notes. G represents government; IC represents inspection center; RC represents repair center; M represents Manufacturer; R represents Retailer; TPC represents third-party collector.

As mentioned above, most studies have considered the effect of CEA on decision-making and found that the consumer has a positive effect on green products. However, most studies present CEA as consumers' preference or sensitivity to green products. In contrast to these works, we consider the CEA as a function of the CEA fluctuation ratio and quantify the total CEA by word-of-mouth and compute the whole CEA level of the ELVs owners.

Based on the key criterion of the model, Table 1 lists the differences between our research and previous studies. Our research is closely related to Gorji *et al.* [15], who studied the effect of government subsidies on the ELV recycling. Our work is different from theirs in three aspects. First, the government intervention form is different. They mainly studied government subsidies to improve the recycling quantity of ELVs. However, we study not only the reward but also penalty, *i.e.*, RPM. We emphasize how the government should set a reasonable regulation form and what the optimal intensity is according to the actual situation. Second, the principle of government intervention work differently. In their research, the subsidy to TBC is an exogenous variable and is considered as a recycling price subsidy, which has a direct effect on the ELVs supply volume. However, in our paper, in addition to recycling volumes, the RPM depends on the market situation, and directly influences the profits of the TBC: it is an endogenous variable. Third, CEA is considered in the ELVs supply function. Word-of-mouth plays an important role in the spread of CEA. Therefore, similar to Chen *et al.* [4], we introduce the fluctuation ratio of CEA to evaluate the total CEA of the whole supply chain and investigate the effect of CEA on the optimal decisions of the players of ELVs supply.

3. METHODS

3.1. Problem description

We consider an ELV recycling supply chain with the government and participants including a TBC and a DC, taking into consideration of CEA. The supply chain structure is shown in Figure 2.

The TBC, which could be a car retailer, a third-party recycler, or the car manufacturer's recycling department, is responsible for ELV recycling by exerting collection efforts τ from car owners who are environmentally conscious and pliable to be impacted by word-of-mouth in terms of green behaviour. The DC purchases the ELVs from the TBC and invests in dismantling technology. After professional dismantling, identification and classification, the available parts are sold to a remanufacturer, and the scrapped parts are sold to a disposal center. The government regulates the TBC by implementing RPM to improve environment.

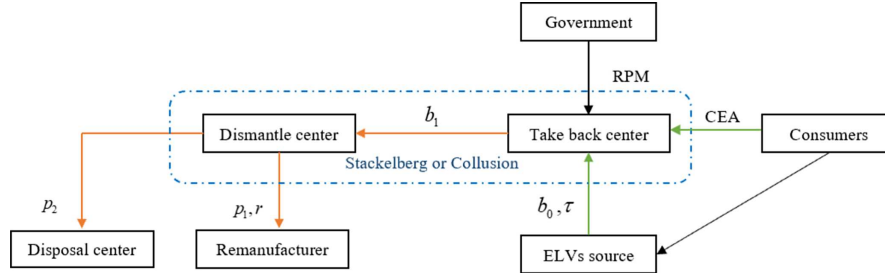


FIGURE 2. Problem structure.

Two behaviour models, Stackelberg and Collusion behaviour models are considered. The government is the leader who first determines the intensity of RPM that is applied to the TBC. In the Stackelberg behaviour model, the first follower, DC, decides the transfer prices b_1 of ELVs and available parts p_1 and the investment level r . The second follower, TBC, decides the recycling price b_0 and collection effort level τ . In the Collusion behaviour model, the TBC and DC vertically cooperate to maximize the group's profits. The notations and symbols are presented in Table 2.

Assumption 3.1. *CEA and word-of-mouth effect.*

Increasing CEA makes consumers more aware of the recycling of waste products, which will promote the recycling of ELVs. Consumers often recommend products and services to one another. Word of mouth can encourage a consumer to consider a brand or product. The right messages expand within interested networks, affecting purchase rates and market share. Assume that CEA can be spread by word-of-mouth. We denote t ($0 < t < 1$) as the fluctuation ratio of CEA with the word-of-mouth effect. As mentioned in Chen *et al.* [4], the CEA of first person who recycles an ELV is 1, then the second person who is influenced *via* the first person with the word-of-mouth, such as friends' recommendation or celebrity public platform influence, keeps environment awareness t , and the third person is t^2 . Thus, we obtain the total CEA level of the reverse supply chain by summing $\sum_{n=0}^{\infty} t^n = \frac{1}{1-t}$. CEA is a function of the CEA fluctuation ratio t . Since $\frac{d(\sum_{n=0}^{\infty} t^n)}{dt} = \frac{1}{(1-t)^2} > 0$ the larger the CEA fluctuation ratio is, the larger the CEA.

Assumption 3.2. *Demand function.*

According to Chen and Ulya [3], the recycling willingness of consumers is affected by the recycling price, convenience and environmental awareness. Assume that the supply function of ELVs q_0 is linear with recycling price b_0 and recycling efforts τ . q_t is the recycling function taking into consideration of the total CEA. The greater the price the TBC pays and the stronger the CEA, the more ELVs circulate into the recycling system legally. Therefore, the supply functions of ELVs with and without CEA are as follows.

$$q_0 = \delta + \rho b_0 + \eta \tau \quad (1)$$

$$q_t = \frac{\delta + \rho b_0 + \eta \tau}{1 - t} \quad (2)$$

We assume that the ELVs are classified into two types after professional treatment by the DC, available cars that are in remanufactured condition and scrapped cars that are so poor that the remanufactured value is paltry compared to those sold to the disposal center. In addition, the demand is affected by the dismantling level of the available parts r , which plays a vital role in cost savings and product quality in subsequent remanufacturing processes. The demand function of the available parts is denoted as follows.

$$q_1 = \alpha - \beta p_1 + \theta r \quad (3)$$

TABLE 2. Notation.

Symbol	Description
Indices	
i	Index of supply chain members ($i = TBC, DC, G, C$)
j	Index of two models ($j = st, cn$)
Parameters	
δ	The base supply of ELVs
ρ	Price elasticity of supply of ELVs
α	The base market potential of the available parts
β	Price elasticity of demand of the available parts
η	Collection level elasticity of the supply of ELVs
θ	Dismantle level elasticity of the supply of the available parts
t	The fluctuation ratio of the CEA with the word-of-mouth effect
q_0	The supply of ELVs without the impact of CEA
q_t	The supply of ELVs with the impact of CEA
q_1	The quantity demand of the available parts
q_2	The quantity demand of the scrapped parts
p_2	Sale price of the scrapped parts
ε	Cost coefficient of ELVs collection effort level
μ	Cost coefficient of available parts dismantle level
e	The amount of carbon emission savings achieved by ELV recycling
ζ	The monetary value of reducing one unit carbon emission
Decision variables	
p_1	Sale price of the available parts
b_0	Recycling price of ELVs
b_1	Transfer price of ELVs
τ	Collection efforts of ELVs
r	Dismantle level of the available parts
k	The RPM intensity established by the government
Dependent variables	
Π_i^j	The profit of supply chain members under different models

The price of scrapped cars depends mainly on the steel industry, so we set the price of the scrapped cars as a constant. The market is cleared, that is, all ELVs recycled by the TBC are sold to the DC, so the quantity of scrapped cars is

$$q_2 = q_t - q_1 \quad (4)$$

Assumption 3.3. *Cost.*

According to the demand functions in assumption 2, the TBC pays additional costs to recycle more ELVs, such as for convenient recycling facilities, public education and advertisements. The DC pays extra costs, such as for inspection operations and professional dismantling operations, to provide higher quality products to the remanufacturer. Assume that the cost functions of the collection effort level and dismantle level are $\frac{1}{2}\varepsilon\tau^2$ and $\frac{1}{2}\mu r^2$, respectively, where μ and ε denote the investment efficiency. The smaller their values are, the higher the efficiency. This type of cost function is considered in much of the literature [2, 28, 29, 33].

Assumption 3.4. *Period.*

For the ELVs reverse supply chain [15, 46, 54, 57], a single-period is considered [44], in which the available parts are reused once, which is in line with Chinese law regarding ELVs that stipulates that remanufactured parts must have a “manufacturing” mark. This assumption can also be interpreted as a mature stage of ELV recycling.

3.2. Model formulation

3.2.1. Stackelberg behaviour model

In this mode, after the government decides the RPM intensity k , the DC makes decisions by considering the response function of the TBC. Then, TBC makes its optimal decisions based on the DC’s decision. The profit functions for each player can be expressed as follows:

$$\Pi_{TBC}^{st} = (b_1 - b_0)q_t + k(q_t - q_0) - \frac{1}{2}\varepsilon\tau^2, \quad (5)$$

$$\Pi_{DC}^{st} = (p_1 - b_1)q_1 + (p_2 - b_1)q_2 - \frac{1}{2}\mu r^2, \quad (6)$$

$$\Pi_G^{st} = \zeta eq_t + k(q_0 - q_t) + \frac{(\alpha - \beta p_1 + \theta r)^2}{2\beta}. \quad (7)$$

In equation (5), the first term is the sales revenue of ELVs to DC, the second term is the reward or penalty of government, and the third term is the investment in collection efforts of ELVs. In equation (6), the first term is the revenue of available cars to the remanufacturer, the second term is the revenue of scrapped cars transferred to the disposal center, and the third term is the investment in dismantling technology. In equation (7), the first term is the environment revenue of the government, the second term is the cost of RPM, and the third term is the remanufacturer surplus which is measured by $\int_{\frac{\alpha+\theta r-q_1}{\beta}}^{\frac{\alpha+\theta r}{\beta}} q_1 dp_1 = \frac{(\alpha - \beta p_1 + \theta r)^2}{2\beta}$. This type of consumer surplus has been considered in many studies, such as Gorji *et al.* [15], Sinayi and Rasti-Barzoki [46], Kopel and Brand [24], Panda *et al.* [37].

