https://doi.org/10.1016/j.enpol.2021.112166

# Conventional Automotive Supply Chains under China's Dual-Credit Policy: Fuel Economy, Production and Coordination

Haicheng Ma[a], Gaoxiang Lou[a,*], Tijun Fan[a], Hing Kai Chan[b], Sai Ho Chung[c]

[a]*Business School, East China University of Science and Technology, Shanghai 200237, China*

[b]*Nottingham University Business School China, University of Nottingham Ningbo China, Ningbo 315100, China*

[c]*Department of Industrial & Systems Engineering, Hong Kong Polytechnic University, Hong Kong, China*

## Abstract

As a sustainability policy in emerging markets, the dual-credit policy was implemented in China to reduce corporate average fuel consumption and to promote new energy vehicles (NEVs). Through a game theoretic approach, the fuel economy improvement level and the production of traditional internal combustion engine vehicles (ICEVs) and NEVs are discussed. Research and development cost sharing contracts and ICEV revenue sharing contracts are designed to coordinate conventional automotive supply chains. We compare the current and revised dual-credit policy, identify some policy flaws and propose amendments. The dual-credit policy does not always help automotive supply chains to improve fuel economy, reduce the production of high fuel consumption vehicles, and produce more low fuel consumption vehicles and NEVs. The implementation and selection of coordination contracts are explored. Both of the above contracts may not be able to coordinate the supply chain, and cost sharing contracts may be better than revenue sharing contracts in some cases. Finally, we present some

---

*Corresponding authors. *E-mail addresses:* gxlou@ecust.edu.cn (G. Lou).

Define all key abbreviations in the paper: Corporate average fuel consumption (CAFC); High fuel consumption vehicle (HFCV); Internal combustion engine vehicle (ICEV); Low fuel consumption vehicle (LFCV); New energy vehicle (NEV).

management insights into the response to the dual-credit policy.

*Keywords:* Dual-credit policy; Automotive supply chain; Fuel economy; Coordination contract; Emerging market.

## 1. Introduction

Over the past 20 years, fuel consumption standards in emerging markets, such as China, South Korea, Saudi Arabia, Brazil, and Mexico, have often been higher than those in developed markets, such as the European Union and Japan (ICCT, 2017). Higher automotive fuel consumption has brought serious environmental problems and energy crises to emerging markets. In China, 6.6 billion tons carbon emissions will be generated through road traffic by 2020 (Han et al., 2017), and the oil import dependency rate (i.e., the ratio of oil import to total oil consumption) has far exceeded the safety line, climbing to 70% (CNPC, 2019).

However, consumer enthusiasm for low fuel consumption vehicles (LFCVs) and new energy vehicles (NEVs) in emerging markets is growing rapidly. Ford's survey of 11 major markets in the Asia Pacific region revealed rapid growth in consumer fuel economy preferences, of which nearly 60% of mainland Chinese consumers prefer fuel economy over power performance (Ford, 2016). As the world's largest electric vehicle market (Crabtree, 2019), China is leading the way in consumer appetites for NEVs, which are far greater than in developed markets, such as Europe and the United States (OC&C, 2019).

Recognizing these issues, governments in emerging markets have implemented various sustainability policies to reduce fuel consumption of internal combustion engine vehicles (ICEVs) (ICCT, 2020) and promote NEVs (Wang et al., 2017; Vidhi and Shrivastava, 2018), which are considered to be conducive to energy transformation and decarbonization in the transportation sector (Piacentino et al., 2020). Energy-saving policies are not believed to prevent economic growth in emerging markets (Bakirtas and Akpolat, 2018).

In September 2017, the Chinese government creatively introduced the dual-credit policy (MIIT, 2017), aiming to facilitate passenger vehicle manufacturers and imported passenger vehicle suppliers in China in reducing corporate average fuel consumption (CAFC) and producing more NEVs. On the one hand, automakers need to calculate the annual CAFC credits based on the difference between the standard value of CAFC set by the government and the actual value of CAFC based on actual production. On the other hand, the policy requires automakers to produce a certain percentage of NEV every year, and calculate the corresponding NEV credits based on the difference between the actual and the required NEV production. Automakers need to report the annual dual-credit situation, and conduct credit transactions on the corresponding government platform in the second year. Negative NEV credits and negative CAFC credits must be offset by purchasing the same amount of positive NEV credits. Among them, negative NEV credits are only calculated from 2019 to ease corporate pressure. It is worth noting that, in September 2019, the government proposed a draft amendment to the dual-credit policy (hereafter referred to the revised dual-credit policy) (MIIT, 2019b). The new amendments include no longer considering NEV when calculating actual CAFC and granting a certain percentage of NEV credits rewards to LFCV, etc., and the latter has been implemented in June 2020 (MIIT, 2020b).

Under the dual-credit policy, global automakers are facing huge challenges. Fig. 1 describes the overall situation of dual-credits. Surprisingly, the positive NEV credits in 2019 are difficult to meet the negative NEV credits and the growing negative CAFC credits. The proportion of automakers that do not meet CAFC standards is climbing. The dual-credit policy has attracted the attention of multinational automakers, which must meet local regulations. However, in 2019, as many as 85% of imported passenger vehicle suppliers failed to meet CAFC standards, and only 37% supplied NEVs (MIIT, 2020a).

[Put Fig.1 here]

Besides, the dual-credit policy has a significant spillover effect on upstream engine suppliers. There is no doubt that research and development (R & D) of engine technology are among the main methods to improve fuel economy, which will reduce CAFC, and there remains 30% potential for improvements in the engine efficiency of Chinese engine suppliers (Zhao et al., 2016). After the policy was promulgated, China's automotive engine production fell for the first time in seven consecutive years (CIIN, 2019). Although the dual-credit policy has been implemented for automakers, the scope of the influence has been extended to the entire automotive supply chain. We refer to the supply chain composed of engine suppliers and automakers as the conventional automotive supply chain to distinguish the new energy vehicle supply chain, which is mainly composed of battery suppliers and pure NEV manufacturers. In China, many automakers have their engine suppliers, forming a centralized supply chain. However, some domestic brand automakers often do not have advanced engine technology and must purchase engines from foreign or joint venture brands, thus forming a decentralized supply chain with engine suppliers. For example, the main customers of Aerospace Mitsubishi include some domestic brand automakers, such as Brilliance Auto, Great Wall Motor, and BAIC Motor (www.same.com.cn).

Since investment in R & D to improve fuel economy often brings high costs and the spillover of benefits, it is of great practical significance to coordinate supply chains. We consider two common coordination contracts in the sustainable supply chain: (1) cost sharing contracts for R & D investment, which are commonly used in supply chains with higher R & D costs (Zhu et al., 2018; Hong and Guo, 2019); and (2) revenue sharing contracts, which are often used to coordinate green or low-carbon supply chains (Song and Gao, 2018; Ji et al., 2020).

In summary, this paper focuses on the following issues in the context of China's dual-credit policy.

(1) In terms of corporate decision-making, how do engine suppliers decide on the fuel economy of engines? How do automakers decide on production?

(2) In terms of policy effects, what effect will the dual-credit policy exert? We will focus on fuel economy, the production of high fuel consumption vehicles (HFCVs), LFCVs and NEVs, and the profits of engine suppliers and automakers.

(3) In terms of supply chain coordination, how can R & D cost sharing contracts and ICEV revenue sharing contracts be designed to coordinate supply chain profits? How do automakers choose contracts to achieve higher profits and better policy effects?

The main contributions are as follows.

(1) Methodologically, existing research mainly uses data simulation rather than theoretical analysis to study the dual-credit policy (see Section 2.5). However, we use game theory to gain some new insights.

(2) In terms of research content, we study the revised dual-credit policy to fill the gap in the existing research (see Section 2.5). Besides, unlike all previous literature (see Sections 2.4 and 2.5), supply chain coordination under the dual-credit policy is explored.

(3) Concerning the contribution to coordination contracts in the field of sustainable supply chains, different conclusions from the existing literature (see Sections 2.4 and 5.2) are reached. We believe

that, in the face of different policy pressures, cost sharing contracts might be better than revenue sharing contracts, providing new insights for academic researchers and corporate managers.

(4) In practice, we provide enterprises in the conventional automotive supply chain with different optimal decisions for improvements in fuel economy and production based on different initial CAFC credits for each vehicle (see Section 4.1), which could help corporate managers to optimize sustainable operations. Besides, some policy flaws are obtained, which can only be partially confirmed by previous literature (see Section 4.2). These outcomes provide important reference values for policymakers.

The remaining chapters are arranged as follows. Section 2 analyzes relevant literature. Section 3 establishes a Stackelberg game model. Section 4 analyzes some policy effects on the conventional automotive supply chain. Section 5 designs and compares two types of coordination contracts. Section 6 describes the main conclusions, management insights, and future research directions.

## 2. Literature review

### 2.1 Operations management in emerging markets

Our research background is related to emerging markets, which has become a popular topic in the field of operations management in recent years (Zhou et al., 2016; Yi et al., 2017; Khuntia et al., 2018; Tong et al., 2018; Choi and Luo, 2019). Some literature explores the automotive industry in emerging markets. Gurca and Ravishankar (2016) used an electric vehicle producer in India as an example to explore the support of bricolage strategy for technological innovation in emerging markets, while Jonnalagedda and Saranga (2019) compared two strategies of multinational automakers for product design in emerging markets, including adapted product design and customized simultaneous design.

Our paper also explores operational management issues in emerging markets (i.e., China), but the difference is that we focus on the impact of sustainability policies (i.e., the dual-credit policy) on sustainable supply chain management in emerging markets.

### 2.2 Sustainable operations

Traditional operations management requires sustainable innovation to be a useful toolkit for advancing the sustainability agenda (Van Wassenhove, 2019). Many scholars have continued to develop and utilize operations management methods to explore sustainable operations in different contexts, such as the game-theoretical approach (Li et al., 2018; Agrawal and Lee, 2019; Safarzadeh and Rasti-Barzoki, 2019a, 2019b; Li et al., 2020a), optimization modeling (Wang et al., 2018; Dara et al., 2020; Shen et al., 2020), quantitative empirical analysis (Corbett et al., 2018) and multi-methodological approaches (Choi et al., 2019b).

In the automotive industry, sustainable operations have also been extensively studied recently. Seles et al. (2016) explored the green bullwhip effect through a case study of a Brazilian automotive battery company and emphasized the impact of the institutional environment. Keivanpour et al. (2017) proposed a hybrid model to analyze automakers' green practice strategic choices in response to end-of-life vehicle recycling. Umpfenbach et al. (2018) considered environmental regulations and sustainability goals, introduced assortment planning models for automotive products, and validated the model with a case study from a global automaker. Li et al. (2020d) revealed the relationship among the pressure, practice, and performance of green supply chain management under quick response technology through data and case studies from Chinese firms including Beijing Benz.

Our paper also explores sustainable operations in the automotive industry, such as R & D activities for fuel economy, production of NEVs, and sustainable supply chain coordination. The difference is that we research the context of the dual-credit policy.

### 2.3 Automotive supply chains

The automotive supply chain is often composed of upstream component suppliers (including engine suppliers), core automakers and downstream retailers. Traditional operations management is brought more challenges by the complex and giant automotive supply chain system. Recent studies have explored the operations management issues of the automotive supply chain from various aspects, such as the factors of sustainable practices in the automotive supply chain (Liu et al., 2016; Mathivathanan et al., 2018), the adoption of lean production strategies in different stages of the automotive supply chain (Marodin et al., 2016; Qamar et al., 2018), the impact of the interdependence of components and the proximity of the supply chain on the quality of automotive products (Agrawal et al., 2017; Bray et al., 2019), order management (Olbert et al., 2016; Ishfaq and Narayanan, 2019), risk management (Murphy et al., 2019; Vanalle et al., 2020) and transportation disruption (Fartaj et al., 2020) in the automotive supply chain, etc.

The above studies focus on the optimization of the internal management, but some other studies focus on the impact of external policy factors on the automotive supply chain. For example, Huang et al. (2013) argued that consumer subsidies for the purchase of electric vehicles (EV) can reduce the demand for ICEV and the profit of the automotive supply chain composed of automakers and retailers that only produces ICEV, but increase the demand for EV and the profit of the supply chain that produces both EV and ICEV. Luo et al. (2014) proposed a comprehensive price discount incentive plan including price discount rate and subsidy ceiling for the automotive supply chain composed of automakers and retailers to effectively increase EV sales. Li et al. (2020b) assumed that the dual-credit policy can promote across-chain cooperation between the ICEV supply chain and the NEV supply chain, and found that the implementation of the dual-credit policy will make the production schedule more uneven and reduce the profit of the entire supply chain system composed of automakers and retailers.

Our paper also considers the impact of external policy on the production and profits of the automotive supply chain. The difference is that we simultaneously focus on the fuel economy decision and expand the automotive supply chain to upstream engine suppliers. We draw out key supply chain members, namely engine suppliers and automakers, who are deeply affected by the dual-credit policy and play a key role in improving fuel economy.

### 2.4 Coordination contracts in the sustainable supply chain

Coordination contracts constitute a major means to coordinate the sustainable supply chain. For different sustainable operation issues, many researchers have designed a variety of coordination contracts, such as two-part tariff contracts (Biswas et al., 2018; Hong and Guo, 2019; Hosseini-Motlagh et al., 2019), quantity discount contracts (Heydari et al., 2017), cost sharing contracts (Zhu et al., 2018; Hong and Guo, 2019) and revenue sharing contracts (Song and Gao, 2018; Ji et al., 2020).

Due to the high R & D costs and spillover benefits in the automotive supply chain, we focus on cost sharing contracts and revenue sharing contracts in the sustainable supply chain, which have been compared by fewer researchers from different perspectives. Yenipazarli (2017) compared the impacts of the two contracts from the upstream ecological innovation effects and supply chain profits and found that, as the fixed costs of environmental improvements increase, the revenue sharing contract is more conducive to collaboration. Yang and Chen (2018) and Li et al. (2019) argued that, from the perspectives of both emission reduction and corporate profits, the revenue sharing contract, designed to maximize the profits of downstream enterprises, is better than the corresponding cost sharing contract. However, Raj et al. (2018) considered corporate social responsibility and found that, from a profit perspective, the contract preferences of suppliers and buyers are not the same, but revenue sharing contracts remain more conducive to upstream green R & D than cost sharing contracts. Yu et al. (2020) obtained through a differential game that revenue sharing contracts are more favorable for low-carbon supply chains and manufacturers, but the sharing ratio is an exogenous variable. In short, the above literature reported that the revenue sharing contracts established by downstream enterprises to maximize their profits are better than the corresponding cost sharing contracts.

However, we provide different views from the above literature. In our model, from both a policy effect and a profit perspective, the cost sharing contract can be better than the revenue sharing contract in some cases. Besides, there has been no research on supply chain coordination under the dual-credit policy.

### 2.5 The dual-credit policy

Existing research on the dual-credit policy can be divided into two levels. At the macro-level, it focuses on the profitability of the plug-in electric vehicle (Ou et al., 2018), the promotion of electric vehicles (EVs) (Wang et al., 2018), the development of EV technology (Zhao et al., 2019b), the emissions from road transportation (Zhao et al., 2019a; He et al., 2020), the impact of policy transition on the private motorization rate and the battery market (Hsieh et al, 2020), as well as the comparison and interaction research with NEV subsidy policies (Li et al., 2018; Chen et al., 2018).

At the micro-level, researchers mainly use game theory and optimization methods to discuss automakers' decisions. Li et al. (2020a) considered battery recycling and consumers’ environmental awareness and provided a method to decide NEV credit price based on a Stackelberg game model. Li et al. (2020b) established mixed-integer linear programming (MILP) and used a heuristic algorithm combined with data simulation to explore production decisions of ICEVs and NEVs under subsidy policies and the dual-credit policy considering the competition and cross-chain cooperation. Li et al. (2020c) developed a dynamic equilibrium model and established a hybrid complementary problem (MCP) to set annual NEV credit ratio requirements. Lou et al. (2020) developed a new optimization model to discuss the production and R & D decisions of automakers with different initial fuel consumption and drew some useful policy recommendations. Wang et al. (2020) discussed the choice of two green technology innovations for automakers, including ICEV's energy-saving technology and NEV's production technology. Besides, Zhou et al. (2019) extended the dual-credit policy to general traditional manufacturers to form a generalized dual-credit system.

All of the aforementioned literature mainly adopted data simulation methods, and few theoretical studies have been conducted using pure theoretical analysis. Li et al. (2020a) only considered the game between pure fuel vehicle manufacturers and NEV manufacturers. However, most automakers in reality are mixed production. Lou et al. (2020) analyzed how automakers that produce both ICEV and NEV respond to the dual-credit policy, but only R & D and production of ICEV are considered. Our research is an extension based on Lou et al. (2020). The differences are: (1) we also considered NEV's production decisions; (2) we extended the optimization problem to the supply chain and designed a Stackelberg game model; (3) we studied the revised dual-credit policy. As far as we know, there has been no research studying the revised dual-credit policy. Our paper considers these changes to better predict and explain the impact of the dual-credit policy.

