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Operational Strategy Selection for Vehicle Manufacturers in the Battery Swapping Supply Chain

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Abstract

The vehicle–battery separation (VBS) model offers a viable framework for promoting new energy vehicle (NEV) adoption. To facilitate its broader diffusion, this study examines a supply chain comprising a vehicle manufacturer and a third-party operator for the battery leasing and swapping (BLS) services under this business model, from the perspective of automakers. Within this framework, three service operation strategies are developed for the automaker: (1) self-operated swapping services (VYN strategy); (2) self-operated leasing services (VNY strategy); and (3) full outsourcing of both services (VNN strategy). A comparative analysis yields three main findings. First, the automaker achieves the highest profit under strategy VNY, whereas the third-party operator prefers to cooperate with an automaker that adopts strategy VNN. Second, whether VNN or VNY yields higher total supply chain profit is determined by swapping price sensitivity and the vehicle's base price: the VNN strategy is optimal when both parameters are low, and the VNY strategy is optimal otherwise. Third, to promote the adoption of battery-swappable vehicles, automakers should outsource battery swapping services (i.e., adopt strategy VNY or VNN). By contrast, leasing operations are better outsourced (through VYN or VNN) when the goal is to grow the swapping service market.

Keywords: vehicle–battery separation model; vehicle manufacturer; battery leasing and swapping services; operational strategy; Stackelberg game

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1. Introduction

The VBS framework based on BLS services has emerged as an important business model for addressing the challenges associated with the large-scale adoption of NEVs [1]. As key participants in this model, vehicle manufacturers are actively developing and expanding VBS ecosystems. These ecosystems typically involve two stages: vehicle sales and vehicle usage [2]. During the sales stage, vehicle manufacturers produce battery-swappable vehicles by leveraging their advantages in vehicle design and manufacturing capabilities. Meanwhile, to reduce consumers' initial purchase costs and mitigate battery degradation risks, vehicle manufacturers separate battery ownership from vehicle ownership by reselling batteries or providing battery leasing solutions [3]. During the usage stage, vehicle manufacturers deploy battery swapping networks to provide swapping services and alleviate consumers' range anxiety. For example, NIO and Geely are representative vehicle manufacturers that have adopted this operational model.

Although the comprehensive deployment of the VBS model can enhance the competitiveness of vehicle manufacturers, simultaneously investing in battery-swappable vehicles, battery assets, and energy replenishment networks imposes substantial financial pressure on these firms. To enhance operational efficiency and alleviate financial burdens, vehicle manufacturers outsource certain services to third-party operators. Consequently, the selection of an appropriate outsourcing strategy for BLS service operations has become a critical strategic decision for these manufacturers. Based on this, the following research questions are addressed in this paper:

(1) Under different operational strategies, how should vehicle manufacturers and third-party operators determine the optimal prices for their respective products and services?
(2) How should vehicle manufacturers choose their outsourcing operations strategies, and how should third-party operators choose their operational strategies?
(3) Which operational strategy can most effectively accelerate the market uptake of battery-swappable vehicles and related services? Moreover, which strategy better supports the sustainable growth of the VBS model?

These questions are examined through a battery-swapping supply chain that includes vehicle manufacturers and third-party operators. Based on the vehicle–battery lifespan disparity and the duration of leasing contracts under the VBS model, three outsourcing strategies for automakers' BLS services are developed: provision of swapping only (VYN), provision of leasing only (VNY), and full outsourcing of both (VNN). The three strategies are then compared to derive practical implications for the operation of the battery swapping supply chain.

The key findings are summarized below.

(1) VNY yields the greatest profit for the automaker, while the third-party operator achieves the best outcome when partnering with a VNN-adopting manufacturer.
(2) The profit-maximizing strategy for the supply chain is contingent on swapping price sensitivity and the base vehicle price: VNN is preferred when both factors are sufficiently low; otherwise, VNY dominates.
(3) For the purpose of market expansion, outsourcing swapping services (via VNY or VNN) is recommended to boost vehicle adoption, whereas outsourcing leasing services (via VYN or VNN) is advised to foster the swapping service market.

The paper proceeds as follows. Section 2 surveys the existing literature. Section 3 lays out the research problem and underlying assumptions. Section 4 presents the strategy models. Section 5 compares these strategies. Section 6 presents a numerical experiment. Section 7 offers concluding observations and discusses future research directions.

2. Literature Review

The analysis centers on three dimensions of the VBS model: the leasing service, the swapping service, and the supply chain.

2.1. Battery Leasing Service

Research on battery leasing services mainly focuses on pricing decisions and strategy selection. Xie et al. [4] investigated how NEV manufacturers and battery asset companies set leasing prices under various maintenance service cooperation models. Ma et al. [5] explored the pricing issues of the battery supply chain under battery leasing and battery cascade utilization models. In addition, several studies have addressed the strategy selection of battery leasing services. In a supply chain involving battery suppliers and vehicle manufacturers, Li et al. [6] investigated the optimal choices among battery sales, leasing, and hybrid sales strategies for vehicle manufacturers. Considering consumers' resale

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anxiety, Hu et al. [7] examined the strategic choices of NEV manufacturers between battery sale and battery-as-a-service strategy in a market with both NEVs and fuel vehicles. Liu et al. [8] further investigated the choice between battery sales and leasing strategies in the context of AI-enabled battery cascade utilization. Fang et al. [9] incorporated battery quality considerations and investigated three battery utilization business models: the pure sales strategy, the pure leasing strategy, and a hybrid strategy. Zhou et al. [10] investigated battery rental and sales strategies for NEVs from the perspective of durable goods, incorporating battery age, condition, and residual value considerations into the battery swapping process.

Overall, prior work on battery leasing services has largely centered on pricing issues and comparisons between sales and leasing models, while the operational strategy design for leasing services within the supply chain has received limited attention. The present study addresses this gap by examining leasing service strategy selection in a battery swapping supply chain, with explicit consideration of the lifespan gap between batteries and the vehicle body during the leasing period.

2.2. Battery Swapping Service

Existing work on battery swapping services has largely centered on service pricing and operational decision-making. Lee and Kim [11] estimated consumer valuation of battery swapping services through a contingent valuation approach, offering empirical support for operator pricing decisions. Zhao et al. [12] proposed a cooperative Stackelberg game approach to determine the battery swapping price for heavy-duty trucks. Wang et al. [13] examined the swapping pricing strategies of NEV manufacturers in the presence of battery leasing models and subsidies. A number of studies have also concentrated on the strategic decisions regarding battery swapping. Considering customer satisfaction and battery utilization, Zhang et al. [14] analyzed the applicability of battery matching strategies for battery swapping services through a two-stage game model under uncertainty. Zhang et al. [15] analyzed the decision of electric vehicle charging providers on whether to offer fast charging or battery swapping services. Yang et al. [16] explored the trade-off between operating battery swapping services in-house and outsourcing them to third-party operators in a competitive environment involving two automobile manufacturers.

Overall, existing research on battery swapping services rarely considers BLS services simultaneously. Moreover, studies have paid limited attention to the interactions between the two services from a supply chain perspective. To address this gap, this paper jointly investigates BLS services within a supply chain framework, with the aim of examining the interactions between the two services and their impacts on operational decisions and supply chain performance.