Proposition 3.5. *The TBC profit function Π_{TBC}^{st} is a concave function with regard to b_0 and τ . For any given b_1 and k , by solving $\frac{\partial \Pi_{TBC}^{st}}{\partial b_0} = 0$, and $\frac{\partial \Pi_{TBC}^{st}}{\partial \tau} = 0$, the TBC’s reaction functions are obtained as follows.*

$$b_0(b_1, k) = \frac{(b_1 + kt)((1-t)\varepsilon\rho - \eta^2) - (1-t)\varepsilon\delta}{2(1-t)\varepsilon\rho - \eta^2}, \quad (8)$$

$$\tau(b_1, k) = \frac{\eta(kt\rho + \delta + \rho b_1)}{2(1-t)\varepsilon\rho - \eta^2}. \quad (9)$$

Proposition 3.6. *The DC profit function Π_{DC}^{st} is a concave function with regard to b_1 , p_1 and r .*

By substituting equations (8)–(9) into equation (6), we obtain the DC profit $\Pi_{DC}^{st}(p_1, b_1, r)$. By solving $\frac{\partial \Pi_{DC}^{st}}{\partial p_1}(p_1, b_1, r) = 0$, $\frac{\partial \Pi_{DC}^{st}}{\partial b_1}(p_1, b_1, r) = 0$, $\frac{\partial \Pi_{DC}^{st}}{\partial r}(p_1, b_1, r) = 0$, we can obtain the sale price, transfer price and dismantling level as follows, respectively.

$$p_1 = \frac{(\beta\mu - \theta^2)p_2 + \alpha\mu}{2\beta\mu - \theta^2} \quad (10)$$

$$b_1(k) = \frac{\rho(p_2 - kt) - \delta}{2\rho} \quad (11)$$

$$r = \frac{(\alpha - \beta p_2)\theta}{2\beta\mu - \theta^2}. \quad (12)$$

By substituting equations (10)–(12) into equation (7), we obtain the government profit function $\Pi_G^{st}(k)$.

$$\Pi_G^{st}(k) = \frac{\beta\mu^2(\alpha^2 + \beta p_2^2 - 2\alpha\beta p_2)}{2(\theta^2 - 2\beta\mu)^2} + \frac{\varepsilon(kt - e\zeta)\rho(kt\rho + \delta + \rho p_2)}{2(\eta^2 + 2(t-1)\varepsilon\rho)}.$$

Taking the second-order partial derivatives of $\Pi_G^{st}(k)$ with respect to k yields,

$$\frac{\partial^2 \Pi_G^{st}(K)}{\partial K^2} = -\frac{2t^2\rho^2\varepsilon}{2(2(1-t)\varepsilon\rho - \eta^2)} < 0$$

so $\Pi_G^{st}(k)$ is a concave function with respect to k . By solving $\frac{\partial \Pi_G^{st}(k)}{\partial k} = 0$, we can obtain the equilibrium reward-penalty intensity.

Theorem 3.7. *In the Stackelberg behaviour model, the equilibrium sale price, transfer price and dismantle level of the DC are as follows:*

$$p_1^{st*} = \frac{(\beta\mu - \theta^2)p_2 + \alpha\mu}{2\beta\mu - \theta^2} \quad (13)$$

$$b_1^{st*} = \frac{(3p_2 - e\zeta)\rho - \delta}{4\rho} \quad (14)$$

$$r^{st*} = \frac{\theta(\alpha - \beta p_2)}{2\beta\mu - \theta^2} \quad (15)$$

The equilibrium recycling price and collection effort level of the TBC are as follows:

$$b_0^{st*} = \frac{(e\zeta + p_2)((1-t)\varepsilon\rho - \eta^2) - (1-t)\varepsilon\delta}{4(2(1-t)\varepsilon\rho - \eta^2)} - \frac{3\delta}{4\rho} \quad (16)$$

$$\tau^{st*} = \frac{\eta(e\zeta\rho + \rho p_2 + \delta)}{4(2(1-t)\varepsilon\rho - \eta^2)} \quad (17)$$

The equilibrium reward-penalty intensity of the government is:

$$k^{st*} = \frac{e\zeta - p_2}{2t} - \frac{\delta}{2t\rho} \quad (18)$$

Combining equations (13)–(18) with equations (5)–(7) yields the corresponding profits of the TBC, DC and government.

$$\begin{aligned} \Pi_{TBC}^{st*} &= \frac{\varepsilon(e\zeta\rho + \rho p_2 + \delta)^2}{32(2(1-t)\varepsilon\rho - \eta^2)}, \\ \Pi_{DC}^{st*} &= \frac{\varepsilon((e\zeta\rho + \delta) + \rho p_2)^2}{16(2(1-t)\varepsilon\rho - \eta^2)} + \frac{\mu(\alpha - \beta p_2)^2}{2(2\beta\mu - \theta^2)}, \\ \Pi_G^{st*} &= \frac{(\rho e\zeta + \rho p_2 + \delta)^2\varepsilon}{8(2(1-t)\varepsilon\rho - \eta^2)} + \frac{\mu^2\beta(\alpha - \beta p_2)^2}{2(2\beta\mu - \theta^2)^2}. \end{aligned}$$

3.2.2. Collusion behaviour model

In this model, there is cooperation between the DC and TBC, and they jointly make decisions with the goal of maximizing total profit. The total profits of the TBC and DC are as follows.

$$\Pi_C^{cn} = p_1q_1 + p_2q_2 - b_0q_t + k(q_t - q_0) - \frac{1}{2}\varepsilon\tau^2 - \frac{1}{2}\mu r^2 \quad (19)$$

Proposition 3.8. *In the Collusion behaviour model, Π_G^{cn} is a concave function with respect to b_0 , τ , p_1 and r .*

Solving $\frac{\partial \Pi_G^{cn}}{\partial b_0} = 0$, $\frac{\partial \Pi_G^{cn}}{\partial \tau} = 0$, $\frac{\partial \Pi_G^{cn}}{\partial p_1} = 0$, the TBC's and DC's reaction functions are as follows.

$$b_0(k) = \frac{kt((1-t)\varepsilon\rho - \eta^2) + ((1-t)\varepsilon\rho - \eta^2)p_2 - (1-t)\varepsilon\delta}{2(1-t)\varepsilon\rho - \eta^2} \quad (20)$$

$$\tau(k) = \frac{\eta(kt\rho + \rho p_2 + \delta)}{2(1-t)\varepsilon\rho - \eta^2} \quad (21)$$

$$p_1 = \frac{\alpha + r\theta + \beta p_2}{2\beta} \quad (22)$$

$$r = \frac{(\alpha - \beta p_2)\theta}{2\beta\mu - \theta^2} \quad (23)$$

By substituting equations (20)–(23) into equation (7), we obtain the government profit function $\Pi_G^{cn}(k)$,

$$\Pi_G^{cn}(k) = \frac{\beta\mu^2(\alpha^2 + \beta p_2^2 + \alpha\beta p_2)}{2(\theta^2 - 2\beta\mu)^2} + \frac{\varepsilon\rho(kt - e\zeta)(\rho k + \delta + \rho p_2)}{\eta^2 - 2(1-t)\varepsilon\rho}.$$

Taking the second-order partial derivatives of $\Pi_G^{cn}(k)$ with respect to k yields,

$$\frac{\partial^2 \Pi_G^{cn}(k)}{\partial k^2} = -\frac{2t^2\rho^2\varepsilon}{2(1-t)\varepsilon\rho - \eta^2} < 0.$$

Therefore, $\Pi_G^{cn}(k)$ is a concave function with respect to k . By solving $\frac{\partial \Pi_G^{cn}(k)}{\partial k} = 0$, we can obtain the equilibrium reward-penalty intensity.

Theorem 3.9. *In Collusion behaviour model, the equilibrium sale price and dismantle level of the DC are*

$$p_1^{cn*} = \frac{(\beta\mu - \theta^2)p_2 + \alpha\mu}{2\beta\mu - \theta^2} \quad (24)$$

$$r^{cn*} = \frac{(\alpha - \beta p_2)\theta}{2\beta\mu - \theta^2}. \quad (25)$$

The equilibrium recycling price and collection effort level of the TBC are

$$b_0^{cn*} = \frac{(e\zeta + p_2)((1-t)\varepsilon\rho - \eta^2) - (1-t)\varepsilon\delta}{2(2(1-t)\varepsilon\rho - \eta^2)} - \frac{\delta}{2\rho} \quad (26)$$

$$\tau^{cn*} = \frac{\eta(e\zeta\rho + \rho p_2) + \delta}{2(2(1-t)\varepsilon\rho - \eta^2)} \quad (27)$$

The equilibrium reward-penalty intensity of the government is

$$k^{cn*} = \frac{e\zeta - p_2}{2t} - \frac{\delta}{2t\rho}. \quad (28)$$

According to equations (18) and (28), $k^{st*} = k^{cn*}$. As the regulator, governments formulate a minimum standard of recycling for the TBC. In 2020, the National Development and Reform Commission and other departments in China proposed supporting and guiding key areas to complete the goal of phasing out 1 million vehicles by means of rewards instead of subsidies. To stimulate the recycling industry, Wang [50] proposed

TABLE 3. The optimal decision under the Stackelberg and collusion behaviour.

