

Article

Optimal Production Strategies with Credit Sharing for Automakers under the Dual-Credit Policy

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Abstract: This paper investigates strategic production selections in scenarios of credit sharing between cooperative fuel vehicle (FV) automakers and new energy vehicle (NEV) automakers under the dual-credit policy. Three cooptation production strategies are formulated: the simultaneous production strategy, the FV priority production strategy, and the NEV priority production strategy. On the basis of these three production strategies, this study examines the optimal strategy for both parties in scenarios of no credit sharing, credit sharing dominated by the FV automaker, and credit sharing dominated by the NEV automaker. The simultaneous production strategy is the most conducive to both parties' coexistence in the vehicle market, and the FV or NEV priority production strategy can be adopted to realize the Pareto optimization of their total profit in certain applicable intervals. Credit sharing will greatly change both parties' applicable intervals and optimal strategy selections, and credit sharing dominated by FV automakers has been proven to effectively improve their social welfare with a low credit price. Interestingly, a high credit price is sometimes more important for the development of NEVs than the NEV cruising range and substitutability under the dual-credit policy. This study also demonstrates the impact of the credit coefficient, credit equilibrium, and NEV substitutability on both parties' production decisions and credit sharing. Our study has important managerial implications and can be utilized as strategic guidance for FV/NEV automakers to pursue cooptation under the dual-credit policy.

Keywords: dual-credit policy; production strategy; cooptation; credit sharing; new energy vehicle

MSC: 90B06



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1. Introduction

The dual-credit policy is a new vehicle industry policy officially implemented by the Chinese government in 2019 (Jia et al., 2024; He et al., 2020 [1,2]). As an alternative to the NEV subsidy policy, the dual-credit policy encourages automakers to reduce the fuel consumption of FVs and increase the production of NEVs (Yu et al., 2023; Lou et al., 2020 [3,4]). If automakers have surplus total credits, they can sell them in the credit market for extra profit. If automakers have insufficient total credits, they must compensate for this insufficiency by buying credits from the credit market. Under the dual-credit policy, automakers that produce a high proportion of FVs, such as “Great Wall Motors Co. Ltd. (GWM), Hebei, China” and “Volkswagen, Shanghai, China”, face tremendous pressure from negative credits. However, automakers that actively produce NEVs, such as “BAIC Motor, Beijing, China” and “BYD Auto, Guangdong, China”, obtain the benefits of positive credits (Li et al., 2020 [5]). Therefore, many traditional FV automakers, especially foreign automakers in China, are actively seeking cooperation with NEV automakers to respond to the dual-credit policy.

There are various types of cooperation between FV automakers and NEV automakers under the dual-credit policy. For example, some automakers, such as BAIC, jointly produce FVs and NEVs through cooperation between holding subsidiaries, an approach that can

be named internal cooperation. Others, such as GWM and the “Hebei Yujie EV Company (Yogomo), Hebei, China”, participate in limited cooperation between automakers, with GWM preferentially obtaining NEV credits from Yogomo by holding 25% of Yogomo’s shares. Other types of cooperation, such as that between “BYD, Guangdong, China” and “Toyota, Japan”, “JAC, Anhui, China” and “Volkswagen, Shanghai, China”, and “Zotye, Zhejiang, China” and “Ford, USA”, involve jointly funding the establishment of a subsidiary to produce NEVs. This cooperation occurs not only within automakers but also between automakers and even between competitors. Through such cooperation, both parties strive to achieve brand sharing, technology sharing, and credit sharing to better respond to market competition under the dual-credit policy. Therefore, what kind of cooperation is most conducive to the maximization of the parties’ social welfare and the development of NEVs is the focus of this study.

Although cooperating parties can complement each other’s advantages, allowing the other party to continue to have its own core technologies may be a double-edged sword (Ma et al., 2023; Li et al., 2019 [6,7]). Brand and technology sharing will inevitably increase the substitutability and competitiveness of the company’s products. For example, BAIC produced its own NEV brand, BAIC BJEV (EU260), based on its FV brand, such as the BAIC Shenbao, which led some BAIC brand followers to switch from FVs to NEVs. For cooperative companies such as BYD and Toyota, their new vehicle products will face similar competition. Therefore, those automakers have to consider how to prioritize the development of FVs and NEVs. Obviously, different production strategies will have a profound impact on their profits and market competitive advantages.

Credit sharing is one of the most important driving forces for cooperation between automakers (Wu et al., 2022; Lou et al., 2020 [3,8]). However, the Chinese government clearly stipulates in the dual-credit policy that only when two parties hold 25% of each other’s shares can they be allowed to share credits. Therefore, whether to share credits and which party will dominate the credit sharing is another important factor affecting both parties’ production decisions. For BAIC, an automaker with outstanding NEV development, the subsidiary BAIC BJEV will dominate credit sharing. GWM, a large FV automaker, will dominate credit sharing in cooperation with Yogomo. Thus, automakers that hold no more than 25% of each other’s shares will independently bear credit costs and credit benefits. We are also curious about how credit sharing changes their optimal strategy selections.

To investigate these issues, we consider a complex relationship between FV automakers and competitive NEV automakers that cooperate in production and credit sharing under the dual-credit policy. The vehicles offered by the two parties are imperfectly substitutable; that is, FVs can be fully substituted for NEVs, but the reverse does not hold true. There are three cooperation production strategies between the two parties: the simultaneous production strategy, the FV priority production strategy, and the NEV priority production strategy. To provide a full picture of the outcomes of the three production strategies, the following study will consider three scenarios: no credit sharing, credit sharing dominated by FV automakers, and credit sharing dominated by the NEV automaker. These scenarios are realistic in the practice of the dual-credit policy in China. The main contribution of this study is that we not only consider the impact of credit prices on FV automakers and NEV automakers but also comprehensively study the impact of credit cooperation on their production strategies. This can help these automakers better deal with dual-credit policy and maximize their credit benefits.

The remainder of this paper is organized as follows: after relevant studies are reviewed in Section 2, the model notations and assumptions are presented in Section 3. Section 4 explores the optimal cooperation strategies of both parties without credit sharing according to market size, credit price, and production cost and carries out sensitivity analyses of the credit coefficient and NEV substitutability. Section 5 further investigates the impact of credit sharing dominated by FV/NEV automakers on both parties’ production decisions and strategy selections. Then, a comparative analysis is performed from the perspectives of production quantities, strategy length, total profit, and total credits in Section 6. Finally, we

draw conclusions and provide suggestions for future studies in Section 7. All of the proofs are presented in Appendix A.

2. Literature Review

The dual-credit policy has had a great impact on China's vehicle industry and has attracted many scholars to this research field. Jia et al. (2024) [2] established an evolutionary game model to simulate and compare the effects of different policies on GMV deployment. Xiao et al. (2023) [9] constructed NEV-FV competitive models to study the effect of greenness-based subsidy policy and dual-credit policy on prices, quantities, profits, consumer surplus, and social welfare. Ou et al. (2018) [10] summarized the dual-credit policy and developed FV and NEV credit models to quantify the impacts of this policy on consumer choices. Li et al. (2020) [11] examined the impacts of the subsidy policy and dual-credit policy on NEV and FV production decisions. Obviously, there is an essential difference between the dual-credit policy and the NEV subsidy policy. The former is a production subsidy, and the latter is a consumption subsidy (Li et al., 2018; Ma et al., 2017 [12,13]). Therefore, how the dual-credit policy affects the development of NEVs and the decision-making behavior of automakers has become a focus of attention. Zhao et al. (2019) [14] established a bottom-up framework to estimate the impacts of regulation on the technological trends of battery electric vehicles under the dual-credit policy in China. Zhou et al. (2019) [15] generalized the dual-credit policy and investigated its effects on green technology investments and pricing decisions in a two-echelon supply chain.

In addition, some scholars further explored the production and pricing decisions of automakers under the dual-credit policy. Zhao et al. (2024) [16] constructed a tripartite evolutionary game model based on the tripartite Hotelling model, which involves NEV enterprises, FV enterprises, and governments under the dual-credit policy. Yu et al. (2021) [17] used Stackelberg game paradigms to model a two-stage auto supply chain under the dual-credit policy. Lou et al. (2020) [3] developed a decision-making model to optimize the fuel economy improvement level and the production of internal combustion engine vehicles (ICEVs) under the dual-credit policy. Li et al. (2020) [5] formulated a multiperiod credit market dynamic equilibrium model to investigate the ongoing sustainable development of NEV credits. Although these studies have provided a better understanding of the dual-credit policy, they have not considered the coopetition relationship between FV automakers and NEV automakers or the impact of credit sharing on their decisions.

This work is also closely related to the study of coopetition between firms. Previous studies have explored various management fields, including outsourcing decisions (Heese et al., 2020; Chen et al., 2019; Yan et al., 2019 [18–20]), strategic alliances (Rai, 2016; Lee and Johnson, 2010; Bello et al., 2010 [21–23]), and supply chain operations (Ge et al., 2014; Wilhelm, 2011; Chen et al., 2020 [24–26]). Some scholars have further examined the advantages and disadvantages of coopetition strategies for participating firms and investigated the optimal choice of coopetition strategies (Mantovani and Ruiz-Aliseda, 2016; Xu et al., 2010 [27,28]). Venkatesh et al. (2006) [29] indicated that the co-optor strategy is the most optimal among the three distribution strategies for manufacturers of proprietary component brands. Chen et al. (2019) [30] found that the optimal strategy for coopetition is determined not only by the degree of production substitution but also by the interfirm power relationship and the difference in production efficiency between the two manufacturers.

Although cooperation can bring many benefits, whether to prioritize the development of FVs or NEVs is always a controversial issue for automakers. According to the traditional theory of market competition, both parties will strive to act as leaders in the cooperative relationship to gain the first-mover advantage () (Feng et al., 2020; Pun, 2013 [31,32]). However, this often causes losses to the overall interests of both parties () (Guan et al., 2019; Lukas et al., 2016 [33,34]). Under the dual-credit policy, not only will the development of NEVs affect both parties' competitive advantage, but each party will also directly affect the other's credit benefits, which will make their coopetition decisions more complicated. Fol-

lowing on from these studies, we will investigate production competition strategies from the perspective of total profits and consider the impact of credit sharing on optimal strategies.

This work is also related to studies of sharing in supply chains, including information sharing (Johnsen et al., 2020 [35]); revenue sharing (Dye and Yang, 2016 [36]), and cost sharing (Li et al., 2021 [37]). Li et al. (2020) ([38]) investigated a manufacturer's information acquisition and subsidization strategies in a supply chain featuring two competing retailers that sell substitutable products and have private demand information. Huo et al. (2020) [39] empirically investigated the impact of information sharing on different types of supply chain-learning and their influences on flexible performance. Avinadav (2020) [40] studied marketing and operational decisions in a two-echelon supply chain in which a retailer and a manufacturer used a revenue-sharing contract to sell a perishable product. Zhao et al. (2020) [41] presented all participants' equilibrium strategies and corresponding profits under a consignment contract with revenue sharing. Fan et al. (2020) [42] considered a two-echelon supply chain in which an upstream manufacturer and a downstream retailer share the product liability cost caused by quality defects. These studies prove that sharing has an enormous impact on the operation and coordination of the supply chain. In addition, some scholars have also addressed price sharing (Adhikari et al., 2020 [43]), resource sharing (Im et al., 2019 [44]), and knowledge sharing (Yiu et al., 2020 [45]) in the supply chain. However, credit sharing has not yet been studied. The implementation of the dual-credit policy will increase FV automakers' credit costs and NEV automakers' credit benefits. Therefore, credit sharing can be regarded as a special combination of revenue sharing and cost sharing that will be examined from the production strategy perspective in this study.

3. Notation and Assumptions

In this study, FV automakers and NEV automakers with products that are partially substitutable engage in a quantity-setting Cournot competition in the vehicle market (Cheng and Fan, 2021 [46]). Therefore, we adopt the traditional competitive reverse demand function, which is commonly used in the marketing and operations fields to investigate production competition (Chen et al., 2019; Wang et al., 2013 [18,47]).

$$\begin{cases} p_m = \phi - q_m - rq_n \\ p_n = \phi - q_n - q_m. \end{cases} \quad (1)$$

where ϕ represents the upper bound on market size, p_m/p_n is FV/NEV automakers' retail price, and q_m/q_n is their production quantities. r is the substitution rate of NEVs for FVs (Hsieh and Lai, 2020; Hopp and Xu, 2008 [48,49]). Due to the high production cost, low cruising distance, and inconvenience of power replenishment, NEVs are usually regarded as inferior to FVs. The latter are assumed to be perfect substitutes for the former, but the reverse is not true. For simplicity, the FV automakers' marginal production cost is normalized to zero, and the NEV automakers' marginal production cost is Δc (Gray and Roth, 2009 [50]).

The dual-credit policy will increase the credit cost of FV automakers and increase the credit benefits of NEV automakers. The credit cost of FV automakers is mainly derived from two factors. One factor is the production ratio of NEVs required by the government, and the other is the NEV credits required for fuel consumption levels that fail to meet the standard set by the government. The credit cost caused by the former is fixed, and the credit cost caused by the latter depends on the actual energy-saving efforts of FV automakers. For simplicity, let β_m be the FV credit coefficient; that is, the FV automakers will bear the $\beta_m p_e$ credit cost for each FV produced, where p_e is the credit price. Obviously, the larger the β_m , the greater the credit cost faced by FV automakers. Similarly, the NEV automaker will obtain positive NEV credits from the production of NEVs based on cruising distance. Let β_n be the NEV credit coefficient. A higher cruising distance corresponds to more positive credits received for each NEV. A higher credit coefficient for NEVs means a higher cruising range; therefore, each NEV produced will obtain more credits.

We consider three production strategies for the relationship between FV automakers and NEV automakers: the simultaneous production strategy (S1), the FV priority production strategy (S2), and the NEV priority production strategy (S3). In the simultaneous production strategy, the two parties compete in terms of quantity by simultaneously choosing production quantities. Both parties are economically rational and act strategically to maximize their profits depending on the other party's decisions. In the FV or NEV priority production strategy, the two parties play a Stackelberg game, with one as the leader and the other as the follower.