2.3. Battery Swapping Supply Chain

Prior work on the battery swapping supply chain has centered on station construction and operations, as well as subsidy policies. Wang and Du [17], for instance, examined how government subsidies affect the construction of battery swapping stations within a supply chain comprising vehicle manufacturers, swapping operators, and consumers. Jiang et al. [18] compared two battery swapping operation modes and examined the decision regarding the ownership of battery swapping stations in a supply chain involving battery suppliers and automobile manufacturers. Similarly, Li et al. [19] analyzed the selection of battery swapping station construction entities in a supply chain consisting of electric vehicle manufacturers, battery suppliers, and swapping electric vehicle manufacturers. In addition, subsidy policies have also attracted research interest in the battery swapping context. Wu and Zhang [20] explored the interactions between government subsidies, corporate social responsibility, and operational decisions in a supply chain with

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battery manufacturers and swapping operators. Li and Yuan [21] investigated the impact of four types of battery swapping subsidies on supply chain pricing decisions in a supply chain involving battery manufacturers (BM), vehicle companies (VC), and battery leasing firms, whereas the subsequent study [22] addressed operation strategy under battery manufacturer dominance.

Although this study is related to Li and Yuan [21,22] in the battery-swapping supply chain context, it differs in three substantive respects. First, structurally, whereas [21] and [22] focus on supply chains dominated by battery manufacturers (examining subsidies and service strategies, respectively), the model developed here is set in an automaker-led supply chain. Second, methodologically, this study extends [22] by endogenizing the battery price as a function of the vehicle-body price—thereby capturing the price-coupling effect that [22] treats as exogenous—and by incorporating leasing-duration effects that [21] did not consider. Third, empirically, the model is calibrated using operational data from NIO, in contrast to the CATL-based parameters used in both the Li and Yuan studies. To further illustrate how this study differs from our previous work [22], Table 1 provides a side-by-side comparison of supply chain members, game leadership, and other key characteristics. Overall, rather than an incremental extension, this study represents a systematic extension along three dimensions: supply chain power structure, pricing mechanism, and empirical foundation.

Table 1. Comparisons with related literature.

Dimension	LI and Yuan [22]	This Study
Supply chain members	BM and VC	VC and third-party operator
Game leader (GL)	BM	VC
Decision variables	Vehicle-body price, the prices of two services	The prices of two services
Price composition	Separate prices for vehicle-body and battery	Battery-inclusive vehicle pricing
Strategy set	Four self-/outsourcing strategies for services	Three outsourcing strategies
Optimal decision of GL	Hinging on the vehicle-body price	Outsourcing the swapping service

In summary, existing studies on battery swapping supply chains have two limitations. First, most studies focus on battery swapping operations while overlooking battery leasing, which is an essential component of the VBS framework and a prerequisite for the large-scale adoption of battery swapping services. Second, although existing research considers various supply chain participants, such as battery manufacturers, automobile manufacturers, and battery swapping operators, the role of third-party operators in battery swapping service provision has received limited attention. To address these gaps, this study devises three operational strategies for BLS services within a battery swapping supply chain that includes vehicle manufacturers and third-party operators.

Table 2 highlights the main distinctions between this study and prior research. Three contributions are offered in this paper: (1) It develops an integrated analytical framework that explicitly accounts for both the product side (battery-swappable vehicles) and the service side (leasing and swapping), while incorporating the pricing linkage between the battery and the vehicle body. (2) It addresses the mismatch between vehicle and battery lifecycles by explicitly incorporating their different service lifetimes into the analytical model. (3) It examines three outsourcing strategies for BLS service operations under the VBS model in a supply chain dominated by vehicle manufacturers.

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Table 2. Summary of key distinctions between this study and prior literature.

Literature	Battery Leasing Service	Battery Swapping Service	Battery Swapping Supply Chain
Li et al. [6]	√		
Liu et al. [8]	√		
Zhao et al. [12]		√	
Yang et al. [16]		√	
Wang and Du [17]	√	√	
Jiang et al. [18]		√	√
Wu and Zhang [20]		√	√
This paper	√	√	√

3. Model Description and Assumptions

3.1. Problem Description

As illustrated in Figure 1, the battery swapping supply chain is composed of a vehicle manufacturer and a third-party operator. The manufacturer offers a range of VBS-related products and services—including battery-swappable vehicle bodies, leasing, and swapping—and may outsource the service components to the third party to relieve financial pressure. On the one hand, considering the high capital requirements of battery assets and the need for centralized battery management and maintenance, vehicle manufacturers can transfer battery ownership to third-party operators at a price p_b. On the other hand, given the expanding market potential of battery swapping services, vehicle manufacturers can authorize third-party operators to provide battery swapping services at a price h, thereby reducing operational burdens and generating additional revenue. Based on the outsourcing status of the two service types, three operational strategies are considered: provision of swapping only (VYN strategy), provision of leasing only (VNY strategy), and full outsourcing of both (VNN strategy). Despite variations in the allocation of decision rights across the three strategies, the manufacturer remains the Stackelberg leader in all cases. Accordingly, the three strategies constitute different organizational arrangements within the same market.

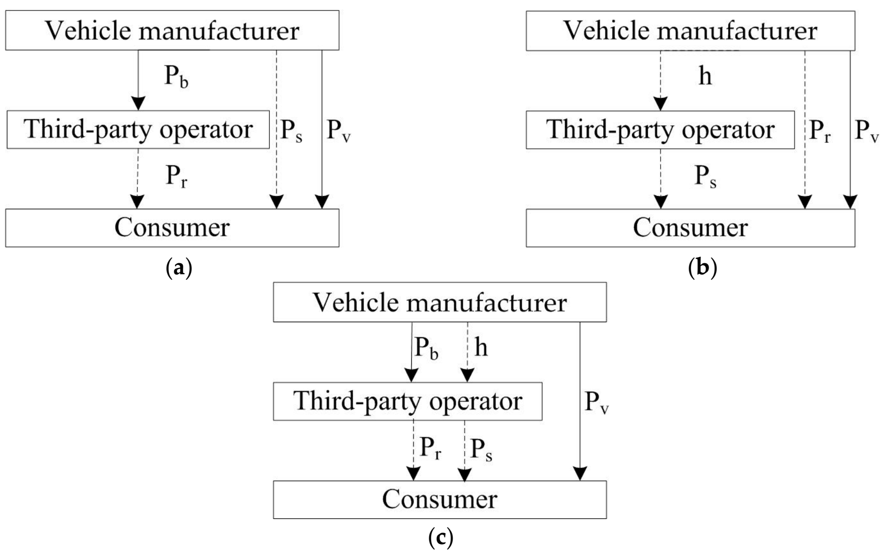

Figure 1. Service operation strategies of the vehicle manufacturer. (**a**) VYN strategy. (**b**) VNY strategy. (**c**) VNN strategy.