## 3. The model and methods

### 3.1 Parameters and assumptions

We discussed a conventional automotive supply chain, which are composed of an engine supplier and a conventional automaker. The conventional automaker is defined as the automaker that produces both ICEV and NEV to distinguish the NEV manufacturer, such as NIO and Tesla, which only produces NEV so that it is not affected by the CAFC credit regulation. Automotive industry in China is still dominated by ICEV, and China's top ten automakers in sales are all conventional automakers (MIIT, 2020a). We define the supply chain composed of conventional automakers and upstream engine suppliers as conventional automotive supply chains to distinguish NEV supply chains, which are composed of NEV manufacturers and corresponding battery suppliers.

The engine supplier improves the fuel economy of the engine through R & D investment and produces and sells engines at the beginning of the year. The automaker produces ICEVs and NEVs with existing technologies and sells them to the consumer market. And then, the automaker calculates credits and participates in the credit transaction in the second year to offset all negative credits or to sell excess positive NEV credits. Related parameters are described in Table 1.

[Put Table 1 here]

The main assumptions are as follows.

(1) ICEV production and NEV production are determined by market demand. We consider a simple linear demand function, which is widely used in the research on supply chain management (Cui et al., 2016; Choi et al., 2019a; Hosseini-Motlagh et al., 2019) and the dual-credit policy (Li et al., 2020b, 2020c; Lou et al., 2020), to simplify the model without losing generality. The market demand function for ICEVs and NEVs are as follows:

$$q_{\mathrm{i}}(p_{\mathrm{i}}, x) = a_{\mathrm{i}} - b_{\mathrm{i}} p_{\mathrm{i}} + \theta x \tag{1}$$

$$q_{\mathrm{n}}(p_{\mathrm{n}}) = a_{\mathrm{n}} - b_{\mathrm{n}} p_{\mathrm{n}} \tag{2}$$

The corresponding inverse demand functions are:

$$p_{\mathrm{i}}(q_{\mathrm{i}},x)=\frac{a_{\mathrm{i}}-q_{\mathrm{i}}+\theta x}{b_{\mathrm{i}}} \tag{3}$$

$$p_{\mathrm{n}}(q_{\mathrm{n}})=\frac{a_{\mathrm{n}}-q_{\mathrm{n}}}{b_{\mathrm{n}}} \tag{4}$$

First, in the market demand function of ICEVs, the higher that the fuel economy improvement level is, the higher that the market demand is, indicating that consumers have certain fuel economy preferences, as described by Dumortiera et al. (2015) and Ford (2016). Second, we did not consider the changes in demand brought about by the advancement of NEV technology. From a policy perspective, the focus of the policy is to reduce CAFC and encourage the production of NEVs. From an enterprise perspective, it is impossible to reduce the cost of CAFC credits by only producing ICEVs without improving the fuel economy, but positive NEV credits can be obtained by only producing NEVs without improving NEV technology. Therefore, we mainly consider NEV production, not NEV technology development, to simplify the model. Besides, because we are mainly concerned with the impact of the dual-credit policy, not the impact of market parameters, we assume that $a_{\mathrm{i}}=a_{\mathrm{n}}=a$ and $b_{\mathrm{i}}=b_{\mathrm{n}}=b$ to facilitate mathematical calculations. Finally, we did not consider the competition between the two markets, so competitive markets will be an important research direction.

(2) Without loss of generality, in order to reduce the complexity of the expression and facilitate calculations, we assume that the variable production cost is 0. It will not change the correctness of the propositions and theorems, and is widely used in the field of operation and supply chain management, such as Yang et al. (2017), Xu et al. (2018), Guo and Wu (2018).

(3) The cost of R & D investment to improve the fuel economy is described as $k\,x^2/2$. Similar assumptions can be found in Hong and Guo (2019), Zhou et al. (2019) and Lou et al. (2020).

(4) To simplify the model and focus on the impact of upstream suppliers on fuel economy, we assume that the fuel economy improvement level obtained by the upstream engine supplier by

improving the engine technology R&D level (i.e., $x$) is an endogenous decision variable, and other efforts made by the automaker to improve fuel economy are regarded as an exogenous variable. And since the cost of the automaker's efforts to improve fuel economy is mainly a fixed cost that has nothing to do with each decision variable, it is not considered and does not affect the form of the optimal solution.

(5) Based on the draft amendment to the dual-credit policy (MIIT, 2019b) and future policy trends, in order to simplify the calculation and obtain a closed-form solution that can be qualitatively analyzed, we assume that the actual CAFC is only related to the decision variable of fuel economy improvement level and has nothing to do with other decision variables. The same assumption is also reflected in Wang et al. (2020).

Besides, as assumed and explained in Lou et al. (2020), we also propose the following assumptions.

(6) The value of positive CAFC credits is not considered because of low value and non-tradability in the credit transaction market.

(7) Automakers produce ICEVs with only one level of fuel consumption. That is, the automakers' ICEVs have the same fuel consumption level, which is either that of HFCVs (the fuel consumption has not reached the standard) or LFCVs (the fuel consumption has reached the standard). Therefore, automakers can only reduce the pressure on CAFC credits by improving the fuel economy rather than adjusting the product portfolio.

(8) With so many automakers involved, the credit transaction market can be considered a perfectly competitive market, and the credit transaction price is considered an exogenous variable.

(9) Credit calculations and transactions are conducted once per year, so we consider a one-year decision cycle.

### 3.2 The game model

We build a game model, which are widely used in sustainable supply chains (Agrawal and Lee, 2019; Safarzadeh and Rasti-Barzoki, 2019a, 2019b) and the dual-credit policy (Li et al., 2018; Li et al., 2020a).

Under the dual-credit policy (superscript D), the optimization problem of the centralized supply chain (superscript c) is described as follows:

$$\underset{x,q_{\mathrm{i}},q_{\mathrm{n}}}{\mathrm{Max}}\,\pi_{\mathrm{sc}}^{\mathrm{Dc}} = p_{\mathrm{i}}q_{\mathrm{i}} + p_{\mathrm{n}}q_{\mathrm{n}} - kx^2/2 + [\mathrm{Min}(\mathrm{CAFCC},0) + \mathrm{NEVC}]p_{\mathrm{c}} \tag{5}$$

According to MIIT (2017, 2019b), CAFC credits are expressed as $\mathrm{CAFCC} = (\alpha + x)(q_{\mathrm{i}} + q_{\mathrm{n}})$. Based on assumption (5), the actual CAFC is only related to the decision variable $x$. The standard CAFC is only determined by the vehicle quality and its ratio to the target value specified by the policy, and it can be assumed that it is unchanged. Then at the end of the year, the difference between the standard and the actual CAFC is $\alpha + x$. It can be determined from assumption (6) that we should calculate the minimum value between CAFC credits and zero to measure the cost of CAFC credits.

Besides, NEV credits are expressed as $\mathrm{NEVC} = \beta q_{\mathrm{n}} - \gamma\rho q_{\mathrm{i}}$. The actual value is the NEV production multiplied by the average positive NEV credits per NEV produced. The standard value is the ICEV production multiplied by the proportion requirements for NEV production. The LFCV production in 2021 is calculated at 0.5 times when calculating the NEV standard value (MIIT, 2019b, 2020b). Therefore, if $\alpha + x \geq 0$, then $\gamma = 0.5$; if $\alpha + x < 0$, then $\gamma = 1$.

In the decentralized supply chain (superscript d), a Stackelberg game is played by upstream and downstream enterprises. The game sequence is shown in Fig. 2.

[Put Fig.2 here]

The profit function of upstream and downstream enterprises in the decentralized supply chain is described as follows.

(1) When coordination contracts are not implemented:

$$\pi_{\mathrm{s}}^{\mathrm{Dd}}(x,w)=wq_{\mathrm{i}}-kx^2/2 \tag{6}$$

$$\pi_{\mathrm{m}}^{\mathrm{Dd}}(q_{\mathrm{i}},q_{\mathrm{n}})=(p_{\mathrm{i}}-w)q_{\mathrm{i}}+p_{\mathrm{n}}q_{\mathrm{n}}+[\mathrm{Min(CAFCC,0)}+\mathrm{NEVC}]p_{\mathrm{c}} \tag{7}$$

(2) When the cost sharing contract (superscript CS) is implemented:

$$\pi_{\mathrm{s}}^{\mathrm{CS}}(x,w)=wq_{\mathrm{i}}-(1-\lambda)kx^2/2 \tag{8}$$

$$\pi_{\mathrm{m}}^{\mathrm{CS}}(\lambda,q_{\mathrm{i}},q_{\mathrm{n}})=(p_{\mathrm{i}}-w)q_{\mathrm{i}}+p_{\mathrm{n}}q_{\mathrm{n}}-\lambda kx^2/2+[\mathrm{Min(CAFCC,0)}+\mathrm{NEVC}]p_{\mathrm{c}} \tag{9}$$

(3) When the revenue sharing contract (superscript RS) is implemented:

$$\pi_{\mathrm{s}}^{\mathrm{RS}}(x,w)=wq_{\mathrm{i}}-kx^2/2+\mu p_{\mathrm{i}}q_{\mathrm{i}} \tag{10}$$

$$\pi_{\mathrm{m}}^{\mathrm{RS}}(\mu,q_{\mathrm{i}},q_{\mathrm{n}})=[(1-\mu)p_{\mathrm{i}}-w]q_{\mathrm{i}}+p_{\mathrm{n}}q_{\mathrm{n}}+[\mathrm{Min(CAFCC,0)}+\mathrm{NEVC}]p_{\mathrm{c}} \tag{11}$$

We also consider the no-policy scenario (superscript N) for comparison. The corresponding profit function can be obtained by removing the credit costs and benefits from the above equations.

The subgame perfect Nash equilibrium of the above Stackelberg game can be obtained by backward induction. Optimization theory is used to obtain a unique equilibrium solution. The solution procedures are presented in Appendix A.

### 3.3 Simulation data

To render the results more intuitive, we use Mathematica software to simulate the scenario of 2021 using numerical simulation methods. See Table 2 for specific parameter values.

[Put Table 2 here]

Drawing on the parameter values in Lou et al. (2020), the basis of each parameter calibration is as follows.

(1) The potential market demand is 300,000 vehicles, indicating that the brands are popular.

(2) China's automobile market is highly elastic. In our model, the value of $b$ is 10, which causes the ICEV production to be 80,000 units and the price to be 24,000 CNY under the no-policy scenario; thus, the point elasticity of market demand price is -3, and the point elasticity of NEV market demand price is -1, indicating that the NEV market is weak in competition.

(3) Considering rising fuel economy preferences and inflation, we use a higher value of 5,000 CNY to measure the expected net present value for consumers when fuel economy improves by 1 liter/100 kilometers, which is the same as Lou et al. (2020) and within the range described by Greene et al. (2008). Therefore, the increase in demand for improvements in fuel economy per unit is 50,000 vehicles.

(4) The value of $k$ is so large that the fuel economy improvement level is 0.4 liters/100 kilometers under the no-policy scenario. In reality, automakers' annual fuel economy improvement levels are mostly distributed in 0 to 1 liter/100 kilometers (MIIT, 2018b, 2019a, 2020a). As the CAFC target value set by the Chinese government decreases by 0.5 liters/100 kilometers per year (MIIT, 2015), it is slightly inadequate in our model, reflecting the necessity of implementing the dual-credit policy.

(5) The initial CAFC credits for each vehicle are mostly distributed in -5 to 1 liter/100 kilometers (MIIT, 2019a, 2020a).

(6) The positive NEV credits generated by each NEV are distributed in 1 to 6 credits (MIIT, 2019b, 2020b). We set the value at 3 to simulate the scenario in 2021.

(7) The requirement for the proportion of NEV production in 2021 is 14% (MIIT, 2019b, 2020b).

(8) The revised dual-credit policy significantly increases the difficulty of obtaining positive NEV

credits. Therefore, the credit transaction price is expected to rise, compared to the price of 850 CNY in 2018. Here, we use the value of 2,000 CNY to simulate the credit transaction market in 2022. In the simulation of Li et al. (2018), the upper limit of this parameter is as high as 20,000 CNY.

Sections 4 and 5 describe the results and discussion in detail.

## 4. Analysis of optimal decisions and policy effects under the dual-credit policy

### 4.1 Optimal decisions

As designed by Lou et al. (2020), we classify automakers into three categories (H-type, E-type, and L-type) based on the CAFC at the end of the year, which means that the actual CAFC is higher than, equal to and lower than the standard CAFC, respectively. The corresponding supply chains (suppliers) are called H-type, E-type, and L-type supply chains (suppliers), which are denoted by the subscripts H, E, and L, respectively. All expressions and Proofs can be found in Appendix A.

**Proposition 1** *Under the revised dual-credit policy, when* $k > \underline{k}_1$, $a > \underline{a}$ *and* $\alpha > \underline{\alpha}$, *there are positive optimal decisions for conventional automotive supply chains. The type of supply chain is related to the initial CAFC credits for each vehicle (*$\alpha$*). Specifically, in the centralized (decentralized) supply chain, if* $\alpha > \alpha_{\mathrm{EL}}^{\mathrm{c}}$ *(*$\alpha > \alpha_{\mathrm{EL}}^{\mathrm{d}}$*), it is an L-type supply chain; if* $\alpha_{\mathrm{EL}}^{\mathrm{c}} \geq \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{c}}$ *(*$\alpha_{\mathrm{EL}}^{\mathrm{d}} \geq \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{d}}$*), it is an E-type supply chain; and if* $\alpha_{\mathrm{HE}}^{\mathrm{c}} > \alpha > \underline{\alpha}$ *(*$\alpha_{\mathrm{HE}}^{\mathrm{d}} > \alpha > \underline{\alpha}$*), it is an H-type supply chains.*

Among them, $k > \underline{k}_1$ is the condition for the existence and uniqueness of the optimal solution to ensure that all of the profit functions are concave, indicating that enhancing fuel economy requires a sufficiently high cost. $a > \underline{a}$ and $\alpha > \underline{\alpha}$ are conditions under which the optimal solution is positive. It can be considered that the potential market size is sufficiently large, and the difference between the standard and the actual CAFC cannot be too small; otherwise, the automaker will be unable to produce.

It can be found that the initial CAFC credits for each vehicle ( $\alpha$ ) determine the type of supply chain. $\alpha_{\mathrm{HE}}$ and $\alpha_{\mathrm{EL}}$ represent the dividing lines of H-type and E-type and E-type and L-type, respectively, and $\alpha_{\mathrm{HE}} < \alpha_{\mathrm{EL}}$ can be proved.

The result of Proposition 1 is a good depiction of reality. In reality, there are indeed three types of automakers: H-type automakers, such as BMW, Mercedes-Benz, and SAIC-GM, E-type automakers, such as Dongfeng Yueda Kia in 2017 and China FAW Group in 2018, and L-type automakers, such as Chery Automobile, Jiangnan Automobile and GAC Toyota (MIIT, 2018b, 2019a, 2020a). This outcome shows that our model can better simulate reality.

### 4.2 Policy effects

The main purpose of the dual-credit policy is to motivate automakers to reduce CAFC and produce more NEVs, indicating that automakers must continuously improve fuel economy, reduce HFCV production, and increase LFCV and NEV production. By comparing the no-policy scenario and the revised dual-credit policy scenario, we obtain the following theorems.

**Theorem 1** *The impact of the dual-credit policy is as follows. For H-type supply chains with low initial CAFC credits for each vehicle, it can reduce their fuel economy improvement level and NEV production. For H-type supply chains with high initial CAFC credits for each vehicle, it can increase their HFCV production. For L-type and E-type supply chains with high initial CAFC credits for each vehicle, it might be detrimental to the improvements in fuel economy and the increase in LFCV production.*

*(1) If* $\alpha < \alpha_{\mathrm{xH}}^{\mathrm{c}}$ *(*$\alpha < \alpha_{\mathrm{xH}}^{\mathrm{d}}$*) in the centralized (decentralized) supply chain, then* $x_{\mathrm{H}}^{\mathrm{D*}} < x^{\mathrm{N*}}$*; if* $\alpha > \alpha_{\mathrm{xE}}^{\mathrm{c}}$ *(*$\alpha > \alpha_{\mathrm{xE}}^{\mathrm{d}}$*) in the centralized (decentralized) supply chain, then* $x_{\mathrm{E}}^{\mathrm{D*}} < x^{\mathrm{N*}}$*;* $x_{\mathrm{L}}^{\mathrm{D*}} < x^{\mathrm{N*}}$.

*(2) If* $\alpha > \alpha_{\mathrm{qiH}}^{\mathrm{c}}$ *(*$\alpha > \alpha_{\mathrm{qiH}}^{\mathrm{d}}$*) in the centralized (decentralized) supply chain, then* $q_{\mathrm{iH}}^{\mathrm{D*}} > q_{\mathrm{i}}^{\mathrm{N*}}$ *; if* $\alpha > \alpha_{\mathrm{qiE}}^{\mathrm{c}}$ *(*$\alpha > \alpha_{\mathrm{qiE}}^{\mathrm{d}}$*) in the centralized (decentralized) supply chain, then* $q_{\mathrm{iE}}^{\mathrm{D*}} < q_{\mathrm{i}}^{\mathrm{N*}}$*;* $q_{\mathrm{iL}}^{\mathrm{D*}} < q_{\mathrm{i}}^{\mathrm{N*}}$.