	Stackelberg behaviour model	Collusion behaviour model
p_1	$p_1^{st*} = \frac{(\beta\mu - \theta^2)p_2 + \alpha\mu}{2\beta\mu - \theta^2}$	$p_1^{cn*} = \frac{(\beta\mu - \theta^2)p_2 + \alpha\mu}{2\beta\mu - \theta^2}$
b_1	$b_1^{st*} = \frac{3p_2 - e\zeta}{4} - \frac{\delta}{4\rho}$	—
r	$r^{st*} = \frac{(\alpha - \beta p_2)\theta}{2\beta\mu - \theta^2}$	$r^{cn*} = \frac{(\alpha - \beta p_2)\theta}{2\beta\mu - \theta^2}$
b_0	$b_0^{st*} = \frac{(e\zeta + p_2)(A\rho - \eta^2) - A\delta}{4(2A\rho - \eta^2)} - \frac{3\delta}{4\rho}$	$b_0^{cn*} = \frac{(e\zeta + p_2)(A\rho - \eta^2) - A\delta}{2(2A\rho - \eta^2)} - \frac{\delta}{2\rho}$
τ	$\tau^{st*} = \frac{\eta B}{4(2A\rho - \eta^2)}$	$\tau^{cn*} = \frac{\eta B}{2(2A\rho - \eta^2)}$
k	$k^{st*} = \frac{e\zeta - p_2}{2t} - \frac{\delta}{2t\rho}$	$k^{cn*} = \frac{e\zeta - p_2}{2t} - \frac{\delta}{2t\rho}$
q_t	$q_t^{st*} = \frac{\varepsilon\rho B}{4(2A\rho - \eta^2)}$	$q_t^{cn*} = \frac{\varepsilon\rho B}{2(A\rho - \eta^2)}$
q_1	$q_1^{st*} = \frac{\beta\mu(\alpha - \beta p_2)}{2\beta\mu - \theta^2}$	$q_1^{cn*} = \frac{\beta\mu(\alpha - \beta p_2)}{2\beta\mu - \theta^2}$
TBC	$\Pi_{TBC}^{st*} = \frac{\varepsilon B^2}{32(2A\rho - \eta^2)}$	$\Pi_{TBC}^{cn*} = \frac{\varepsilon B(\delta + e\zeta\rho + 4\rho b_1 - 3\rho p_2)}{8(2A\rho - \eta^2)}$
DC	$\Pi_{DC}^{st*} = \frac{\mu(\alpha - \beta p_2)^2}{2(2\beta\mu - \theta^2)} + \frac{\varepsilon B^2}{16(2A\rho - \eta^2)}$	$\Pi_{DC}^{cn*} = \frac{\mu(\alpha - \beta p_2)^2}{2(2\beta\mu - \theta^2)} + \frac{\varepsilon\rho B(p_2 - b_1)}{2(2A\rho - \eta^2)}$
Government	$\Pi_G^{st*} = \frac{(\alpha - \beta p_2)^2\beta\mu^2}{2(2\beta\mu - \theta^2)^2} + \frac{\varepsilon B^2}{8(2A\rho - \eta^2)}$	$\Pi_G^{cn*} = \frac{(\alpha - \beta p_2)^2\beta\mu^2}{2(2\beta\mu - \theta^2)^2} + \frac{\varepsilon B^2}{4(2A\rho - \eta^2)}$

Notes. $A = (1 - t)\varepsilon$, $B = e\zeta\rho + \rho p_2 + \delta$.

an RPM for the government. They directly proposed that a reward should be given when the collection rate exceeds the government's standard, otherwise a penalty should be given. In this study, the RPM is given as follows: when the economic value of emissions reductions is sufficiently large, *i.e.*, $\frac{\delta}{\rho} + p_2 < e\zeta$, the government will implement the reward policy; otherwise, a penalty policy will be implemented for the TBC. As shown in equation (1), the larger ρ is, the more ELVs are recycled by the TBC, and the more likely the reward policy is taken. Therefore, the criterion of RPM in our study is set based mainly on recycling quantity which is consistent with the standard recycling rate of Wang *et al.* [50]. Some literature [5, 50, 62] set the recycling rate/quantities as exogenous variables, but in our study, the intensity of RPM is set as a decision variable. Substituting the above equilibrium solutions into equations (7) and (19), yields

$$\begin{aligned}\Pi_C^{cn*} &= \frac{(\alpha - \beta p_2)^2\mu}{2(2\beta\mu - \theta^2)} + \frac{(\rho p_2 + e\zeta\rho + \delta)^2\varepsilon}{8(2(1 - t)\varepsilon\rho - \eta^2)}, \\ \Pi_G^{cn*} &= \frac{(\alpha - \beta p_2)^2\beta\mu^2}{2(2\beta\mu - \theta^2)^2} + \frac{(\rho p_2 + (e\zeta\rho + \delta))^2\varepsilon}{4(2(1 - t)\varepsilon\rho - \eta^2)}\end{aligned}$$

3.2.3. Comparison of the equilibrium solutions and parametric sensitivity analysis

In this section, we compare and analyse the optimal results under different behaviour models, and investigate the effects of various factors on the optimal results. The optimal decisions under the Stackelberg and Collusion behaviour are summarized in Table 3.

On the basis of Table 3, the following Propositions 3.10 and 3.11 are obtained.

Proposition 3.10. *For the DC, government and TBC, the optimal solutions have the following relations*

$$p_1^{st*} = p_1^{cn*}, r^{st*} = r^{cn*}, k^{st*} = k^{cn*}, b_0^{st*} < b_0^{cn*}, \tau^{cn*} = 2\tau^{st*}, q_t^{cn*} = 2q_t^{st*}, q_1^{cn*} = q_1^{st*}.$$

Proposition 3.10 indicates that the optimal recycling price and collection effort level of the TBC are higher under Collusion behaviour than under Stackelberg behaviour, while the optimal decisions of the DC and government are equivalent under the two behaviours. Therefore, Collusion behaviour can efficiently promote collection efforts and increase the recycling price of the TBC. Furthermore, the TBC can occupy greater market share under Collusion behaviour.

Proposition 3.11. $\Pi_G^{st*} < \Pi_G^{cn*}$, $\Pi_{TBC}^{st*} + \Pi_{DC}^{st*} < \Pi_C^{cn*}$.

Proposition 3.11 indicates that each player obtains higher profits under Collusion behaviour model. This is because motivated by a higher recycling price of ELVs and collection efforts, as proposed in Proposition 3.10, consumers are more willing to recycle their ELVs *via* the formal TBC, resulting in higher profits of the TBC and DC. Meanwhile, the reduction in carbon emissions increases as more ELVs circulate into the recycling system, which helps the government achieve better environmental performance. Therefore the TBC and DC are more willing to cooperate to achieve higher profits, and the government should take measures to encourage their cooperation.

Proposition 3.12. *when $p_2 > \frac{3}{13}(e\zeta + \frac{\delta}{\rho})$ and $p_2 - \frac{3B}{16\rho} < b_1 < p_2 - \frac{B}{8\rho}$, $\Pi_{TBC}^{cn*} > \Pi_{TBC}^{st*}$ and $\Pi_{DC}^{cn*} > \Pi_{DC}^{st*}$.*

Proposition 3.12 indicates that when the transfer price of ELVs from the TBC to DC satisfies certain conditions both the TBC and DC will achieve greater profits and the supply chain will be optimally coordinated. According to proposition 3.11, Collusion behaviour can achieve greater supply chain profits, but only a reasonable transfer price can ensure that the TBC and DC obtain higher profits than in the non-cooperative model. Therefore, it is advisable for players to focus on the transfer price when developing contracts in which the price is not too low to impair the TBC's profits and is not too high to impair the DC's profits to achieve a win-win situation.

4. DISCUSSION

Due to the complexity of the model, numerical analyses are used to examine the impact of some parameters on the optimal decisions of the two models.

According to the Ministry of Commerce of the People's Republic of China, the number of vehicles recovered in the first nine months of 2021 was 2.106 million, an increase of 35.9% year-on-year. Based on this growth rate, the number of recovered vehicles is estimated to reach 2.808 million vehicles in 2022. Therefore, we set the base supply of ELVs $\delta = 300$. China reached 395 million vehicles holdings in 2021. Furthermore, remanufacture parts account for 60%–70% of the maintenance market in Europe and the United States, while that value in China is only 3%–5%⁴. Assume that the maintenance and repair rate of vehicles is 1% and that the future objective for shared remanufactured parts is 20%; thus we set the base market potential of available parts. According to Liu *et al.* [32], the predicted total emission reduction is 3816.1 kg CO₂ eq/vehicle, so we set $e = 4$. Based on these assumptions, the values of the other parameters are set as follows: $\rho = 5$, $\theta = 4$, $\eta = 2$, $\varepsilon = 60$, $\beta = 0.3$, $\mu = 80$, $\zeta = 100$ and $p_2 = 300$. The ranges of the parameters are as follows. The value of t ranges from 0 to 1; p_2 ranges from 0 to 400, e ranges from 0 to 10 and ε and μ range from 10 to 100.