4. Coopetition Production Strategy without Credit Sharing

This section begins with the scenario in which the shareholding ratio of the two parties has not reached the standard set by the government, so credits cannot be shared. Thus, the FV automaker and NEV automaker will independently bear credit costs and credit benefits. The profit function of both parties is as follows.

$$\pi_m = q_m(\phi - q_m - rq_n) - \beta_m q_m p_e, \quad (2)$$

$$\pi_n = q_n(\phi - q_n - q_m - \Delta c) + \beta_n q_n p_e, \quad (3)$$

which are concave and differentiable. Note that in these two profit functions, the first term is the profit from selling products in the vehicle market, whereas the second is the costs and benefits from credit trading in the credit market. The total profit of both parties is represented by $\pi_z = \pi_m + \pi_n$.

Three production strategies are examined to determine which is optimal for automakers without credit sharing. Then, the impact of vehicle market size, credit price, credit coefficient, and NEV substitutability on production decisions is investigated.

4.1. Equilibrium Outcomes of Three Production Strategies

In the simultaneous production strategy (S1), the optimal solution can be obtained by the first-order derivative condition, $\frac{\partial \pi_m}{\partial q_m} = 0$, $\frac{\partial \pi_n}{\partial q_n} = 0$. For production strategies S2 and S3, the reverse induction method is needed to solve them. For example, for production strategy S2, the optimal response function of NEV automakers is first obtained according to the first-order derivative condition, $\frac{\partial \pi_n}{\partial q_n} = 0$. Then, the reaction function is substituted into Equation (2), and the optimal solution for the FV automaker is obtained according to the first-order derivative condition, $\frac{\partial \pi_m}{\partial q_m} = 0$. The closed-form expressions of the game equilibrium outcomes under the three production strategies are summarized in the following proposition.

Proposition 1. *In the simultaneous production strategy (S1), the equilibrium production quantities and profits are as follows:*

$$q_m^{S1} = \frac{(2-r)\phi + r\Delta c - (2\beta_m + r\beta_n)p_e}{4-r}, \quad q_n^{S1} = \frac{\phi - 2\Delta c + (\beta_m + 2\beta_n)p_e}{4-r};$$

$$\pi_m^{S1} = \frac{[(2-r)\phi + r\Delta c - (2\beta_m + r\beta_n)p_e]^2}{(4-r)^2}, \quad \pi_n^{S1} = \frac{[\phi - 2\Delta c + (\beta_m + 2\beta_n)p_e]^2}{(4-r)^2}, \quad \pi_z^{S1} = \pi_m^{S1} + \pi_n^{S1}.$$

In the FV priority production strategy (S2), the equilibrium production quantities and profits are as follows:

$$q_m^{S2} = \frac{(2-r)\phi + r\Delta c - (2\beta_m + r\beta_n)p_e}{2(2-r)}, \quad q_n^{S2} = \frac{(2-r)\phi - (4-r)\Delta c + [2\beta_m + (4-r)\beta_n]p_e}{4(2-r)};$$

$$\pi_m^{S2} = \frac{[(2-r)\phi + r\Delta c - (2\beta_m + r\beta_n)p_e]^2}{8(2-r)}, \quad \pi_n^{S2} = \frac{[(2-r)\phi - (4-r)\Delta c + (2\beta_m + (4-r)\beta_n)p_e]^2}{16(2-r)^2}, \quad \pi_z^{S2} = \pi_m^{S2} + \pi_n^{S2}.$$

In the NEV priority production strategy (S3), the equilibrium production quantities and profits are as follows:

$$q_m^{S3} = \frac{(4-3r)\phi + 2r\Delta c - [(4-r)\beta_m + 2r\beta_n]p_e}{4(2-r)}, \quad q_n^{S3} = \frac{\phi - 2\Delta c + (\beta_m + 2\beta_n)p_e}{2(2-r)};$$

$$\pi_m^{S3} = \frac{[(4-3r)\phi + 2r\Delta c - ((4-r)\beta_m + 2r\beta_n)p_e]^2}{16(2-r)^2}, \quad \pi_n^{S3} = \frac{[\phi - 2\Delta c + (\beta_m + 2\beta_n)p_e]^2}{8(2-r)}, \quad \pi_z^{S3} = \pi_m^{S3} + \pi_n^{S3}.$$

Proposition 1 provides several conclusions about the impact of market size, NEV production cost, and credit price on the equilibrium outcomes. In the three production strategies S1–S3, a greater market size always results in a larger production quantity and profit for both parties. However, the NEV production cost and credit price have opposite impacts on the two automakers. A high NEV production cost will be beneficial to the FV automaker but detrimental to the NEV automaker, while a high credit price will be beneficial to the NEV automaker but detrimental to the FV automaker. As the NEV production cost decreases and the credit price increases, NEVs will gain a greater competitive advantage over FVs. Moreover, the following lemmas are obtained by drawing on Proposition 1.

Lemma 1. For the three production strategies, $q_m^{S2} > q_m^{S1} > q_m^{S3}$, and $q_n^{S3} > q_n^{S1} > q_n^{S2}$.

Lemma 1 implies that there is a first-mover advantage for both the FV automakers and the NEV automaker. The FV automaker will gain a greater competitive advantage under the FV priority production strategy, while the NEV automaker will gain a greater competitive advantage under the NEV priority production strategy. Therefore, in the scenario of no credit sharing, both parties have the motivation to become the leader of the production strategy.

Lemma 2. For the three production strategies,

(1) when the FV automaker tries to reduce β_m , the production quantities of FVs will increase, and the production quantities of NEVs will decrease, while when the NEV automaker tries to promote β_n , the production quantities of FVs will decrease, and the production quantities of NEVs will increase;

(2) the production quantities of FVs increased by reducing β_m are greater than the production quantities of NEVs increased by promoting β_n .

Lemma 2 implies that, as the credit cost coefficient of FVs, reducing β_m is conducive to maintaining the competitive advantage of FVs, and as β_n is the credit benefit coefficient of NEVs, increasing β_n helps increase the competitive advantage of NEVs. There are two main ways to reduce β_m : one is to reduce the fuel consumption level of FVs, and the other is to reduce the production ratio of NEVs prescribed by the government. As the dual-credit policy becomes more stringent, the production ratio of NEVs will also increase. Therefore, FV automakers can maintain their competitive advantage only by investing in reducing fuel consumption under the dual-credit policy. For NEV automakers, increasing the cruising range is the main way to increase β_n . However, FVs already occupy a major share of the vehicle market and have a first-mover advantage, forcing NEV automakers to make greater efforts to gain a competitive advantage.

Lemma 3. For the three production strategies,

(1) q_m^{S1} and q_m^{S3} decrease in r and q_n^{S1} and q_n^{S3} increase in r , and
 (2) when $p_e \geq p_e^0$, q_m^{S2} decreases in r and q_n^{S2} increases in r ; when $0 \leq p_e < p_e^0$, q_m^{S2} increases in r and q_n^{S2} decreases in r .

Lemma 3 implies that with the increase in NEV substitutability, the production quantities of NEVs will increase, and FVs will be gradually replaced by NEVs. However, under the FV priority production strategy and when the credit price is low, counterintuitive

results appear. The increase in NEV substitutability will not increase the market share of NEVs but will further strengthen the competitive advantage of FVs. This scenario has been a common phenomenon in the early implementation of the dual-credit policy. The credit market is not yet mature, and the credit price is generally low (only RMB 300/unit in China in 2019). Therefore, the increase in the NEV substitutability will lead to counterattacks by FVs with first-mover advantages, such as price wars. Only when the credit price reaches a certain height can NEVs gain enough credit advantage to compete with FVs. In short, during the early implementation of the dual-credit policy, increasing the credit price is more conducive to the development of NEVs than increasing NEV substitutability.

Drawing on Proposition 1, the conditions of vehicle market size that make FVs and NEVs coexist in the vehicle market (i.e., $q_m \geq 0$, $q_n \geq 0$) under the three production strategies are derived in Proposition 2.

Proposition 2. *For the three production strategies, FVs and NEVs can coexist in the market only when the vehicle market size meets the following conditions:*

$$\begin{aligned} (1) \quad & \phi \geq \max\{\phi_m^{S1}, \phi_n^{S1}\}, \phi_m^{S1} = \frac{-r\Delta c + (2\beta_m + r\beta_n)p_e}{2-r}, \phi_n^{S1} = 2\Delta c - (\beta_m + 2\beta_n)p_e; \\ (2) \quad & \phi \geq \max\{\phi_m^{S2}, \phi_n^{S2}\}, \phi_m^{S2} = \frac{-r\Delta c + (2\beta_m + r\beta_n)p_e}{2-r}, \phi_n^{S2} = \frac{(4-r)\Delta c - [2\beta_m + (4-r)\beta_n]p_e}{2-r}; \\ (3) \quad & \phi \geq \max\{\phi_m^{S3}, \phi_n^{S3}\}, \phi_m^{S3} = \frac{-2r\Delta c + [(4-r)\beta_m + 2r\beta_n]p_e}{4-3r}, \phi_n^{S3} = 2\Delta c - (\beta_m + 2\beta_n)p_e. \end{aligned}$$

Proposition 2 implies that when the vehicle market size is large enough relative to the NEV production cost and credit price that $\phi > \max\{\phi_m^{S1}, \phi_n^{S1}\}$, then FVs and NEVs will coexist in the vehicle market. ϕ_m^{S1} is the minimum market size for FVs in the vehicle market under the simultaneous production strategy (S1), while ϕ_n^{S1} is the minimum market size for NEVs in the vehicle market. Otherwise, the simultaneous production strategy (S1) will be reduced to a monopoly setting in which the FV automaker or NEV automaker will be expelled from the vehicle market. Similar properties and conclusions are observed in production strategies S2–S3.

When $\phi_m^{S1} = \phi_n^{S1}$, we can obtain the critical line $p_e^0 = \frac{\Delta c}{\beta_m + \beta_n}$. When $0 \leq p_e < p_e^0$, then $\phi_m^{S1} < \phi_n^{S1}$; when $p_e \geq p_e^0$, then $\phi_m^{S1} \geq \phi_n^{S1}$. p_e^0 is not only the critical line between ϕ_m^{S1} and ϕ_n^{S1} but also the critical line between ϕ_m^{S2} and ϕ_n^{S2} and ϕ_m^{S3} and ϕ_n^{S3} . Thus, p_e^0 is a very important critical line for the competitive advantage of FVs and NEVs regardless of production strategy. When the credit price is relatively low, it will be easier for FVs to gain a foothold in the vehicle market, and when the credit price is high, the credit benefits will be high enough for NEVs to gain a competitive advantage.

This critical line depends mainly on two key factors: the production cost gap Δc between the two parties because a decrease in NEV production cost will increase the likelihood of NEVs gaining a competitive advantage, and the credit coefficient of both parties, β_m and β_n , because a higher β_n will increase the likelihood of NEVs gaining a competitive advantage. Therefore, the higher the NEV production cost and the lower the fuel consumption level of FVs, the higher the p_e^0 , which will be more conducive for FVs to maintain competitive advantages. In contrast, as the NEV production cost decreases and the NEV cruising range increases, p_e^0 will decrease, which will help NEVs gain a competitive advantage. Interestingly, the critical line p_e^0 has nothing to do with NEV substitutability because under the dual-credit policy, the key factor that determines whether FVs and NEVs can coexist in the vehicle market is not substitutability but the gap between the two parties' production costs and credit coefficients.

Table 1 shows that the market size threshold for each production strategy depends on the credit price level. When $p_e \geq p_e^0$, if $\phi \in [\phi_m^{S3}, +\infty)$, then the production of FVs and NEVs under each production strategy is non-negative, i.e., production strategies S1–S3 are all applicable under this condition. If $\phi \in [\phi_m^{S1}/\phi_m^{S2}, \phi_m^{S3})$, then production strategy S3 is no longer applicable, and only production strategies S1 and S2 are applicable. If $\phi \in [0, \phi_m^{S1}/\phi_m^{S2})$, then the FV automaker will be expelled from the vehicle market, and

there will be no room for production cooperation. A similar situation results if $0 \leq p_e < p_e^0$ in the three production strategies.

Table 1. Vehicle market size for the application of the three production strategies.

Credit Price	Market Size	Production Strategies
$p_e \geq p_e^0$	$[\phi_m^{S3}, +\infty)$	S1/S2/S3
	$[\phi_m^{S1}/\phi_m^{S2}, \phi_m^{S3})$	S1/S2
	$[0, \phi_m^{S1}/\phi_m^{S2})$	Only NEVs
$0 \leq p_e < p_e^0$	$[\phi_n^{S2}, +\infty)$	S1/S2/S3
	$[\phi_n^{S1}/\phi_n^{S3}, \phi_n^{S2})$	S1/S3
	$[0, \phi_n^{S1}/\phi_n^{S3})$	Only FVs

4.2. Optimal Production Strategies

Although market size has a great impact on the selection of a production strategy, it is relatively stable and can, therefore, be regarded as an exogenous variable. In fact, we pay more attention to the impact of changes in credit prices and NEV production costs on production strategy. In this section, we explore the optimal production strategy for the total profit of both parties via comparisons between the three production strategies S1–S3. If $\phi \leq \phi_m^{S1}/\phi_m^{S2}$ when $p_e \geq p_e^0$ or if $\phi \leq \phi_n^{S1}/\phi_n^{S3}$ when $0 \leq p_e < p_e^0$, then either FVs or NEVs are always expelled from the vehicle market, and the other is always the monopolist. We focus on the coexistence of FVs and NEVs, and the two reduced cases are omitted here. On the basis of Proposition 2, the optimal production strategies without credit sharing are summarized in Proposition 3.

Proposition 3. For the three production strategies S1–S3, as shown in Figure 1,

- (1) all critical lines for production quantities $p_e \sim f(\Delta c)$ intersect at point $(\frac{\beta_m + \beta_n}{\beta_m} \phi, \frac{\phi}{\beta_m})$;
- (2) if $p_e \in [p_{e11}/p_{e21}, +\infty)$ or $p_e \in [0, p_{e12}/p_{e32})$, then FVs or NEVs will not coexist in the vehicle market, and the applicable intervals of the three production strategies S1–S3 are $A - C(p_{e12}/p_{e32} \leq p_e \leq p_{e11}/p_{e21})$, $A - B_4(p_{e22} \leq p_e \leq p_{e11}/p_{e21})$, and $B_1 - C(p_{e12}/p_{e32} \leq p_e \leq p_{e31})$, respectively;
- (3) in interval B_1 ($p_{e13b} \leq p_e \leq p_{e31}$), the NEV priority production strategy S3 will be the optimal strategy; in interval B_4 ($p_{e22} \leq p_e \leq p_{e12a}$), the FV priority production strategy S2 will be the optimal strategy; otherwise, the simultaneous production strategy S1 will be the optimal strategy.