3.2. Assumptions

Assumption 1. *The VBS model is built upon the observation that battery-swapping vehicles remain in service considerably longer than a single power battery, meaning that the vehicle's service life will require multiple battery replacements [21]. Denote the vehicle's service life by* t_v*, and the battery's service life by* t_b*. The quantity of batteries required throughout the vehicle's lifespan is then given by* t_v/t_b*. Moreover, the leasing duration* $t_s = t_v$*.*

Assumption 2. *Following Li and Yuan [22] and Avci et al. [23], we specify the vehicle utility function as:* $U_v(D_v) = (a - t_s p_r)D_v - \frac{1}{2}D_v^2$ *, maxing* $U_v(D_v) - p_v D_v$ *yields vehicle demand* $D_v = a - t_s p_r - p_v$*, subject to* $D_v \geq 0$*, which entails* $p_v \leq \alpha - t_s p_r$*. Here,* α *(*$\alpha > 0$*) is the market size,* p_r *(*$p_r > 0$*) is the annual battery rental price, and* t_s *is the vehicle's expected service lifetime (in years). Consequently,* $t_s p_r$ *represents the total lifetime leasing expenditure.* p_v *(*$p_v \in [0, \alpha - t_s p_r]$*) is the base price of the vehicle (excluding the battery), that is, the vehicle body price. As in Li and Yuan [22], the coefficient on price in the demand function is normalized to one.*

The demand for battery swapping services is derived from D_v and is further affected by the swapping price p_s. According to Li and Yuan [22] and Yoo et al. [24], the utility function is $U_s(D_s \mid D_v) = \frac{D_v}{\theta} D_s - \frac{1}{2\theta} D_s^2$, maxing $U_s(D_s \mid D_v) - p_s D_s$ yielding $D_s = D_v - \theta p_s$, subject to $D_s \geq 0$, which entails $p_v \leq D_s/\theta$. Here θ (the initial domain is $\theta \in (0,\ 1)$, while the effective feasible domain of the model is $\theta \in (1/4,\ 1)$) is the relative swapping price sensitivity, and p_s ($p_s \in [0, D_s/\theta]$) is the total lifetime swapping service expenditure (swapping price).

Assumption 3. *Following the cost structure in Li and Yuan [21], the investment in a battery swapping station, denoted as* c_B*, consists of site, equipment, and battery expenditures. As documented in Hu et al. [25] and Wang and Du [17], operators reserve a stock of spare batteries proportional to the vehicle demand to guarantee service continuity. Let* δ *denote the equilibrium battery ratio. Given that the unit production cost of a battery is* c_b*, the aggregate battery cost is* $\delta c_b D_v$ *. Moreover, let* γ *represent the share of battery cost in station investment, so* $c_B = \delta c_b D_v/\gamma$ *. To simplify the model, the balanced battery cost ratio is defined as* $\lambda = \delta/\gamma$*. Thus,* $c_B = \lambda c_b D_v$.

Assumption 4. *In the VBS framework, the vehicle (without its battery) and the battery pack are priced separately, with the battery typically accounting for a substantial portion of the total vehicle price. To facilitate modeling, we further assume that the battery price is a fixed proportion of the base vehicle price (i.e., the price without the battery), denoted by* $p_b = \omega p_v$*, where* ω *denotes the ratio of battery price to base vehicle price.*

The parameters employed in this work are listed in Tables 3 and 4.

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Table 3. Decision variable table.

Parameters	Definition
h	Authorized price for battery swapping
p_r	Battery rental price
p_s	Battery swapping price

Table 4. Variable table.

Parameters	Definition	Parameters	Definition
θ	Swapping price sensitivity	p_v	The base price of the vehicle
t_s	The leasing duration	p_b	Battery price
t_v	The vehicle's service life	D_v	Demand for vehicles
t_b	Lifespan of battery	D_s	Demand for battery swapping services
c_b	Battery unit cost	π_v	Profit of vehicle manufacturers
c_B	Investment of battery swapping station	π_t	Profit of third-party operators
c_s	Operating costs of battery swapping	π_T	Profit of supply chain
μ	Proportion of cost sharing for battery swapping operation	CS	Consumer surplus
λ	Balanced battery cost ratio	SW	Social welfare
ω	Ratio of battery price to base vehicle price		

4. Model Construction

4.1. VYN Strategy

Under the VYN strategy, vehicle manufacturers play dual roles as suppliers of battery-swappable vehicle bodies and providers of battery swapping services. Specifically, vehicle manufacturers sell battery-swappable vehicle bodies to consumers at a price p_v and provide battery swapping services through their own swapping networks at a price p_s. Meanwhile, to reduce the financial burden associated with battery assets, vehicle manufacturers transfer battery ownership to third-party operators at a price p_b. After acquiring battery ownership, third-party operators manage batteries and provide leasing services, with a service fee of p_r.

Under this strategy, the third-party operator owns and manages the batteries but bears the per-swap operating cost μc_s associated with the vehicle manufacturer's provision of swapping services. Here, μ is the proportion of cost sharing for swapping operation. The sequence of decisions is as follows: the vehicle manufacturer chooses the swapping service price p_s first; the third-party operator then responds by choosing the leasing price p_r. The profit functions are:

$$\pi_v^{\mathrm{VYN}} = p_v D_v + \left(p_s - c_s\left(1-\mu\right)\right) D_s - \lambda c_b D_v + \left(t_s / t_b\right)\left(\omega p_v - c_b\right) D_v \tag{1}$$

$$\pi_t^{\mathrm{VYN}} = \left(t_s p_r - \left(t_s / t_b\right) \omega p_v\right) D_v - \mu c_s D_s \tag{2}$$

Proof. Detailed derivations are provided in Appendix A. □

Proposition 1. *Under VYN, the equilibrium outcomes for the manufacturer and operator are:*

$$p_r^{\text{VYN}} = \frac{t_s \omega p_v + a t_b + \mu c_s t_b - p_v t_b}{2 t_s t_b} \quad (3)$$

$$p_s^{\text{VYN}} = \frac{2\theta c_s t_b - 2\mu\theta c_s t_b - t_s \omega p_v + a t_b - \mu c_s t_b - p_v t_b}{4 t_b \theta} \quad (4)$$

$$D_v^{\text{VYN}} = \frac{a t_b - t_s \omega p_v - \mu c_s t_b - p_v t_b}{2 t_b} \quad (5)$$

$$D_s^{\text{VYN}} = \frac{2\mu\theta c_s t_b - t_s \omega p_v - 2\theta c_s t_b + a t_b - \mu c_s t_b - p_v t_b}{4 t_b} \quad (6)$$

$$\pi_v^{\text{VYN}} = \frac{\left\{ \begin{array}{l} 2X_2\left(4\theta c_b X_1 - c_s t_b\left(6\mu\theta - \mu - 2\theta\right) + a t_b\left(4\theta - 1\right)\right) p_v - X_2^2\left(8\theta - 1\right) p_v^2 \\ + t_b\left(t_b\left(2\theta c_s\left(\mu - 1\right) + a - \mu c_s\right)^2 - 8\theta X_1\left(a - \mu c_s\right) c_b\right) \end{array} \right\}}{16\theta t_b^2} \quad (7)$$

$$\pi_t^{\text{VYN}} = \frac{X_2^2 p_v^2 - t_b X_2\left(2a - \mu c_s\right) p_v + t_b^2\left(2\mu\theta c_s^2\left(1 - \mu\right) + a^2 - a\mu c_s\right)}{4 t_b^2} \quad (8)$$

Here, $X_1 = \lambda t_b + t_s$, $X_2 = \omega t_s + t_b$.