*(3) If* $\alpha < \alpha_{\mathrm{qnH}}^{\mathrm{c}}$ *(*$\alpha < \alpha_{\mathrm{qnH}}^{\mathrm{d}}$*) in the centralized (decentralized) supply chain, then* $q_{\mathrm{nH}}^{\mathrm{D*}} < q_{\mathrm{n}}^{\mathrm{N*}}$ *;* $q_{\mathrm{nE}}^{\mathrm{D*}} = q_{\mathrm{nL}}^{\mathrm{D*}} > q_{\mathrm{n}}^{\mathrm{N*}}$.

Theorem 1 verifies the simulation results in the previous literature. Ou et al. (2018) simulated the situation from 2016 to 2020 with realistic data and pointed out that the dual-credit policy could bring more high-profitable HFCV compared to only implementing CAFC regulations. Li et al. (2018) believed that if ICEV's profits can offset the credit costs, then the automaker will not reduce production. Wang et al. (2018) simulated the situation in 2020 and 2025 and also believed that the policy might be harmful to CAFC reduction.

Theorem 1 also verifies some of the conclusions that Lou et al. (2020) obtained through optimization modeling. But the differences are: (1) we reveal the impact on NEV production, which is not provided by Lou et al. (2020); (2) we conclude that the revised dual-credit policy can reduce LFCV production, which is conditionally restricted in the paper by Lou et al. (2020) (the specific condition is that the NEV credit is negative). The reason for the differences is that thanks to the modification of the credit calculation method suggested by the revised dual-credit policy, we can make decisions about NEV production, while Lou et al. (2020) assumed that it is an exogenous variable.

We can explain the conclusions about NEV and LFCV production from the perspective of credit cost. Because CAFC credits are directly related to the sum of ICEV and NEV production, the H-type supply chain will reduce the total production may including NEV to reduce CAFC credit costs. Besides, the higher the ICEV production, the higher the standard value of NEV credits. Therefore, the supply chain that has reached the CAFC standard may reduce LFCV production to ease the pressure of NEV credit costs.

As shown in Fig. 3, we use the decentralized supply chain as an example and use numerical simulations to more intuitively show the results of Theorem 1.

[Put Fig.3 here]

However, the conclusion about NEVs in Theorem 1 is a prediction of the future, but it has not been verified in reality or the previous literature. If the recommendations in the revised dual-credit policy are adopted in the future, the aforementioned adverse effects on NEV will likely appear.

**Theorem 2** *The dual-credit policy will result in lower profits for engine suppliers in a decentralized supply chain, that is,* $\pi_{\mathrm{s}}^{\mathrm{Dd}*} < \pi_{\mathrm{s}}^{\mathrm{Nd}*}$.

Regardless of CAFC credits or NEV credits, the increase in ICEV production will increase the cost of credits, so the marginal cost of ICEVs will increase. Therefore, for the entire conventional automotive supply chain, all enterprises will be damaged as a result. However, automakers can earn NEV credits by producing NEVs. As long as NEV production is sufficient, their profits can rise, as shown in Fig. 4. Although the policy is aimed at automakers, its impact will extend to upstream engine suppliers and adversely affect them due to the existence of the supply chain system. Therefore, it is necessary to coordinate the conventional automotive supply chain.

[Put Fig.4 here]

Through Theorems 1 and 2, we can well understand why, in reality, engine suppliers have experienced a significant decline in production and profits (CIIN, 2019). The government might, therefore, consider intervening in the form of financial subsidies.

### 4.3 Revision effects

Figures 3 and 4 also show the difference between the revised and the current dual-credit policy. In this section, we mainly discuss the effects of the new regulation, which is “in 2021, 2022, and 2023, the LFCV production is calculated at 0.5 times, 0.3 times, and 0.2 times, respectively, when calculating the NEV standard value” (MIIT, 2019b, 2020b). Let $\gamma \equiv 1$, and the optimal decisions and profits before the addition of the above regulation can be obtained. By simple comparison, we can obtain Theorem 3.

**Theorem 3** *The addition of the above new regulation is conducive to the improvements in fuel economy, the increase in LFCVs and NEVs, and the profits of engine suppliers and automakers, and it could allow more automakers to meet the CAFC standard. Specifically, whether in a centralized or decentralized supply chain,* $x^{\mathrm{D}*} \geq x^{\mathrm{D}*}(\gamma \equiv 1)$ , $q_{\mathrm{iLFCV}}^{\mathrm{D}*} \geq q_{\mathrm{iLFCV}}^{\mathrm{D}*}(\gamma \equiv 1)$ , $q_{\mathrm{n}}^{\mathrm{D}*} \geq q_{\mathrm{n}}^{\mathrm{D}*}(\gamma \equiv 1)$ , $\pi_{\mathrm{s}}^{\mathrm{D}*} \geq \pi_{\mathrm{s}}^{\mathrm{D}*}(\gamma \equiv 1)$, $\pi_{\mathrm{m}}^{\mathrm{D}*} \geq \pi_{\mathrm{m}}^{\mathrm{D}*}(\gamma \equiv 1)$, $\pi_{\mathrm{sc}}^{\mathrm{D}*} \geq \pi_{\mathrm{sc}}^{\mathrm{D}*}(\gamma \equiv 1)$, $\alpha_{\mathrm{EL}} < \alpha_{\mathrm{EL}}(\gamma \equiv 1)$ *and* $\alpha_{\mathrm{HE}} < \alpha_{\mathrm{HE}}(\gamma \equiv 1)$.

Theorem 3 shows a good effect of policy revision. The above regulation can be regarded as a reward for NEV credits for LFCVs, which not only can promote the production of LFCVs but can also ease the pressure of NEV credits, thereby alleviating some of the problems in Theorems 1 and 2 to some extent. However, these problems have not been fundamentally resolved.

Part of the reasons for Theorems 1 and 2 are related to the calculation of credits. The total production in the CAFC credit expression still contains NEVs, which is unreasonable. For automakers that do not meet CAFC standards, producing more NEVs will increase the cost of CAFC credits. Besides, an increase in ICEV production will increase the standard value of the NEV credit, which could cause some automakers to reduce ICEV production to earn more NEV credits, resulting in a decline in LFCV production. For the engine supplier, even if the fuel economy is sufficiently high, ICEV production will also bring NEV credit costs. Therefore, the production and profits of engine suppliers will be adversely affected. In short, as Wang et al. (2017) and Lou et al. (2020) suggested, we also recommend that the policy should separate two credit regulations. Policymakers could consider completely decoupling NEVs from CAFC credits, and NEV credits should not be related to ICEV production.

## 5. Coordination of conventional automotive supply chain under the dual-credit policy

### 5.1 Contract design

Assume that automakers will implement R & D cost sharing contracts or ICEV revenue sharing contracts to coordinate supply chains. We can get the contracts design schemes as shown in Proposition 2. All expressions and Proofs can be found in Appendix A.

**Proposition 2** *The implementation of coordination contracts can change the type of supply chains, turning more H-type supply chains into E-type and more E-type supply chains into L-type. That is,* $\alpha_{\mathrm{HE}}^{\mathrm{CS}} < \alpha_{\mathrm{HE}}^{\mathrm{d}}$, $\alpha_{\mathrm{HE}}^{\mathrm{RS}} < \alpha_{\mathrm{HE}}^{\mathrm{d}}$, $\alpha_{\mathrm{EL}}^{\mathrm{CS}} < \alpha_{\mathrm{EL}}^{\mathrm{d}}$ *and* $\alpha_{\mathrm{EL}}^{\mathrm{RS}} < \alpha_{\mathrm{EL}}^{\mathrm{d}}$. *The optimal sharing ratios of the cost sharing contract and the revenue sharing contract are as follows when* $k > \underline{k}_2$ *and* $a > \underline{a}$ *are satisfied.*

*(1) If* $\alpha > \alpha_{\mathrm{EL}}^{\mathrm{CS}}$, *then* $\lambda_{\mathrm{L}}^{*} = \theta^2 / 8bk$; *if* $\alpha_{\mathrm{EL}}^{\mathrm{CS}} \geq \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{d}}$, *then* $\lambda_{\mathrm{E}}^{*} = 0$; *if* $\alpha_{\mathrm{HE}}^{\mathrm{d}} > \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{CS}}$, *then* $\lambda_{\mathrm{E}}^{*} = \lambda_{\mathrm{E}}(\alpha)$; *if* $\alpha_{\mathrm{HE}}^{\mathrm{CS}} > \alpha > \underline{\alpha}$, *then* $\lambda_{\mathrm{H}}^{*} = \lambda_{\mathrm{H}}(\alpha)$.

*(2) If* $\alpha > \alpha_{\mathrm{EL}}^{\mathrm{RS}}$, *then* $\mu_{\mathrm{L}}^{*} = \theta^2 / 2bk$; *if* $\alpha_{\mathrm{EL}}^{\mathrm{RS}} \geq \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{d}}$, *then* $\mu_{\mathrm{E}}^{*} = 0$; *if* $\alpha_{\mathrm{HE}}^{\mathrm{d}} > \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{RS}}$, *then* $\mu_{\mathrm{E}}^{*} = \mu_{\mathrm{E}}(\alpha)$; *if* $\alpha_{\mathrm{HE}}^{\mathrm{CS}} > \alpha > \underline{\alpha}^{\mathrm{RS}}$, *then* $\mu_{\mathrm{H}}^{*} = \mu_{\mathrm{H}}(\alpha)$.

For the same reason, $k$ should be sufficiently large to guarantee the existence and uniqueness of the optimal solution to ensure that all profit functions are concave under two coordination contracts. Besides, the above conditions can be guaranteed such that $\lambda^{*}, \mu^{*} \in [0,1)$. Fig. 5 depicts how the sharing ratios change with the initial CAFC credits for each vehicle ($\alpha$). When $\alpha$ is smaller, the sharing ratio increases as $\alpha$ decreases.

[Put Fig.5 here]

Automakers and suppliers decide whether to implement and accept coordination contracts based on changes in profits. Due to the change in the type of supply chain described in Proposition 2, the impact of coordinated contracts on profits may become different.

**Theorem 4** *Due to the change in the type of supply chain, the implementation of coordination contracts may be detrimental to the profits of automakers in some cases. In the decentralized supply chain, compared with the scenario without a coordination contract (Dd), the profits of each enterprise when implementing a cost sharing contract (CS) or a revenue sharing contract (RS) are as follows.*

*(1) If* $\alpha > \alpha_{\mathrm{T}}^{\mathrm{CS}}$*, then* $\pi_{\mathrm{m}}^{\mathrm{CS}*} > \pi_{\mathrm{m}}^{\mathrm{Dd}*}$ *and* $\pi_{\mathrm{s}}^{\mathrm{CS}*} > \pi_{\mathrm{s}}^{\mathrm{Dd}*}$*; if* $\alpha_{\mathrm{T}}^{\mathrm{CS}} > \alpha > \alpha_{\mathrm{EL}}^{\mathrm{CS}}$*, then* $\pi_{\mathrm{m}}^{\mathrm{CS}*} < \pi_{\mathrm{m}}^{\mathrm{Dd}*}$ *and* $\pi_{\mathrm{s}}^{\mathrm{CS}*} > \pi_{\mathrm{s}}^{\mathrm{Dd}*}$*; if* $\alpha_{\mathrm{EL}}^{\mathrm{CS}} \geq \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{d}}$*, then* $\pi_{\mathrm{m}}^{\mathrm{CS}*} = \pi_{\mathrm{m}}^{\mathrm{Dd}*}$ *and* $\pi_{\mathrm{s}}^{\mathrm{CS}*} = \pi_{\mathrm{s}}^{\mathrm{Dd}*}$*; if* $\alpha_{\mathrm{HE}}^{\mathrm{d}} > \alpha > \underline{\alpha}$*, then* $\pi_{\mathrm{m}}^{\mathrm{CS}*} > \pi_{\mathrm{m}}^{\mathrm{Dd}*}$ *and* $\pi_{\mathrm{s}}^{\mathrm{CS}*} > \pi_{\mathrm{s}}^{\mathrm{Dd}*}$.

*(2) If* $\alpha > \alpha_{\mathrm{T}}^{\mathrm{RS}}$*, then* $\pi_{\mathrm{m}}^{\mathrm{RS}*} > \pi_{\mathrm{m}}^{\mathrm{Dd}*}$ *and* $\pi_{\mathrm{s}}^{\mathrm{RS}*} > \pi_{\mathrm{s}}^{\mathrm{Dd}*}$*; if* $\alpha_{\mathrm{T}}^{\mathrm{RS}} > \alpha > \alpha_{\mathrm{EL}}^{\mathrm{RS}}$*, then* $\pi_{\mathrm{m}}^{\mathrm{RS}*} < \pi_{\mathrm{m}}^{\mathrm{Dd}*}$ *and* $\pi_{\mathrm{s}}^{\mathrm{RS}*} > \pi_{\mathrm{s}}^{\mathrm{Dd}*}$*; if* $\alpha_{\mathrm{EL}}^{\mathrm{RS}} \geq \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{d}}$*, then* $\pi_{\mathrm{m}}^{\mathrm{RS}*} = \pi_{\mathrm{m}}^{\mathrm{Dd}*}$ *and* $\pi_{\mathrm{s}}^{\mathrm{RS}*} = \pi_{\mathrm{s}}^{\mathrm{Dd}*}$*; if* $\alpha_{\mathrm{HE}}^{\mathrm{d}} > \alpha > \underline{\alpha}^{\mathrm{RS}}$*, then* $\pi_{\mathrm{m}}^{\mathrm{RS}*} > \pi_{\mathrm{m}}^{\mathrm{Dd}*}$ *and* $\pi_{\mathrm{s}}^{\mathrm{RS}*} > \pi_{\mathrm{s}}^{\mathrm{Dd}*}$.

The coordination contract will not be implemented when the profit of any enterprise decreases or both enterprises remain unchanged after the implementation of the coordination contract. It is known from Theorem 4 that, when $\alpha_{\mathrm{T}}^{\mathrm{CS}} > \alpha > \alpha_{\mathrm{EL}}^{\mathrm{CS}}$ and $\alpha_{\mathrm{T}}^{\mathrm{RS}} > \alpha > \alpha_{\mathrm{EL}}^{\mathrm{RS}}$, the profits of automakers under coordination contracts decrease, while the profits of suppliers become larger, so the supplier has an incentive to promote the implementation of coordination contracts. It can be proved that, under the above two conditions, the total profit of the supply chain under the coordination contracts becomes larger. Therefore, as long as the supplier compensates the manufacturer for loss of profit through some method, coordination can be achieved. We consider a fixed transfer payment $T$, and the implementation of the coordination contracts is shown in Theorem 5.

**Theorem 5** *The implementation of the two coordination contracts is as follows.*

*(1) if* $\alpha_{\text{EL}}^{\text{CS}} \geq \alpha \geq \alpha_{\text{HE}}^{\text{d}}$ *(*$\alpha_{\text{EL}}^{\text{RS}} \geq \alpha \geq \alpha_{\text{HE}}^{\text{d}}$*), then the cost sharing contract (revenue sharing contract) will not be implemented;*

*(2) if* $\alpha_{\text{T}}^{\text{CS}} > \alpha > \alpha_{\text{EL}}^{\text{CS}}$ *(*$\alpha_{\text{T}}^{\text{RS}} > \alpha > \alpha_{\text{EL}}^{\text{CS}}$*), then the supplier transfers* $T^{\text{CS}} \in (\pi_{\text{m}}^{\text{Dd*}} - \pi_{\text{m}}^{\text{CS*}}, \pi_{\text{s}}^{\text{CS*}} - \pi_{\text{s}}^{\text{Dd*}})$ *(*$T^{\text{RS}} \in (\pi_{\text{m}}^{\text{Dd*}} - \pi_{\text{m}}^{\text{RS*}}, \pi_{\text{s}}^{\text{RS*}} - \pi_{\text{s}}^{\text{Dd*}})$*) to the manufacturer and coordination can be reached;*

*(3) In other cases, the cost sharing contract (revenue sharing contract) can be implemented and be able to coordinate supply chain profits.*

Besides, we explore the effect of coordinating contracts from the perspective of policy effects.