All the critical lines related to credit price p_e in Proposition 3 are derived from the critical lines related to vehicle market size ϕ in Proposition 2. For simplicity and to guarantee meaningful outcomes, let $\Delta c \leq \frac{\beta_m + \beta_n}{\beta_m} \phi$ and $p_e \leq \frac{\phi}{\beta_m}$. Figure 1 illustrates the applicable interval of the three production strategies and the optimal strategy for maximizing both parties' total profits in each interval. p_{e11} , p_{e12} , p_{e21} , p_{e22} , p_{e31} , and p_{e32} are the critical lines of production quantities q_m and q_n , while p_{e12a} , p_{e12b} , p_{e13a} , p_{e13b} , p_{e23a} , and p_{e23b} are the critical lines of total profit for each production strategy. It should be noted that the parameter settings in Figure 1, especially the FV/NEV credit coefficients β_m and β_n , are set based on the simulation of China's BAIC EU260 and other automobile products. The changing rules of these parameters have been proved in our proposition.

In Figure 1, the applicable interval of production strategies S1–S3 is divided into two parts symmetrically by p_e^0 . The interval below p_e^0 belongs to the competitive advantage area of FVs, and that above p_e^0 is more conducive to the development of NEVs. The gap in production cost between the two parties is another important factor. When NEV production cost Δc is high ($\Delta c \rightarrow \frac{\beta_m + \beta_n}{\beta_m} \phi$), regardless of how high the credit price p_e is, NEV automakers will choose to abandon the vehicle market due to unprofitability. In this scenario, the government often introduces subsidy policies to support the development of NEVs.

However, even if Δc decreases to interval C, it is still difficult for the two parties to achieve production cooperation due to the weak competitiveness of NEVs. When Δc further decreases, and the credit price remains at a low level, that is, in the B_4 interval, the two parties will choose the FV priority production strategy (S2) to achieve a *Pareto* improvement of total profits. Interestingly, if Δc continues to fall or p_e continues to rise, i.e., in the $B_2 - B_3$ interval, the NEV automakers will tend to compete rather than cooperate. In such a scenario, NEV technology is relatively mature, and the competitive situation is more conducive for NEV automakers to occupy a larger market share and earn profits. Since $B_2 - B_3$ is a fiercely competitive interval for FVs and NEVs, the necessity of a NEV subsidy policy will decrease, and the incentive value of the dual-credit policy will increase. On the right side of Figure 1, the red circle represents the optimal strategy in this area.

A similar situation results if $p_e \geq p_{e0}$ in interval $A - B_2$ for the three production strategies, in which case the NEV automaker will dominate the vehicle market. Similarly, as the competitiveness of the FV automaker continues to decline with a high credit price, both parties will choose the NEV priority production strategy (S3) as their optimal strategy in interval B_1 . Obviously, when the credit price is higher than the critical line, the importance of the credit price to the competitive advantage will be greater than the production cost gap between the two parties.

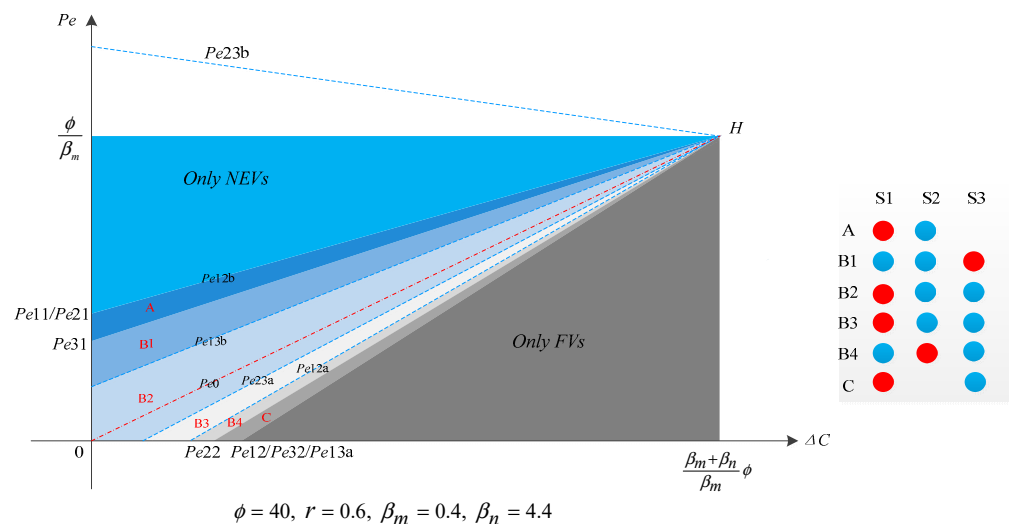


Figure 1. Optimal production strategies without credit sharing.

The development of NEV technology often requires a process. Therefore, the NEV production cost will remain relatively stable for a period of time. For a particular Δc , the selection of the production strategy will depend mainly on the credit price p_e , and the existence condition of each production strategy will change from a certain interval to a line segment, as shown in Figure 1. Let L^{s1} , L^{s2} , and L^{s3} be the lengths of the three production strategies S1–S3, respectively. Then, we obtain the following:

$$L^{s1} = p_{e11} - p_{e12} = \frac{(4-r)[(\beta_m + \beta_n)\phi - \beta_m \overline{\Delta c}]}{(\beta_m + 2\beta_n)(2\beta_m + r\beta_n)},$$

$$L^{s2} = p_{e21} - p_{e22} = \frac{4(2-r)[(\beta_m + \beta_n)\phi - \beta_m \overline{\Delta c}]}{(2\beta_m + r\beta_n)[2\beta_m + (4-r)\beta_n]},$$

$$L^{s3} = p_{e31} - p_{e32} = \frac{4(2-r)[(\beta_m + \beta_n)\phi - \beta_m \overline{\Delta c}]}{(\beta_m + 2\beta_n)[(4-r)\beta_m + 2r\beta_n]},$$

where $\overline{\Delta c}$ is a certain NEV production cost for a period of time. Again, comparing the lengths of the three production strategies $L^{s1} - L^{s3}$ leads to the following lemma.

Lemma 4. For the length of the three production strategies,

- (1) $L^{s1} > L^{s2} > L^{s3}$, i.e., the simultaneous production strategy (S1) is the longest, and the NEV priority production strategy (S3) is the shortest, and
- (2) all strategy lengths L^{s1} , L^{s2} , L^{s3} decrease in β_m , β_n , and r .

Lemma 4 implies that the simultaneous production strategy (S1) has the largest applicable interval and can allow FVs and NEVs to coexist in the vehicle market to the greatest extent. However, the FV priority development strategy (S2) will hinder the development of NEVs and increase the survival challenges of NEVs. In addition, the strategy length is affected by the credit coefficient and NEV substitutability. Counterintuitively, when FV automakers try to reduce fuel consumption, the strategy length of all production strategies will not be shortened due to the increased advantages of FVs; rather, the strategy length is extended. The reason may be the relief of the FV credit pressure, and the decline in competition will give NEVs more room for survival in the vehicle market. However, if the NEV cruising range and substitutability are increased, the length of all production strategies will be reduced and encroach on the market share of FVs. Therefore, reducing fuel consumption will lead to a win-win situation for FVs and NEVs, but increasing cruising range and substitutability will accelerate the transformation of the vehicle market to a monopoly market dominated by NEVs.

Finally, we discuss the credit equilibrium of the three production strategies. Let $V = \beta_n q_n - \beta_m q_m$ be the total credits of each production strategy. When $V \geq 0$, the automakers have obtained positive credits; otherwise, the credits are negative and need to be supplemented by purchasing NEV credits from the credit market. Again, comparing the total credits of the three production strategies $V^{s1} - V^{s3}$ leads to the following lemma.

Lemma 5. For the three production strategies, the total credits satisfy $V^{s3} > V^{s1} > V^{s2}$. Moreover, the NEV priority production strategy (S3) most easily achieves credit equilibrium, and the FV priority production strategy (S2) has the greatest difficulty achieving credit equilibrium.

Lemma 5 implies that the NEV priority production strategy (S3) benefits from the first-mover advantage of NEVs and thus obtains more positive NEV credits. In contrast, the FV priority production strategy (S2) is more conducive to FVs, resulting in more negative NEV credits. At present, many automakers adopt the FV priority production strategy (S2), but the credit market is not yet mature, and there are great uncertainties in the price and supply of credits. As a result, these automakers will face greater risks in credit trading.

5. Coopetition Production Strategy with Credit Sharing

Credit sharing is one of the main forms of cooperation between FV automakers and NEV automakers under the dual-credit policy. At present, the Chinese government stipulates that only if the shareholding ratio exceeds 25% can credits be shared between cooperative automakers. In this section, we will discuss the two main credit-sharing scenarios. One is credit sharing dominated by FV automakers, such as the relationship between GWM and Yagomo. The other is credit sharing dominated by the NEV automaker, such as the relationships between BYD and Toyota and BAIC Shenbao (X35) and BAIC BJEV (EU260). In the former scenario, the credit costs and credit benefits will be borne by the FV automaker, while in the latter scenario, the NEV automaker will bear the credit costs and credit benefits. Similarly, we will discuss the equilibrium solutions, the optimal production strategies, and some important properties for both parties under these two credit-sharing scenarios.

5.1. Credit Sharing Dominated by the FV Automaker

The FV automaker will bear the credit costs and credit benefits when it dominates the credit sharing. For example, in the cooperation between GWM and Yagomo, Yagomo's NEV credits will be transferred to GWM to meet GWM's great demand for positive NEV

credits. As a transaction, GWM will hold a 25% stake in Yogomo and provide Yogomo with advanced vehicle manufacturing technologies to enhance the competitiveness of its NEVs in the vehicle market. The profit function of both parties in this scenario can be obtained as follows.

$$\pi_{m_FV} = q_m(\phi - q_m - rq_n) + (\beta_n q_n - \beta_m q_m)p_e, \quad (4)$$

$$\pi_{n_FV} = q_n(\phi - q_n - q_m - \Delta c). \quad (5)$$

Similar to Section 4, according to Equations (4) and (5), the equilibrium solutions of both parties under the three production strategies can be deduced in the following proposition.

Proposition 4. *The equilibrium production quantities of both parties, with credit sharing dominated by the FV automaker, are as follows:*

$$\begin{aligned} q_{m_FV}^{S1} &= \frac{(2-r)\phi + r\Delta c - 2\beta_m p_e}{4-r}, & q_{n_FV}^{S1} &= \frac{\phi - 2\Delta c + \beta_m p_e}{4-r}; \\ q_{m_FV}^{S2} &= \frac{(2-r)\phi + r\Delta c - (2\beta_m + \beta_n)p_e}{2(2-r)}, & q_{n_FV}^{S2} &= \frac{(2-r)\phi - (4-r)\Delta c + (2\beta_m + \beta_n)p_e}{4(2-r)}; \\ q_{m_FV}^{S3} &= \frac{(4-3r)\phi + 2r\Delta c - (4-r)\beta_m p_e}{4(2-r)}, & q_{n_FV}^{S3} &= \frac{\phi - 2\Delta c + \beta_m p_e}{2(2-r)}. \end{aligned}$$

According to Proposition 4, credit sharing dominated by the FV automaker will cause the following changes in the equilibrium production quantities compared with the scenario of no credit sharing.

$$\begin{aligned} \Delta q_{m_FV}^{S1} &= \frac{r\beta_n p_e}{4-r}, & \Delta q_{n_FV}^{S1} &= -\frac{2\beta_n p_e}{4-r}; \\ \Delta q_{m_FV}^{S2} &= -\frac{(1-r)\beta_n p_e}{2(2-r)}, & \Delta q_{n_FV}^{S2} &= -\frac{(3-r)\beta_n p_e}{4(2-r)}; \\ \Delta q_{m_FV}^{S3} &= \frac{r\beta_n p_e}{2(2-r)}, & \Delta q_{n_FV}^{S3} &= -\frac{\beta_n p_e}{2-r}. \end{aligned}$$

Under the simultaneous production strategy (S1) and the NEV priority production strategy (S3), credit sharing dominated by the FV automaker will increase the production of FVs and reduce the production of NEVs. Obviously, under these two production strategies, the FV automaker has an incentive to convert its credit advantages into production advantages. However, it is counterintuitive that under the FV priority production strategy (S2), the production of FVs will not increase but will decline. It may be that the credit advantage of the FV automaker eases the competition between the two parties, thereby weakening the motivation of the FV automaker to use its first-mover advantage to maintain its market share. In other words, credit sharing can enable the two parties to avoid price wars to a certain extent and achieve a win-win situation.

Again, the following lemmas are obtained by drawing on Proposition 4.

Lemma 6. *For the three production strategies with credit sharing dominated by the FV automaker, $q_{m_FV}^{S1}$, $q_{m_FV}^{S2}$ and $q_{m_FV}^{S3}$ decrease in p_e and increase in Δc , and $q_{n_FV}^{S1}$ and $q_{n_FV}^{S2}$ and $q_{n_FV}^{S3}$ increase in p_e and decrease in Δc .*

Lemma 6 implies that a high credit price and low production cost are undoubtedly more conducive to the development of NEVs. This conclusion is consistent with the scenario of no credit sharing. Therefore, regardless of whether credits are shared, maintaining a reasonable credit price is a necessary condition for the dual-credit policy to be effective.

Lemma 7. *For the three production strategies with credit sharing dominated by the FV automaker,*

- (1) *under all three production strategies S1–S3, when the FV automaker tries to reduce β_m , the production of FVs will increase, and the production of NEVs will decrease;*
- (2) *the production of FVs and NEVs under the simultaneous production strategy (S1) and the NEV priority production strategy (S3) will have nothing to do with β_n ;*
- (3) *under the FV priority production strategy (S2), when the NEV automaker tries to increase β_n , the production of FVs will decrease, and the production of NEVs will increase.*

Lemma 7 implies that credit sharing dominated by the FV automaker will not change the impact of the FV credit coefficient on both parties' production but will change the impact of the NEV credit coefficient on both parties' production. Especially under production strategies S1 and S3, because the NEV automaker no longer enjoys credit benefits, it loses the influence of the NEV credit coefficient on the production decisions of both parties. However, under the FV priority production strategy (S2), the FV automaker must consider NEV production to optimize its credit benefits. This instead prompts the NEV credit coefficient to become a key constraint for the development of FVs. Therefore, even if current automakers, such as GWM, generally adopt the FV priority production strategy (S2) and even take advantage of credit sharing, NEV automakers, such as Yagomo, can still gain market competitive advantages by increasing their cruising range.