4.2. VNY Strategy

Under the VNY strategy, vehicle manufacturers provide battery-swappable vehicle bodies and battery leasing services to consumers, while third-party operators are responsible for providing battery swapping services. As in the VYN strategy, the VNY strategy requires vehicle manufacturers who hold battery ownership to bear the operating cost μc_s. Specifically, vehicle manufacturers charge consumers p_v for the vehicle body and p_r for leasing services. In addition, vehicle manufacturers establish battery swapping systems compatible with their battery standards and authorize third-party operators to provide battery swapping services at an authorization price h. After obtaining the authorization, third-party operators charge consumers p_s for battery swapping services. The order of decisions is: the vehicle manufacturer chooses the rental price p_r and authorization fee h, after which the third-party operator responds by choosing the swapping fee p_s. The profit functions are:

$$\pi_v^{\text{VNY}} = p_v D_v + \left(t_s p_r - \left(t_s / t_b\right) c_b\right) D_v - \mu c_s D_s + h D_s - \lambda c_b D_v \quad (9)$$

$$\pi_t^{\text{VNY}} = \left(p_s - c_s\left(1 - \mu\right) - h\right) D_s \quad (10)$$

Proof. Detailed derivations are provided in Appendix B. □

Proposition 2. *The equilibrium outcomes for the two parties under VNY are as follows:*

$$h^{\text{VNY}} = \frac{4\theta c_s t_b\left(2\mu - 1\right) - 2\lambda c_b t_b - \mu c_s t_b + 2a t_b - 2c_b t_s}{t_b\left(8\theta - 1\right)} \quad (11)$$

$$p_r^{\text{VNY}} = \frac{4\lambda\theta c_b t_b + 4a\theta t_b + 4\theta c_b t_s + \theta c_s t_b - 8\theta p_v t_b - a t_b + p_v t_b}{t_b t_s (8\theta - 1)} \tag{12}$$

$$p_s^{\text{VNY}} = \frac{2\theta c_s t_b - 3\lambda c_b t_b + 3a t_b - 3c_b t_s - c_s t_b}{t_b (8\theta - 1)} \tag{13}$$

$$D_v^{\text{VNY}} = \frac{\theta(4a t_b - 4\lambda c_b t_b - 4c_b t_s - c_s t_b)}{t_b (8\theta - 1)} \tag{14}$$

$$D_s^{\text{VNY}} = \frac{\theta(a t_b - \lambda c_b t_b - 2\theta c_s t_b - c_b t_s)}{t_b (8\theta - 1)} \tag{15}$$

$$\pi_v^{\text{VNY}} = \frac{\left(2X_1^2 c_b^2 - t_b X_1 (4a - c_s) c_b + t_b^2 \left(\theta c_s^2 + 2a^2 - a c_s\right)\right)\theta}{(8\theta - 1) t_b^2} \tag{16}$$

$$\pi_t^{\text{VNY}} = \frac{\theta(a t_b - \lambda c_b t_b - 2\theta c_s t_b - c_b t_s)^2}{t_b^2 (8\theta - 1)^2} \tag{17}$$

4.3. VNN Strategy

Under the VNN strategy, vehicle manufacturers focus only on the production and sales of battery-swappable vehicle bodies, while BLS services are fully outsourced to third-party operators. Specifically, vehicle manufacturers charge consumers p_v for the battery-swappable vehicle body. Meanwhile, vehicle manufacturers transfer the ownership of batteries compatible with the lifecycle of battery-swappable vehicles to third-party operators at a price $(t_s/t_b)\omega p_v$ and authorize them to provide battery swapping services at a price h. Upon securing battery ownership and the operational authorization for swapping services, the third-party operator provides leasing services at price p_r and swapping services at price p_s. The game proceeds in the following order: the vehicle manufacturer first sets the authorization price h; the third-party operator subsequently sets the lease fee p_r and swapping charge p_s. The profit functions are:

$$\pi_v^{\text{VNN}} = p_v D_v + (t_s/t_b)(\omega p_v - c_b) D_v + h D_s - \lambda c_b D_v \tag{18}$$

$$\pi_t^{\text{VNN}} = (t_s p_r - (t_s/t_b)\omega p_v) D_v + (p_s - c_s - h) D_s \tag{19}$$

Proof. Detailed derivations are provided in Appendix C. □

Proposition 3. *VNN yields the following equilibrium outcomes:*

$$h^{\text{VNN}} = \frac{\lambda c_b t_b - 2\omega p_v t_s - 2\theta c_s t_b + a t_b + c_b t_s - 2p_v t_b}{4\theta t_b} \tag{20}$$

$$p_r^{\text{VNN}} = \frac{2X_3(\omega t_s - t_b) p_v + 8a\theta t_b + \lambda c_b t_b + 2\theta c_s t_b - 3a t_b + c_b t_s}{4 t_b t_s X_3} \tag{21}$$

$$p_s^{\mathrm{VNN}} = \frac{(2\theta-1)X_1c_b - 2X_3X_2p_v + t_b\left(4\theta^2c_s + 6a\theta - 2\theta c_s - a\right)}{4\theta t_b X_3} \tag{22}$$

$$D_v^{\mathrm{VNN}} = \frac{8a\theta t_b - 2X_3X_2p_v - 2\theta c_s t_b - at_b - X_1c_b}{4t_bX_3} \tag{23}$$

$$D_s^{\mathrm{VNN}} = \frac{\theta\left(at_b - \lambda c_b t_b - 2\theta c_s t_b - c_b t_s\right)}{2t_bX_3} \tag{24}$$

$$\pi_v^{\mathrm{VNN}} = \frac{\begin{Bmatrix} 4X_3X_2\left(\lambda c_b t_b + at_b + c_b t_s\right)p_v - 4X_2^2X_3p_v^2 + X_1^2 \\ -2t_bX_1\left(8a\theta - 2\theta c_s - a\right) + t_b^2\left(a - 2\theta c_s\right)^2 \end{Bmatrix}}{8t_b^2X_3} \tag{25}$$

$$\pi_t^{\mathrm{VNN}} = \frac{\begin{Bmatrix} 4X_2^2X_3p_v^2 - 8at_bX_3X_2p_v + X_1^2c_b^2 - 2t_bX_1\left(a - 2\theta c_s\right)c_b \\ +t_b^2\left(4\theta^2c_s^2 + 16a^2\theta - 4a\theta c_s - 3a^2\right) \end{Bmatrix}}{16t_b^2X_3} \tag{26}$$

Here, $X_3 = 4\theta - 1$.

5. Model Analysis

5.1. Model Comparison

Corollary 1. *Table 5 reports the comparison of leasing prices across the three strategies.*

Table 5. Comparison of leasing prices.

Condition 1	Condition 2	Condition 3	Comparison Results
$p_v < p_v^1$	$\theta < \theta^1$	$c_b < c_b^1$	$p_r^{\mathrm{VYN}} > p_r^{\mathrm{VNY}} > p_r^{\mathrm{VNN}}$
		$c_b \ge c_b^1$	$p_r^{\mathrm{VYN}} > p_r^{\mathrm{VNN}} > p_r^{\mathrm{VNY}}$
	$\theta \ge \theta^1$		$p_r^{\mathrm{VYN}} > p_r^{\mathrm{VNY}} > p_r^{\mathrm{VNN}}$
$p_v \ge p_v^1$	$\theta < \theta^1$		$p_r^{\mathrm{VYN}} > p_r^{\mathrm{VNN}} > p_r^{\mathrm{VNY}}$
	$\theta \ge \theta^1$	$c_b < c_b^1$	$p_r^{\mathrm{VYN}} > p_r^{\mathrm{VNN}} > p_r^{\mathrm{VNY}}$
		$c_b \ge c_b^1$	$p_r^{\mathrm{VYN}} > p_r^{\mathrm{VNY}} > p_r^{\mathrm{VNN}}$

Here, $c_b^1 = -\left(at_b - 2\theta c_s t_b - 2(8\theta-1)X_3X_2p_v\right)/\left(\left(64\theta^2 - 24\theta + 1\right)X_1\right)$, $\theta^1 = \left(3+\sqrt{5}\right)/16$, $p_v^1 = t_b\left(a - 2\theta c_s\right)/\left(2\left(8\theta-1\right)X_2X_3\right)$.