**Theorem 6** *In a decentralized supply chain, compared with the scenario without a coordination contract (Dd), the optimal decisions when implementing a cost sharing contract (CS) or a revenue sharing contract (RS) are as follows (here, we subscript LFCV and HFCV to distinguish the type of ICEV).*

*(1) If* $\alpha > \alpha_{\text{EL}}^{\text{CS}}$ *(*$\alpha > \alpha_{\text{EL}}^{\text{RS}}$*), then* $x^{\text{CS*}} > x^{\text{Dd*}}$ *(*$x^{\text{RS*}} > x^{\text{Dd*}}$*); if* $\alpha_{\text{HE}}^{\text{d}} > \alpha > \underline{\alpha}$ *(*$\alpha_{\text{HE}}^{\text{d}} > \alpha > \underline{\alpha}^{\text{RS}}$*), then* $x^{\text{CS*}} > x^{\text{Dd*}}$ *(*$x^{\text{RS*}} > x^{\text{Dd*}}$*).*

*(2) If* $\alpha > \alpha_{\text{EL}}^{\text{CS}}$ *(*$\alpha > \alpha_{\text{EL}}^{\text{RS}}$*), then* $q_{\text{iLFCV}}^{\text{CS*}} > q_{\text{iLFCV}}^{\text{Dd*}}$ *(*$q_{\text{iLFCV}}^{\text{RS*}} > q_{\text{iLFCV}}^{\text{Dd*}}$*); if* $\alpha_{\text{HE}}^{\text{d}} > \alpha \geq \alpha_{\text{HE}}^{\text{CS}}$ *(*$\alpha_{\text{HE}}^{\text{d}} > \alpha \geq \alpha_{\text{HE}}^{\text{RS}}$*), then* $q_{\text{iLFCV}}^{\text{CS*}} > q_{\text{iHFCV}}^{\text{Dd*}}$ *(*$q_{\text{iLFCV}}^{\text{RS*}} > q_{\text{iHFCV}}^{\text{Dd*}}$*); if* $\alpha_{\text{HE}}^{\text{CS}} > \alpha > \underline{\alpha}$ *(*$\alpha_{\text{HE}}^{\text{RS}} > \alpha > \underline{\alpha}^{\text{RS}}$*), then* $q_{\text{iHFCV}}^{\text{CS*}} > q_{\text{iHFCV}}^{\text{Dd*}}$ *(*$q_{\text{iHFCV}}^{\text{RS*}} > q_{\text{iHFCV}}^{\text{Dd*}}$*).*

*(3) If* $\alpha > \alpha_{\text{EL}}^{\text{CS}}$ *(*$\alpha > \alpha_{\text{EL}}^{\text{RS}}$*), then* $q_{\text{n}}^{\text{CS*}} = q_{\text{n}}^{\text{Dd*}}$ *(*$q_{\text{n}}^{\text{RS*}} = q_{\text{n}}^{\text{Dd*}}$*); if* $\alpha_{\text{HE}}^{\text{d}} > \alpha > \underline{\alpha}$ *(*$\alpha_{\text{HE}}^{\text{d}} > \alpha > \underline{\alpha}^{\text{RS}}$*),*

*then* $q_{\mathrm{n}}^{\mathrm{CS*}} > q_{\mathrm{n}}^{\mathrm{Dd*}}$ *(*$q_{\mathrm{n}}^{\mathrm{RS*}} > q_{\mathrm{n}}^{\mathrm{Dd*}}$*).*

From Theorem 6, it can be seen that, on the whole, the implementation of cost sharing contracts or revenue sharing contracts can effectively coordinate supply chain profits and improve policy effectiveness. However, when the initial CAFC credits for each vehicle are smaller, the coordination contract will also increase the HFCV production while improving fuel economy, due to the obvious positive correlation between ICEV production and fuel economy improvement in the demand function.

### 5.2 Contract comparison

We compare two types of coordination contracts in terms of profit and policy effects. The following theorem is obtained.

**Theorem 7** *Regardless of profit or policy effects, for L-type and some E-type supply chains, revenue sharing contracts are better than cost sharing contracts. In other words, if* $\alpha > \alpha_{\mathrm{EL}}^{\mathrm{CS}}$*, then* $\pi_{\mathrm{m}}^{\mathrm{RS*}} > \pi_{\mathrm{m}}^{\mathrm{CS*}}$*,* $\pi_{\mathrm{s}}^{\mathrm{RS*}} > \pi_{\mathrm{s}}^{\mathrm{CS*}}$*,* $x^{\mathrm{RS*}} > x^{\mathrm{CS*}}$*,* $q_{\mathrm{i}}^{\mathrm{RS*}} > q_{\mathrm{i}}^{\mathrm{CS*}}$ *and* $q_{\mathrm{n}}^{\mathrm{RS*}} = q_{\mathrm{n}}^{\mathrm{CS*}}$*. However, for H-type supply chains, cost sharing contracts can be better than revenue sharing contracts.*

In Theorem 7, when the initial CAFC credits for each vehicle meet certain conditions (see Appendix A), the cost sharing contract in the H-type supply chain is better than the revenue sharing contract. This outcome means that, for automakers that have reached the CAFC standard, ICEV revenue sharing contracts should be used as an indirect incentive, but for those automakers who must urgently improve fuel economy, a more direct approach, such as R & D cost sharing contracts, should be adopted. Therefore, cost sharing contracts might be better than revenue sharing contracts, which is different from the views of some of the literature in the field of sustainable supply chains (Yenipazarli, 2017; Raj et al., 2018; Yang and Chen, 2018). For example, Yenipazarli (2017) reported that, from the perspective of the impact of environmental innovation of upstream enterprises on the overall economic and environmental performance, revenue sharing is more suitable for collaboration. However, we believe that, if downstream enterprises face different policy pressures, the conclusions of the above literature might not be valid. In our model, when downstream enterprises face greater policy pressures, the more direct coordination method of R & D cost sharing contracts might be more beneficial to the innovation investments of upstream enterprises, thereby improving the environmental performance and profits of the entire supply chain.

Figs. 6 and 7 show the results of the above theorems more intuitively.

[Put Fig.6 and Fig.7 here]

The following can be seen from Fig. 6. (1) In some cases, as shown in the enlarged part, the implementation of the coordination contract will reduce the profit of the automaker (see Theorem 4), but at this time, the profit of the supplier and the supply chain will increase. Therefore, as long as the supplier gives the automaker a certain profit subsidy, it can promote the implementation of the coordination contract (see Theorem 5). (2) When the initial CAFC credits for each vehicle are large, the profits of automakers, suppliers and supply chains under revenue sharing contracts are greater (see Theorem 7). (3) When the initial CAFC credits for each vehicle are smaller, cost sharing contracts are more conducive to improving the profits of automakers (see Theorem 7). However, for the suppliers and supply chains, revenue sharing contracts might be better. At this time, if the suppliers grant a certain profit subsidy to the automakers, the type of coordination contracts can be changed.

The following can be seen from Fig. 7. (1) Overall, the implementation of the coordination contract is conducive to improving fuel economy and increasing the production (see Theorem 6). (2) When the initial CAFC credits for each vehicle are large, under the revenue sharing contract, the fuel economy improvement level and LFCV production are both higher. At this time, the revenue sharing contract is better (see Theorem 7). (3) When the initial CAFC credits for each vehicle are smaller, the policy effect produced by the cost sharing contract is better (see Theorem 7).

## 6. Conclusion and policy implications

### 6.1 Conclusions

Under the dual-credit policy, global automakers are facing huge challenges. Fuel economy and production decisions are optimized through game theory. In order to coordinate the conventional automobile supply chain, R & D cost sharing contracts and ICEV revenue sharing contracts are designed and compared. We provided different optimal strategies for enterprises in the supply chain with different initial CAFC credits for each vehicle, pointed out the possible disadvantages of the dual-credit policy, and explored coordination contracts.

We have reached some main conclusions about the dual-credit policy. (1) For some automakers, it may be harmful to fuel economy and cause HFCV production to increase while LFCV or NEV production decreases. (2) It will result in lower profits for engine suppliers. (3) The new regulation about the NEV credit reward for LFCVs will have good policy effects. (4) R & D cost sharing contracts and ICEV revenue sharing contracts may not coordinate the supply chain, and sometimes, some profit subsidies given by the supplier to the automaker can facilitate the implementation of coordination contracts. Besides, when the initial CAFC credits for each vehicle are low, cost sharing contracts may be better than revenue sharing contracts.

### 6.2 Management insights

Our research provides important management insights as shown below.

**Conventional automotive supply chains:** The dual-credit policy has a significant impact on local or multinational automotive supply chains, which produce or sell passenger vehicles in China.

(1) In reality, due to the pressure of the dual-credit policy, many automakers strive to increase NEV production, reduce HFCV production, and improve the fuel economy of engines. These choices might not be the best for all automakers because these practices do not necessarily lead to the highest economic performance. As described in Section 4, different optimization strategies should be selected according to the initial CAFC credits for each vehicle. This choice means that H-type automakers do not necessarily have to increase NEV production or reduce HFCV production. Specifically, when the initial CAFC credits for each vehicle are sufficiently low, they should reduce the production of NEVs and HFCVs to reduce the cost of CAFC credits; when the initial CAFC credits for each vehicle are high, they should increase the production of NEVs and HFCVs to obtain higher profits. For L-type and some E-type automakers, increasing NEV production and reducing the production of ICEVs and even of LFCVs will be the best choice. For engine suppliers, when the initial CAFC credits for each vehicle are sufficiently high or low, reducing R & D investment in fuel economy will be the most beneficial. Conversely, in other cases, they should work to improve fuel economy to reduce the loss of profits from the dual-credit policy. The above specific action plans provide new perspectives for corporate managers.

(2) As described in Section 5, we provide automakers with specifics on how to design and select R & D cost sharing contracts and ICEV revenue sharing contracts. When coordinating conventional automotive supply chains, except for some E-type supply chains, the above two coordination contracts have proved to be effective and can bring better policy effects. Sometimes for E-type supply chains with high initial CAFC credits for each vehicle, some profit subsidies given by the supplier to the

automaker can facilitate the implementation of the coordination contracts. Therefore, enterprises in the supply chain should actively seek cooperation to jointly respond to the dual-credit policy. When choosing a coordination contract, the revenue sharing contract designed by automakers to maximize their profits is not always better than the corresponding cost sharing contract, which is different from some of the literature in the field of sustainable supply chains (see Sections 2.4 and 5.2). Specifically, when the initial CAFC credits for each vehicle are sufficiently high, the revenue sharing contract is a better choice; when the initial CAFC credits for each vehicle are low, and it is difficult to come up to the CAFC standard, the cost sharing contract might be better. These insights have important reference value for managers of conventional automotive supply chains.

**Policymakers in China:** (1) A comprehensive policy implementation plan that flexibly combines the dual-credit policy and other supporting policies such as R&D subsidies is necessary. Policymakers need to consider implementing additional R&D subsidies or other policy support for certain automakers with lower initial CAFC credits for each vehicle to help them improve their fuel economy. Otherwise, according to Theorem 1, the dual-credit policy may be detrimental to the improvements in their fuel economy and the production of NEV. (2) Policymakers should consider separating the two credit regulations, which was also proposed by Wang et al. (2017) and Lou et al. (2020). We have described specific amendments. NEVs should be completely decoupled from the calculation of CAFC credit, and the standard value of NEV credits should not be related to ICEV production. Otherwise, as described in Theorems 1 and 2, the dual-credit policy may adversely affect the fuel economy, the LFCV and NEV production of some automakers, and reduce the profits of upstream engine suppliers. (3) The government can consider implementing certain subsidies to the R & D activities of upstream engine suppliers to make up for the loss of profits. Otherwise, the dual-credit policy will not benefit their survival and R & D investment.

**Other emerging markets:** The dual-credit policy provides important references and practical value to emerging markets facing the same problems as those described in the introduction. Although the dual-credit policy is still being continuously improved, as a new sustainability policy, it aims to both reduce fuel consumption and promote the development of NEVs by establishing a market-oriented mechanism, which provides a model for governments in other emerging markets.

### 6.3 Future studies

In the future, our model could be further optimized, such as considering the competitive automotive market and considering the development of NEV technology, which will render the model more complicated and pose challenges for the optimization solution. Besides, we can also explore various forms of contracts, such as cost sharing contracts or revenue sharing contracts under bargaining, and the combination of the two types of contracts, which will also greatly increase the difficulty of solving. Therefore, an effective algorithm might be necessary. Finally, the process and risk of credit transactions will be important topics, which will involve more enterprises, including conventional automakers and NEV automakers. The corresponding research results will help to improve the operation of the automotive supply chain.

## Acknowledgments

The authors gratefully acknowledge the editor and two reviewers for their valuable comments and the financial support provided by the National Natural Science Foundation of China (Nos. 71573087, 71972070, 71972071 and 72074076) and the Fundamental Research Funds for the Central Universities.

## References

Agrawal, A., Muthulingam, S., Rajapakshe, T., 2017. How sourcing of interdependent components affects quality in automotive supply chains. Prod. Oper. Manag. 26, 1512-1533. https://doi.org/10.1111/poms.12700.

Agrawal, V., Lee, D., 2019. The effect of sourcing policies on suppliers' sustainable practices. Prod. Oper. Manag. 28(4), 767-787. https://doi.org/10.1111/poms.12943.

Bakirtas, T., Akpolat, A.G., 2018. The relationship between energy consumption, urbanization, and economic growth in new emerging-market countries. Energy 147, 110-121. https://doi.org/10.1016/j.energy.2018.01.011.

Biswas, I., Raj, A., Srivastava, S.K., 2018. Supply chain channel coordination with triple bottom line approach. Transport. Res. E-Log. 115, 213-226. https://doi.org/10.1016/j.tre.2018.05.007.

Bray, R.L., Serpa, J.C., Colak, A., 2019. Supply chain proximity and product quality. Manag. Sci. 65, 4079-4099. https://doi.org/10.1287/mnsc.2018.3161.

Chen, K., Zhao, F., Hao, H., Liu, Z., 2018. Synergistic impacts of China’s subsidy policy and New Energy Vehicle Credit Regulation on the technological development of battery electric vehicles. Energies 11(11), 3193. https://doi.org/10.3390/en11113193.

Choi, T.M., Cai, Y.J., Shen, B., 2019b. Sustainable fashion supply chain management: a system of systems analysis. IEEE T. Eng. Manage. 66(4), 730-745. https://doi.org/10.1109/tem.2018.2857831.

Choi, T.M., Luo, S.Y., 2019. Data quality challenges for sustainable fashion supply chain operations in emerging markets: roles of blockchain, government sponsors and environment taxes. Transport. Res. E-Log. 131, 139-152. https://doi.org/10.1016/j.tre.2019.09.019.

Choi, T.M., Ma, C., Shen, B., Sun, Q., 2019a. Optimal pricing in mass customization supply chains with risk-averse agents and retail competition. Omega-Int. J. Manage. S. 88, 150-161. https://doi.org/10.1016/j.omega.2018.08.004.

CNPC, 2019. 2018 domestic and foreign oil and gas industry development reports. Beijing China.

Corbett, J., Wardle, K., Chen, C.L., 2018. Toward a sustainable modern electricity grid: the effects of smart metering and program investments on demand-side management performance in the US electricity sector 2009-2012. IEEE T. Eng. Manage. 65(2), 252-263. https://doi.org/10.1109/tem.2017.2785315.

Crabtree, G., 2019. The coming electric vehicle transformation. Science 366(6464), 422-424. https://doi.org/10.1126/science.aax0704.

Cui, Q.Q., Chiu, C.H., Dai, X., Li, Z.F., 2016. Store brand introduction in a two-echelon logistics system with a risk-averse retailer. Transport. Res. E-Log. 90, 69-89. https://doi.org/10.1016/j.tre.2015.10.005.

Dara, S., Abdulqader, H., Al Wahedi, Y., Berrouk, A.S., 2020. Countrywide optimization of natural gas supply chain: from wells to consumers. Energy 196, 117125. https://doi.org/10.1016/j.energy.2020.117125.

Dumortiera, J., Siddikia, S., Carleyb, S., Cisneyb, J., Krausec, R.M., Lanec, B.W., Ruppb, J.A., Grahamb, J.D., 2015. Effects of providing total cost of ownership information on consumers' intent to purchase a hybrid or plug-in electric vehicle. Transport. Res. A-Pol. 72, 71-86. https://doi.org/10.1016/j.tra.2014.12.005.

Fartaj, S.-R., Kabir, G., Eghujovbo, V., Ali, S.M., Paul, S.K., 2020. Modeling transportation disruptions in the supply chain of automotive parts manufacturing company. Int. J. Prod. Econ.

222, 107511. https://doi.org/10.1016/j.ijpe.2019.09.032.

Greene, D., German, J., Delucchi M., 2008. Fuel economy: the case for market failure. Cannon J., Sperling D. (eds) Reducing Climate Impacts in the Transportation Sector. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6979-6_11.

Guo, L., Wu, X., 2018. Capacity sharing between competitors. Manag. Sci. 64, 3554-3573. https://doi.org/10.1287/mnsc.2017.2796.

Gurca, A., Ravishankar, M.N., 2016. A bricolage perspective on technological innovation in emerging markets. IEEE T. Eng. Manage. 63(1), 53-66. https://doi.org/10.1109/tem.2015.2494501.