Lemma 8. *For the three production strategies with credit sharing dominated by the FV automaker,*
 (1) $q_{m_FV}^{S1}$ and $q_{m_FV}^{S3}$ decrease in r and $q_{n_FV}^{S1}$ and $q_{n_FV}^{S3}$ increase in r , and
 (2) when p_e ($p_e^{H2} \leq p_e \leq p_{e21}$) is high, $q_{m_FV}^{S2}$ decreases in r and $q_{n_FV}^{S2}$ increases in r , and when p_e ($p_{e22} \leq p_e < p_e^{H2}$) is low, $q_{m_FV}^{S2}$ increases in r and $q_{n_FV}^{S2}$ decreases in r .

Lemma 8 implies that in most cases, credit sharing dominated by the FV automaker does not change the relationship between the production quantities of both parties and NEV substitutability. The higher the NEV substitutability is, the stronger the competitiveness of NEVs. However, under the FV priority production strategy (S2), there are counterintuitive results. When the credit price is low, the production quantities of NEVs will not increase because of the increase in their substitutability but rather will decrease. The reason may be that due to the low credit price, the dual-credit policy has not effectively changed the competitive advantages of both parties. As NEV substitutability improves, FV automakers will use first-mover advantages, such as price wars, to suppress NEVs and maintain their market position. Once the credit price increases, FV automakers will have to consider the credit benefits generated by the growth of NEVs and thus tend to cooperate rather than suppress. Therefore, in the scenario of credit sharing dominated by the FV automaker, it is counterproductive to improve NEV substitutability, and increasing the credit price is more important for the development of NEVs.

Drawing on Proposition 4, the conditions of vehicle market size that make FVs and NEVs coexist in the vehicle market (i.e., $q_m \geq 0$, $q_n \geq 0$) under these three production strategies with credit sharing dominated by FV automakers are derived in Proposition 5.

Proposition 5. *For the three production strategies with credit sharing dominated by the FV automaker, FVs and NEVs can coexist in the market only when the vehicle market size meets the following conditions:*

$$\begin{aligned} (1) \quad & \phi \geq \max\{\phi_{m_FV}^{S1}, \phi_{n_FV}^{S1}\}, \phi_{m_FV}^{S1} = \frac{-r\Delta c + 2\beta_m p_e}{2-r}, \phi_{n_FV}^{S1} = 2\Delta c - \beta_m p_e; \\ (2) \quad & \phi \geq \max\{\phi_{m_FV}^{S1}, \phi_{n_FV}^{S1}\}, \phi_{m_FV}^{S2} = \frac{-r\Delta c + (2\beta_m + \beta_n)p_e}{2-r}, \phi_{n_FV}^{S2} = \frac{(4-r)\Delta c - (2\beta_m + \beta_n)p_e}{2-r}; \\ (3) \quad & \phi \geq \max\{\phi_{m_FV}^{S1}, \phi_{n_FV}^{S1}\}, \phi_{m_FV}^{S3} = \frac{-2r\Delta c + (4-r)\beta_m p_e}{4-3r}, \phi_{n_FV}^{S3} = 2\Delta c - \beta_m p_e. \end{aligned}$$

Compared with the scenario without credit sharing, the critical market size of each production strategy with credit sharing dominated by the FV automaker also changes as follows. Obviously, under production strategies S1 and S3, credit sharing dominated by the FV automaker reduces the critical market size of FVs and increases the critical market size of NEVs. Thus, under these two production strategies, NEVs will have more difficulty surviving in the vehicle market, and FVs will survive more easily. Interestingly, under the

FV priority production strategy (S2), the critical market size of FVs also becomes larger. In other words, it is more difficult for both parties to coexist in the vehicle market.

$$\begin{aligned}\Delta\phi_{m_FV}^{S1} &= -\frac{r\beta_n p_e}{2-r}; \Delta\phi_{n_FV}^{S1} = 2\beta_n p_e; \\ \Delta\phi_{m_FV}^{S2} &= \frac{(1-r)\beta_n p_e}{2-r}; \Delta\phi_{n_FV}^{S2} = \frac{(3-r)\beta_n p_e}{2-r}; \\ \Delta\phi_{m_FV}^{S3} &= -\frac{2r\beta_n p_e}{4-3r}; \Delta\phi_{n_FV}^{S3} = 2\beta_n p_e.\end{aligned}$$

Similarly, let $\phi_{m_FV}^{S1} = \phi_{n_FV}^{S1}$, $\phi_{m_FV}^{S2} = \phi_{n_FV}^{S2}$ and $\phi_{m_FV}^{S3} = \phi_{n_FV}^{S3}$; then, we can obtain the critical lines $p_{e_FV}^{0-S1} = \frac{\Delta c}{\beta_m}$, $p_{e_FV}^{0-S2} = \frac{2\Delta c}{2\beta_m + \beta_n}$, and $p_{e_FV}^{0-S3} = \frac{\Delta c}{\beta_m}$, respectively, and $0 \leq p_{e_FV}^{0-S2} \leq p_{e_FV}^{0-S1} / p_{e_FV}^{0-S3}$. The market size threshold for each production strategy with credit sharing dominated by the FV automaker is summarized in Table 2. For example, when $0 \leq p_e < \frac{r\Delta c}{r\beta_m + \beta_n}$, if $\phi \geq \phi_n^{S2}$, production strategies S1–S3 are all applicable, and if $\phi_n^{S1} / \phi_n^{S3} \leq \phi < \phi_n^{S2}$, NEVs will be expelled from the vehicle market under the FV priority production strategy (S2). Therefore, only production strategies S1 and S3 will be applicable under this condition. Then, if $\phi < \phi_n^{S1} / \phi_n^{S3}$, these three production strategies will no longer be applicable and will degenerate into a monopoly setting with only FVs. Similar conclusions apply to other intervals of p_e and ϕ . Therefore, only when the credit price or market size is large enough will both parties have enough options to improve production strategies and credit benefits.

Table 2. Market size for the three production strategies with credit sharing dominated by the FV automaker.

Credit Price	Market Size	Production Strategies
$p_e \geq p_{e_FV}^{0-S1} / p_{e_FV}^{0-S3}$	$[\phi_m^{S2}, +\infty)$ $[\phi_m^{S3}, \phi_m^{S2})$ $[\phi_m^{S1}, \phi_m^{S3})$ $[0, \phi_m^{S1})$	S1/S2/S3 S1/S3 S1 Only NEVs
$\frac{(4-r)\Delta c}{(4-r)\beta_m + \beta_n} \leq p_e < p_{e_FV}^{0-S1} / p_{e_FV}^{0-S3}$	$[\phi_m^{S2}, +\infty)$ $[\phi_n^{S1} / \phi_n^{S3}, \phi_m^{S2})$ $[0, \phi_n^{S1} / \phi_n^{S3})$	S1/S2/S3 S1/S3 Only FVs
$p_{e_FV}^{0-S2} \leq p_e < \frac{(4-r)\Delta c}{(4-r)\beta_m + \beta_n}$	$[\phi_n^{S1} / \phi_n^{S3}, +\infty)$ $[\phi_m^{S2}, \phi_n^{S1} / \phi_n^{S3})$ $[0, \phi_m^{S2})$	S1/S2/S3 S2 Only FVs
$\frac{r\Delta c}{r\beta_m + \beta_n} \leq p_e < p_{e_FV}^{0-S2}$	$[\phi_n^{S1} / \phi_n^{S3}, +\infty)$ $[\phi_m^{S2}, \phi_n^{S1} / \phi_n^{S3})$ $[0, \phi_m^{S2})$	S1/S2/S3 S2 Only FVs
$0 \leq p_e < \frac{r\Delta c}{r\beta_m + \beta_n}$	$[\phi_n^{S2}, +\infty)$ $[\phi_n^{S1} / \phi_n^{S3}, \phi_n^{S2})$ $[0, \phi_n^{S1} / \phi_n^{S3})$	S1/S2/S3 S1/S3 Only FVs

Considering the effect of changes in credit prices and NEV production cost on production strategies with credit sharing dominated by the FV automaker leads to the following proposition.

Proposition 6. For the three production strategies with credit sharing dominated by the FV automaker, as shown in Figure 2,

(1) the critical lines for production quantities under production strategies S1–S3 intersect at points $H1\left(\phi, \frac{\phi}{\beta_m}\right)$, $H2\left(\phi, \frac{2\phi}{2\beta_m + \beta_n}\right)$, and $H3\left(\phi, \frac{\phi}{\beta_m}\right)$, respectively;

(2) the applicable intervals of the three production strategies S1–S3 are $p_{e12} / p_{e32} \leq p_e \leq p_{e11}$, $p_{e22} \leq p_e \leq p_{e21}$, and $p_{e12} / p_{e32} \leq p_e \leq p_{e31}$, respectively; otherwise, FVs and NEVs will not coexist in the vehicle market;

(3) the optimal production strategy for each applicable interval is shown in Tables 3–5. For example, in interval A(I), the simultaneous production strategy (S1) will be the optimal strategy; in interval B(I), the NEV priority production strategy (S3) will be the optimal strategy; and in interval C₁(I), the FV priority production strategy (S2) will be the optimal strategy.

Table 3. Applicable interval and optimal production strategies under scenario I with credit sharing dominated by the FV automaker.

Interval	S1	S2	S3	Profit Comparison
A	O			π_z^{S1}
B	O		O	$\pi_z^{S3} > \pi_z^{S1}$
C ₁	O	O	O	$\pi_z^{S2} > \pi_z^{S3} > \pi_z^{S1}$
C ₂	O	O	O	$\pi_z^{S3} > \pi_z^{S2} > \pi_z^{S1}$
C ₃	O	O	O	$\pi_z^{S3} > \pi_z^{S1} > \pi_z^{S2}$
C ₄	O	O	O	$\pi_z^{S1} > \pi_z^{S3} > \pi_z^{S2}$
C ₅	O	O	O	$\pi_z^{S1} > \pi_z^{S2} > \pi_z^{S3}$
C ₆	O	O	O	$\pi_z^{S2} > \pi_z^{S1} > \pi_z^{S3}$
D	O		O	$\pi_z^{S1} > \pi_z^{S3}$

Table 4. Applicable interval and optimal production strategies under scenario II with credit sharing dominated by the FV automaker.

Interval	S1	S2	S3	Profit Comparison
A	O			π_z^{S1}
B	O		O	$\pi_z^{S3} > \pi_z^{S1}$
C	O	O	O	$\pi_z^{S2} > \pi_z^{S3} > \pi_z^{S1}$
D		O		π_z^{S2}

Table 5. Applicable interval and optimal production strategies under scenario III with credit sharing dominated by the FV automaker.

Interval	S1	S2	S3	Profit Comparison
A	O			π_z^{S1}
B	O		O	$\pi_z^{S3} > \pi_z^{S1}$
C		O		π_z^{S2}

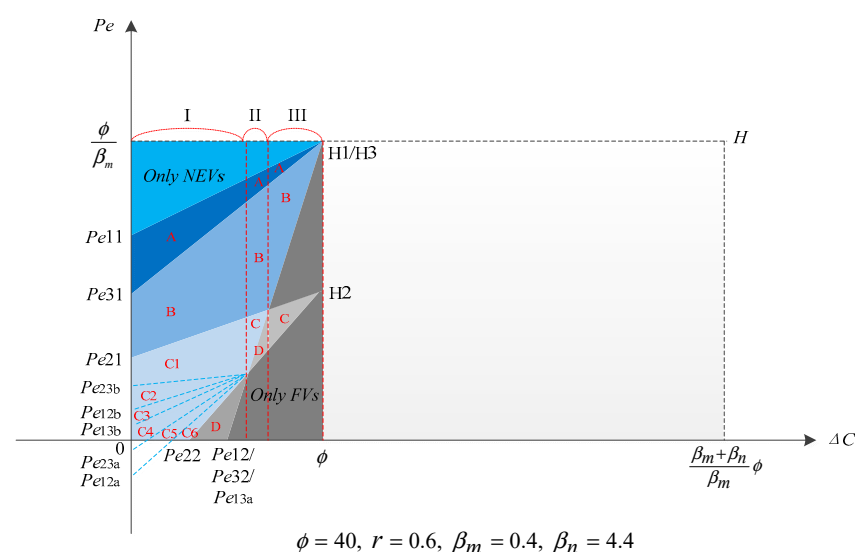


Figure 2. Optimal production strategies with credit sharing dominated by the FV automaker.

There is no doubt that credit sharing has a significant impact on the applicable interval of the production strategy and the selection of the optimal strategy. Comparing Figures 1 and 2, we find that the applicable interval of the three production strategies has been greatly reduced on the horizontal axis. This means that credit sharing dominated by the FV automaker has higher requirements for the NEV production cost. Only when the NEV production cost is reduced to a certain level may the two parties consider credit-sharing cooperation dominated by the FV automaker. At the same time, the critical lines of the credit price of each production strategy have been raised, indicating that credit sharing dominated by the FV automaker also requires a higher credit price. In addition, the applicable interval in this scenario has become more complicated.

In interval I of Figure 2, the applicable interval of all production strategies can be subdivided into nine intervals A – D. In interval A, only the simultaneous production strategy (S1) is applicable, so it is also the optimal production strategy. In interval B, production strategies S1 and S3 are applicable. However, the total profit of production strategy S3 is higher than that of production strategy S1, so production strategy S3 is the optimal strategy. Similarly, in interval C₁, all three production strategies are applicable, and the optimal strategy is production strategy S2. The applicable production strategy for each interval is represented by a black circle, and the optimal production strategy is represented by a red circle, as shown in Table 3. Obviously, in intervals B, C₁, C₂, C₃, and C₆, the FV or NEV priority production strategy can be adopted to realize the Pareto optimization of both parties' total profit.