4.1. The effect of the CEA fluctuation ratio

Proposition 4.1. (1) *For the CEA fluctuation ratio has no influence on optimal production decisions of the DC.*

$$(2) \text{ For the TBC, } \frac{\partial b_0^{cn*}}{\partial t} < \frac{\partial b_0^{st*}}{\partial t} < 0, \frac{\partial \tau^{cn*}}{\partial t} > \frac{\partial \tau^{st*}}{\partial t} > 0.$$

$$(3) \text{ For the government, } \frac{\partial k^{j*}}{\partial t} < 0 \text{ if } e\zeta > \frac{\delta + \rho p_2}{\rho}; \frac{\partial k^{j*}}{\partial t} > 0 \text{ if } e\zeta < \frac{\delta + \rho p_2}{\rho}.$$

$$(4) \text{ For all players and the two models, } \frac{\partial \Pi_i^{j*}}{\partial t} > 0.$$

Proposition 4.1 shows that all payers benefit from the CEA fluctuation ratio. As the CEA fluctuation ratio increases, the TBC increases collection efforts but decreases the recycling price, and the government decreases

⁴<https://baijiahao.baidu.com/s?id=1728685312774319922&wfr=spider&for=pc>

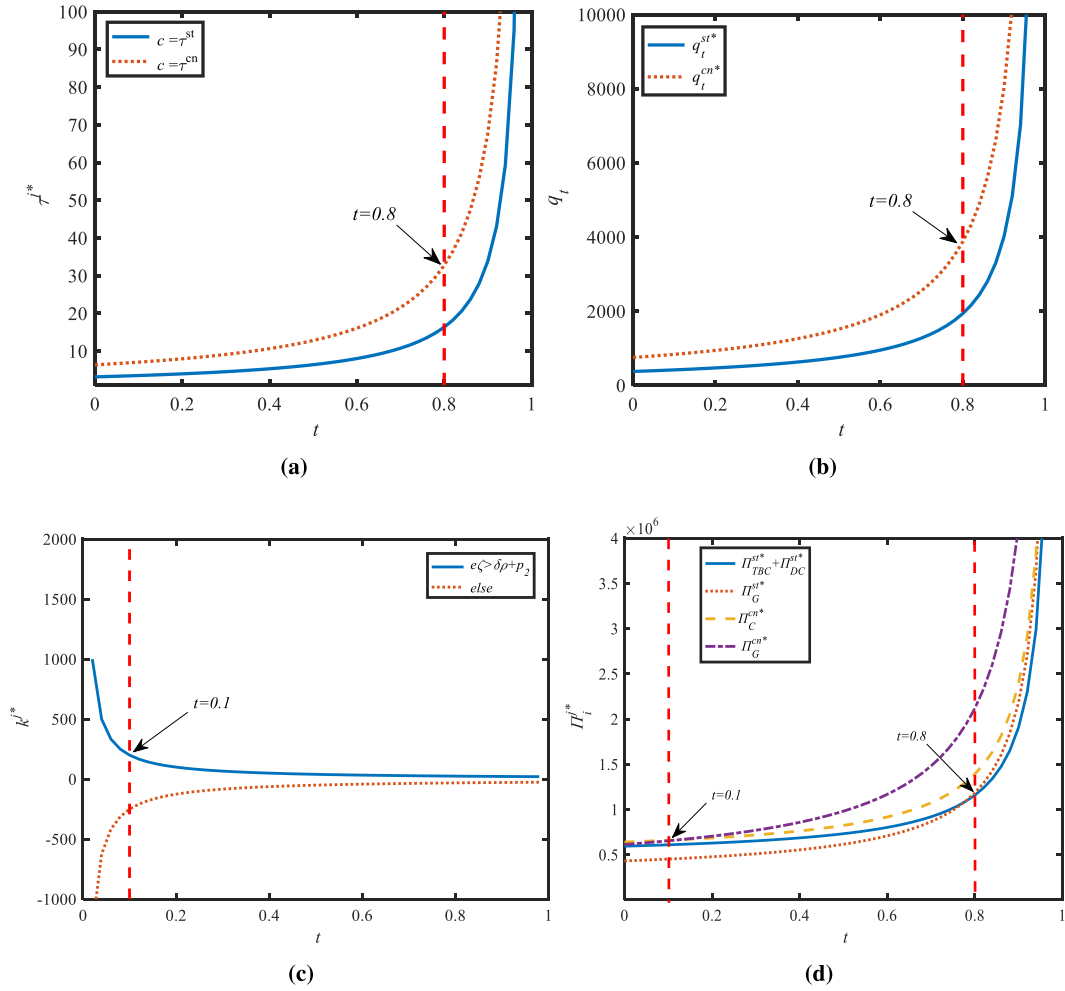


FIGURE 3. Effect of t on τ , q_t , k and Π_i^{j*} . (a) Effect of t on τ . (b) Effect of t on q_t . (c) Effect of t on k . (d) Effect of t on Π_i^{j*} .

the intensity of RPM. This is because when consumers pay more attention to the environment, they will be willing to accept a lower recycling price. Therefore, the TBC is willing to exert greater collection efforts, resulting in a lower intensity of RPM.

As shown in Figures 3a and 3b, collection efforts and recycling quantities suddenly increase around $t = 0.8$, which indicates that when the CEA fluctuation ratio exceeds a certain threshold, the TBC should focus more on recycling efforts to stimulate the consumers to increase the ELV recycling scale. As shown in Figure 3c, the intensity of RPM decreases rapidly with increasing t and tends to zero, indicating that as the CEA fluctuation ratio increases, an increasing number of ELVs are recycled by the TBC, and the government will withdraw regulation. Although the profits of each player increase in t , the growth rates differ. As Figure 3d shows, government revenue exceeds supply chain revenue at $t = 0.8$ and $t = 0.1$ under the Stackelberg and Collusion behaviour models, respectively. Therefore, the Collusion behaviour is more sensitive to the CEA fluctuation ratio than is Stackelberg behaviour in terms of environmental protection.

4.2. The effect of the sale price of the scrapped parts

- Proposition 4.2.** (1) For the DC, $\frac{\partial p_1^{j*}}{\partial p_2} > 0$ if $\mu > \frac{\theta^2}{\beta}$; else, $\frac{\partial p_1^{j*}}{\partial p_2} < 0$. $\frac{\partial r^{j*}}{\partial p_2} < 0$.
- (2) For the TBC, $\frac{\partial b_0^{j*}}{\partial p_2} > 0$, $\frac{\partial \tau^{j*}}{\partial p_2} > 0$.
- (3) For the government, $\frac{\partial k^{j*}}{\partial p_2} < 0$.
- (4) For all players and the two models, $\frac{\partial \Pi_i^{j*}}{\partial p_2} > 0$.

Proposition 4.2 indicates that the change trend of p_1 depends on the investment efficiency μ . As shown in Figure 4a, p_1 is sensitive to a higher μ . The dismantle level of the DC decreases as p_2 increases. Therefore, according to Figure 4c, the demand for available parts decreases due to the decrease in the dismantle level. In this situation, the government policy changes from reward to penalty with decreasing q_1 , which is intuitively shown in Figure 4e. The recycling price and collection efforts increase in p_2 , which implies that a higher sale price of scrapped parts helps the TBC achieve higher recycling scales.

All players benefit from the two models when p_2 increases. However, as shown in Figure 4f, the government revenue always grows faster than the supply chain revenue and this trend is more obvious under a higher investment efficiency. There are two reasons. First, government policy changes from reward to penalty with the increase of p_2 . Second, more ELVs are recycled under a higher supply chain efficiency.

4.3. The effect of carbon emission savings

- Proposition 4.3.** (1) Carbon emission savings have no influence on the optimal production decisions of the DC.
- (2) For the TBC, $\frac{\partial b_0^{cn*}}{\partial e} > \frac{\partial b_0^{st*}}{\partial e} > 0$, $\frac{\partial \tau^{cn*}}{\partial e} > \frac{\partial \tau^{st*}}{\partial e} > 0$.
- (3) For the government, $\frac{\partial k^{j*}}{\partial e} > 0$.
- (4) For all players and the two models, $\frac{\partial \Pi_i^{j*}}{\partial e} > 0$.

Proposition 4.3 and Figure 5a indicate that the optimal recycling price, collection efforts and quantity of recycled ELVs increase in e . The advantages of increasing e are more obvious under Collusion behaviour model. With the reduction of carbon emissions, government RPM changes from penalty to reward because more environmental value is obtained, which is shown in Figure 5b. Motivated by reward, the TBC prefers to exerts more collection efforts and implement higher recycling price to recycle more ELVs.