Han, R., Yu, B.Y., Tang, B.J., Liao, H., Wei, Y.M., 2017. Carbon emissions quotas in the Chinese road transport sector: a carbon trading perspective. Energy Policy 106, 298-309. https://doi.org/10.1016/j.enpol.2017.03.071.

He, X., Ou, S., Gan, Y., Lu, Z., Przesmitzki, S.V., Bouchard, J.L., Sui, L., Amer, A.A., Lin, Z., Yu, R., Zhou, Y., Wang, M., 2020. Greenhouse gas consequences of the China dual credit policy. Nat. Commun. 11(1), 5212. https://doi.org/10.1038/s41467-020-19036-w.

Heydari, J., Govindan, K., Jafari, A., 2017. Reverse and closed loop supply chain coordination by government role. Transport. Res. D-Tr. E. 52, 379-398. https://doi.org/10.1016/j.trd.2017.03.008.

Hong, Z.F., Guo, X.L., 2019. Green product supply chain contracts considering environmental responsibilities. Omega-Int. J. Manage. S. 83, 155-166. https://doi.org/10.1016/j.omega.2018.02.010.

Hosseini-Motlagh, S.M., Nouri-Harzvili, M., Choi, T.M., Ebrahimi, S., 2019. Reverse supply chain systems optimization with dual channel and demand disruptions: sustainability, CSR investment and pricing coordination. Inform. Sciences 503, 606-634.

https://doi.org/10.1016/j.ins.2019.07.021.

Hsieh, I.Y.L., Pan, M.S., Green, W.H., 2020. Transition to electric vehicles in China: implications for private motorization rate and battery market. Energy Policy 144, 111654. https://doi.org/10.1016/j.enpol.2020.111654.

Huang, J., Leng, M., Liang, L., Liu, J., 2013. Promoting electric automobiles: supply chain analysis under a government's subsidy incentive scheme. IIE Trans. 45, 826-844. https://doi.org/10.1080/0740817x.2012.763003.

Ishfaq, R., Narayanan, A., 2019. Incorporating order-fulfillment flexibility in automotive supply chain through vehicle trades. Decis. Sci. 50, 84-117. https://doi.org/10.1111/deci.12313.

Ji, T., Xu, X.P., Yan, X.M., Yu, Y.G., 2020. The production decisions and cap setting with wholesale price and revenue sharing contracts under cap-and-trade regulation. Int. J. Prod. Res. 58(1), 128-147. https://doi.org/10.1080/00207543.2019.1641239.

Jonnalagedda, S., Saranga, H., 2019. To adapt or design: an emerging market dilemma for automakers. Prod. Oper. Manag. 28(3), 550-569. https://doi.org/10.1111/poms.12932.

Keivanpour, S., Ait-Kadi, D., Mascle, C., 2017. Automobile manufacturers' strategic choice in applying green practices: joint application of evolutionary game theory and fuzzy rule-based approach. Int. J. Prod. Res. 55(5), 1312-1335. https://doi.org/10.1080/00207543.2016.1203077.

Khuntia, J., Saldanha, T.J.V., Mithas, S., Sambamurthy, V., 2018. Information technology and sustainability: evidence from an emerging economy. Prod. Oper. Manag. 27(4), 756-773. https://doi.org/10.1111/poms.12822.

Li, G., Li, L., Choi, T.M., Sethi, S.P., 2020d. Green supply chain management in Chinese firms: innovative measures and the moderating role of quick response technology. J. Oper. Manag. 66(7-

8), 958-988. https://doi.org/10.1002/joom.1061.

Li, J.Z., Ku, Y.Y., Liu, C.L., Zhou, Y.P., 2020a. Dual credit policy: promoting new energy vehicles with battery recycling in a competitive environment. J. Clean. Prod. 243, 118456. https://doi.org/10.1016/j.jclepro.2019.118456.

Li, J.Z., Ku, Y.Y., Yu, Y., Liu, C.L., Zhou, Y.P., 2020b. Optimizing production of new energy vehicles with across-chain cooperation under China's dual credit policy. Energy 194, 116832. https://doi.org/10.1016/j.energy.2019.116832.

Li, T., Zhang, R., Zhao, S., Liu, B., 2019. Low carbon strategy analysis under revenue-sharing and cost-sharing contracts. J. Clean. Prod. 212, 1462-1477. https://doi.org/10.1016/j.jclepro.2018.11.282.

Li, Y., Zhang, Q., Liu, B., McLellan, B., Gao, Y., Tang, Y., 2018. Substitution effect of New-Energy Vehicle Credit program and Corporate Average Fuel Consumption regulation for green-car subsidy. Energy 152, 223-236. https://doi.org/10.1016/j.energy.2018.03.134.

Li, Y.M., Zhang, Q., Tang, Y.Y., McLellan, B., Ye, H.Y., Shimoda, H., Ishihara, K., 2020c. Dynamic optimization management of the dual-credit policy for passenger vehicles. J. Clean. Prod. 249, 119384. https://doi.org/10.1016/j.jclepro.2019.119384.

Liu, Y., Srai, J.S., Evans, S., 2016. Environmental management: the role of supply chain capabilities in the auto sector. Supply Chain Manag. 21, 1-19. https://doi.org/10.1108/scm-01-2015-0026.

Lou, G.X., Ma, H.C., Fan, T.J., Chan, H.K., 2020. Impact of the dual-credit policy on improvements in fuel economy and the production of internal combustion engine vehicles. Resour. Conserv. Recy. 156, 104712. https://doi.org/10.1016/j.resconrec.2020.104712.

Luo, C., Leng, M., Huang, J., Liang, L., 2014. Supply chain analysis under a price-discount incentive scheme for electric vehicles. Eur. J. Oper. Res. 235, 329-333. https://doi.org/10.1016/j.ejor.2013.11.021.

Marodin, G.A., Frank, A.G., Tortorella, G.L., Saurin, T.A., 2016. Contextual factors and lean production implementation in the Brazilian automotive supply chain. Supply Chain Manag. 21, 417-432. https://doi.org/10.1108/scm-05-2015-0170.

Mathivathanan, D., Kannan, D., Hag, A.N., 2018. Sustainable supply chain management practices in Indian automotive industry: a multi-stakeholder view. Resour. Conserv. Recy. 128, 284-305. https://doi.org/10.1016/j.resconrec.2017.01.003.

Murphy, F., Putz, F., Mullins, M., Rohlfs, T., Wrana, D., Biermann, M., 2019. The impact of autonomous vehicle technologies on product recall risk. Int. J. Prod. Res. 57, 6264-6277. https://doi.org/10.1080/00207543.2019.1566651.

Olbert, H., Protopappa-Sieke, M., Thonemann, U.W., 2016. Analyzing the effect of express orders on supply chain costs and delivery times. Prod. Oper. Manag. 25, 2035-2050. https://doi.org/10.1111/poms.12588.

Ou, S., Lin, Z., Qi, L., Li, J., He, X., Przesmitzki, S., 2018. The dual-credit policy: quantifying the policy impact on plug-in electric vehicle sales and industry profits in China. Energy Policy 121, 597-610. https://doi.org/10.1016/j.enpol.2018.06.017.

Piacentino, A., Catrini, P., Markovska, N., Guzovic, Z., Mathiesen, B.V., Ferrari, S., Duic, N., Lund, H., 2020. Editorial: sustainable development of energy, water and environment systems. Energy 190, 116432. https://doi.org/10.1016/j.energy.2019.116432.

Qamar, A., Hall, M.A., Collinson, S., 2018. Lean versus agile production: flexibility trade-offs within the automotive supply chain. Int. J. Prod. Res. 56, 3974-3993.

https://doi.org/10.1080/00207543.2018.1463109.

Raj, A., Biswas, I., Srivastava, S.K., 2018. Designing supply contracts for the sustainable supply chain using game theory. J. Clean. Prod. 185, 275-284. https://doi.org/10.1016/j.jclepro.2018.03.046.

Safarzadeh, S., Rasti-Barzoki, M., 2019a. A game theoretic approach for assessing residential energy-efficiency program considering rebound, consumer behavior, and government policies. Appl. Energy 233, 44-61. https://doi.org/10.1016/j.apenergy.2018.10.032.

Safarzadeh, S., Rasti-Barzoki, M., 2019b. A game theoretic approach for pricing policies in a duopolistic supply chain considering energy productivity, industrial rebound effect, and government policies. Energy 167, 92-105. https://doi.org/10.1016/j.energy.2018.10.190.

Seles, B., Jabbour, A., Jabbour, C.J.C., Dangelico, R.M., 2016. The green bullwhip effect, the diffusion of green supply chain practices, and institutional pressures: evidence from the automotive sector. Int. J. Prod. Econ. 182, 342-355. https://doi.org/10.1016/j.ijpe.2016.08.033.

Shen, F., Zhao, L., Du, W., Zhong, W., Qian, F., 2020. Large-scale industrial energy systems optimization under uncertainty: a data-driven robust optimization approach. Appl. Energy 259, 114199. https://doi.org/10.1016/j.apenergy.2019.114199.

Song, H.H., Gao, X.X., 2018. Green supply chain game model and analysis under revenue-sharing contract. J. Clean. Prod. 170, 183-192. https://doi.org/10.1016/j.jclepro.2017.09.138.

Tong, X., Lai, K.H., Zhu, Q.H., Zhao, S.L., Chen, J.H., Cheng, T.C.E., 2018. Multinational enterprise buyers' choices for extending corporate social responsibility practices to suppliers in emerging countries: a multi-method study. J. Oper. Manag. 63, 25-43. https://doi.org/10.1016/j.jom.2018.05.003.

Umpfenbach, E.L., Dalkiran, E., Chinnam, R.B., Murat, A.E., 2018. Promoting sustainability of automotive products through strategic assortment planning. Eur. J. Oper. Res. 269(1), 272-285. https://doi.org/10.1016/j.ejor.2017.08.031.

Van Wassenhove, L.N., 2019. Sustainable innovation: pushing the boundaries of traditional operations management. Prod. Oper. Manag. 28(12), 2930-2945. https://doi.org/10.1111/poms.13114.

Vanalle, R.M., Lucato, W.C., Ganga, G.M.D., Alves Filho, A.G., 2020. Risk management in the automotive supply chain: an exploratory study in Brazil. Int. J. Prod. Res. 58, 783-799. https://doi.org/10.1080/00207543.2019.1600762.

Vidhi, R., Shrivastava, P., 2018. A review of electric vehicle lifecycle emissions and policy recommendations to increase EV penetration in India. Energies 11(3), 483. https://doi.org/10.3390/en11030483.

Wang, S., Zhao, F., Liu, Z., Hao, H., 2018. Impacts of a super credit policy on electric vehicle penetration and compliance with China's Corporate Average Fuel Consumption regulation. Energy 155, 746-762. https://doi.org/10.1016/j.energy.2018.05.042.

Wang, Y.S., Sperling, D., Tal, G., Fang, H.F., 2017. China's electric car surge. Energy Policy 102, 486-490. https://doi.org/10.1016/j.enpol.2016.12.034.

Wang, Z., Zhang, J., Zhao, H., 2020. The selection of green technology innovations under dual-credit policy. Sustainability 12(16), 6343. https://doi.org/10.3390/su12166343.

Xu, J., Hsu, V.N., Niu, B., 2018. The impacts of markets and tax on a multinational firm's procurement strategy in China. Prod. Oper. Manag. 27, 251-264. https://doi.org/10.1111/poms.12798.

Yang, H.X., Chen, W.B., 2018. Retailer-driven carbon emission abatement with consumer environmental awareness and carbon tax: revenue-sharing versus cost-sharing. Omega-Int. J. Manage. S. 78, 179-191. https://doi.org/10.1016/j.omega.2017.06.012.

Yang, L., Zhang, Q., Ji, J., 2017. Pricing and carbon emission reduction decisions in supply chains with vertical and horizontal cooperation. Int. J. Prod. Econ. 191, 286-297. https://doi.org/10.1016/j.ijpe.2017.06.021.

Yenipazarli, A., 2017. To collaborate or not to collaborate: prompting upstream eco-efficient innovation in a supply chain. Eur. J. Oper. Res. 260(2), 571-587. https://doi.org/10.1016/j.ejor.2016.12.035.

Yi, J.T., Hong, J.J., Hsu, W.C., Wang, C.Q., 2017. The role of state ownership and institutions in the innovation performance of emerging market enterprises: evidence from China. Technovation 62-63, 4-13. https://doi.org/10.1016/j.technovation.2017.04.002.

Yu, B., Wang, J., Lu, X., Yang, H., 2020. Collaboration in a low-carbon supply chain with reference emission and cost learning effects: cost sharing versus revenue sharing strategies. J. Clean. Prod. 250, 119460. https://doi.org/10.1016/j.jclepro.2019.119460.

Zhao, F., Chen, K., Hao, H., Wang, S., Liu, Z., 2019b. Technology development for electric vehicles under new energy vehicle credit regulation in China: scenarios through 2030. Clean Technol. Environ. Policy 21(2), 275-289. https://doi.org/10.1007/s10098-018-1635-y.

Zhao, F., Hao, H., Liu, Z., 2016. Technology strategy to meet China’s 5 L/100 km fuel consumption target for passenger vehicles in 2020. Clean Technol. Environ. Policy 18(1), 7-15. https://doi.org/10.1007/s10098-015-1019-5.

Zhao, F., Liu, F., Liu, Z., Hao, H., 2019a. The correlated impacts of fuel consumption improvements and vehicle electrification on vehicle greenhouse gas emissions in China. J. Clean. Prod. 207, 702-716. https://doi.org/10.1016/j.jclepro.2018.10.046.

Zhou, D.Q., Yu, Y., Wang, Q.W., Zha, D.L., 2019. Effects of a generalized dual-credit system on green technology investments and pricing decisions in a supply chain. J. Environ. Manage. 247, 269-280. https://doi.org/10.1016/j.jenvman.2019.06.058.

Zhou, K.Z., Su, C.T., Yeung, A., Viswanathan, S., 2016. Supply chain management in emerging markets. J. Oper. Manag. 46, 1-4. https://doi.org/10.1016/j.jom.2016.07.007.

Zhu, Q.H., Li, X.Y., Zhao, S.L., 2018. Cost-sharing models for green product production and marketing in a food supply chain. Ind. Manage. Data Syst. 118(4), 654-682. https://doi.org/10.1108/imds-05-2017-0181.

CIIN (China Industrial Information Network), 2019. China's automotive engine output declines to 24.917 million units in 2018. https://www.chyxx.com/industry/201902/713052.html. (Accessed 10 November 2019).

Ford, 2016. Ford's fuel economy survey report reveals car buying preferences of Chinese consumers. https://www.ford.com.cn/newsroom/2016/0823/. (Accessed 10 November 2019).

ICCT, 2017. 2017 Global update: Light-duty vehicle greenhouse gas and fuel economy standards. https://theicct.org/node/1474. (Accessed 28 December 2019).

ICCT, 2020. Global transport policies with a focus on vehicles and fuels, including emerging economies in Asia and North and South America. https://www.transportpolicy.net/. (Accessed 3 December 2020).

MIIT, 2015. Interpretation of the fourth stage standard of passenger vehicle fuel consumption. http://www.miit.gov.cn/n1146290/n1146402/n7039597/c7052785/content.html. (Accessed 18 April 2019).

MIIT, 2017. The parallel management method for corporate average fuel consumption and new energy vehicles credits.

http://www.miit.gov.cn/n1146285/n1146352/n3054355/n3057585/n3057592/c5826834/content.html. (Accessed 18 April 2019).

MIIT, 2018a. Announcement on the corporate average fuel consumption and new energy vehicles credits of passenger vehicle companies in 2016. http://www.miit.gov.cn/n1146295/n1146592/n3917132/n4061919/c6080659/content.html. (Accessed 20 April 2019).

MIIT, 2018b. Announcement on the corporate average fuel consumption and new energy vehicles credits of passenger vehicle companies in 2017. http://www.miit.gov.cn/n1146295/n1652858/n1653100/n3767755/c6124752/content.html. (Accessed 20 April 2019).

MIIT, 2019a. Announcement on the corporate average fuel consumption and new energy vehicles credits of passenger vehicle companies in 2018. http://www.miit.gov.cn/n1146295/n1652858/n1653100/n3767755/c6722098/content.html. (Accessed 20 April 2019).

MIIT, 2019b. Decision on amending the parallel management method for corporate average fuel consumption and new energy vehicles credits. http://www.miit.gov.cn/opinion/noticedetail.do?method=notice_detail_show&noticeid=2184. (Accessed 10 November 2019).

MIIT, 2020a. Announcement on the corporate average fuel consumption and new energy vehicles credits of passenger vehicle companies in 2019. http://www.miit.gov.cn/n1146295/n7281310/c7859399/content.html. (Accessed 11 April 2020).

MIIT, 2020b. Decision on amending the parallel management method for corporate average fuel consumption and new energy vehicles credits. http://www.miit.gov.cn/n1146290/n1146402/c7982399/content.html. (Accessed 22 June 2020).