In intervals II and III, the applicable interval of each production strategy will become simpler. In these intervals, the Pareto optimization of total profit can also be achieved by selecting one of the three production strategies.

For a relatively stable NEV production cost $\overline{\Delta c}$ in a certain period, we can also obtain the length of these three production strategies with credit sharing dominated by the FV automaker as follows.

$$L_{FV}^{S1} = \frac{(4-r)(\phi - \overline{\Delta c})}{2\beta_m}; L_{FV}^{S2} = \frac{2(2-r)(\phi - \overline{\Delta c})}{2\beta_m + \beta_n}; L_{FV}^{S3} = \frac{4(2-r)(\phi - \overline{\Delta c})}{(4-r)\beta_m}.$$

Lemma 9. For the three production strategies with credit sharing dominated by the FV automaker,

(1) $L_{FV}^{S1} > L_{FV}^{S3} > L_{FV}^{S2}$; i.e., the simultaneous production strategy (S1) is the longest, and the FV priority production strategy (S2) is the shortest;

(2) under all the production strategies, when the FV automaker tries to reduce β_m , the length of all production strategies will increase, and when the NEV automaker tries to increase β_n , it has no impact on the length of production strategies S1 and S3 but will shorten the length of production strategy S2;

(3) as NEV substitutability r increases, the length of all production strategies will decrease.

Lemma 9 is basically consistent with Lemma 4 without credit sharing. The difference is that under the simultaneous production strategy (S1) and the FV priority production strategy (S3), the NEV automaker will not be able to influence the strategy length for both parties by increasing its cruising range. This implies that in the scenario of credit sharing dominated by the FV automaker, the selection of a production strategy will be more beneficial to the FV automaker than to the NEV automaker.

Similarly, we discuss the total credits of each production strategy with credit sharing dominated by the FV automaker in the following lemma.

Lemma 10. For the three production strategies with credit sharing dominated by the FV automaker,

(1) in the high credit interval $(p_{e-FV}^H < p_e \leq p_{e11})$, $V_{FV}^{S1} > V_{FV}^{S3}$; in the moderate credit interval $(p_{e-FV}^M < p_e \leq p_{e-FV}^H)$, $V_{FV}^{S3} > V_{FV}^{S1}$; in the low credit interval $(p_{e11}/p_{e32} \leq p_e < p_{e-FV}^M)$, $V_{FV}^{S3} > V_{FV}^{S1} > V_{FV}^{S2}$;

(2) the NEV priority production strategy (S3) most easily achieves credit equilibrium, and the FV priority production strategy (S2) has the greatest difficulty achieving credit equilibrium.

Interestingly, in the scenario of credit sharing dominated by the FV automaker, when the credit price is high, production strategy S1 instead of production strategy S3 maximizes the total credits of both parties. The reason is that because the NEV automaker no longer bears credit benefits, regardless of how high the credit price is, its first-mover advantage will not take into account the credit benefits. However, under the simultaneous production strategy (S1), as the FV automaker bears credit benefits, a high credit price will prompt it to reduce certain FV production quantities to obtain higher credit benefits.

5.2. Credit Sharing Dominated by the NEV Automaker

For cooperative companies such as BYD, Toyota, BAIC Shenbao (X35), and BAIC BJEV (EU260), the credit benefits and credit costs are borne by the NEV automaker. In their cooperative relationship, the NEVs are relatively mature and have sufficient positive NEV credits. The profit function of both parties in this scenario can be obtained as follows.

$$\pi_{m_NEV} = q_m(\phi - q_m - rq_n), \quad (6)$$

$$\pi_{n_NEV} = q_n(\phi - q_n - q_m - \Delta c) + (\beta_n q_n - \beta_m q_m)p_e. \quad (7)$$

According to Equations (6) and (7), the equilibrium outcomes of both parties under the three production strategies can be deduced in the following proposition.

Proposition 7. *The equilibrium production quantities of both parties, with credit sharing dominated by the NEV automaker, are as follows:*

$$\begin{aligned} q_{m_NEV}^{S1} &= \frac{(2-r)\phi + r\Delta c - r\beta_n p_e}{4-r}, & q_{n_NEV}^{S1} &= \frac{\phi - 2\Delta c + 2\beta_n p_e}{4-r}; \\ q_{m_NEV}^{S2} &= \frac{(2-r)\phi + r(\Delta c - \beta_n p_e)}{2(2-r)}, & q_{n_NEV}^{S2} &= \frac{(2-r)\phi - (4-r)(\Delta c - \beta_n p_e)}{4(2-r)}; \\ q_{m_NEV}^{S3} &= \frac{(4-3r)\phi + 2r\Delta c - r(\beta_m + 2\beta_n)p_e}{4(2-r)}, & q_{n_NEV}^{S3} &= \frac{\phi - 2\Delta c + (r\beta_m + 2\beta_n)p_e}{2(2-r)}. \end{aligned}$$

Credit sharing dominated by the NEV automaker will cause the following changes in the equilibrium production quantities compared with the scenario of no credit sharing.

$$\begin{aligned} \Delta q_{m_NEV}^{S1} &= \frac{2\beta_m p_e}{4-r}, & \Delta q_{n_NEV}^{S1} &= -\frac{\beta_m p_e}{4-r}; \\ \Delta q_{m_NEV}^{S2} &= \frac{\beta_m p_e}{2-r}, & \Delta q_{n_NEV}^{S2} &= -\frac{\beta_m p_e}{2(2-r)}; \\ \Delta q_{m_NEV}^{S3} &= \frac{(4-r-r^2)\beta_m p_e}{4(2-r)}, & \Delta q_{n_NEV}^{S3} &= -\frac{(1-r)\beta_m p_e}{2(2-r)}. \end{aligned}$$

Regardless of the production strategy, credit sharing dominated by the NEV automaker will increase the production quantities of FVs and reduce the production quantities of NEVs. Interestingly, this conclusion is basically consistent with the scenario of credit sharing dominated by the FV automaker. Therefore, even if the NEV automaker dominates credit sharing, it is not conducive to the development of NEVs. In this scenario, NEV automakers share the credit costs of FV automakers, thereby increasing production costs in disguise.

Proposition 8. *For the three production strategies with credit sharing dominated by the NEV automaker, FVs and NEVs can coexist in the market only when the vehicle market size meets the following conditions:*

$$\begin{aligned} (1) \quad & \phi \geq \max\{\phi_{m_NEV}^{S1}, \phi_{n_NEV}^{S1}\}, \quad \phi_{m_NEV}^{S1} = \frac{r(-\Delta c + \beta_n p_e)}{2-r}, \quad \phi_{n_NEV}^{S1} = 2(\Delta c - \beta_n p_e); \\ (2) \quad & \phi \geq \max\{\phi_{m_NEV}^{S1}, \phi_{n_NEV}^{S1}\}, \quad \phi_{m_NEV}^{S2} = \frac{r(-\Delta c + \beta_n p_e)}{2-r}, \quad \phi_{n_NEV}^{S2} = -\frac{(4-r)(-\Delta c + \beta_n p_e)}{2-r}; \\ (3) \quad & \phi \geq \max\{\phi_{m_NEV}^{S1}, \phi_{n_NEV}^{S1}\}, \quad \phi_{m_NEV}^{S3} = \frac{r[-2\Delta c + (r\beta_m + 2\beta_n)p_e]}{4-3r}, \quad \phi_{n_NEV}^{S3} = 2\Delta c - (r\beta_m + 2\beta_n)p_e. \end{aligned}$$

Compared with the scenario without credit sharing, the critical market size of each production strategy under credit sharing dominated by the FV automaker has also changed. Obviously, regardless of the production strategy, credit sharing dominated by the NEV automaker reduces the critical market size of FVs and increases the critical market size of NEVs. This means that credit sharing makes the threshold for NEV automakers to survive in the vehicle market even higher.

$$\begin{aligned}\Delta\phi_{m_NEV}^{S1} &= -\frac{2\beta_m p_e}{2-r}; \Delta\phi_{n_NEV}^{S1} = \beta_m p_e; \\ \Delta\phi_{m_NEV}^{S2} &= -\frac{2\beta_m p_e}{2-r}; \Delta\phi_{n_NEV}^{S2} = \frac{2\beta_m p_e}{2-r}; \\ \Delta\phi_{m_NEV}^{S3} &= -\frac{(4-r-r^2)\beta_m p_e}{4-3r}; \Delta\phi_{n_NEV}^{S3} = (1-r)\beta_m p_e.\end{aligned}$$

Similarly, when $\phi_{m_NEV}^{S1} = \phi_{n_NEV}^{S1}$, $\phi_{m_NEV}^{S2} = \phi_{n_NEV}^{S2}$ and $\phi_{m_NEV}^{S3} = \phi_{n_NEV}^{S3}$, we can obtain the critical lines $p_{e_NEV}^{0-S1} = \frac{\Delta c}{\beta_n}$, $p_{e_NEV}^{0-S2} = \frac{\Delta c}{\beta_n}$, and $p_{e_NEV}^{0-S3} = \frac{2\Delta c}{r\beta_m + 2\beta_n}$, respectively, and $\leq p_{e_NEV}^{0-S3} \leq p_{e_NEV}^{0-S1}/p_{e_NEV}^{0-S2}$. The market size threshold for each production strategy with credit sharing dominated by the NEV automaker is summarized in Table 6. For example, when $0 \leq p_e < p_{e_NEV}^{0-S3}$, if $\phi \geq \phi_n^{S2}$, production strategies S1–S3 are all applicable; however, if $\phi_n^{S1} \leq \phi < \phi_n^{S2}$, NEVs will be expelled from the vehicle market under the FV priority production strategy (S2). Therefore, only production strategies S1 and S3 will be applicable under this condition. Again, if $\phi_n^{S3} \leq \phi < \phi_n^{S1}$, NEVs will be expelled from the vehicle market under the simultaneous production strategy (S1), and only production strategy S3 will be applicable under this condition. Then, if $\phi < \phi_n^{S3}$, the three production strategies will no longer be applicable, and the situation will degenerate into a monopoly setting with only FVs. Similar conclusions can be drawn for other intervals of p_e and ϕ .

Table 6. Market size for the existence of the three production strategies with credit sharing dominated by the NEV automaker.

Credit Price	Market Size	Production Strategies
$p_e \geq p_{e_NEV}^{0-S1}/p_{e_NEV}^{0-S2}$	$[\phi_m^{S3}, +\infty)$ $[\phi_m^{S1}/\phi_m^{S2}, \phi_m^{S3})$ $[0, \phi_m^{S1}/\phi_m^{S2})$	S1/S2/S3 S1/S2 Only NEVs
$p_{e_NEV}^{0-S3} \leq p_e < p_{e_NEV}^{0-S1}/p_{e_NEV}^{0-S2}$	$[\phi_n^{S2}, +\infty)$ $[\phi_n^{S1}, \phi_n^{S2})$ $[\phi_m^{S3}, \phi_n^{S1})$ $[0, \phi_m^{S3})$	S1/S2/S3 S1/S3 S3 Only FVs
$0 \leq p_e < p_{e_NEV}^{0-S3}$	$[\phi_n^{S2}, +\infty)$ $[\phi_n^{S1}, \phi_n^{S2})$ $[\phi_m^{S3}, \phi_n^{S1})$ $[0, \phi_n^{S3})$	S1/S2/S3 S1/S3 S3 Only FVs

Considering the effect of changes in credit prices and NEV production cost on production strategies with credit sharing dominated by the NEV automaker leads to the following proposition.

Proposition 9. For the three production strategies with credit sharing dominated by the NEV automaker, as shown in Figure 3,

(1) the applicable intervals of the three production strategies S1–S3 are $p_{e12} \leq p_e \leq p_{e11}$, $p_{e22} \leq p_e \leq p_{e21}$, and $p_{e32} \leq p_e \leq p_{e31}$, respectively; otherwise, FVs and NEVs will not coexist in the vehicle market;

(2) the optimal production strategy for each applicable interval is shown in Tables 7–9. For example, in interval A(I), the simultaneous production strategy (S1) will be the optimal strategy; in interval B₁(I), the NEV priority production strategy (S3) will be the optimal strategy; in

intervals $B_2(I)$ and $B_3(I)$ the simultaneous production strategy (S1) will be the optimal strategy; in interval $B_4(I)$, the FV priority production strategy (S2) will be the optimal strategy.

Table 7. Applicable interval and optimal production strategies under scenario I with credit sharing dominated by the NEV automaker.

Interval	S1	S2	S3	Profit Comparison
A	O	O		$\pi_z^{S1} > \pi_z^{S2}$
B_1	O	O	O	$\pi_z^{S3} > \pi_z^{S1} > \pi_z^{S2}$
B_2	O	O	O	$\pi_z^{S1} > \pi_z^{S3} > \pi_z^{S2}$
B_3	O	O	O	$\pi_z^{S1} > \pi_z^{S2} > \pi_z^{S3}$
B_4	O	O	O	$\pi_z^{S2} > \pi_z^{S1} > \pi_z^{S3}$

Table 8. Applicable interval and optimal production strategies under scenario II with credit sharing dominated by the NEV automaker.

Interval	S1	S2	S3	Profit Comparison
A	O	O		$\pi_z^{S1} > \pi_z^{S2}$
B_1	O	O	O	$\pi_z^{S3} > \pi_z^{S1} > \pi_z^{S2}$
B_2	O	O	O	$\pi_z^{S1} > \pi_z^{S3} > \pi_z^{S2}$
B_3	O	O	O	$\pi_z^{S1} > \pi_z^{S2} > \pi_z^{S3}$
B_4	O	O	O	$\pi_z^{S2} > \pi_z^{S1} > \pi_z^{S3}$
C	O		O	$\pi_z^{S1} > \pi_z^{S3}$

Table 9. Applicable interval and optimal production strategies under scenario III with credit sharing dominated by the NEV automaker.