All players benefit from carbon emission savings. As shown in Figure 5c, the Collusion behaviour model outperforms the Stackelberg behaviour model. The government revenue exceeds the supply chain revenue at $e = 1$ and $e = 5.5$. This is because the TBC exerts greater effort and pays higher costs to recycle more ELVs, which reduces its profits, while the government's revenue, which depends on the increasing scale and the improvement of carbon emission reduction, increases. Therefore, the government should formulate policies to support the ELV recycling and encourage cooperation between the TBC and DC.

4.4. The effect of ε and μ separately on the equilibrium results

- Proposition 4.4.** (1) For the TBC, $\frac{\partial b_0^{cn*}}{\partial \varepsilon} > \frac{\partial b_0^{st*}}{\partial \varepsilon}$, $\frac{\partial \tau^{cn*}}{\partial \varepsilon} < \frac{\partial \tau^{st*}}{\partial \varepsilon} < 0$.
- (2) For the DC, $\frac{\partial p_1^{cn*}}{\partial \mu} = \frac{\partial p_1^{st*}}{\partial \mu} < 0$, $\frac{\partial r^{cn*}}{\partial \mu} = \frac{\partial r^{st*}}{\partial \mu} < 0$.

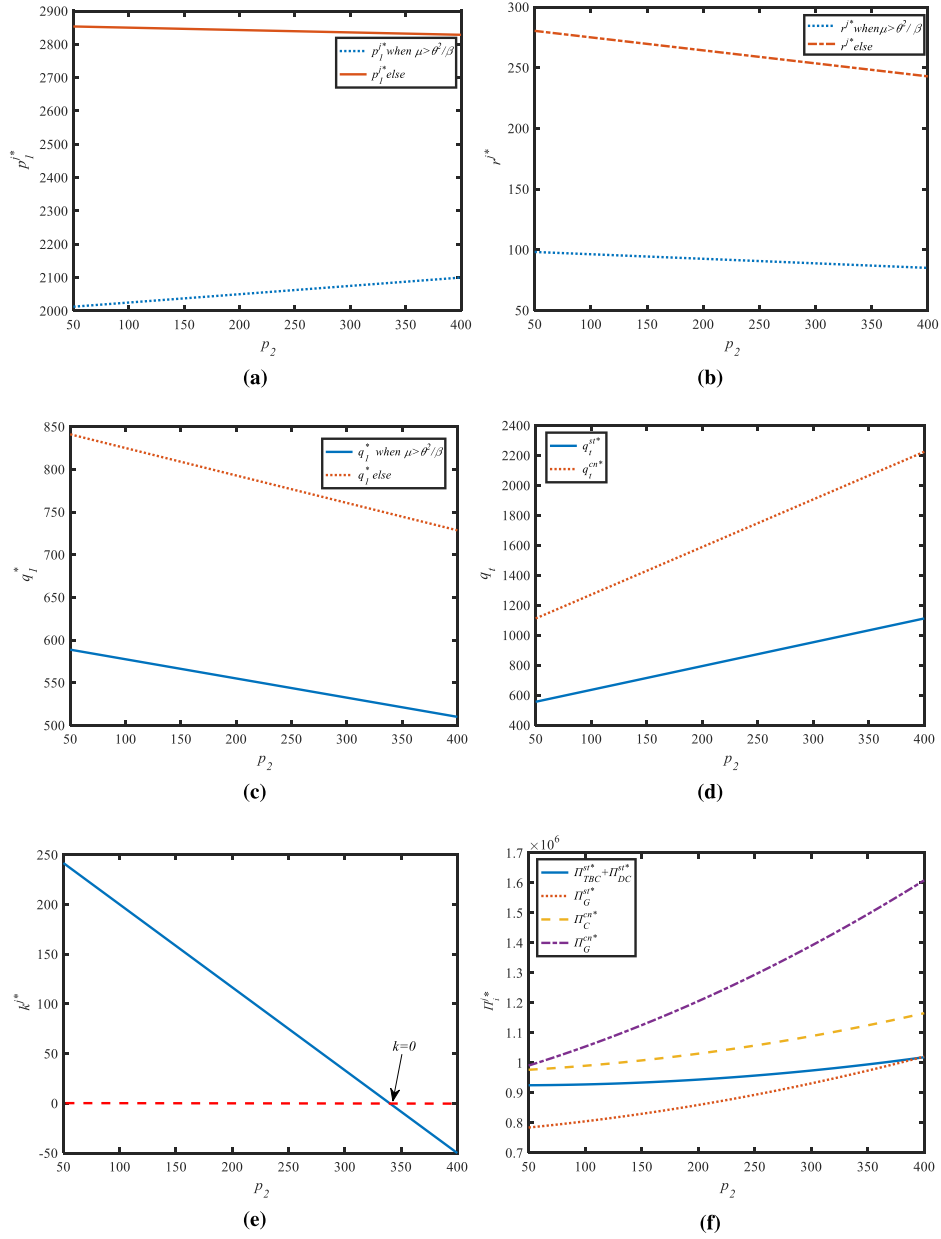


FIGURE 4. Effect of p_2 on p_1 , r , q_1 , q_t , k , Π_i^{j*} when $\mu = 50, 80$. (a) Effect of p_2 on p_1 . (b) Effect of p_2 on r . (c) Effect of p_2 on q_1 . (d) Effect of p_2 on q_t . (e) Effect of p_2 on k . (f) Effect of p_2 on Π_i^{j*} .

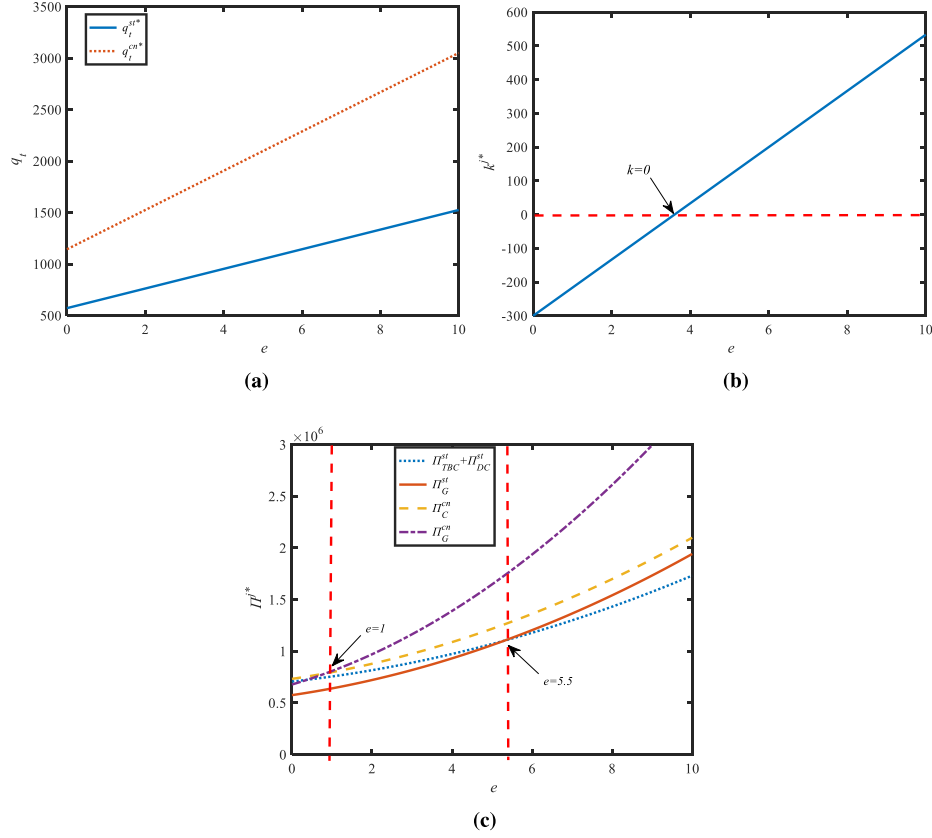


FIGURE 5. Effect of e on k , q_t and Π_i^{j*} . (a) Effect of e on q_t . (b) Effect of e on k . (c) Effect of e on Π_i^{j*} .

(3) For all players and the two models, if $2\beta\mu > \theta^2$, then $\frac{\partial \Pi_i^{j*}}{\partial \varepsilon} < 0$, $\frac{\partial \Pi_i^{j*}}{\partial \mu} < 0$. $\frac{\partial \Pi_C^{st*}}{\partial \varepsilon} = \frac{\partial \Pi_G^{st*}}{\partial \varepsilon}$, and $|\frac{\partial \Pi_C^{cn*}}{\partial \varepsilon}| - |\frac{\partial \Pi_G^{cn*}}{\partial \varepsilon}| < 0$, $|\frac{\partial \Pi_C^{j*}}{\partial \mu}| - |\frac{\partial \Pi_G^{j*}}{\partial \mu}| < 0$.

Proposition 4.4 and Figure 6a indicate that the TBC's collection effort level and recycling quantities decrease with decreasing efficiency of collection efforts. Therefore, the TBC increases the recycling price to recovery more ELVs. Inefficient dismantling results in a decrease in the dismantling level. Therefore, the DC decreases the sale price of available parts to maintain a stable market share. The investment efficiency of the TBC and DC has no direct effect on reward-penalty intensity. Figure 6b shows that if the DC maintains a high dismantle efficiency, that is, μ is located in the space between the two planes, it is better for the DC to give priority to dismantling technology development and adopt a higher sale price for available parts. A DC who located in the space above the higher plane should adopt a low sale price to obtain greater market share than develop technology.