OC&C, 2019. Electric and hybrid car sales expected to pick up as over half of global consumers will now consider. https://www.occstrategy.com/en/. (Accessed 28 December 2019).

**Appendix A: All Proofs.**

**Proof of Proposition 1**

**In a centralized supply chain:**

**Optimization:** Equation (5) can be transformed into a constrained optimal problem. The constraints of the three types of supply chains are as follows.

(1) The constraint of the L-type supply chain is $\alpha + x > 0$, which is loose. $x_{\mathrm{L}}^{\mathrm{Dc}*}$, $q_{\mathrm{iL}}^{\mathrm{Dc}*}$ and $q_{\mathrm{nL}}^{\mathrm{Dc}*}$ can be obtained through the first-order optimal conditions (FOCs). The profit function is concave when $k > \theta^2 / 2b$. $a > \underline{a} = bp_{\mathrm{c}}\beta$ can guarantee positive optimal solutions when $\beta > \rho$, which is true due to the dual-credit policy. Substituting $x_{\mathrm{L}}^{\mathrm{Dc}*}$ into the constraint, we obtain $\alpha > \alpha_{\mathrm{L}} = -\dfrac{\theta(2a - bp_{\mathrm{c}}\rho)}{2(2bk - \theta^2)}$.

(2) The constraint of the E-type supply chain is $\alpha + x = 0$, which is tight. Substituting $x = -\alpha$ into the profit function, we obtain $x_{\mathrm{E}}^{\mathrm{Dc}*}$, $q_{\mathrm{iE}}^{\mathrm{Dc}*}$ and $q_{\mathrm{nE}}^{\mathrm{Dc}*}$ through FOCs. The profit function is always concave. $a > bp_{\mathrm{c}}\beta$ and $\alpha < 0$ can guarantee positive optimal solutions.

(3) The constraint of the H-type supply chain is $\alpha + x < 0$, which is loose. $x_{\mathrm{H}}^{\mathrm{Dc}*}$, $q_{\mathrm{iH}}^{\mathrm{Dc}*}$ and $q_{\mathrm{nH}}^{\mathrm{Dc}*}$ can be obtained through FOCs. The profit function is concave when $k > bp_{\mathrm{c}}{}^2 + p_{\mathrm{c}}\theta + \theta^2 / 2b$. $\alpha > \underline{\alpha} = \rho - a / bp_{\mathrm{c}}$ can guarantee positive optimal solutions. Substituting $x_{\mathrm{H}}^{\mathrm{Dc}*}$ into the constraint, we obtain $\alpha < \alpha_{\mathrm{H}} = -\dfrac{a\left(2bp_{\mathrm{c}} + \theta\right) - bp_{\mathrm{c}}\left(\theta\rho - bp_{\mathrm{c}}\left(\beta - \rho\right)\right)}{2bk - bp_{\mathrm{c}}\theta - \theta^2}$.

**Type selection:** It can be easily proved that $\alpha_{\mathrm{H}} < \alpha_{\mathrm{L}}$ when $a > \underline{a}$ and $k > \theta^2 / 2b$; thus, three types of supply chains exist.

When $\alpha \geq 0$, only constraint (1) can be met, so the supply chain will be of the L-type.

When $0 > \alpha > \alpha_{\mathrm{L}}$, constraint (1) and (2) can be met, we obtain $\pi_{\mathrm{scL}}^{\mathrm{Dc*}} > \pi_{\mathrm{scE}}^{\mathrm{Dc*}}$; thus, the supply chain will be of the L-type.

When $\alpha_{\mathrm{L}} \geq \alpha \geq \alpha_{\mathrm{H}}$, only constraint (2) can be met, so the supply chain will be of the E-type.

When $\alpha_{\mathrm{H}} > \alpha > \underline{\alpha}$, constraints (2) and (3) can be met. Let $\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}$, and $\mathrm{Min}[\mathrm{Solve}[\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}, \alpha]] < \alpha_{\mathrm{H}} < \mathrm{Max}[\mathrm{Solve}[\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}, \alpha]]$ can be obtained. Because the expression is too complicated, we use Solve function instead. It can be proved that $\pi_{\mathrm{scE}}^{\mathrm{Dc*}} - \pi_{\mathrm{scH}}^{\mathrm{Dc*}}$ is continuous and concave about $\alpha$, and there are two solutions to $\mathrm{Solve}[\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}, \alpha]$. Therefore, $\pi_{\mathrm{scE}}^{\mathrm{Dc*}}(\alpha_{\mathrm{H}}) - \pi_{\mathrm{scH}}^{\mathrm{Dc*}}(\alpha_{\mathrm{H}}) > 0 \Leftrightarrow \mathrm{Min}[\mathrm{Solve}[\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}, \alpha]] < \alpha_{\mathrm{H}} < \mathrm{Max}[\mathrm{Solve}[\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}, \alpha]]$. In short, if $\underline{\alpha} < \alpha < \mathrm{Min}[\mathrm{Solve}[\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}, \alpha]]$, then $\pi_{\mathrm{scE}}^{\mathrm{Dc*}} < \pi_{\mathrm{scH}}^{\mathrm{Dc*}}$; thus, the supply chain will be H-type; if $\mathrm{Min}[\mathrm{Solve}[\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}, \alpha]] \leq \alpha < \alpha_{\mathrm{H}}$, then $\pi_{\mathrm{scE}}^{\mathrm{Dc*}} \geq \pi_{\mathrm{scH}}^{\mathrm{Dc*}}$; thus, the supply chain will be E-type.

In summary, we obtain the boundaries of each type: $\alpha_{\mathrm{EL}}^{\mathrm{c}} = \alpha_{\mathrm{L}} = -\dfrac{\theta(2a - bp_{\mathrm{c}}\rho)}{2(2bk - \theta^2)}$, $\alpha_{\mathrm{HE}}^{\mathrm{c}} = \mathrm{Min}[\mathrm{Solve}[\pi_{\mathrm{scE}}^{\mathrm{Dc*}} == \pi_{\mathrm{scH}}^{\mathrm{Dc*}}, \alpha]]$, and $\alpha_{\mathrm{HE}}^{\mathrm{c}} < \alpha_{\mathrm{EL}}^{\mathrm{c}}$. The corresponding optimal solutions are as follows:

(1) If $\alpha > \alpha_{\mathrm{EL}}^{\mathrm{c}}$, then $x_{\mathrm{L}}^{\mathrm{Dc*}} = \dfrac{\theta(2a - bp_{\mathrm{c}}\rho)}{2(2bk - \theta^2)}$, $q_{\mathrm{iL}}^{\mathrm{Dc*}} = \dfrac{bk(2a - bp_{\mathrm{c}}\rho)}{2(2bk - \theta^2)}$, $q_{\mathrm{nL}}^{\mathrm{Dc*}} = (a + bp_{\mathrm{c}}\beta)/2$;

(2) If $\alpha_{\mathrm{EL}}^{\mathrm{c}} \geq \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{c}}$, then $x_{\mathrm{E}}^{\mathrm{Dc*}} = -\alpha$, $q_{\mathrm{iE}}^{\mathrm{Dc*}} = (2a - 2\alpha\theta + bp_{\mathrm{c}}\rho)/4$, $q_{\mathrm{nE}}^{\mathrm{Dc*}} = (a + bp_{\mathrm{c}}\beta)/2$;

(3) If $\alpha_{\mathrm{HE}}^{\mathrm{c}} > \alpha > \underline{\alpha}$, then $x_{\mathrm{H}}^{\mathrm{Dc*}} = \dfrac{a\left(2bp_{\mathrm{c}} + \theta\right) - bp_{\mathrm{c}}\left(\theta\left(-\alpha + \rho\right) + bp_{\mathrm{c}}\left(-2\alpha - \beta + \rho\right)\right)}{2bk - 2b^2 p_{\mathrm{c}}^{\ 2} - 2bp_{\mathrm{c}}\theta - \theta^2}$,

$$q_{\mathrm{iH}}^{\mathrm{Dc*}} = \frac{b\Big(a\left(2k + p_{\mathrm{c}}\theta\right) + bp_{\mathrm{c}}\Big(2k\left(\alpha - \rho\right) + p_{\mathrm{c}}\Big(\left(\alpha + \beta\right)\theta + bp_{\mathrm{c}}\left(\beta + \rho\right)\Big)\Big)\Big)}{2\left(2bk - 2b^2 p_{\mathrm{c}}^{\ 2} - 2bp_{\mathrm{c}}\theta - \theta^2\right)},$$

$$q_{\mathrm{nH}}^{\mathrm{Dc*}} = \frac{a\left(2bk - bp_{\mathrm{c}}\theta - \theta^2\right) + bp_{\mathrm{c}}\left(2bk\left(\alpha + \beta\right) - \left(\alpha + \beta\right)\theta^2 - b^2 p_{\mathrm{c}}^{\ 2}\left(\beta + \rho\right) - bp_{\mathrm{c}}\theta\left(\alpha + 2\beta + \rho\right)\right)}{2\left(2bk - 2b^2 p_{\mathrm{c}}^{\ 2} - 2bp_{\mathrm{c}}\theta - \theta^2\right)}.$$

**In a decentralized supply chain:**

**Backward induction:** In a decentralized supply chain without coordination contracts, the profit function is shown in Equations (6) and (7). Under different types, we adopt backward induction to solve the optimal decisions in each type of supply chain.

First, the response functions $q_{\mathrm{i}}^{\mathrm{Dd}*}(x^{\mathrm{Dd}},w^{\mathrm{Dd}})$ and $q_{\mathrm{n}}^{\mathrm{Dd}*}(x^{\mathrm{Dd}},w^{\mathrm{Dd}})$ can be found by solving FOCs in Equation (7), which is always concave under various types of supply chains.

Second, substituting $q_{\mathrm{i}}^{\mathrm{Dd}*}(x^{\mathrm{Dd}},w^{\mathrm{Dd}})$ and $q_{\mathrm{n}}^{\mathrm{Dd}*}(x^{\mathrm{Dd}},w^{\mathrm{Dd}})$ into Equation (6), we obtain optimal decisions $x^{\mathrm{Dd}*}$ and $w^{\mathrm{Dd}*}$. Equation (6) is concave under various types of supply chains when $k > \left(bp_{\mathrm{c}}+\theta\right)^2/4b$.

Third, substituting $x^{\mathrm{Dd}*}$ and $w^{\mathrm{Dd}*}$ into the response functions, we obtain optimal decisions $q_{\mathrm{i}}^{\mathrm{Dd}*}$ and $q_{\mathrm{n}}^{\mathrm{Dd}*}$. $a > \underline{a} = bp_{\mathrm{c}}\beta$ and $\alpha > \underline{\alpha} = \rho - a/bp_{\mathrm{c}}$ can guarantee positive optimal solutions.

Finally, following the same approach as in the centralized supply chain described above, type selection can be conducted. The difference is that we must compare supplier profits, not supply chain profits, to clarify the boundaries of each type: $\alpha_{\mathrm{EL}}^{\mathrm{d}} = -\dfrac{\theta(2a-bp_{\mathrm{c}}\rho)}{2(4bk-\theta^2)}$, $\alpha_{\mathrm{HE}}^{\mathrm{d}} = \mathrm{Min}[\mathrm{Solve}[\pi_{\mathrm{sE}}^{\mathrm{Dd}*}{==}\pi_{\mathrm{sH}}^{\mathrm{Dd}*},\alpha]]$, and $\alpha_{\mathrm{HE}}^{\mathrm{d}} < \alpha_{\mathrm{EL}}^{\mathrm{d}}$. The corresponding optimal solutions are as follows:

(1) If $\alpha > \alpha_{\mathrm{EL}}^{\mathrm{d}}$, then $x_{\mathrm{L}}^{\mathrm{Dd}*} = \dfrac{\theta(2a-bp_{\mathrm{c}}\rho)}{2(4bk-\theta^2)}$, $q_{\mathrm{iL}}^{\mathrm{Dd}*} = \dfrac{bk(2a-bp_{\mathrm{c}}\rho)}{2(4bk-\theta^2)}$, $q_{\mathrm{nL}}^{\mathrm{Dd}*} = (a+bp_{\mathrm{c}}\beta)/2$, $w_{\mathrm{L}}^{\mathrm{Dd}*} = \dfrac{k\left(2a-bp_{\mathrm{c}}\rho\right)}{4bk-\theta^2}$;

(2) If $\alpha_{\mathrm{EL}}^{\mathrm{d}} \ge \alpha \ge \alpha_{\mathrm{HE}}^{\mathrm{d}}$, then $x_{\mathrm{E}}^{\mathrm{Dd}*} = -\alpha$, $q_{\mathrm{iE}}^{\mathrm{Dd}*} = (2a-2\alpha\theta+bp_{\mathrm{c}}\rho)/8$, $q_{\mathrm{nE}}^{\mathrm{Dd}*} = (a+bp_{\mathrm{c}}\beta)/2$, $w_{\mathrm{E}}^{\mathrm{Dd}*} = (2a-2\alpha\theta-bp_{\mathrm{c}}\rho)/4b$;

(3) If $\alpha_{\mathrm{HE}}^{\mathrm{d}} > \alpha > \underline{\alpha}$, then $x_{\mathrm{H}}^{\mathrm{Dd}*} = \dfrac{\left(bp_{\mathrm{c}}+\theta\right)\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{4bk-b^2p_{\mathrm{c}}^{\,2}-2bp_{\mathrm{c}}\theta-\theta^2}$, $q_{\mathrm{iH}}^{\mathrm{Dd}*} = \dfrac{bk\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{4bk-b^2p_{\mathrm{c}}^{\,2}-2bp_{\mathrm{c}}\theta-\theta^2}$,

$q_{\mathrm{nH}}^{\mathrm{Dd*}} = \frac{a}{2} + \frac{bp_{\mathrm{c}}}{2}\left(\alpha + \beta + \frac{\left(bp_{\mathrm{c}} + \theta\right)\left(a + bp_{\mathrm{c}}\left(\alpha - \rho\right)\right)}{4bk - b^2 p_{\mathrm{c}}{}^2 - 2bp_{\mathrm{c}}\theta - \theta^2}\right)$, $w_{\mathrm{H}}^{\mathrm{Dd*}} = \frac{2k\left(a + bp_{\mathrm{c}}\left(\alpha - \rho\right)\right)}{4bk - b^2 p_{\mathrm{c}}{}^2 - 2bp_{\mathrm{c}}\theta - \theta^2}$.

The equilibrium solution is unique because we guarantee that the profit function is concave at each step by rendering the Hessian matrix negative. The conditions met are $k > \left(bp_{\mathrm{c}} + \theta\right)^2 / 4b$. Due to $bp_{\mathrm{c}}{}^2 + p_{\mathrm{c}}\theta + \theta^2 / 2b > \left(bp_{\mathrm{c}} + \theta\right)^2 / 4b$, we only need to guarantee $k > bp_{\mathrm{c}}{}^2 + p_{\mathrm{c}}\theta + \theta^2 / 2b$.

In summary, the conditions required for Proposition 1 are: $k > \underline{k}_1 = bp_{\mathrm{c}}{}^2 + p_{\mathrm{c}}\theta + \theta^2 / 2b$, $a > \underline{a} = bp_{\mathrm{c}}\beta$ and $\alpha > \underline{\alpha} = \rho - a / bp_{\mathrm{c}}$.

**Proof of Theorems 1 and 2**

Through the above backward induction, we can find the optimal solutions in the no-policy scenario. (1) In a centralized supply chain, $x^{\mathrm{Nc*}} = \frac{a\theta}{2bk - \theta^2}$, $q_{\mathrm{i}}^{\mathrm{Nc*}} = \frac{abk}{2bk - \theta^2}$ and $q_{\mathrm{n}}^{\mathrm{Nc*}} = a / 2$. The profit function is concave if $k > \theta^2 / 2b$. (2) In a decentralized supply chain, $x^{\mathrm{Nd*}} = \frac{a\theta}{4bk - \theta^2}$, $q_{\mathrm{i}}^{\mathrm{Nd*}} = \frac{abk}{4bk - \theta^2}$, $q_{\mathrm{n}}^{\mathrm{Nd*}} = a / 2$, $w^{\mathrm{Nd*}} = \frac{2ak}{4bk - \theta^2}$ and $\pi_{\mathrm{s}}^{\mathrm{Nd*}} = \frac{a^2 k}{8bk - 2\theta^2}$. All of the profit functions are concave if $k > \theta^2 / 4b$.