The proof is analogous to that in Appendix E and is therefore not repeated here.

According to Corollary 1, the VNN and VNY strategies, which outsource battery swapping services, yield the most competitive leasing prices. Specifically, the strategy that minimizes leasing prices depends on the base vehicle price, the sensitivity of the swapping fee, and the cost of battery production. The VNN strategy enables the third-party operator to achieve the lowest leasing price under three conditions: (1) all three parameters (p_v, θ, c_b) are high; (2) all three are low; and (3) p_v is low while θ is high. Under other scenarios, the VNY strategy is more effective in reducing leasing prices.

Therefore, to provide consumers with more competitive battery leasing services, vehicle manufacturers should prioritize outsourcing battery swapping services. However, whether battery leasing services should also be outsourced depends on the combined effects of the above three key factors.

Corollary 2. *Swapping price comparison across the three strategies.*

When $p_v < p_v^{\ 2}$, there is $p_s^{\mathrm{VYN}} < \left\{ p_s^{\mathrm{VNY}}, p_s^{\mathrm{VNN}} \right\}$; when $p_v \geq p_v^{\ 2}$, there is $p_s^{\mathrm{VNN}} < \left\{ p_s^{\mathrm{VYN}}, p_s^{\mathrm{VNY}} \right\}$.

Here, $p_v^{\ 2} = \left(t_b c_s \left(2\theta + 1 \right) X_3 \mu + 2\theta \left(c_b X_1 + a t_b \right) - 4\theta^2 c_s t_b - c_b X_1 \right) / \left(X_3 X_2 \right)$.

The detailed proof is available in Appendix D.

Corollary 2 indicates that the strategy yielding the lowest swapping price is contingent on the base vehicle price. When the price is low, vehicle manufacturers can offer the most competitive swapping services by adopting VYN. Conversely, when the price is high, VNN yields the lowest swapping price. The rationale for this is as follows. A low base vehicle price stimulates demand for battery-swappable vehicles, thereby increasing the demand for swapping services. In this setting, self-operated swapping enables vehicle manufacturers to reduce service prices by capitalizing on the higher service volume. Conversely, high base vehicle prices weaken demand and reduce the economic appeal of self-operated swapping. In such cases, outsourcing to third-party operators—who can achieve cost efficiencies through broader operational scale across multiple markets—enables more competitive pricing.

Corollary 3. *The demand for battery-swappable vehicles under the three strategies is compared in Table 6.*

Table 6. Battery swapping vehicle demand comparison.

Condition 1	Condition 2	Condition 3	Comparison Results
$p_v < p_v^{\ 1}$	$\theta < \theta^1$	$c_b < c_b^{\ 1}$	$D_v^{\mathrm{VNN}} > \left\{ D_v^{\mathrm{VYN}}, D_v^{\mathrm{VNY}} \right\}$
		$c_b \geq c_b^{\ 1}$	$D_v^{\mathrm{VNY}} > \left\{ D_v^{\mathrm{VYN}}, D_v^{\mathrm{VNN}} \right\}$
	$\theta \geq \theta^1$		$D_v^{\mathrm{VNN}} > \left\{ D_v^{\mathrm{VYN}}, D_v^{\mathrm{VNY}} \right\}$
$p_v \geq p_v^{\ 1}$	$\theta < \theta^1$		$D_v^{\mathrm{VNY}} > \left\{ D_v^{\mathrm{VYN}}, D_v^{\mathrm{VNN}} \right\}$
	$\theta \geq \theta^1$	$c_b < c_b^{\ 1}$	$D_v^{\mathrm{VNY}} > \left\{ D_v^{\mathrm{VYN}}, D_v^{\mathrm{VNN}} \right\}$
		$c_b \geq c_b^{\ 1}$	$D_v^{\mathrm{VNN}} > \left\{ D_v^{\mathrm{VYN}}, D_v^{\mathrm{VNY}} \right\}$

The detailed proof is available in Appendix E.

Corollary 3 indicates that vehicle manufacturers can achieve the strongest promotion effect for battery-swappable vehicles only by outsourcing battery swapping services (i.e., adopting VNY or VNN). The optimal choice between these strategies is conditional on the base vehicle price, the sensitivity of the swapping fee, and the cost of battery production. This result is consistent with Corollary 1, which shows that the leasing strategy choice determines leasing price competitiveness and, thereby, market demand.

Therefore, to promote the adoption of battery-swappable vehicles, vehicle manufacturers should prioritize outsourcing battery swapping services. However, whether battery leasing services should also be outsourced depends on the combined influence of the above three key factors.

Corollary 4. *Table 7 reports the comparison of battery swapping service demand across the three strategies.*

Table 7. Demand comparison for swapping services across the three strategies.

Condition 1	Condition 2	Condition 3	Comparison Results
$1/4<\theta<1/2$	$p_v<p_v^{\ 3}$		$D_s^{\mathrm{VYN}}>\{D_s^{\mathrm{VNY}},\ D_s^{\mathrm{VNN}}\}$
	$p_v\ge p_v^{\ 3}$	$c_s<c_s^{\ 1}$	$D_s^{\mathrm{VNN}}>\{D_s^{\mathrm{VYN}},\ D_s^{\mathrm{VNY}}\}$
		$c_s\ge c_s^{\ 1}$	$D_s^{\mathrm{VYN}}>\{D_s^{\mathrm{VNY}},\ D_s^{\mathrm{VNN}}\}$
$1/2\le\theta<1$	$p_v<p_v^{\ 3}$	$c_s<c_s^{\ 1}$	$D_s^{\mathrm{VYN}}>\{D_s^{\mathrm{VNY}},\ D_s^{\mathrm{VNN}}\}$
		$c_s\ge c_s^{\ 1}$	$D_s^{\mathrm{VNN}}>\{D_s^{\mathrm{VYN}},\ D_s^{\mathrm{VNY}}\}$
	$p_v\ge p_v^{\ 3}$		$D_s^{\mathrm{VNN}}>\{D_s^{\mathrm{VYN}},\ D_s^{\mathrm{VNY}}\}$

Here, $c_s^{\ 1}=-\left(2\lambda\theta c_b t_b+2a\theta t_b+2\theta c_b t_s-at_b-X_2X_3p_v\right)/\left(t_b\left(2\theta-1\right)\left(4\mu\theta-\mu-2\theta\right)\right)$, $p_v^{\ 3}=\left(2\lambda\theta c_b t_b+2a\theta t_b+2\theta c_b t_s-at_b\right)/\left(X_2X_3\right)$.

The detailed proof is available in Appendix F.