Interval	S1	S2	S3	Profit Comparison
A	O	O		$\pi_z^{S1} > \pi_z^{S2}$
B_1	O	O	O	$\pi_z^{S3} > \pi_z^{S1} > \pi_z^{S2}$
B_2	O	O	O	$\pi_z^{S1} > \pi_z^{S3} > \pi_z^{S2}$
B_3	O	O	O	$\pi_z^{S1} > \pi_z^{S2} > \pi_z^{S3}$
B_4	O	O	O	$\pi_z^{S2} > \pi_z^{S1} > \pi_z^{S3}$
C	O		O	$\pi_z^{S1} > \pi_z^{S3}$
D			O	π_z^{S3}

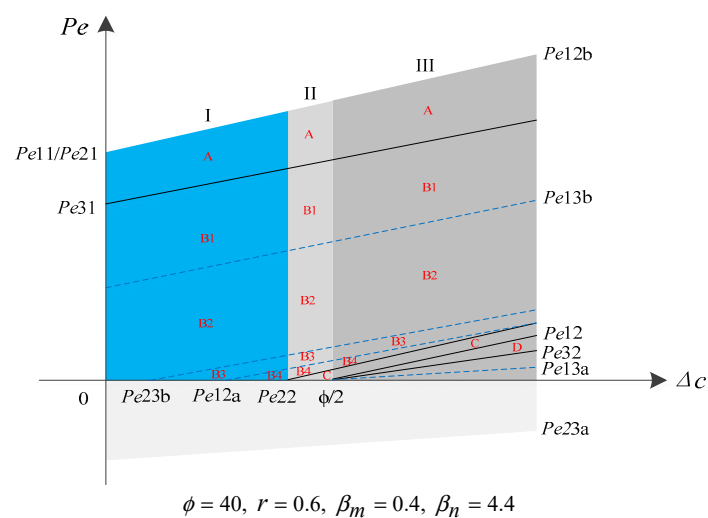


Figure 3. Optimal production strategies with credit sharing dominated by the NEV automaker.

Credit sharing dominated by the NEV automaker also has a significant impact on the applicable interval of both parties' production strategies and the selection of optimal strategies. Comparing Figures 1 and 3, we find that not only is the applicable interval extended on the horizontal axis but also all the critical lines have dropped. This means that in this scenario, all production strategies have lower requirements for the NEV production cost and credit price. In other words, it will be easier for both parties to coexist in the vehicle market. Similarly, the applicable interval in this scenario also becomes more complicated.

In interval I, the applicable interval of all production strategies can be subdivided into five intervals $A - B_4$. In interval A , the simultaneous production strategy (S1) and the FV priority production strategy (S2) will be applicable, and the production strategy S1 is the optimal production strategy. In interval B_1 , all three production strategies, S1–S3, are applicable, and the NEV priority production strategy will maximize both parties' total profits. When the credit price is relatively moderate, i.e., in intervals B_2 and B_3 , the simultaneous production strategy (S1) will be the optimal strategy. However, when the credit price is low, i.e., in interval B_4 , the FV priority production strategy becomes the optimal production strategy. Only in intervals B_1 and B_4 can the FV or NEV priority production strategy be adopted to realize the Pareto optimization of both parties' total profit.

Similarly, in intervals II and III, the applicable interval of all production strategies can be subdivided into six intervals $A - C$ and seven intervals $A - D$, respectively. In these intervals, the Pareto optimization of total profit can also be achieved by selecting one of the three production strategies.

For a relatively stable NEV production cost $\overline{\Delta c}$ in a certain period, we can also obtain the length of the three production strategies with credit sharing dominated by the NEV automaker as follows. Interestingly, in this scenario, the length of all production strategies is fixed and has nothing to do with NEV production cost.

$$L_{NEV}^{S1} = \frac{(4-r)\phi}{2r\beta_n}; L_{NEV}^{S2} = \frac{4(2-r)\phi}{(4-r)r\beta_n}; L_{NEV}^{S3} = \frac{2(2-r)\phi}{r(r\beta_m + 2\beta_n)}.$$

Lemma 11. *For the three production strategies with credit sharing dominated by the NEV automaker,*

(1) $L_{NEV}^{S1} > L_{NEV}^{S2} > L_{NEV}^{S3}$, i.e., the strategy length of the simultaneous production strategy (S1) is the longest, and the strategy length of the NEV priority production strategy (S3) is the shortest;

(2) when FV automakers try to reduce β_m , it has no impact on the strategy length of production strategies S1 and S2 but will extend the strategy length of production strategy S3; and when NEV automakers try to increase β_n , the strategy length of all production strategies will be shortened;

(3) as NEV substitutability r increases, the strategy length of all production strategies will decrease.

Lemma 11 implies that if NEV automakers have both the first-mover advantage and the credit-sharing advantage, it will not be conducive to the coexistence of both parties in the vehicle market. FV automakers can expand their coexistence room by actively reducing fuel consumption. However, the way to reduce fuel consumption does not apply to production strategies S1 and S2. Moreover, with the increase in the cruising range of NEVs, the living room of FVs in the vehicle market will be further occupied by NEVs, and FV automakers will lose part of their production decision-making power.

Similarly, we can also discuss the total credits of each production strategy with credit sharing dominated by the NEV automaker in the following lemma.

Lemma 12. *For the three production strategies with credit sharing dominated by the NEV automaker,*

(1) when $\Delta c > \phi/2$ and credit price is low ($p_e \leq p_{e_NEV}^M$), $V_{NEV}^{S1} > V_{NEV}^{S3} > V_{NEV}^{S2}$; when $\Delta c \leq \phi/2$, $V_{NEV}^{S3} > V_{NEV}^{S1} > V_{NEV}^{S2}$;

(2) the NEV priority production strategy (S3) most easily achieves credit equilibrium, and the FV priority production strategy (S2) has the greatest difficulty achieving credit equilibrium.

In the early stage of the implementation of the dual-credit policy, the credit price is relatively low, and the NEV production cost is relatively high. During this period, if NEV automakers dominate credit sharing, then adopting the simultaneous production strategy (S1) can maximize the two parties' total credits. However, with the rapid development of NEV technologies, once the NEV production cost is reduced to a certain extent, the NEV priority production strategy will be most conducive to maximizing both parties' total credits. Moreover, regardless of which party dominates credit sharing, production strategy S3 is the production strategy that most easily achieves credit equilibrium. This is a revelation for FV automakers that have a large demand for positive NEV credits.

6. Comparative Analysis

In this section, we examine the optimal credit-sharing strategies from the perspectives of production quantities, strategy length, total profit, and total credits. Lemmas 13–16 summarize the comparison results of the three credit sharing strategies: no credit sharing, credit sharing dominated by the FV automaker and credit sharing dominated by the NEV automaker.

Lemma 13. For the three credit-sharing strategies,

- (1) if both parties adopt the simultaneous production strategy (S1), then $q_{m_FV}^{S1} > q_{m_NEV}^{S1} > q_n^{S1}$, $q_n^{S1} > q_{n_NEV}^{S1} > q_{n_FV}^{S1}$;
- (2) if both parties adopt the FV priority production strategy (S2), then $q_{m_NEV}^{S2} > q_m^{S2} > q_{m_FV}^{S2}$, $q_n^{S2} > q_{n_NEV}^{S2} > q_{n_FV}^{S2}$;
- (3) if both parties adopt the NEV priority production strategy (S3), then $q_{m_FV}^{S3} > q_{m_NEV}^{S3} > q_m^{S3}$, $q_n^{S3} > q_{n_NEV}^{S3} > q_{n_FV}^{S3}$.

Lemma 13 implies that under production strategies S1 and S3, the FV automaker will tend to adopt the credit-sharing strategy dominated by the FV automaker to maintain the competitive advantage of FVs in the vehicle market. However, under the FV priority production strategy S2, credit sharing dominated by the NEV automaker is more conducive to maintaining the competitive advantage of FVs in the vehicle market. This is why many FV automakers are actively acquiring NEV automakers and allowing them to bear the credit cost. Counterintuitively, regardless of the production strategy, no credit sharing is the optimal strategy for maintaining the competitive advantage of NEVs. Therefore, NEV automakers often lack incentives to share credits. This has led cooperating FV automakers to provide other compensation measures, such as vehicle manufacturing technologies and brand sharing.

Lemma 14. For the three credit-sharing strategies, $L_{FV}^{S1} > L_{NEV}^{S1} > L^{S1}$, $L_{NFV}^{S2} > L^{S2} > L_{FV}^{S2}$, and $L_{FV}^{S3} > L_{NEV}^{S3} > L^{S3}$.

Lemma 14 implies that if both parties adopt the simultaneous production strategy (S1), then credit sharing dominated by the FV automaker will be the most conducive to their coexistence in the vehicle market. If they adopt the FV priority production strategy (S2), then credit sharing dominated by the NEV automaker will be the optimal strategy from the perspective of strategy length, while credit sharing dominated by the FV automaker will be the optimal strategy under the NEV priority production strategy (S3). Therefore, credit-sharing strategies and production strategy prioritization have counteracting effects on the competitive advantages of the two parties. One party gives priority to production, and the other party dominates credit sharing, which will help balance their competitive advantages.

Lemma 15. For the three credit-sharing strategies, when $p_e \in [0, p_{e1})$, $\pi_{z_FV} > \pi_{z_NEV} > \pi_z$; when $p_e \in [p_{e1}, p_{e2})$, $\pi_{z_FV} > \pi_z > \pi_{z_NEV}$; when $p_e \in [p_{e2}, p_{e3})$, $\pi_z > \pi_{z_FV} > \pi_{z_NEV}$; and when $p_e \in [p_{e3}, +\infty)$, $\pi_z > \pi_{z_NEV} > \pi_{z_FV}$, as shown in Figure 4.

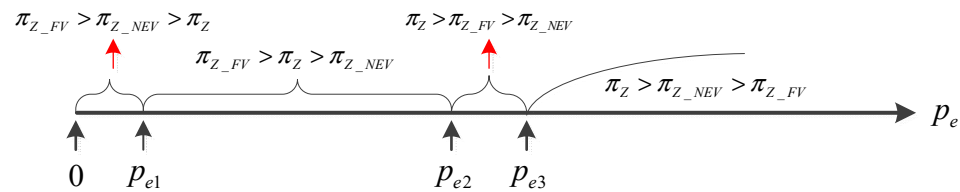


Figure 4. Profit comparison with the three credit sharing strategies.

Lemma 15 implies that when the credit price is relatively low, credit sharing dominated by the FV automaker can maximize the two parties' total profit. This scenario is often applicable to the immature stage of the credit market. Therefore, in the early stage of the implementation of the dual-credit policy, cooperation such as that of GWM and Yogomo is conducive to maximizing social welfare. However, as the credit price increases, no credit sharing is most conducive to maximizing both parties' total profit. It is interesting that regardless of whether the credit price is high or low, credit sharing dominated by the NEV automaker is not conducive to the improvement of both parties' total profits. Therefore, current cooperation, such as that of BYD, Toyota, BAIC Shenbao (X35), and BAIC BJEV (EU260), has actually reduced the efficiency of the dual-credit policy. With the advancement of NEV technologies, such cooperation should gradually switch to production cooperation that independently bears credit costs and credit benefits.

Lemma 16. For the three credit-sharing strategies, $V^{S1} > V_{NEV}^{S1} > V_{FV}^{S1}$, $V^{S2} > V_{NEV}^{S2} > V_{FV}^{S2}$, and $V^{S3} > V_{NEV}^{S3} > V_{FV}^{S3}$.

Lemma 16 implies that regardless of the production strategy, the total credits without credit sharing are the largest, and both parties can obtain the most positive NEV credits. However, the total credits of both parties are always the smallest, with credit sharing dominated by the FV automaker. In fact, no matter what the credit-sharing strategy is, credit sharing will help to reduce the risk of both parties' credit disruption. The current credit market in China is in its infancy and is not yet mature. The credit price is low and fluctuates greatly. At the same time, credit trading is not very convenient. FV automakers such as GWM cannot successfully purchase enough positive NEV credits, while BAIC BJEV cannot sell all its positive NEV credits in time. Therefore, credit sharing can determine both parties' credit demand and credit price in advance, reducing dependence on the credit market.

7. Conclusions

The dual-credit policy is a new and unique industrial policy in China that will have a profound impact on the energy savings of FVs and the development of NEVs. To obtain sufficient positive NEV credits, many FV automakers cooperate with NEV automakers, including technology sharing, brand sharing, and even credit sharing. Therefore, the preferences of the two parties for cooperation in the vehicle market and credit market are intriguing issues that have been underexplored in the literature. This study considers three production strategies and credit-sharing strategies between cooperative FV automakers and NEV automakers and shows that the optimal strategies for both parties depend on the circumstances. Whether the two parties choose the simultaneous production strategy (S1), the FV priority production strategy (S2), or the NEV priority production strategy (S3) depends on multiple factors, including market size, credit price, production cost, and NEV substitutability. Whether to share credits and which party dominates credit sharing will affect the selection of the optimal strategies for both parties.

This study first investigated the impact of the dual-credit policy on both parties' production strategies without credit sharing. A high credit price and low production cost often help NEV automakers obtain a competitive advantage. For FV automakers, reducing fuel consumption is an important way to maintain a competitive advantage under the dual-credit policy. NEV manufacturers can also increase their competitive advantage by increasing the NEV cruising range and substitutability. However, such an approach is far inferior to the advantages that FV automakers can obtain through energy savings. Moreover, under certain conditions, such as the FV priority production strategy with a low credit price, it is counterproductive. Therefore, a high credit price is sometimes more important for the development of NEVs than the NEV cruising range and substitutability under the dual-credit policy.

In addition, we examined the coexistence conditions of FVs and NEVs under the dual-credit policy and found that they are closely related to vehicle market size, credit price and production cost. In fact, although both parties have first-mover advantages, production prioritization strategies often fail to optimize their total profits. Only when the credit price and NEV production cost are in certain applicable intervals can the FV or NEV priority production strategy achieve the Pareto optimization of the parties' total profits. However, in most cases, the simultaneous production strategy, not the production prioritization strategy, is optimal. Moreover, a critical line that determines both parties' competitive advantages is proposed to provide guidance for cooperation and competition between FV automakers and NEV automakers. Finally, we also found that the simultaneous production strategy is most conducive to the coexistence of both parties in the vehicle market. However, for positive NEV credits, the NEV priority production strategy can help them reach credit equilibrium as soon as possible. This has great enlightenment significance for large credit demanders such as GWM.