The higher the efficiency of the TBC and DC, the greater the profits that the players obtain, as shown in Figures 6b and 6c. Under Collusion behaviour, the decreases in ε and μ have a more positive impact on government revenue than on the supply chain. This shows that the government is sensitive to the efficiency of the TBC and DC. Under Stackelberg behaviour, ε has the same impact on the players' profits. However, the government revenue is more sensitive to μ than supply chain profits. Therefore, it is necessary for the government to help the TBC and DC improve efficiency to achieve greater revenue and encourage them to cooperate.

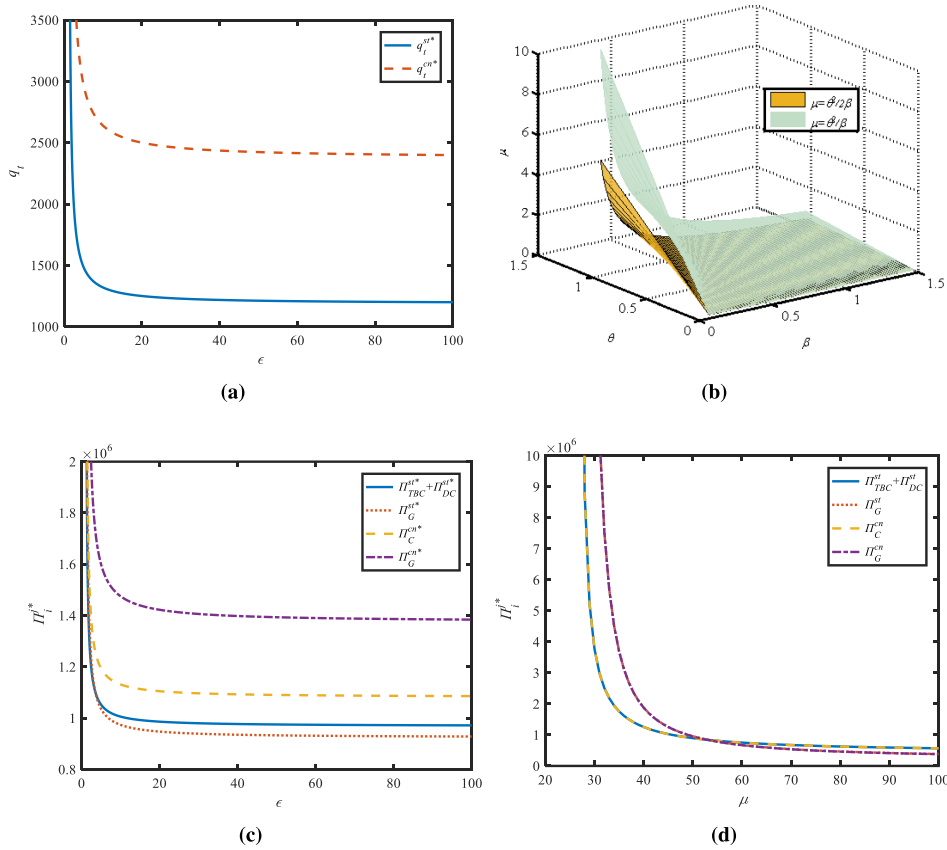


FIGURE 6. Effect of ϵ , μ on q_t and Π_i^{j*} . (a) Effect of ϵ on q_t . (b) The relationship between β_μ and θ^2 . (c) Effect of ϵ on Π_i^{j*} . (d) Effect of μ on Π_i^{j*} .

5. CONCLUSIONS

5.1. Implications for theory and practice

Considering RPM and CEA, this paper examines the optimal pricing and collection effort level of the TBC, the dismantle level of the available parts of the DC and the intensity of RPM under Stackelberg and Collusion behaviour models. This study promotes the development of ELV recycling in two aspects. On the one hand, considering both CEA and government policies, it provides optimal pricing and collection effort and dismantle level advice for relevant enterprises, such as vehicle manufacturers and some third parties directly responsible for recycling and remanufacturing. On the other hand, according to different market conditions, the form (reward and punishment) and intensity of government regulatory policies are proposed. Some conclusions are summarized in Table 4.

From a theoretical perspective, the following conclusions are obtained.

- (1) The Collusion behaviour outperforms the Stackelberg behaviour in terms of recycling quantity, which is consistent with Gorji *et al.* [15], Wang *et al.* [50]. Under the Collusion behaviour model, the TBC provides a higher optimal recycling price, which consistent with the conclusion of Li *et al.* [26], and exerts more collection effort and finally occupies double market share. The Collusion behaviour can achieve more profits than the Stackelberg behaviour, but a reasonable transfer price of the ELVs is a key factor when the TBC

TABLE 4. Summary of results.

	Relationship	t	p_2	e	ε	μ
b_0^{j*}	$b_0^{st*} < b_0^{cn*}$	$\downarrow (cn < st)$	$\uparrow$	$\uparrow (cn > st)$	$\uparrow (cn > st)$	—
τ^{j*}	$\tau^{cn*} = 2\tau^{st*}$	$\uparrow (cn > st)$	$\uparrow$	$\uparrow (cn > st)$	$\downarrow$	—
p_1^{j*}	$p_1^{st*} = p_1^{cn*}$	—	$\uparrow (con.)$	—	—	$\downarrow$
b_1^{st*}	—	—	$\uparrow$	$\downarrow$	—	—
r^{j*}	$r^{st*} = r^{cn*}$	—	$\downarrow$	—	—	$\downarrow$
k^{j*}	$k^{st*} = k^{cn*}$	$\downarrow (con.)$	$\downarrow$	$\uparrow$	—	—
Π_{TBC}^{j*}	—	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$
Π_{DC}^{j*}	—	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$
Π_G^{j*}	$\Pi_G^{st*} < \Pi_G^{cn*}$	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$

Notes. “—” denotes that the effect of the parameters is not pronounced. “con.” denotes condition.

and DC make cooperation contracts. Furthermore, the optimal decisions are more sensitive to the change of parameters under the Collusion behaviour model, which indicates that cooperation is a good choice for enterprises that want to obtain higher profits.

- (2) The larger the CEA fluctuation ratio is, the larger the CEA is. The CEA fluctuation ratio does not affect the decisions of the DC, it has a negative impact on the recycling price and RPM intensity, but a positive effect on recycling efforts. The TBC, DC and government can benefit from the CEA fluctuation ratio. Furthermore, as the CEA fluctuation ratio increases, the intensity of RPM decreases. Thus, when the government rewards the TBC, the government should withdraw rewards as the CEA fluctuation ratio increases. Therefore, the CEA fluctuation ratio alleviates regulatory pressure.
- (3) The sale price of scrapped parts increases the recycling price, transfer price and collection efforts, but decreases the dismantling level of the available parts and the RPM intensity. Therefore, a higher sale price of scrapped parts helps the TBC achieve higher recycling scales. For the DC, when the sale price of scrapped parts increases, the optimal sale price of available parts depends on dismantling efficiency of the available parts. Increasing the sale price of scrapped parts can provide more benefits to all players involved. Government revenue is higher and grows faster than the supply chain revenue.
- (4) Carbon emission savings have a positive effect on the recycling price, collection efforts and RPM intensity. With the reduction of carbon emissions savings, government RPM transfers from penalty to reward, which encourages the TBC to complete more recycling quantity. All the players can benefit from carbon emission savings. The advantages of increasing carbon emission savings are more obvious under Collusion behaviour model, so the government should implement policies to support the ELV recycling and encourage the cooperation of the TBC and DC.
- (5) As the TBC collection efficiency decreases, that is, ε increases, the collection effort level and recycling quantities decrease, but the recycling price increases. The increase in the recycling price is greater under the Collusion behaviour model. DC dismantling efficiency has a positive effect on the sale price of the available parts and a larger effect on the government than on the supply chain under the two behaviour models. Therefore, government should take measures to help the TBC and DC improve their operation and investment efficiency and encourage them to cooperate to promote collection and dismantle efficiency.

From a practical perspective, we propose several recommendations.

- (1) The government plays a crucial role in promoting the circular economy and addressing the management of ELVs. First, whether the government chooses to reward or penalize depends on the scale of ELV recycling and carbon emission reduction. The results show that the quantity of ELV recycling under the Collusion behaviour model is twice as high as under the Stackelberg behaviour model. Therefore, the government should guide the TBC and DC to cooperate. Second, higher CEA fluctuation ratio can promote ELVs

collection. The government should take measures to enhance the level of CEA, which can be achieved by publicity campaigns, such as public service announcements and education. Finally, the government should provide enterprises policy support to enhance the efficiency and effectiveness of ELV recycling and promote the circular economy. For example, in China, the government has clearly proposed increasing support for land use to dismantle projects of the certified DC, providing green loans, and encouraging the cooperation between DCs and research institutions to develop dismantling technology.

- (2) As previous conclusions indicate that the collection and dismantling efficiency plays a critical role in ELV recycling. DCs should invest in dismantling technology and achieve breakthroughs. For example, in response to the pilot implementation plan for extended producer responsibility of automotive products, 62 DC enterprises participated in a project in cooperation with autoproducers in terms of capital and R&D. TBCs, on the one hand, should pay more attention to recycling efforts rather than raising collection prices. On the other hand, CEA has a positive effect on recycling quantities; therefore, TBCs should take measures, such as trade-in, cash subsidies, and online and offline synchronization, to appeal to more consumers to participate in ELV recycling. Furthermore, cooperation between TBCs and DCs is a good choice. It is better for them to cooperate to achieve an overall win-win situation.