According to Corollary 4, either the VYN strategy or the VNN strategy demonstrates greater advantages in stimulating swapping service demand. Specifically, the optimal strategy depends on swapping price sensitivity, vehicle's base price, and battery swapping operating cost. The VNN strategy is most effective in three cases: (1) both θ and p_v are high ($1/2\le\theta<1$ and $p_v\ge p_v^{\ 3}$); (2) θ is high, while p_v is low and c_s is high ($1/2\le\theta<1$, $p_v<p_v^{\ 3}$ and $c_s\ge c_s^{\ 1}$); and (3) θ is low, while p_v is high, and c_s is low ($1/4<\theta<1/2$, $p_v\ge p_v^{\ 3}$ and $c_s<c_s^{\ 1}$). Under other conditions, vehicle manufacturers can achieve higher demand by adopting the VYN strategy.

This result can be explained as follows.

When the vehicle's base price is high, the demand for vehicles and leasing services is relatively dampened. Under such conditions, if consumers are highly sensitive to swapping prices, outsourcing both services (VNN) enables third-party operators to realize operational centralization and exploit economies of scale, thereby reducing service costs and drawing more consumers. Conversely, when the vehicle's base price is high, but consumers' sensitivity to swapping fees is low, price reductions are unlikely to effectively stimulate demand. In this case, if battery swapping operating costs are also low, outsourcing both services becomes economically attractive. The third-party operator can absorb the operational burden, while the vehicle manufacturer avoids the fixed costs associated with self-operating a low-volume service.

When the vehicle's base price is low, demand for vehicles and leasing services is relatively robust. If the swapping price sensitivity is high and operating costs are high, self-operation imposes a heavy cost burden on the vehicle manufacturer. By contrast, outsourcing both services to a third-party operator converts fixed costs into variable costs and leverages the operator's centralized management advantages, thereby reducing service costs and strengthening market demand.

Therefore, to promote battery swapping service adoption, vehicle manufacturers should prioritize outsourcing battery leasing services. However, whether battery swapping services should also be outsourced depends on the combined effects of swapping fee sensitivity, the vehicle's base price, and battery swapping operating cost.

5.2. Model Sensitivity Analysis

This paper further examines the influence of three key parameters, such as swapping fee sensitivity, the base vehicle price, and the cost of battery production under these three strategies.

Corollary 5. *The impacts of* θ *is as follows:*

(1) $\partial p_r^{\text{VYN}}/\partial\theta = 0$, $\partial p_s^{\text{VYN}}/\partial\theta < 0$, $\partial D_v^{\text{VYN}}/\partial\theta = 0$, $\partial D_s^{\text{VYN}}/\partial\theta < 0$, $\partial \pi_v^{\text{VYN}}/\partial\theta < 0$, $\partial \pi_t^{\text{VYN}}/\partial\theta > 0$; *when* $\theta < \theta^2$, $\partial \pi_T^{\text{VYN}}/\partial\theta < 0$, *when* $\theta \ge \theta^2$, $\partial \pi_T^{\text{VYN}}/\partial\theta \ge 0$;

(2) $\partial p_r^{\text{VNY}}/\partial\theta > 0$, $\partial p_s^{\text{VNY}}/\partial\theta < 0$, $\partial D_v^{\text{VNY}}/\partial\theta < 0$, $\partial D_s^{\text{VNY}}/\partial\theta < 0$, $\partial \pi_v^{\text{VNY}}/\partial\theta < 0$, $\partial \pi_t^{\text{VNY}}/\partial\theta < 0$, $\partial \pi_T^{\text{VNY}}/\partial\theta < 0$;

(3) $\partial p_r^{\text{VNN}}/\partial\theta > 0$, $\partial p_s^{\text{VNN}}/\partial\theta < 0$, $\partial D_v^{\text{VNN}}/\partial\theta < 0$, $\partial D_s^{\text{VNN}}/\partial\theta < 0$, $\partial \pi_v^{\text{VNN}}/\partial\theta < 0$, $\partial \pi_t^{\text{VNN}}/\partial\theta < 0$, $\partial \pi_T^{\text{VNN}}/\partial\theta < 0$.

Here, $\theta^2 = (at_b - \mu c_s t_b - \omega p_v t_s - p_v t_b) \big/ \left(2 t_b c_s \sqrt{1-\mu^2}\right)$.

Proof. Differentiating the relevant variables and functions under the three strategies gives the results in Corollary 5. The detailed derivations are omitted for conciseness. The same reasoning applies to Corollaries 6 and 7, and their proofs are therefore not repeated here. □

Corollary 5—(1) indicates that under the VYN strategy, an increase in swapping price sensitivity leads to a decrease in the swapping price, accompanied by a decline in the demand for battery swapping services. Consequently, vehicle manufacturers' profits decrease, whereas the profit of third-party operators increases. Regarding the overall supply chain, when swapping price sensitivity is initially low, an increase in sensitivity reduces total supply chain profit. However, when sensitivity is already high, further increases in sensitivity improve total supply chain profit.

Corollary 5—(2) and Corollary 5—(3) demonstrate that the effects of swapping price sensitivity on prices, demand, and profits are consistent under the VNY and VNN strategies. Specifically, an increase in swapping fee sensitivity drives up the leasing fee while pushing down the swapping fee, which curtails demand for both battery-swappable vehicles and swapping services. As a result, the profits of both the vehicle manufacturer and the third-party operator decline, dampening total supply chain profit.

Overall, swapping price sensitivity exerts heterogeneous effects on firm profitability under different operational strategies. In most cases, an increase in swapping price sensitivity reduces firm profits. However, under the VYN strategy, third-party operators' profits increase with higher swapping price sensitivity.

Corollary 6. *The effects of* p_v *are as follows:*

(1) $\partial p_r^{\text{VYN}}/\partial p_v < 0$, $\partial p_s^{\text{VYN}}/\partial p_v < 0$, $\partial D_v^{\text{VYN}}/\partial p_v < 0$, $\partial D_s^{\text{VYN}}/\partial p_v < 0$; *when* $p_v < p_v^{\,4}$, $\partial \pi_v^{\text{VYN}}/\partial p_v > 0$, *when* $p_v \ge p_v^{\,4}$, $\partial \pi_v^{\text{VYN}}/\partial p_v \le 0$; $\partial \pi_t^{\text{VYN}}/\partial p_v < 0$, $\partial \pi_T^{\text{VYN}}/\partial p_v < 0$;

(2) $\partial p_r^{\text{VNY}}/\partial p_v < 0$, $\partial p_s^{\text{VNY}}/\partial p_v = 0$, $\partial D_v^{\text{VNY}}/\partial p_v = 0$, $\partial D_s^{\text{VNY}}/\partial p_v = 0$, $\partial \pi_v^{\text{VNY}}/\partial p_v = 0$, $\partial \pi_t^{\text{VNY}}/\partial p_v = 0$, $\partial \pi_T^{\text{VNY}}/\partial p_v = 0$;

(3) $\partial p_r^{\text{VNN}}/\partial p_v < 0$, $\partial p_s^{\text{VNN}}/\partial p_v < 0$, $\partial D_v^{\text{VNN}}/\partial p_v < 0$, $\partial D_s^{\text{VNN}}/\partial p_v = 0$, $\partial \pi_v^{\text{VNN}}/\partial p_v > 0$; *when* $p_v < p_v^{\,5}$, $\partial \pi_t^{\text{VNN}}/\partial p_v < 0$, *when* $p_v \ge p_v^{\,5}$, $\partial \pi_t^{\text{VNN}}/\partial p_v \ge 0$; *when* $p_v < p_v^{\,6}$, $\partial \pi_T^{\text{VNN}}/\partial p_v > 0$, *when* $p_v \ge p_v^{\,6}$, $\partial \pi_T^{\text{VNN}}/\partial p_v \le 0$.