This study also further explored the optimal production strategy for the two parties in the scenario of credit sharing dominated by the FV automaker and the NEV automaker. There is no doubt that credit sharing has an important impact on both parties' applicable interval, optimal strategy selection and credit equilibrium. The coexistence conditions and optimal strategies of the two parties in the vehicle market with credit sharing are far more complicated than those without credit sharing. Generally, the party that dominates credit sharing will increase the production of FVs while reducing the production of NEVs. However, it is counterintuitive that under the FV priority production strategy (S2), the production of FVs does not increase but rather declines. This is precisely the current production strategy adopted by the Chinese vehicle industry. Although the relationship between production quantity, credit price, and production cost holds in the scenario of credit sharing, the relationship between production quantity and the FV/NEV credit coefficient and NEV substitutability changes and even becomes irrelevant or reversed. These conclusions provide guidance for automakers on how to effectively invest in energy savings and NEV cruising range to improve cooperation efficiency. In addition, we conducted a comparative analysis of all the strategies proposed in this study from the perspectives of production quantities, strategy length, total profit, and total credits. We found that maintaining competition between the two parties and letting FV automakers dominate credit sharing is the optimal strategy in most cases. In addition, it is often an undesirable strategy for NEV automakers to dominate credit sharing.

Furthermore, automakers such as Great Wall Motors, which mainly produce FVs, are facing a large gap in NEV credits. If they fail to speed up the production of NEVs or obtain sufficient NEV credits by investing in NEV automakers such as Hebei Yujie, they will face severe punishment from the government. However, this study proves that it is not the optimal strategy for automakers like Great Wall Motors to prioritize the production of NEVs. Instead, they should allow the original FV brands and Hebei Yujie's NEVs to maintain relative independence and internal competition and adopt a synchronous production strategy to improve the efficiency of credit utilization. For large NEV automakers such as BAIC, BYD, and Tesla, surplus NEV credits are one of the biggest

challenges they face. Credit income is one of the most important sources of income for these automakers. Therefore, reducing the risk of credit sales through credit cooperation with FV automakers is an important part of their production planning. For these automakers, adopting a FV production priority strategy or a synchronous production strategy is more conducive to improving the efficiency of credit utilization because this can not only increase the market demand and price of NEV credits but also promote the advancement of FV energy-saving technology.

This study provides a new angle from which to view the relationship between FV automakers and NEV automakers under the dual-credit policy. Similar to many other studies using modeling approaches, we made several assumptions. However, coopetition activities are highly complex in practice. Thus, if we relax these assumptions, we can identify directions for future research. For instance, the Cournot model is adopted in this research because it is widely used and has the advantage of being analytically more tractable. Nevertheless, FVs and NEVs may not fully share a vehicle market, and price decisions are sometimes more important to consumers than production decisions. Some consumers insist on buying FVs, while others must buy NEVs (for example, in cities such as Beijing, where they are restricted from purchasing FVs). Thus, a Bertrand pricing model with the potential markets for FVs and NEVs must be considered. In addition, the costs of energy saving and NEV cruising range improvements are also key factors that determine both parties' credit coefficient and competitive advantage. Furthermore, this research assumed that FVs are regarded as superior to NEVs for vehicle consumers. In reality, this assumption does not always hold true. An increasing number of NEVs, such as the BAIC BJEV and Tesla, have become more attractive than similar types of FVs. It would be interesting for future research to consider a richer model that includes these additional factors.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Proofs

Proof of Lemma 1.

$$\begin{aligned} q_m^{S2} - q_m^{S1} &= \frac{r[(2-r)\phi + r\Delta c - (2\beta_m + r\beta_n)p_e]}{2(4-r)(2-r)} > 0, \quad q_m^{S1} - q_m^{S3} = \frac{r^2[\phi - 2\Delta c + (\beta_m + 2\beta_n)p_e]}{4(4-r)(2-r)} > 0; \\ q_n^{S3} - q_n^{S1} &= \frac{r[\phi - 2\Delta c + (\beta_m + 2\beta_n)p_e]}{2(4-r)(2-r)} > 0, \quad q_n^{S1} - q_n^{S2} = \frac{r[(2-r)\phi + r\Delta c - (2\beta_m + r\beta_n)p_e]}{4(4-r)(2-r)} > 0. \\ \text{Thus, } q_m^{S2} &> q_m^{S1} > q_m^{S3}, \quad q_n^{S3} > q_n^{S1} > q_n^{S2}. \end{aligned}$$

This Lemma is proven. $\square$

Proof of Lemma 2.

(1) $\frac{\partial q_m^{S1}}{\partial \beta_m} = -\frac{2p_e}{4-r}, \frac{\partial q_m^{S2}}{\partial \beta_m} = -\frac{p_e}{2-r}, \frac{\partial q_m^{S3}}{\partial \beta_m} = -\frac{(4-r)p_e}{4(2-r)}, \frac{\partial q_m^{S1}}{\partial \beta_n} = -\frac{rp_e}{4-r}, \frac{\partial q_m^{S2}}{\partial \beta_n} = -\frac{rp_e}{2(2-r)}, \frac{\partial q_m^{S3}}{\partial \beta_n} = -\frac{rp_e}{2(2-r)}$. It is easy to find that the first derivative of q_m for all production strategies S1–S3 with respect to β_m, β_n is negative.

$\frac{\partial q_n^{S1}}{\partial \beta_m} = \frac{p_e}{4-r}, \frac{\partial q_n^{S2}}{\partial \beta_m} = \frac{p_e}{2(2-r)}, \frac{\partial q_n^{S3}}{\partial \beta_m} = \frac{p_e}{2(2-r)}, \frac{\partial q_n^{S1}}{\partial \beta_n} = \frac{2p_e}{4-r}, \frac{\partial q_n^{S2}}{\partial \beta_n} = \frac{(4-r)p_e}{4(2-r)}, \frac{\partial q_n^{S3}}{\partial \beta_n} = \frac{p_e}{2-r}$. It is easy to find that the first derivative of q_n for all production strategies S1–S3 with respect to β_m, β_n is positive.

(2) Assume that the β_m is reduced by $-\Delta\beta$ and β_n is increased by $\Delta\beta, \Delta\beta \geq 0$. We can calculate the change in FV production quantities and NEV production quantities by the

change in credit coefficient, which are $\Delta q_{n-\beta_m}$, $\Delta q_{n-\beta_n}$, respectively. The difference in the change in NEV production is $\Delta q_{n-\beta_m}^{S1} - \Delta q_{n-\beta_n}^{S1} = \frac{(1-r)p_e}{4-r} \Delta\beta > 0$, $\Delta q_{n-\beta_m}^{S2} - \Delta q_{n-\beta_n}^{S2} = \frac{p_e}{4} \Delta\beta > 0$, $\Delta q_{n-\beta_m}^{S3} - \Delta q_{n-\beta_n}^{S3} = \frac{(2-3r)p_e}{4(2-r)} \Delta\beta > 0$. Obviously, they are all positive.

This Lemma is proven. $\square$

Proof of Lemma 3.

$$(1) \quad \frac{\partial q_m^{S1}}{\partial r} = -\frac{2[\phi-2\Delta c+(\beta_m+2\beta_n)p_e]}{(4-r)^2} < 0, \quad \frac{\partial q_m^{S3}}{\partial r} = -\frac{\phi-2\Delta c+(\beta_m+2\beta_n)p_e}{2(2-r)^2} < 0;$$

$$\frac{\partial q_n^{S1}}{\partial r} = \frac{\phi-2\Delta c+(\beta_m+2\beta_n)p_e}{(4-r)^2} > 0, \quad \frac{\partial q_n^{S3}}{\partial r} = \frac{\phi-2\Delta c+(\beta_m+2\beta_n)p_e}{2(2-r)^2} > 0.$$

$$(2) \quad \frac{\partial q_m^{S2}}{\partial r} = \frac{\Delta c-(\beta_m+\beta_n)p_e}{(2-r)^2}, \quad \frac{\partial q_n^{S2}}{\partial r} = -\frac{\Delta c-(\beta_m+\beta_n)p_e}{(2-r)^2}; \text{ Let } p_{e0} = \frac{\Delta c}{\beta_m+\beta_n}, \text{ Thus, when } p_e \geq p_{e0},$$

$$\frac{\partial q_m^{S2}}{\partial r} < 0, \quad \frac{\partial q_n^{S2}}{\partial r} > 0; \text{ when } 0 \leq p_e < p_{e0}, \quad \frac{\partial q_m^{S2}}{\partial r} > 0, \quad \frac{\partial q_n^{S2}}{\partial r} < 0.$$

This Lemma is proven. $\square$

Proof of Proposition 3.

According to the conditions that $q_m > 0$, $q_n > 0$, the following critical lines about p_e can be obtained.

$$p_{e11} = \frac{r\Delta c+(2-r)\phi}{2\beta_m+r\beta_n}, \quad p_{e12} = \frac{2\Delta c-\phi}{\beta_m+2\beta_n};$$

$$p_{e21} = \frac{r\Delta c+(2-r)\phi}{2\beta_m+r\beta_n}, \quad p_{e22} = \frac{(4-r)\Delta c-(2-r)\phi}{2\beta_m+(4-r)\beta_n};$$

$$p_{e31} = \frac{2r\Delta c+(4-3r)\phi}{(4-r)\beta_m+2r\beta_n}, \quad p_{e32} = \frac{2\Delta c-\phi}{\beta_m+2\beta_n}.$$

When $\Delta c \leq \frac{\beta_m+\beta_n}{\beta_m}\phi$, then $p_{e11} - p_{e31} = \frac{r^2[(\beta_m+\beta_n)\phi-\beta_m\Delta c]}{(2\beta_m+r\beta_n)[(4-r)\beta_m+2r\beta_n]} > 0$, $p_{e31} - p_{e22} = \frac{[16-r(12-r)][(\beta_m+\beta_n)\phi-\beta_m\Delta c]}{(2\beta_m+(4-r)\beta_n)[(4-r)\beta_m+2r\beta_n]} > 0$, $p_{e22} - p_{e12} = \frac{r[(\beta_m+\beta_n)\phi-\beta_m\Delta c]}{(\beta_m+2\beta_n)[2\beta_m+(4-r)\beta_n]} > 0$. Thus $p_{e11}/p_{e21} > p_{e31} > p_{e22} > p_{e12}/p_{e32}$.

p_{e12a} , p_{e12b} , p_{e13a} , p_{e13b} , p_{e23a} , and p_{e24b} are the critical lines of the total profit of production strategies S1–S3, respectively. When $p_{e12a} \leq p_e \leq p_{e12b}$, then $\pi_z^{S1} \geq \pi_z^{S2}$, otherwise, $\pi_z^{S1} < \pi_z^{S2}$. When $p_{e13a} \leq p_e \leq p_{e13b}$, then $\pi_z^{S1} \geq \pi_z^{S3}$, otherwise, $\pi_z^{S1} < \pi_z^{S3}$. When $p_{e23a} \leq p_e \leq p_{e23b}$, then $\pi_z^{S3} \geq \pi_z^{S2}$, otherwise, $\pi_z^{S3} < \pi_z^{S2}$.

This proposition is proven. $\square$

Proof of Lemma 4.

$$(1) \quad L^{S1} - L^{S2} = \frac{r[(\beta_m+\beta_n)\phi-\beta_m\Delta c]}{(\beta_m+2\beta_n)[2\beta_m+(4-r)\beta_n]} > 0, \quad L^{S2} - L^{S3} = \frac{4r(2-r)(r\beta_m^2-\beta_m^2)[(\beta_m+\beta_n)\phi-\beta_m\Delta c]}{(\beta_m+2\beta_n)(2\beta_m+r\beta_n)[2\beta_m+(4-r)\beta_n][(4-r)\beta_m+2r\beta_n]} > 0, \text{ Thus } L^{S1} > L^{S2} > L^{S3}.$$

$$(2) \text{ It is easy to prove that, } \frac{\partial L^{S1}}{\partial \beta_m} < 0, \frac{\partial L^{S2}}{\partial \beta_m} < 0, \frac{\partial L^{S3}}{\partial \beta_m} < 0; \frac{\partial L^{S1}}{\partial \beta_n} < 0, \frac{\partial L^{S2}}{\partial \beta_n} < 0, \frac{\partial L^{S3}}{\partial \beta_n} < 0;$$

$$\frac{\partial L^{S1}}{\partial r} < 0, \frac{\partial L^{S2}}{\partial r} < 0, \frac{\partial L^{S3}}{\partial r} < 0.$$

This Lemma is proven. $\square$

Proof of Lemma 5.

$$V^{S3} - V^{S1} = \frac{r(r\beta_m+2\beta_n)[\phi-2\Delta c+(\beta_m+2\beta_n)p_e]}{4(4-r)(2-r)}, \quad V^{S1} - V^{S2} = \frac{r(2\beta_m+\beta_n)[(2-r)\phi+r\Delta c-(2\beta_m+r\beta_n)p_e]}{4(4-r)(2-r)};$$

thus, $V^{S3} > V^{S1} > V^{S2}$.