Comparing them with the result of Proposition 1, we obtain Theorems 1 and 2. Among them, the expressions of some parameters in Theorem 1 are as follows:

(1) $\alpha_{\mathrm{xH}}^{\mathrm{c}} = -\frac{2ab\left(2k + p_{\mathrm{c}}\theta\right)}{(2bk - \theta^2)(2bp_{\mathrm{c}} + \theta)} - \frac{bp_{\mathrm{c}}\left(\beta - \rho\right) + \theta\rho}{2bp_{\mathrm{c}} + \theta}$, $\alpha_{\mathrm{xH}}^{\mathrm{d}} = \rho - \frac{a\left(4bk + bp_{\mathrm{c}}\theta + \theta^2\right)}{\left(bp_{\mathrm{c}} + \theta\right)\left(4bk - \theta^2\right)}$, $\alpha_{\mathrm{xE}}^{\mathrm{c}} = -\frac{a\theta}{2bk - \theta^2}$ and $\alpha_{\mathrm{xE}}^{\mathrm{d}} = -\frac{a\theta}{4bk - \theta^2}$;

(2) $\alpha_{\mathrm{qiH}}^{\mathrm{c}} = \frac{2k\rho - bp_{\mathrm{c}}{}^2\left(\beta + \rho\right) - p_{\mathrm{c}}\beta\theta}{2k + p_{\mathrm{c}}\theta} - \frac{a\left(4b^2kp_{\mathrm{c}} + 6bk\theta - \theta^3\right)}{b(2bk - \theta^2)(2k + p_{\mathrm{c}}\theta)}$, $\alpha_{\mathrm{qiH}}^{\mathrm{d}} = -\frac{abp_{\mathrm{c}} + 2a\theta - 4bk\rho + \theta^2\rho}{4bk - \theta^2}$, $\alpha_{\mathrm{qiE}}^{\mathrm{c}} = -\frac{2a\theta^2 + bp_{\mathrm{c}}\left(2bk - \theta^2\right)\rho}{4bk\theta - 2\theta^3}$ and $\alpha_{\mathrm{qiE}}^{\mathrm{d}} = -\frac{2a\theta^2 + bp_{\mathrm{c}}\left(4bk - \theta^2\right)\rho}{8bk\theta - 2\theta^3}$;

(3) $\alpha_{\mathrm{qnH}}^{\mathrm{c}} = -\dfrac{2bk\beta - \beta\theta^2 + a\left(2bp_{\mathrm{c}} + \theta\right) - b^2 p_{\mathrm{c}}{}^2\left(\beta + \rho\right) - bp_{\mathrm{c}}\theta\left(2\beta + \rho\right)}{2bk - bp_{\mathrm{c}}\theta - \theta^2}$ and

$\alpha_{\mathrm{qnH}}^{\mathrm{d}} = -\dfrac{4bk\beta - \beta\theta^2 + a\left(bp_{\mathrm{c}} + \theta\right) - b^2 p_{\mathrm{c}}{}^2\left(\beta + \rho\right) - bp_{\mathrm{c}}\theta\left(2\beta + \rho\right)}{4bk - bp_{\mathrm{c}}\theta - \theta^2}$.

**Proof of Theorem 3**

Let $\gamma \equiv 1$, and the optimal solutions before the addition of the new regulation can be obtained by the method in the proof of Proposition 1, as described below.

(1) In a centralized supply chain, $x_{\mathrm{L}}^{\mathrm{Dc*}}(\gamma \equiv 1) = \dfrac{\theta\left(a - bp_{\mathrm{c}}\rho\right)}{2bk - \theta^2} > x_{\mathrm{L}}^{\mathrm{Dc*}}$, $q_{\mathrm{iL}}^{\mathrm{Dc*}}(\gamma \equiv 1) = \dfrac{bk\left(a - bp_{\mathrm{c}}\rho\right)}{2bk - \theta^2} > q_{\mathrm{iL}}^{\mathrm{Dc*}}$, $q_{\mathrm{nL}}^{\mathrm{Dc*}}(\gamma \equiv 1) = q_{\mathrm{nL}}^{\mathrm{Dc*}}$, $x_{\mathrm{E}}^{\mathrm{Dc*}}(\gamma \equiv 1) = x_{\mathrm{E}}^{\mathrm{Dc*}}$, $q_{\mathrm{iE}}^{\mathrm{Dc*}}(\gamma \equiv 1) = (a - \alpha\theta - bp_{\mathrm{c}}\rho)/2 > q_{\mathrm{iE}}^{\mathrm{Dc*}}$, $q_{\mathrm{nE}}^{\mathrm{Dc*}}(\gamma \equiv 1) = q_{\mathrm{nE}}^{\mathrm{Dc*}}$, $x_{\mathrm{H}}^{\mathrm{Dc*}}(\gamma \equiv 1) = x_{\mathrm{H}}^{\mathrm{Dc*}}$, $q_{\mathrm{iH}}^{\mathrm{Dc*}}(\gamma \equiv 1) = q_{\mathrm{iH}}^{\mathrm{Dc*}}$, $q_{\mathrm{nH}}^{\mathrm{Dc*}}(\gamma \equiv 1) = q_{\mathrm{nH}}^{\mathrm{Dc*}}$, $\alpha_{\mathrm{EL}}^{\mathrm{c}}(\gamma \equiv 1) = -\dfrac{\theta\left(a - bp_{\mathrm{c}}\rho\right)}{2bk - \theta^2} > \alpha_{\mathrm{EL}}^{\mathrm{c}}$ and $\alpha_{\mathrm{HE}}^{\mathrm{c}}(\gamma \equiv 1) = -\dfrac{a\left(2bp_{\mathrm{c}} + \theta\right) - bp_{\mathrm{c}}\left(\theta\rho - bp_{\mathrm{c}}\left(\beta - \rho\right)\right)}{2bk - bp_{\mathrm{c}}\theta - \theta^2} = \alpha_{\mathrm{H}} > \alpha_{\mathrm{HE}}^{\mathrm{c}}$. The profit functions are concave under various types of supply chains when $k > bp_{\mathrm{c}}{}^2 + p_{\mathrm{c}}\theta + \theta^2/2b$.

(2) In a decentralized supply chain, $x_{\mathrm{L}}^{\mathrm{Dd*}}(\gamma \equiv 1) = \dfrac{\theta\left(a - bp_{\mathrm{c}}\rho\right)}{4bk - \theta^2} > x_{\mathrm{L}}^{\mathrm{Dd*}}$, $q_{\mathrm{iL}}^{\mathrm{Dd*}}(\gamma \equiv 1) = \dfrac{bk\left(a - bp_{\mathrm{c}}\rho\right)}{4bk - \theta^2} > q_{\mathrm{iL}}^{\mathrm{Dd*}}$, $q_{\mathrm{nL}}^{\mathrm{Dd*}}(\gamma \equiv 1) = q_{\mathrm{nL}}^{\mathrm{Dd*}}$, $x_{\mathrm{E}}^{\mathrm{Dd*}}(\gamma \equiv 1) = x_{\mathrm{E}}^{\mathrm{Dd*}}$, $q_{\mathrm{iE}}^{\mathrm{Dd*}}(\gamma \equiv 1) = (a - \alpha\theta - bp_{\mathrm{c}}\rho)/4 > q_{\mathrm{iE}}^{\mathrm{Dd*}}$, $q_{\mathrm{nE}}^{\mathrm{Dd*}}(\gamma \equiv 1) = q_{\mathrm{nE}}^{\mathrm{Dd*}}$, $x_{\mathrm{H}}^{\mathrm{Dd*}}(\gamma \equiv 1) = x_{\mathrm{H}}^{\mathrm{Dd*}}$, $q_{\mathrm{iH}}^{\mathrm{Dd*}}(\gamma \equiv 1) = q_{\mathrm{iH}}^{\mathrm{Dd*}}$, $q_{\mathrm{nH}}^{\mathrm{Dd*}}(\gamma \equiv 1) = q_{\mathrm{nH}}^{\mathrm{Dd*}}$, $\alpha_{\mathrm{EL}}^{\mathrm{d}}(\gamma \equiv 1) = -\dfrac{\theta\left(a - bp_{\mathrm{c}}\rho\right)}{4bk - \theta^2} > \alpha_{\mathrm{EL}}^{\mathrm{d}}$ and $\alpha_{\mathrm{HE}}^{\mathrm{d}}(\gamma \equiv 1) = -\dfrac{\left(bp_{\mathrm{c}} + \theta\right)\left(a - bp_{\mathrm{c}}\rho\right)}{4bk - bp_{\mathrm{c}}\theta - \theta^2} > \alpha_{\mathrm{HE}}^{\mathrm{d}}$. The profit functions are concave under various types of supply chains when $k > \left(bp_{\mathrm{c}} + \theta\right)^2/4b$.

Comparing them with the result of Proposition 1, we obtain Theorem 3.

**Proof of Proposition 2**

**Cost sharing contract:**

**Backward induction:** The profit function is shown in Equations (8) and (9). Under different types, we adopt backward induction to solve the optimal decisions in each type of supply chain.

First, the response functions $q_{\mathrm{i}}^{\mathrm{CS}*}(x^{\mathrm{CS}}, w^{\mathrm{CS}}, \lambda)$ and $q_{\mathrm{n}}^{\mathrm{CS}*}(x^{\mathrm{CS}}, w^{\mathrm{CS}}, \lambda)$ can be found through solving FOCs in Equation (9), which is always concave under various types of supply chains.

Second, substituting $q_{\mathrm{i}}^{\mathrm{CS}*}(x^{\mathrm{CS}}, w^{\mathrm{CS}}, \lambda)$ and $q_{\mathrm{n}}^{\mathrm{CS}*}(x^{\mathrm{CS}}, w^{\mathrm{CS}}, \lambda)$ into Equation (8), we obtain the response functions $x^{\mathrm{CS}*}(\lambda)$ and $w^{\mathrm{CS}*}(\lambda)$. Equation (8) is concave under various types of supply chains when $k > \theta^2 / 4b(1-\lambda_{\mathrm{L}})$, $k > \left(bp_{\mathrm{c}} + \theta\right)^2 / 4b(1-\lambda_{\mathrm{H}})$ and $\lambda < 1$.

Third, substituting $x^{\mathrm{CS}*}(\lambda)$ and $w^{\mathrm{CS}*}(\lambda)$ into $q_{\mathrm{i}}^{\mathrm{CS}*}(x^{\mathrm{CS}}, w^{\mathrm{CS}}, \lambda)$ and $q_{\mathrm{n}}^{\mathrm{CS}*}(x^{\mathrm{CS}}, w^{\mathrm{CS}}, \lambda)$, we obtain $q_{\mathrm{i}}^{\mathrm{CS}*}(\lambda)$ and $q_{\mathrm{n}}^{\mathrm{CS}*}(\lambda)$. $a > \underline{a} = bp_{\mathrm{c}}\beta$, $\alpha > \underline{\alpha} = \rho - a / bp_{\mathrm{c}}$ and $0 \le \lambda < 1$ can guarantee positive optimal solutions.

Fourth, the supplier must make a type selection under the given $\lambda$. Following the same approach as described in the proof of Proposition 1, we obtain $\alpha_{\mathrm{EL}}^{\mathrm{CS}}(\lambda) = -\dfrac{\theta\left(2a - bp_{\mathrm{c}}\rho\right)}{2\left(4bk\left(1-\lambda\right) - \theta^2\right)}$, $\alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda) = \mathrm{Min}[\mathrm{Solve}[\pi_{\mathrm{sE}}^{\mathrm{CS}*}(\lambda) == \pi_{\mathrm{sH}}^{\mathrm{CS}*}(\lambda), \alpha]]$ and $\alpha_{\mathrm{EL}}^{\mathrm{CS}}(\lambda) > \alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda)$. It can be proved that $\alpha_{\mathrm{EL}}^{\mathrm{CS}}(\lambda)$ and $\alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda)$ decreases as $\lambda$ increases.

Then, the automaker must decide on $\lambda$ under different $\alpha$, and it is necessary to ensure that the profit of the supplier under the cost sharing contract is greater than the profit when the coordination contract is not implemented. Since the constraint is loose, we must only compare the profit of the supplier afterward (see Theorem 4). The constraints on $\alpha$ are as follows.

(1) In an L-type supply chain, $\alpha > \alpha_{\mathrm{EL}}^{\mathrm{CS}}(\lambda)$, and $0 < \lambda_{\mathrm{L}}^* = \theta^2 / 8bk < 1$ can be easily obtained by FOCs. Equation (9) is concave when $k > 3\theta^2 / 8b$. Substituting $\lambda_{\mathrm{L}}^*$ into the constraint, we obtain

$\alpha > \alpha_{\mathrm{EL}}^{\mathrm{CS}} = \mathrm{Solve}[\alpha_{\mathrm{EL}}^{\mathrm{CS}}(\lambda_{\mathrm{L}}^{*}(\alpha)) == \alpha, \alpha] = -\dfrac{\theta(2a - bp_{\mathrm{c}}\rho)}{8bk - 3\theta^2}$. It can be proved that $\alpha_{\mathrm{EL}}^{\mathrm{CS}} < \alpha_{\mathrm{EL}}^{\mathrm{d}}$.

(2) In an H-type supply chain, $\alpha < \alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda)$, and $0 < \lambda_{\mathrm{H}}^{*} = \lambda_{\mathrm{H}}(\alpha) < 1$ can be easily obtained by FOCs and $\alpha > \underline{\alpha} = \rho - a / bp_{\mathrm{c}}$. We can get

$$\lambda_{\mathrm{H}}(\alpha) = \frac{a\left(b^3 p_{\mathrm{c}}{}^3 - bp_{\mathrm{c}}\theta^2 + \theta^3 + b^2 p_{\mathrm{c}}\left(16k - p_{\mathrm{c}}\theta\right)\right) + bp_{\mathrm{c}}\theta^3\left(\alpha - \rho\right) - A}{8bk\left(a\left(3bp_{\mathrm{c}} + \theta\right) + bp_{\mathrm{c}}\left(\theta\left(\alpha - \rho\right) + bp_{\mathrm{c}}\left(3\alpha + 2\beta - \rho\right)\right)\right)},$$

where

$$A = -b^4 p_{\mathrm{c}}{}^4\left(\alpha - 4\beta - 5\rho\right) + b^2 p_{\mathrm{c}}{}^2\theta^2\left(\alpha + 4\beta + 3\rho\right) + b^3 p_{\mathrm{c}}{}^2\left(-16k\left(\alpha + \beta\right) + p_{\mathrm{c}}\theta\left(\alpha + 8\beta + 7\rho\right)\right).$$

Equation (9) is concave when $k > (7b^2 p_{\mathrm{c}}{}^2 + 6bp_{\mathrm{c}}\theta + 3\theta^2) / 8b$. Substituting $\lambda_{\mathrm{H}}^{*}$ into the constraint, we obtain $\alpha < \alpha_{\mathrm{HE}}^{\mathrm{CS}} = \mathrm{Solve}[\alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda_{\mathrm{H}}^{*}(\alpha)) == \alpha, \alpha]$. In addition, $\alpha > \underline{\alpha} = \rho - a / bp_{\mathrm{c}}$ must be satisfied. Since $\alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda)$ decreases as $\lambda$ increases, it can be proved that $\alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda_{\mathrm{H}}^{*}(\alpha)) < \alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda = 0) = \alpha_{\mathrm{HE}}^{\mathrm{d}}$; thus, $\alpha_{\mathrm{HE}}^{\mathrm{CS}} < \alpha_{\mathrm{HE}}^{\mathrm{d}}$.

(3) In an E-type supply chain, $\alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda) \le \alpha \le \alpha_{\mathrm{EL}}^{\mathrm{CS}}(\lambda)$. Since $\alpha_{\mathrm{EL}}^{\mathrm{CS}} < \alpha_{\mathrm{EL}}^{\mathrm{d}}$ and $\alpha_{\mathrm{HE}}^{\mathrm{CS}} < \alpha_{\mathrm{HE}}^{\mathrm{d}}$, we consider the range of $\alpha_{\mathrm{HE}}^{\mathrm{CS}} \le \alpha \le \alpha_{\mathrm{EL}}^{\mathrm{CS}}$. If $\alpha_{\mathrm{HE}}^{\mathrm{CS}} \le \alpha < \alpha_{\mathrm{HE}}^{\mathrm{d}}$, the equality constraint $\alpha = \alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda)$ is satisfied, and $0 < \lambda_{\mathrm{E}}^{*} = \lambda_{\mathrm{E}}(\alpha) = \mathrm{Solve}[\alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda) == \alpha, \lambda] < 1$ can be easily obtained. Among them

$$\lambda_{\mathrm{E}}(\alpha) = \frac{8\alpha\left(a\left(bp_{\mathrm{c}} + \theta\right) + \alpha\left(4bk - bp_{\mathrm{c}}\theta - \theta^2\right)\right) - 4bp_{\mathrm{c}}\left(a + \alpha\left(2bp_{\mathrm{c}} + \theta\right)\right)\rho + 3b^2 p_{\mathrm{c}}{}^2\rho^2 - B}{32bk\alpha^2},$$

where

$$B = \sqrt{bp_{\mathrm{c}}\rho\left(bp_{\mathrm{c}}\rho - 4bp_{\mathrm{c}}\alpha - 4\alpha\theta\right)\left(3bp_{\mathrm{c}}\rho - 4bp_{\mathrm{c}}\alpha - 4a\right)\left(3bp_{\mathrm{c}}\rho - 4a + 4\alpha\theta\right)}.$$

If $\alpha_{\mathrm{HE}}^{\mathrm{d}} \le \alpha \le \alpha_{\mathrm{EL}}^{\mathrm{CS}}$, the inequality constraint $\alpha_{\mathrm{HE}}^{\mathrm{CS}}(\lambda) < \alpha < \alpha_{\mathrm{EL}}^{\mathrm{CS}}(\lambda)$ is satisfied, and Equation (9) decreases as $\lambda$ increases; thus, $\lambda_{\mathrm{E}}^{*} = 0$.