Here, $p_v^{\,4} = \left(4\theta(c_b X_1 + at_b) - 6\mu\theta c_s t_b + \mu c_s t_b + 2\theta c_s t_b - at_b\right) \big/ \left((8\theta - 1) X_2\right)$, $p_v^{\,5} = at_b / X_2$, $p_v^{\,6} = X_1 c_b / X_2$.

Corollary 6—(1) indicates that, under the VYN strategy, an increase in the vehicle's base price lowers the prices of two services, dampening demand for battery-swappable vehicles and swapping services. Consequently, third-party operator profits and total supply chain profit decline. For vehicle manufacturers, however, the profit effect of a vehicle's base price increase is conditional on the initial price level: when the price is low, raising it improves manufacturer profits; otherwise, profits decrease.

Corollary 6—(2) shows that, under the VNY strategy, an increase in the vehicle's base price affects only the leasing fee, which declines, while the swapping price, demand, and all firm profits remain unchanged.

Corollary 6—(3) reveals that under the VNN strategy, an increase in the vehicle's base price reduces the two service prices, while decreasing the demand for battery-swappable vehicles and increasing vehicle manufacturers' profits. For third-party operators and total supply chain profit, the effect of the vehicle's base price is conditional on the initial price level.

Overall, although a reduction in the vehicle's base price tends to boost vehicle adoption, such a strategy does not necessarily translate into higher profitability for vehicle manufacturers. Specifically, under the VYN strategy, a price reduction strategy enhances profitability only when the vehicle's initial base price is relatively high.

Corollary 7. *The effects of* c_b *are as follows:*

(1) $\partial p_r^{\text{VYN}}/\partial c_b = 0$, $\partial p_s^{\text{VYN}}/\partial c_b = 0$, $\partial D_v^{\text{VYN}}/\partial c_b = 0$, $\partial D_s^{\text{VYN}}/\partial c_b = 0$, $\partial \pi_v^{\text{VYN}}/\partial c_b < 0$, $\partial \pi_t^{\text{VYN}}/\partial c_b = 0$, $\partial \pi_T^{\text{VYN}}/\partial c_b < 0$;

(2) $\partial p_r^{\text{VNY}}/\partial c_b > 0$, $\partial p_s^{\text{VNY}}/\partial c_b < 0$, $\partial D_v^{\text{VNY}}/\partial c_b < 0$, $\partial D_s^{\text{VNY}}/\partial c_b < 0$, $\partial \pi_v^{\text{VNY}}/\partial c_b < 0$, $\partial \pi_t^{\text{VNY}}/\partial c_b < 0$, $\partial \pi_T^{\text{VNY}}/\partial c_b < 0$;

(3) $\partial p_r^{\text{VNN}}/\partial c_b > 0$; *when* $1/4 < \theta < 1/2$, $\partial p_s^{\text{VNN}}/\partial c_b < 0$, *when* $1/2 \le \theta < 1$, $\partial p_s^{\text{VNN}}/\partial c_b \ge 0$; $\partial D_v^{\text{VNN}}/\partial c_b < 0$, $\partial D_s^{\text{VNN}}/\partial c_b < 0$, $\partial \pi_v^{\text{VNN}}/\partial c_b < 0$, $\partial \pi_t^{\text{VNN}}/\partial c_b < 0$, $\partial \pi_T^{\text{VNN}}/\partial c_b < 0$.

Corollary 7—(1) indicates that under the VYN strategy, an increase in battery production cost reduces vehicle manufacturers' profits, while service price and demand remain unchanged. Since battery production costs affect neither vehicle demand nor swapping service demand, third-party operators' profits remain unchanged. However, despite the stability of third-party profits, the rise in battery production cost directly erodes vehicle manufacturers' profitability, leading to a decline in total supply chain profit.

Corollary 7—(2) and Corollary 7—(3) indicate that regardless of the operational strategy, higher battery production costs ultimately reduce battery swapping service demand through their effects on leasing prices or swapping prices, thereby diminishing overall supply chain profitability.

Overall, vehicle manufacturers are strongly motivated to pursue cost reductions in battery production as a means to enhance profitability.

6. Numerical Examples

Given the growing importance of swapping price sensitivity and vehicle price fluctuations in the VBS model, numerical analysis is carried out to assess their influence on equilibrium outcomes. The supply chain profit is $\pi_T = \pi_s + \pi_v + \pi_t$, consumer surplus is expressed as: $CS = \int_0^{D_v} (D_v - x)dx + \int_0^{D_s} \left(\frac{D_s - x}{\theta}\right)dx = D_v^2/2 + D_s^2/(2\theta)$, and social welfare is $SW = \pi_T + CS$. In CS, the first term measures the surplus from vehicle ownership, while the second measures the incremental surplus from swapping services. These two integrals measure distinct utility dimensions: vehicle ownership and swapping service usage. Although the swapping segment is endogenously nested within the vehicle market, the first integral does not include the utility from swapping services—it only accounts for the value of owning the vehicle. The second integral therefore adds the incremental surplus that vehicle owners obtain from using swapping services. The sum of the two integrals thus represents the total consumer surplus.

The numerical experiments are conducted with the following parameter specifications:

(1) The market size of NEVs. Drawing on Yang et al. [16] and Wang and Du [17], we set the battery swapping vehicle market size $a = 100 \times 10^4$.
(2) The lifecycles of vehicles and batteries. Referring to the study by Hu et al. [25], the service life of battery swapping vehicles $t_s = 10$. The battery warranty period for most models under NIO is 8 years. Therefore, the service life of the battery is $t_b = 8$.
(3) The production cost of batteries. This paper takes NIO's 75 kWh lithium battery pack as an example. Following industry practice, we set the unit production cost of ternary lithium battery cells as 0.5 RMB/Wh. Therefore, the production cost of batteries can be calculated as: $c_b = 75 \times 1000 \times 0.5 \approx 3.8 \times 10^4$.
(4) Operating costs of battery swapping. As in Yang et al. [16], the per-use operating cost of NIO's second-generation battery swap station is approximately RMB 90. In addition, based on NIO's operational practices and Hu et al. [25], it is assumed that a battery-swapping vehicle undergoes approximately 700 battery swaps over its lifecycle (assuming a vehicle lifespan of 10 years). Accordingly, the overall cost of battery swapping operations is obtained as $c_s = 700 \times 90 = 6.3 \times 10^4$.
(5) The price of the base vehicle. This paper takes NIO's popular model ES6 Standard Edition (no battery version) as an example, with an official price of 268,000 RMB. Therefore, assuming the price of the base vehicle $p_v = 26.8 \times 10^4$.
(6) The proportion of battery to the vehicle's base price. Taking the NIO ES6 Standard Edition as an example, under its purchase plan, consumers who opt for the battery leasing plan receive a price reduction of 70,000 RMB, which implies that the battery price is approximately 70,000 RMB. Therefore, assuming the proportion of battery to vehicle's base price $\omega = 7/26.8 \approx 0.3$.
(7) The balanced battery cost ratio. NIO's second-generation swapping station incurs a construction cost of approximately 2 million RMB (excluding battery packs), and the station is equipped with 13 standard battery packs. According to NIO, the price of each 75 kWh battery pack is about 70,000 RMB, resulting in a total battery cost of approximately 900,000 RMB. This suggests that battery costs account for roughly 45% of the total investment in a swapping station, which means the share of battery cost in station investment $\gamma \approx 0.45$. In addition, following Wang and Du [17] and Hu et al. [25], the equilibrium battery ratio δ is set to 0.1. From this, it can be concluded that the proportion of balanced battery costs $\lambda = \delta/\gamma \approx 0.2$.
(8) Proportion of cost sharing for battery swapping operation. Following Li and Yuan [21], the proportion of cost sharing is $\mu = 0.1$.