This Lemma is proven. $\square$

Proof of Lemma 6.

$$\frac{\partial q_m^{S1}}{\partial p_e} = -\frac{2\beta_m}{4-r} < 0, \quad \frac{\partial q_m^{S2}}{\partial p_e} = -\frac{2\beta_m+\beta_n}{2(2-r)} < 0, \quad \frac{\partial q_m^{S3}}{\partial p_e} = -\frac{(4-r)\beta_m}{4(2-r)} < 0;$$

$$\frac{\partial q_m^{S1}}{\partial \Delta c} = \frac{r}{4-r} > 0, \quad \frac{\partial q_m^{S2}}{\partial \Delta c} = \frac{r}{2(2-r)} > 0, \quad \frac{\partial q_m^{S3}}{\partial \Delta c} = \frac{r}{2(2-r)} > 0;$$

$$\frac{\partial q_n^{S1}}{\partial p_e} = \frac{\beta_m}{4-r} > 0, \quad \frac{\partial q_n^{S2}}{\partial p_e} = \frac{2\beta_m+\beta_n}{4(2-r)} > 0, \quad \frac{\partial q_n^{S3}}{\partial p_e} = \frac{\beta_m}{2(2-r)} > 0;$$

$$\frac{\partial q_n^{S1}}{\partial \Delta c} = -\frac{2}{4-r} < 0, \quad \frac{\partial q_n^{S2}}{\partial \Delta c} = -\frac{4-r}{4(2-r)} < 0, \quad \frac{\partial q_n^{S3}}{\partial \Delta c} = -\frac{1}{2-r} < 0.$$

This Lemma is proven. $\square$

Proof of Lemma 7.

$$\begin{aligned}\frac{\partial q_{m_FV}^{S1}}{\partial \beta_m} &= -\frac{2p_e}{4-r} < 0, \quad \frac{\partial q_{m_FV}^{S2}}{\partial \beta_m} = -\frac{p_e}{2-r} < 0, \quad \frac{\partial q_{m_FV}^{S3}}{\partial \beta_m} = -\frac{(4-r)p_e}{4(2-r)} < 0; \\ \frac{\partial q_{n_FV}^{S1}}{\partial \beta_n} &= \frac{p_e}{4-r} > 0, \quad \frac{\partial q_{n_FV}^{S2}}{\partial \beta_n} = \frac{p_e}{2(2-r)} > 0, \quad \frac{\partial q_{n_FV}^{S3}}{\partial \beta_n} = \frac{p_e}{2(2-r)} > 0; \\ \frac{\partial q_{m_FV}^{S2}}{\partial \beta_n} &= -\frac{2p_e}{2(2-r)} < 0, \quad \frac{\partial q_{n_FV}^{S2}}{\partial \beta_n} = \frac{2p_e}{4(2-r)} > 0.\end{aligned}$$

This Lemma is proven. $\square$

Proof of Lemma 8.

$$\begin{aligned}(1) \quad \frac{\partial q_{m_FV}^{S1}}{\partial r} &= -\frac{2(\phi-2\Delta c+\beta_m p_e)}{(4-r)^2} < 0, \quad \frac{\partial q_{m_FV}^{S3}}{\partial r} = -\frac{\phi-2\Delta c+\beta_m p_e}{2(2-r)^2} < 0; \quad \frac{\partial q_{n_FV}^{S1}}{\partial r} = \frac{\phi-2\Delta c+\beta_m p_e}{(4-r)^2} > 0, \\ \frac{\partial q_{n_FV}^{S3}}{\partial r} &= \frac{\phi-2\Delta c+\beta_m p_e}{2(2-r)^2} > 0. \\ (2) \quad \frac{\partial q_{m_FV}^{S2}}{\partial r} &= \frac{2\Delta c-(2\beta_m+\beta_n)p_e}{2(2-r)^2}, \quad \frac{\partial q_{n_FV}^{S2}}{\partial r} = \frac{-2\Delta c+(2\beta_m+\beta_n)p_e}{4(2-r)^2}. \quad \text{When } p_e > \frac{2\Delta c}{2\beta_m+\beta_n}, \text{ then} \\ \frac{\partial q_{m_FV}^{S2}}{\partial r} &< 0, \quad \frac{\partial q_{n_FV}^{S2}}{\partial r} > 0; \text{ otherwise, } \frac{\partial q_{m_FV}^{S2}}{\partial r} > 0, \quad \frac{\partial q_{n_FV}^{S2}}{\partial r} < 0.\end{aligned}$$

This Lemma is proven. $\square$

Proof of Lemma 9.

$$\begin{aligned}(1) \quad L_{-FV}^{S1} - L_{-FV}^{S3} &= \frac{r^2(\phi-\Delta c)}{2(4-r)\beta_m} > 0, \quad L_{-FV}^{S3} - L_{-FV}^{S2} = \frac{2(2-r)(r\beta_m+2\beta_n)(\phi-\Delta c)}{\beta_m(4-r)(2\beta_m+\beta_n)} > 0, \text{ Thus,} \\ L_{-FV}^{S1} &> L_{-FV}^{S3} > L_{-FV}^{S2}. \\ (2) \quad \frac{\partial L_{-FV}^{S1}}{\partial \beta_m} &= -\frac{(4-r)(\phi-\Delta c)}{2\beta_m^2} < 0, \quad \frac{\partial L_{-FV}^{S2}}{\partial \beta_m} = -\frac{4(2-r)(\phi-\Delta c)}{(2\beta_m+\beta_n)^2} < 0, \quad \frac{\partial L_{-FV}^{S3}}{\partial \beta_m} = -\frac{4(2-r)(\phi-\Delta c)}{(4-r)\beta_m^2} < 0; \\ \frac{\partial L_{-FV}^{S2}}{\partial \beta_n} &= -\frac{2(2-r)(\phi-\Delta c)}{(2\beta_m+\beta_n)^2} < 0. \\ (3) \quad \frac{\partial L_{-FV}^{S1}}{\partial r} &= -\frac{\phi-\Delta c}{2\beta_m} < 0, \quad \frac{\partial L_{-FV}^{S2}}{\partial r} = -\frac{2(\phi-\Delta c)}{2\beta_m+\beta_n} < 0, \quad \frac{\partial L_{-FV}^{S3}}{\partial r} = -\frac{8(\phi-\Delta c)}{(4-r)^2\beta_m} < 0.\end{aligned}$$

This Lemma is proven. $\square$

Proof of Lemma 10.

Let $V_{FV}^{S1} = V_{FV}^{S2}$, $V_{FV}^{S1} = V_{FV}^{S3}$, $V_{FV}^{S2} = V_{FV}^{S3}$, we can obtain the critical lines that $p_{e_FV}^M = \frac{r[(2-r)\phi+r\Delta c]}{2r\beta_m+(4-r)\beta_n}$, $p_{e11}/p_{e32} = \frac{2\Delta c-\phi}{\beta_m}$, and $p_{e_FV}^H = \frac{r[(\beta_m+\beta_n)\phi-\beta_n\Delta c]}{r\beta_m+\beta_n(2\beta_m+\beta_n)}$, respectively. Additionally, $p_{e_FV}^H > p_{e_FV}^M > p_{e11}/p_{e32}$. Considering the applicable interval, we can obtain the conclusions as shown in the lemma. This Lemma is proven. $\square$

Proof of Lemma 11.

$$\begin{aligned}(1) \quad L_{-NEV}^{S1} - L_{-NEV}^{S2} &= \frac{r\phi}{2(4-r)\beta_n} > 0, \quad L_{-NEV}^{S2} - L_{-NEV}^{S3} = \frac{2(2-r)(2\beta_m+\beta_n)\phi}{\beta_n(4-r)(r\beta_m+2\beta_n)} > 0, \text{ Thus,} \\ L_{-NEV}^{S1} &> L_{-NEV}^{S2} > L_{-NEV}^{S3}. \\ (2) \quad \frac{\partial L_{-NEV}^{S3}}{\partial \beta_m} &= -\frac{2(2-r)\phi}{(r\beta_m+2\beta_n)^2} < 0; \quad \frac{\partial L_{-NEV}^{S1}}{\partial \beta_n} = -\frac{(4-r)\phi}{2r\beta_n^2} < 0, \quad \frac{\partial L_{-NEV}^{S2}}{\partial \beta_n} = -\frac{4(2-r)\phi}{r(4-r)\beta_n^2} < 0, \\ \frac{\partial L_{-NEV}^{S3}}{\partial \beta_n} &= -\frac{4(2-r)\phi}{r(r\beta_m+2\beta_n)^2} < 0. \\ (3) \quad \frac{\partial L_{-NEV}^{S1}}{\partial r} &= -\frac{2\phi}{r^2\beta_n} < 0, \quad \frac{\partial L_{-NEV}^{S2}}{\partial r} = -\frac{4[8-r(4-r)]\phi}{r^2(4-r)^2\beta_n} < 0, \quad \frac{\partial L_{-NEV}^{S3}}{\partial r} = -\frac{2[r(4-r)\beta_m+4\beta_n]\phi}{r^2(r\beta_m+2\beta_n)^2} < 0.\end{aligned}$$

This Lemma is proven. $\square$

Proof of Lemma 12.

Let $V_{NEV}^{S1} = V_{NEV}^{S2}$, $V_{NEV}^{S1} = V_{NEV}^{S3}$, $V_{NEV}^{S2} = V_{NEV}^{S3}$, we can obtain the critical lines that, $p_{e11} = \frac{(2-r)\phi+r\Delta c}{r\beta_n}$, $p_{e_NEV}^M = \frac{-\phi+2\Delta c}{(4-r)\beta_m+2\beta_n}$, $p_{e_NEV}^L = \frac{-(\beta_m+\beta_n)\phi+\beta_n\Delta c}{r\beta_m+\beta_n(2\beta_m+\beta_n)}$, respectively. Additionally, $p_{e11} > p_{e_NEV}^M > p_{e_NEV}^L$. Considering the applicable interval, we can obtain the conclusions as shown in the lemma. This Lemma is proven. $\square$

Proof of Lemma 13.

$$(1) q_{m_FV}^{S1} - q_{m_NEV}^{S1} = \frac{(r\beta_n - 2\beta_m)p_e}{4-r} > 0, q_{m_NEV}^{S1} - q_m^{S1} = \frac{2\beta_m p_e}{4-r} > 0; q_n^{S1} - q_{n_NEV}^{S1} = \frac{\beta_m p_e}{4-r}, q_{n_NEV}^{S1} - q_{n_FV}^{S1} = \frac{(2\beta_n - \beta_m)p_e}{4-r} > 0. \text{ Thus, } q_{m_FV}^{S1} > q_{m_NEV}^{S1} > q_m^{S1}, q_n^{S1} > q_{n_NEV}^{S1} > q_{n_FV}^{S1}.$$

$$(2) q_{m_NEV}^{S2} - q_m^{S2} = \frac{\beta_m p_e}{2-r} > 0, q_m^{S2} - q_{m_FV}^{S2} = \frac{(1-r)\beta_n p_e}{2(2-r)} > 0; q_n^{S2} - q_{n_NEV}^{S2} = \frac{\beta_m p_e}{2(2-r)}, q_{n_NEV}^{S2} - q_{n_FV}^{S2} = \frac{[(3-r)\beta_n - 2\beta_m]p_e}{4(2-r)} > 0. \text{ Thus, } q_{m_NEV}^{S2} > q_m^{S2} > q_{m_FV}^{S2}, q_n^{S2} > q_{n_NEV}^{S2} > q_{n_FV}^{S2}.$$

$$(3) q_{m_FV}^{S3} - q_{m_NEV}^{S3} = \frac{[2r\beta_n - (4-r-r^2)\beta_m]p_e}{4(2-r)} > 0, q_{m_NEV}^{S3} - q_m^{S3} = \frac{(4-r-r^2)\beta_m p_e}{4(2-r)} > 0; q_n^{S3} - q_{n_NEV}^{S3} = \frac{(1-r)\beta_m p_e}{2(2-r)}, q_{n_NEV}^{S3} - q_{n_FV}^{S3} = \frac{[2\beta_n - (1-r)\beta_m]p_e}{2(2-r)} > 0. \text{ Thus, } q_{m_FV}^{S3} > q_{m_NEV}^{S3} > q_m^{S3}, q_n^{S3} > q_{n_NEV}^{S3} > q_{n_FV}^{S3}.$$

This Lemma is proven. $\square$

Proof of Lemma 14.

$$L_{FV}^{S1} - L_{NEV}^{S1} = \frac{(4-r)[(r\beta_n - \beta_m)\phi - r\beta_n \Delta c]}{2r\beta_m \beta_n} > 0, L_{NEV}^{S1} - L^{S1} = \frac{(4-r)\beta_m[(4-r)\beta_n + 2\beta_m]\phi + 2r\beta_n \Delta c}{2r\beta_n(\beta_m + 2\beta_n)(2\beta_m + r\beta_n)} > 0, \text{ thus } L_{FV}^{S1} > L_{NEV}^{S1} > L^{S1}. \text{ Similarly, we can prove that if } L_{NFV}^{S2} - L^{S2} > 0, L^{S2} - L_{FV}^{S2} > 0, \text{ then } L_{NFV}^{S2} > L^{S2} > L_{FV}^{S2}; \text{ if } L_{FV}^{S3} - L_{NEV}^{S3} > 0, L_{NEV}^{S3} - L^{S3} > 0, \text{ then } L_{FV}^{S3} > L_{NEV}^{S3} > L^{S3}.$$

This Lemma is proven. $\square$

Proof of Lemma 15.

p_{e1} , p_{e2} , and p_{e3} are the critical lines of π_z , π_{z_FV} , and π_{z_NEV} , respectively. Additionally, $0 \leq p_{e1} < p_{e2} < p_{e3}$. For example, when $p_e > p_{e2} = \frac{r[(4-3r)\phi + 2r\Delta c]}{r(4-r)\beta_m + [4-(2-r)r]\beta_n}$, then $\pi_z > \pi_{z_FV}$; otherwise, $\pi_z \leq \pi_{z_FV}$. When $p_e > p_{e1}$, then $\pi_z > \pi_{z_NEV}$; otherwise, $\pi_z \leq \pi_{z_NEV}$. When $p_e > p_{e3}$, then $\pi_{z_NEV} > \pi_{z_FV}$; otherwise, $\pi_{z_NEV} < \pi_{z_FV}$. Therefore, we can obtain the conclusions in the lemma according to their relative position.

This Lemma is proven. $\square$

Proof of Lemma 16.

$$V^{S1} - V_{NEV}^{S1} = \frac{\beta_m(2\beta_m + \beta_n)p_e}{4-r} > 0, V_{NEV}^{S1} - V_{FV}^{S1} = \frac{[2\beta_n^2 - (1-r)\beta_m\beta_n - 2\beta_m^2]p_e}{4-r} > 0; V^{S2} - V_{NEV}^{S2} = \frac{\beta_m(2\beta_m + \beta_n)p_e}{2(2-r)} > 0, V_{NEV}^{S2} - V_{FV}^{S2} = \frac{[(3-r)\beta_n + 2\beta_m](\beta_n - 2\beta_m)p_e}{4(2-r)} > 0; V^{S3} - V_{NEV}^{S3} = \frac{\beta_m[2(1-r)\beta_n + (4-r-r^2)\beta_m]p_e}{4(2-r)} > 0, V_{NEV}^{S3} - V_{FV}^{S3} = \frac{[4\beta_n^2 + 2(2r-1)\beta_m\beta_n - (4-r-r^2)\beta_m]p_e}{4(2-r)} > 0. \text{ Thus, } V^{S1} > V_{NEV}^{S1} > V_{FV}^{S1}, V^{S2} > V_{NEV}^{S2} > V_{FV}^{S2}, V^{S3} > V_{NEV}^{S3} > V_{FV}^{S3}.$$

This Lemma is proven. $\square$

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