5.2. Limitations and directions for further research

This study has the following two limitations that need to be addressed in future research. First, the demand is assumed to be certain in our models. In reality, uncertainty demand is common and is important to operation management [27, 40, 59]. The TBC and DC may face random demand, so the uncertain demand can be discussed in future studies. Second, we consider only a one-period model. CEA and investment efficiency are constantly changing under the influence of government support and enterprise endeavors, which are variables that change over time. Therefore, a dynamic multiperiod analysis is more realistic and interesting.

APPENDIX A. PROOF OF PROPOSITION 1

Taking the second-order partial derivatives of Π_{TBC}^{st} with respect to b_0 and τ ,
 $\frac{\partial \Pi_{TBC}^{st}}{\partial b_0^2} = -\frac{2\rho}{1-t}$, $\frac{\partial \Pi_{TBC}^{st}}{\partial b_0 \partial \tau} = -\frac{\eta}{1-t}$, $\frac{\partial \Pi_{TBC}^{st}}{\partial \tau \partial b_0} = -\frac{\eta}{1-t}$, $\frac{\partial \Pi_{TBC}^{st}}{\partial \tau^2} = -\varepsilon$. Let Δ_1 and Δ_2 denote the first and second-order principal minors of Hessian matrix of Π_{TBC}^{st} , since $0 < t < 1$, $2\varepsilon\rho(1-t) > \eta^2$, then $\Delta_1 = \frac{-2\rho}{1-t} < 0$. $\Delta_2 = \frac{2(1-t)\varepsilon\rho - \eta^2}{(1-t)^2} > 0$. So Π_{TBC}^{st} is concave function with regard to b_0 and τ .

APPENDIX B. PROOF OF PROPOSITION 2

Taking the second-order partial derivatives of Π_{DC}^{st} with respect to b_1 , p_1 and r . The Hessian matrix of Π^{DC} is as follow.

$$H_{DC} = \begin{pmatrix} -2\beta & 0 & \theta \\ 0 & -\frac{2\varepsilon\rho}{2(1-t)\varepsilon\rho - \eta^2} & 0 \\ \theta & 0 & -\mu \end{pmatrix}$$

Since $0 < t < 1$, $2\varepsilon\rho(1-t) > \eta^2$, then $|H_1^{DC}| = -2\beta < 0$, $|H_2^{DC}| = \frac{4\beta\varepsilon\rho^2}{2(1-t)\varepsilon\rho - \eta^2} > 0$ and $|H_3^{DC}| = -\frac{4\beta\varepsilon\rho^2}{2(1-t)\varepsilon\rho - \eta^2}\mu < 0$. So Π_{DC}^{st} is concave function with regard to b_1 , p_1 and r .

APPENDIX C. PROOF OF PROPOSITION 3

Taking the second-order partial derivatives of Π_C^n with respect to b_0 , τ , p_1 and r . The Hessian matrix of Π^C is

$$H^C = \begin{pmatrix} \frac{2\rho}{-1+t} & 0 & \frac{\eta}{-1+t} & 0 \\ 0 & -2\beta & 0 & \theta \\ \frac{-\eta}{1-t} & 0 & -\varepsilon & 0 \\ 0 & \theta & 0 & -\mu \end{pmatrix}$$

Since $0 < t < 1$, $2\varepsilon\rho(1-t) > \eta^2$ and $\theta^2 - 2\mu\beta < 0$, so $-\frac{2\rho}{1-t} < 0$, $2\beta\frac{2\rho}{1-t} > 0$, $\frac{2(\eta^2-2(1-t)\varepsilon\rho)\beta}{(1-t)^2} < 0$, and $\frac{(\eta^2-2(1-t)\varepsilon\rho)(\theta^2-2\mu\beta)}{(1-t)^2} > 0$. So Π_C^{cn} is concave function with regard to b_0 , τ , r , p_1 and r .

APPENDIX D. PROOF OF PROPOSITION 6

Solving $\Pi_i^{cn*} > \Pi_i^{st*}$, then

$$\frac{\varepsilon B(\delta + e\zeta\rho + 4\rho b_1 - 3\rho p_2)}{8(2(1-t)\varepsilon\rho - \eta^2)} - \frac{\varepsilon B}{32(2A\rho - \varepsilon t a^2)} > 0,$$

$$\frac{\mu(\alpha - \beta p_2)^2}{2(2\beta\mu - \theta^2)} + \frac{\varepsilon\rho B(p_2 - b_1)}{2(2A\rho - \eta^2)} - \frac{\mu(\alpha - \beta p_2)^2}{2(2\beta\mu - \theta^2)} - \frac{\varepsilon B^2}{16(2A\rho - \eta^2)} > 0.$$

So $p_2 > \frac{3}{13}(e\zeta + \frac{\delta}{\rho})$ and $p_2 - \frac{3B}{16\rho} < b_1 < p_2 - \frac{B}{8\rho}$.

APPENDIX E. PROOF OF PROPOSITION 7

(2) Taking the first-order derivations of b_0^{j*} , τ^{j*} with regard to t , we can obtain that

$$\frac{\partial b_0^{st*}}{\partial t} = -\frac{\varepsilon\eta^2(e\zeta\rho + \delta + \rho p_2)}{4(\eta^2 - 2(1-t)\varepsilon\rho)^2} < 0, \frac{\partial b_0^{cn*}}{\partial t} = -\frac{\varepsilon\eta^2(e\zeta\rho + \delta + \rho p_2)}{2(\eta^2 - 2(1-t)\varepsilon\rho)^2} < 0, \frac{\partial b_0^{cn*}}{\partial t} < \frac{\partial b_0^{st*}}{\partial t}$$

$$\frac{\partial \tau^{st*}}{\partial t} = \frac{\varepsilon\eta\rho(e\zeta\rho + \delta + \rho p_2)}{2(\eta^2 - 2(1-t)\varepsilon\rho)^2} > 0, \frac{\partial \tau^{cn*}}{\partial t} = \frac{\varepsilon\eta\rho(e\zeta\rho + \delta + \rho p_2)}{(\eta^2 - 2(1-t)\varepsilon\rho)^2} > 0, \frac{\partial \tau^{cn*}}{\partial t} > \frac{\partial \tau^{st*}}{\partial t}.$$

(3) Taking the first-order derivations of k^{j*} with regard to t , $\frac{\partial k^{j*}}{\partial t} = \frac{\delta + \rho p_2 - e\zeta\rho}{2t^2\rho}$.

So, $\frac{\partial k^{j*}}{\partial t} < 0$ if $e\zeta > \frac{\delta + \rho p_2}{\rho}$; $\frac{\partial k^{j*}}{\partial t} > 0$ if $e\zeta < \frac{\delta + \rho p_2}{\rho}$.

(4)

$$\frac{\partial \Pi_{TBC}^{st*}}{\partial t} = \frac{\varepsilon^2\rho(e\zeta\rho + \delta + \rho p_2)^2}{16(\eta^2 - 2(1-t)\varepsilon\rho)^2} > 0, \frac{\partial \Pi_{DC}^{st*}}{\partial t} = \frac{\varepsilon^2\rho(e\zeta\rho + \delta + \rho p_2)^2}{8(\eta^2 - 2(1-t)\varepsilon\rho)^2} > 0, \frac{\partial \Pi_G^{st*}}{\partial t} = \frac{\varepsilon^2\rho(e\zeta\rho + \delta + \rho p_2)^2}{4(\eta^2 - 2(1-t)\varepsilon\rho)^2} > 0.$$

$$\frac{\partial \Pi_C^{cn*}}{\partial t} = \frac{\varepsilon^2\rho(e\zeta\rho + \delta + \rho p_2)^2}{4(\eta^2 - 2(1-t)\varepsilon\rho)^2} > 0, \frac{\partial \Pi_G^{cn*}}{\partial t} = \frac{\varepsilon^2\rho(e\zeta\rho + \delta + \rho p_2)^2}{2(\eta^2 - 2(1-t)\varepsilon\rho)^2} > 0$$

APPENDIX F. PROOF OF PROPOSITION 8

(1) Taking the first-order derivative of p_1^{j*} with regard to p_2 , we can obtain $\frac{\partial p_1^{j*}}{\partial p_2} = \frac{\beta\mu - \theta^2}{2\beta\mu - \theta^2}$, so if $\mu > \frac{\theta^2}{\beta}$, $\frac{\partial p_1^{j*}}{\partial p_2} > 0$; $\frac{\theta^2}{2\beta} < \mu < \frac{\theta^2}{\beta}$, $\frac{\partial p_1^{j*}}{\partial p_2} < 0$.

Taking the first-order derivative of r^{j*} with respect to p_2 , $\frac{\partial r^{j*}}{\partial p_2} = -\frac{\beta\theta}{2\beta\mu - \theta^2} < 0$.