Finally, substituting $\lambda^{*}$ into the above response functions, we obtain $x^{\mathrm{CS}*}$, $w^{\mathrm{CS}*}$, $q_{\mathrm{i}}^{\mathrm{CS}*}$ and $q_{\mathrm{n}}^{\mathrm{CS}*}$. The above conditions for ensuring that the equilibrium solution is unique and existing can be reduced to $k > (3(bp_{\mathrm{c}} + \theta)^2 + 4b^2 p_{\mathrm{c}}{}^2) / 8b$. The conditions to ensure that the optimal solution is positive are $a > \underline{a} = bp_{\mathrm{c}}\beta$ and $\alpha > \underline{\alpha} = \rho - a / bp_{\mathrm{c}}$.

## Revenue sharing contract

The same method above can be used to obtain $\mu^*$, as well as $\alpha_{\mathrm{EL}}^{\mathrm{RS}} = -\frac{\theta(2a - bp_{\mathrm{c}}\rho)}{8bk - 4\theta^2} < \alpha_{\mathrm{EL}}^{\mathrm{d}}$, $\alpha_{\mathrm{HE}}^{\mathrm{RS}} = \mathrm{Solve}[\alpha_{\mathrm{HE}}^{\mathrm{RS}}(\mu_{\mathrm{H}}^*(\alpha)) == \alpha, \alpha] < \alpha_{\mathrm{HE}}^{\mathrm{d}}$, $\mu_{\mathrm{L}}^* = \theta^2 / 2bk$, $\mu_{\mathrm{E}}(\alpha) = 2\lambda_{\mathrm{E}}(\alpha)$ and $\mu_{\mathrm{H}}(\alpha) = \frac{(bp_{\mathrm{c}} + \theta)\left(a\left(bp_{\mathrm{c}}(5k - p_{\mathrm{c}}\theta) + \theta(k - p_{\mathrm{c}}\theta)\right) - bp_{\mathrm{c}}\theta\left(p_{\mathrm{c}}(\alpha + \beta)\theta + k(-\alpha + \rho)\right)\right) - C}{2bk\left(a\left(k + p_{\mathrm{c}}(bp_{\mathrm{c}} + \theta)\right) + bp_{\mathrm{c}}\left(p_{\mathrm{c}}(\alpha + \beta)(bp_{\mathrm{c}} + \theta) + k(\alpha - \rho)\right)\right)}$, where $C = bp_{\mathrm{c}}(bp_{\mathrm{c}} + \theta)\left(b^2 p_{\mathrm{c}}^3(\beta + \rho) + bp_{\mathrm{c}}\left(k(-5\alpha - 4\beta + \rho) + p_{\mathrm{c}}\theta(\alpha + 2\beta + \rho)\right)\right)$. The condition for ensuring that the equilibrium solution is unique and existing is $k > (bp_{\mathrm{c}} + \theta)(bp_{\mathrm{c}} + \theta + \sqrt{(bp_{\mathrm{c}} + \theta)^2 + 4b^2 p_{\mathrm{c}}^2}) / 4b$. Let $\mu^* < 1$, and we obtain $\alpha > \underline{\alpha}^{\mathrm{RS}} = \mathrm{Max}\{\underline{\alpha}, \mathrm{Solve}[\mu_{\mathrm{H}}^*(\alpha) == 1, \alpha]\}$.

Combining the above two contracts, we can get the condition that the optimal solution exists and is positive, namely $a > \underline{a} = bp_{\mathrm{c}}\beta$ and $k > \underline{k}_2 = \mathrm{Max}\{(3(bp_{\mathrm{c}} + \theta)^2 + 4b^2 p_{\mathrm{c}}^2) / 8b, (bp_{\mathrm{c}} + \theta)(bp_{\mathrm{c}} + \theta + \sqrt{(bp_{\mathrm{c}} + \theta)^2 + 4b^2 p_{\mathrm{c}}^2}) / 4b\}$.

**Proof of Theorems 4, 5, 6 and 7**

On the basis of Proposition 2, the optimal solutions and profits can be found.

(1) Under the cost sharing contract, if $\alpha > \alpha_{\mathrm{EL}}^{\mathrm{CS}}$, then $x^{\mathrm{CS}*} = \frac{\theta(2a - bp_{\mathrm{c}}\rho)}{2\left(4bk(1 - \lambda_{\mathrm{L}}^*) - \theta^2\right)}$, $q_{\mathrm{i}}^{\mathrm{CS}*} = \frac{bk(1 - \lambda_{\mathrm{L}}^*)(2a - bp_{\mathrm{c}}\rho)}{2\left(4bk(1 - \lambda_{\mathrm{L}}^*) - \theta^2\right)}$ and $q_{\mathrm{n}}^{\mathrm{CS}*} = (a + bp_{\mathrm{c}}\beta)/2$; if $\alpha_{\mathrm{EL}}^{\mathrm{CS}} \geq \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{d}}$, then $x^{\mathrm{CS}*} = -\alpha$, $q_{\mathrm{i}}^{\mathrm{CS}*} = (2a - 2\alpha\theta - bp_{\mathrm{c}}\rho)/8$ and $q_{\mathrm{n}}^{\mathrm{CS}*} = (a + bp_{\mathrm{c}}\beta)/2$; if $\alpha_{\mathrm{HE}}^{\mathrm{d}} > \alpha \geq \alpha_{\mathrm{HE}}^{\mathrm{CS}} > \underline{\alpha}$, then $x^{\mathrm{CS}*} = \frac{(bp_{\mathrm{c}} + \theta)\left(a + bp_{\mathrm{c}}(\alpha - \rho)\right)}{4bk(1 - \lambda_{\mathrm{E2}}^*) - (bp_{\mathrm{c}} + \theta)^2}$, $q_{\mathrm{i}}^{\mathrm{CS}*} = \frac{bk(1 - \lambda_{\mathrm{E2}}^*)\left(a + bp_{\mathrm{c}}(\alpha - \rho)\right)}{4bk(1 - \lambda_{\mathrm{E2}}^*) - (bp_{\mathrm{c}} + \theta)^2}$ and $q_{\mathrm{n}}^{\mathrm{CS}*} = \frac{a + bp_{\mathrm{c}}}{2}\left(\alpha + \beta + \frac{(bp_{\mathrm{c}} + \theta)\left(a + bp_{\mathrm{c}}(\alpha - \rho)\right)}{4bk(1 - \lambda_{\mathrm{E2}}^*) - (bp_{\mathrm{c}} + \theta)^2}\right)$; if $\alpha_{\mathrm{HE}}^{\mathrm{CS}} > \alpha > \underline{\alpha}$, then $x^{\mathrm{CS}*} = \frac{(bp_{\mathrm{c}} + \theta)\left(a + bp_{\mathrm{c}}(\alpha - \rho)\right)}{4bk(1 - \lambda_{\mathrm{H}}^*) - (bp_{\mathrm{c}} + \theta)^2}$, $q_{\mathrm{i}}^{\mathrm{CS}*} = \frac{bk(1 - \lambda_{\mathrm{H}}^*)\left(a + bp_{\mathrm{c}}(\alpha - \rho)\right)}{4bk(1 - \lambda_{\mathrm{H}}^*) - (bp_{\mathrm{c}} + \theta)^2}$ and

$$q_{\mathrm{n}}^{\mathrm{CS}*}=\frac{a+bp_{\mathrm{c}}}{2}\left(\alpha+\beta+\frac{\left(bp_{\mathrm{c}}+\theta\right)\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{4bk\left(1-\lambda_{\mathrm{H}}^{*}\right)-\left(bp_{\mathrm{c}}+\theta\right)^{2}}\right).$$

(2) Under the revenue sharing contract, if $\alpha>\alpha_{\mathrm{EL}}^{\mathrm{RS}}$, then $x^{\mathrm{RS}*}=\dfrac{\theta\left(2a-bp_{\mathrm{c}}\rho\right)}{2\left(2bk\left(2-\mu_{\mathrm{L}}^{*}\right)-\theta^{2}\right)}$, $q_{\mathrm{i}}^{\mathrm{RS}*}=\dfrac{bk\left(2a-bp_{\mathrm{c}}\rho\right)}{2\left(2bk\left(2-\mu_{\mathrm{L}}^{*}\right)-\theta^{2}\right)}$ and $q_{\mathrm{n}}^{\mathrm{RS}*}=\left(a+bp_{\mathrm{c}}\beta\right)/2$; if $\alpha_{\mathrm{EL}}^{\mathrm{RS}}\geq\alpha\geq\alpha_{\mathrm{HE}}^{\mathrm{d}}$, then $x^{\mathrm{RS}*}=-\alpha$, $q_{\mathrm{i}}^{\mathrm{RS}*}=\dfrac{2a-2\alpha\theta-bp_{\mathrm{c}}\rho}{4\left(2-\mu_{\mathrm{E1}}^{*}\right)}$ and $q_{\mathrm{n}}^{\mathrm{RS}*}=\left(a+bp_{\mathrm{c}}\beta\right)/2$; if $\alpha_{\mathrm{HE}}^{\mathrm{d}}>\alpha\geq\alpha_{\mathrm{HE}}^{\mathrm{RS}}>\underline{\alpha}^{\mathrm{RS}}$, then $x^{\mathrm{RS}*}=\dfrac{\left(bp_{\mathrm{c}}+\theta\right)\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{2bk\left(2-\mu_{\mathrm{E2}}^{*}\right)-\left(bp_{\mathrm{c}}+\theta\right)^{2}}$, $q_{\mathrm{i}}^{\mathrm{RS}*}=\dfrac{bk\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{2bk\left(2-\mu_{\mathrm{E2}}^{*}\right)-\left(bp_{\mathrm{c}}+\theta\right)^{2}}$ and $q_{\mathrm{n}}^{\mathrm{RS}*}=\dfrac{a+bp_{\mathrm{c}}}{2}\left(\alpha+\beta+\dfrac{\left(bp_{\mathrm{c}}+\theta\right)\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{2bk\left(2-\mu_{\mathrm{E2}}^{*}\right)-\left(bp_{\mathrm{c}}+\theta\right)^{2}}\right)$; if $\alpha_{\mathrm{HE}}^{\mathrm{RS}}>\alpha>\underline{\alpha}^{\mathrm{RS}}$, then $x^{\mathrm{RS}*}=\dfrac{\left(bp_{\mathrm{c}}+\theta\right)\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{2bk\left(2-\mu_{\mathrm{H}}^{*}\right)-\left(bp_{\mathrm{c}}+\theta\right)^{2}}$, $q_{\mathrm{i}}^{\mathrm{RS}*}=\dfrac{bk\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{2bk\left(2-\mu_{\mathrm{H}}^{*}\right)-\left(bp_{\mathrm{c}}+\theta\right)^{2}}$ and

$$q_{\mathrm{n}}^{\mathrm{RS}*}=\frac{a+bp_{\mathrm{c}}}{2}\left(\alpha+\beta+\frac{\left(bp_{\mathrm{c}}+\theta\right)\left(a+bp_{\mathrm{c}}\left(\alpha-\rho\right)\right)}{2bk\left(2-\mu_{\mathrm{H}}^{*}\right)-\left(bp_{\mathrm{c}}+\theta\right)^{2}}\right).$$

By substituting the above optimal solutions into Equations (8)-(11), the corresponding profits can be obtained. Through simple comparisons, we obtain Theorems 4, 6 and 7. In addition, $\alpha_{\mathrm{EL}}^{\mathrm{RS}}>\alpha_{\mathrm{T}}^{\mathrm{RS}}>\alpha_{\mathrm{EL}}^{\mathrm{CS}}>\alpha_{\mathrm{T}}^{\mathrm{CS}}>\alpha_{\mathrm{EL}}^{\mathrm{d}}$ can be easily proved, where

$$\alpha_{\mathrm{T}}^{\mathrm{CS}}\text{=Solve}[\pi_{\mathrm{m}}^{\mathrm{CS}*}(\lambda_{\mathrm{L}}^{*})\text{==}\pi_{\mathrm{mE}}^{\mathrm{Dd}*},\alpha]=\frac{\left(2a-bp_{\mathrm{c}}\rho\right)}{2\theta}\left(1-\sqrt{\frac{8bk+\theta^{2}}{8bk-3\theta^{2}}}\right)$$

and

$$\alpha_{\mathrm{T}}^{\mathrm{RS}}\text{=Solve}[\pi_{\mathrm{m}}^{\mathrm{RS}*}(\mu_{\mathrm{L}}^{*})\text{==}\pi_{\mathrm{mE}}^{\mathrm{Dd}*},\alpha]=\frac{\left(2a-bp_{\mathrm{c}}\rho\right)}{2\theta}\left(1-\sqrt{\frac{2bk}{2bk-\theta^{2}}}\right).$$

In Theorem 5, when $\alpha_{\mathrm{T}}^{\mathrm{CS}}>\alpha>\alpha_{\mathrm{EL}}^{\mathrm{CS}}$ ($\alpha_{\mathrm{T}}^{\mathrm{RS}}>\alpha>\alpha_{\mathrm{EL}}^{\mathrm{RS}}$), $\pi_{\mathrm{sc}}^{\mathrm{CS}*}>\pi_{\mathrm{sc}}^{\mathrm{Dd}*}$ ($\pi_{\mathrm{sc}}^{\mathrm{RS}*}>\pi_{\mathrm{sc}}^{\mathrm{Dd}*}$) can be easily proved. Therefore, $\pi_{\mathrm{m}}^{\mathrm{Dd}*}-\pi_{\mathrm{m}}^{\mathrm{CS}*}<T^{\mathrm{CS}}<\pi_{\mathrm{s}}^{\mathrm{CS}*}-\pi_{\mathrm{s}}^{\mathrm{Dd}*}$ ($\pi_{\mathrm{m}}^{\mathrm{Dd}*}-\pi_{\mathrm{m}}^{\mathrm{RS}*}<T^{\mathrm{RS}}<\pi_{\mathrm{s}}^{\mathrm{RS}*}-\pi_{\mathrm{s}}^{\mathrm{Dd}*}$).

In Theorem 7, for the H-type supply chain, we obtain $\pi_{\mathrm{mH}}^{\mathrm{CS}*}>\pi_{\mathrm{mH}}^{\mathrm{RS}*}$ when $\alpha>\text{Max[Solve}[\pi_{\mathrm{mH}}^{\mathrm{CS}*}==\pi_{\mathrm{mH}}^{\mathrm{RS}*},\alpha]]$, but $\pi_{\mathrm{sH}}^{\mathrm{RS}*}>\pi_{\mathrm{sH}}^{\mathrm{CS}*}$ when $\alpha>\text{Max[Solve}[\pi_{\mathrm{sH}}^{\mathrm{CS}*}==\pi_{\mathrm{sH}}^{\mathrm{RS}*},\alpha]]$. In the comparison of optimal decisions, $x_{\mathrm{H}}^{\mathrm{CS}*} > x_{\mathrm{H}}^{\mathrm{RS}*}$ when $\alpha > \mathrm{Solve}[x_{\mathrm{H}}^{\mathrm{CS}*} == x_{\mathrm{H}}^{\mathrm{RS}*}, \alpha]$, $q_{\mathrm{iH}}^{\mathrm{CS}*} < q_{\mathrm{iH}}^{\mathrm{RS}*}$ when $\alpha > \mathrm{Solve}[q_{\mathrm{iH}}^{\mathrm{CS}*} == q_{\mathrm{iH}}^{\mathrm{RS}*}, \alpha]$, and $q_{\mathrm{nH}}^{\mathrm{CS}*} > q_{\mathrm{nH}}^{\mathrm{RS}*}$ when $\alpha > \mathrm{Solve}[q_{\mathrm{nH}}^{\mathrm{CS}*} == q_{\mathrm{nH}}^{\mathrm{RS}*}, \alpha]$. It is worth noting that, during the numerical simulation, we found that all of the above conditions regarding $\alpha$ are always satisfied in the feasible region, indicating that $\pi_{\mathrm{mH}}^{\mathrm{CS}*} > \pi_{\mathrm{mH}}^{\mathrm{RS}*}$, $\pi_{\mathrm{sH}}^{\mathrm{RS}*} > \pi_{\mathrm{sH}}^{\mathrm{CS}*}$, $x_{\mathrm{H}}^{\mathrm{CS}*} > x_{\mathrm{H}}^{\mathrm{RS}*}$, $q_{\mathrm{iH}}^{\mathrm{CS}*} < q_{\mathrm{iH}}^{\mathrm{RS}*}$ and $q_{\mathrm{nH}}^{\mathrm{CS}*} > q_{\mathrm{nH}}^{\mathrm{RS}*}$ are always true in simulation experiments.