(2) Taking the first-order derivatives of b_0^{j*} and τ^{j*} , we can obtain

$$\frac{\partial b_0^{st*}}{\partial p_2} = \frac{(1-t)\varepsilon\rho - \eta^2}{4(2(1-t)\varepsilon\rho - \eta^2)}, \frac{\partial b_0^{cn*}}{\partial p_2} = \frac{(1-t)\varepsilon\rho - \eta^2}{2(2(1-t)\varepsilon\rho - \eta^2)}$$

$$\frac{\partial \tau^{st*}}{\partial p_2} = \frac{\eta\rho}{4(2(1-t)\varepsilon\rho - \eta^2)}, \frac{\partial \tau^{cn*}}{\partial p_2} = \frac{\eta\rho}{2(2(1-t)\varepsilon\rho - \eta^2)}$$

Since $(1-t)\varepsilon\rho > \eta^2$, so $\frac{\partial b_0^{j*}}{\partial p_2} > 0$ and $\frac{\partial \tau^{cn*}}{\partial p_2} > 0$.

(3) Taking the first-order derivations of k^{j*} , we obtain $\frac{\partial k^{j*}}{\partial p_2} = \frac{-1}{2t} < 0$.

(4) Taking the first-order derivatives of Π_i^{j*} , we can obtain

$$\begin{aligned}\frac{\partial \Pi_{TBC}^{st*}}{\partial p_2} &= \frac{\varepsilon\rho(e\zeta\rho + \delta + \rho p_2)}{16(2(1-t)\varepsilon\rho - \eta^2)} > 0, \quad \frac{\partial \Pi_{DC}^{st*}}{\partial p_2} = \frac{\varepsilon\rho(e\zeta\rho + \delta + \rho p_2)}{8(2(1-t)\varepsilon\rho - \eta^2)} > 0, \\ \frac{\partial \Pi_G^{st*}}{\partial p_2} &= \frac{\varepsilon\rho(e\zeta\rho + \delta + \rho p_2)}{4(2(1-t)\varepsilon\rho - \eta^2)} - \frac{\beta^2\mu^2(\alpha - \beta p_2)}{(2\beta\mu - \theta^2)^2} > 0, \quad \frac{\partial \Pi_C^{cn*}}{\partial p_2} = \frac{\varepsilon\rho(e\zeta\rho + \delta + \rho p_2)}{4(2(1-t)\varepsilon\rho - \eta^2)} > 0, \\ \frac{\partial \Pi_G^{cn*}}{\partial p_2} &= \frac{\varepsilon\rho(e\zeta\rho + \delta + \rho p_2)}{2(2(1-t)\varepsilon\rho - \eta^2)} - \frac{\beta^2\mu^2(\alpha - \beta p_2)}{(2\beta\mu - \theta^2)^2} > 0.\end{aligned}$$

APPENDIX G. PROOF OF PROPOSITION 9

(2) Taking the first-order derivatives of b_0 , τ^{j*} with regard to e , we can obtain

$$\begin{aligned}\frac{\partial b_0^{st*}}{\partial e} &= \frac{\zeta((1-t)\varepsilon\rho - \eta^2)}{4(2(1-t)\varepsilon\rho - \eta^2)} > 0, \quad \frac{\partial b_0^{cn*}}{\partial e} = \frac{\zeta((1-t)\varepsilon\rho - \eta^2)}{2(2(1-t)\varepsilon\rho - \eta^2)} > 0, \\ \frac{\partial \tau^{st*}}{\partial e} &= \frac{\eta\zeta\rho}{4(2(1-t)\varepsilon\rho - \eta^2)} > 0, \quad \frac{\partial \tau^{cn*}}{\partial e} = \frac{\eta\zeta\rho}{2(2(1-t)\varepsilon\rho - \eta^2)} > 0.\end{aligned}$$

(3) Taking the first-order of k^{j*} , $\frac{\partial k^{j*}}{\partial e} = \frac{\zeta}{2t} > 0$.

(4) Taking the first and second-order derivatives of Π_i^{j*} with regard to e , since $2(1-t)\varepsilon\rho > \eta^2$, then

$$\begin{aligned}\frac{\partial \Pi_{TBC}^{st*}}{\partial e} &= \frac{\varepsilon\zeta\rho(e\zeta\rho + \delta + \rho p_2)}{16(2(1-t)\varepsilon\rho - \eta^2)} > 0, \quad \frac{\partial \Pi_G^{st*}}{\partial e} = \frac{\varepsilon\zeta\rho(e\zeta\rho + \delta + \rho p_2)}{4(2(1-t)\varepsilon\rho - \eta^2)} > 0, \quad \frac{\partial \Pi_{DC}^{st*}}{\partial e} = \frac{\varepsilon\zeta\rho(e\zeta\rho + \delta + \rho p_2)}{8(2(1-t)\varepsilon\rho - \eta^2)} > 0, \\ \frac{\partial \Pi_C^{cn*}}{\partial e} &= \frac{\varepsilon\zeta\rho(e\zeta\rho + \delta + \rho p_2)}{4(2(1-t)\varepsilon\rho - \eta^2)} > 0, \quad \frac{\partial \Pi_G^{cn*}}{\partial e} = \frac{2\varepsilon\zeta\rho B}{4(2(1-t)\varepsilon\rho - \eta^2)} > 0.\end{aligned}$$

APPENDIX H. PROOF OF PROPOSITION 10

(1) Taking the first-order of b_0^{j*} , τ^{j*} with regard to ε , then

$$\begin{aligned}\frac{\partial b_0^{st*}}{\partial \varepsilon} &= \frac{(1-t)\eta^2(e\zeta\rho + \delta + \rho p_2)}{4(2(1-t)\varepsilon\rho - \eta^2)^2} > 0, \quad \frac{\partial b_0^{cn*}}{\partial \varepsilon} = \frac{(1-t)\eta^2(e\zeta\rho + \delta + \rho p_2)}{2(2(1-t)\varepsilon\rho - \eta^2)^2} > 0, \\ \frac{\partial \tau^{st*}}{\partial \varepsilon} &= -\frac{(1-t)\eta\rho(e\zeta\rho + \delta + \rho p_2)}{2(2(1-t)\varepsilon\rho - \eta^2)^2} < 0, \quad \frac{\partial \tau^{cn*}}{\partial \varepsilon} = -\frac{(1-t)\eta\rho(e\zeta\rho + \delta + \rho p_2)}{(2(1-t)\varepsilon\rho - \eta^2)^2} < 0.\end{aligned}$$

(2) Taking the first-order derivations of p_1^{j*} , r^{j*} with regard to μ , then

$$\frac{\partial p_1^{j*}}{\partial \mu} = -\frac{\theta^2(\alpha - \beta p_2)}{(\theta^2 - 2\beta\mu)^2} < 0, \quad \frac{\partial r^{j*}}{\partial \mu} = -\frac{2\theta\beta(\alpha - \beta p_2)}{(\theta^2 - 2\beta\mu)^2} < 0.$$

(3) Taking the first-order derivations of Π_i^{j*} with regard to μ , ε , then

$$\frac{\partial \Pi_{DC}^{st*}}{\partial \mu} = \frac{\partial \Pi_C^{cn*}}{\partial \mu} = -\frac{\theta^2(\alpha - \beta p_2)^2}{2(2\beta\mu - \theta^2)^2} < 0.$$

When $2\beta\mu > \theta^2$, $\frac{\partial \Pi_G^{j*}}{\partial \mu} = -\frac{\beta\theta^2\mu(\alpha-\beta p_2)^2}{(2\beta\mu-\theta^2)^3} < 0$. $|\frac{\partial \Pi_C^{j*}}{\partial \mu}| - |\frac{\partial \Pi_G^{j*}}{\partial \mu}| = -\frac{\theta^4(\alpha-\beta p_2)^2}{2(2\beta\mu-\theta^2)^3} < 0$. It is easy to obtain that

$$\begin{aligned}\frac{\partial \Pi_{TBC}^{st*}}{\partial \varepsilon} &= -\frac{\eta^2(e\zeta\rho + \delta + \rho p_2)^2}{32(2(1-t)\varepsilon\rho - \eta^2)^2} < 0, \quad \frac{\partial \Pi_C^{cn*}}{\partial \varepsilon} = -\frac{\eta^2(e\zeta\rho + \delta + \rho p_2)^2}{8(2(1-t)\varepsilon\rho - \eta^2)^2} < 0, \\ \frac{\partial \Pi_G^{st*}}{\partial \varepsilon} &= -\frac{\eta^2(e\zeta\rho + \delta + \rho p_2)^2}{8(2(1-t)\varepsilon\rho - \eta^2)^2} < 0, \quad \frac{\partial \Pi_G^{cn*}}{\partial \varepsilon} = -\frac{\eta^2(e\zeta\rho + \delta + \rho p_2)^2}{4(2(1-t)\varepsilon\rho - \eta^2)^2} < 0. \\ |\frac{\partial \Pi_C^{cn*}}{\partial \varepsilon}| - |\frac{\partial \Pi_G^{cn*}}{\partial \varepsilon}| &= -\frac{\eta^2(e\zeta\rho + \delta + \rho p_2)^2}{8(2(1-t)\varepsilon\rho - \eta^2)^2} < 0, \quad \frac{\partial \Pi_C^{st*}}{\partial \varepsilon} = \frac{\partial \Pi_G^{st*}}{\partial \varepsilon}.\end{aligned}$$

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