Table 8 presents the parameters described above.

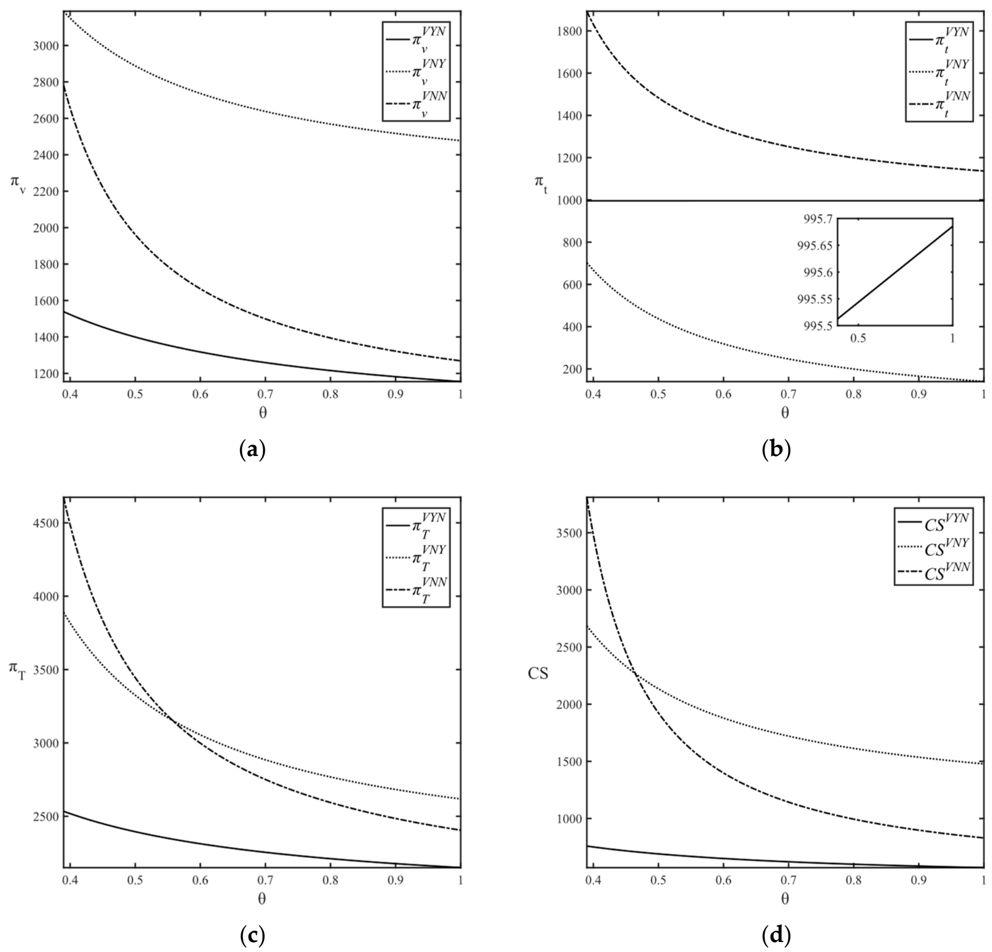
Table 8. Parameter settings.

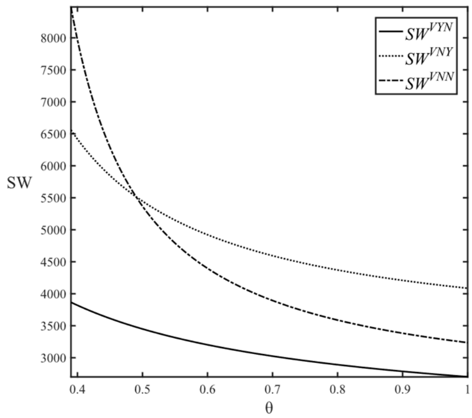
Notation	Actual Value	Units	Scaled Value	Source
α	100×10^4	vehicles	100	Yang et al. [16] and Wang and Du [17]
t_s	10	year	10	Hu et al. [25]
t_b	8	year	8	NIO's data
c_b	3.8×10^4	CNY	3.8	NIO's data

c_s	6.3×10^4	CNY	6.3	Yang et al. [16] and Hu et al. [25]
p_v	26.8×10^4	CNY	26.8	NIO's data
ω	0.3	-	0.3	NIO's data
λ	0.2	-	0.2	Li and Yuan [22]
μ	0.1	-	0.1	Li and Yuan [21]

6.1. The Influence of Swapping Price Sensitivity

According to Figure 2, higher consumer responsiveness to swapping fees generally lowers the earnings of vehicle manufacturers and third-party operators, while also dampening system-wide performance—including supply chain profit, CS, and SW—under most strategies. The only exception is that the profits of third-party operators increase under the VYN strategy. This suggests that higher swapping price sensitivity is broadly detrimental to profitability and overall system performance. However, when vehicle manufacturers only self-operate battery swapping services, third-party operators can benefit from increased consumer price sensitivity.





(**e**)

Figure 2. The influence of θ. (**a**) The influence of θ on π_v. (**b**) The influence of θ on π_t. (**c**) The influence of θ on π_T. (**d**) The influence of θ on CS. (**e**) The influence of θ on SW.

Furthermore, the VNY strategy enables vehicle manufacturers to achieve the highest profits, whereas third-party operators can maximize their profits only when cooperating with vehicle manufacturers adopting the VNN strategy. Regarding overall system performance, when swapping price sensitivity is low, the VNN strategy achieves the optimal performance. Conversely, when price sensitivity is high, the VNY strategy performs better.

6.2. The Influence of Base Vehicle Price

The effect of the vehicle's base price is examined under two scenarios—low and high swapping price sensitivity. Based on NIO's operational data, the feasible range of the vehicle's base price is set as $[20,50]$.

(1) Low swapping price sensitivity;

This subsection focuses on low swapping price sensitivity, i.e., $\theta = 0.4$.

According to Figure 3, at low levels of swapping price sensitivity, VNY leaves both firm profits and system performance unaffected by vehicle's base price fluctuations. Under the VNN and VYN strategies, however, vehicle manufacturer profits exhibit an inverted-U pattern as the vehicle's base price rises. This suggests that a moderate increase in the vehicle's base price can improve manufacturer profitability by enhancing the perceived value of the product. Yet, once the price exceeds a certain threshold, the resulting contraction in demand for battery-swappable vehicles outweighs the higher unit profit, thereby eroding manufacturer profits.

In contrast, the profits of third-party operators and system performance decline monotonically with the vehicle's base price. A higher vehicle's base price dampens demand for battery-swappable vehicles, thereby eroding third-party operators' revenues and weakening system performance.

Moreover, the optimal strategies for firm-level profits and system-wide performance are consistent with the price of the base vehicle. VNN is superior at low price levels, whereas VNY is preferred at high price levels.

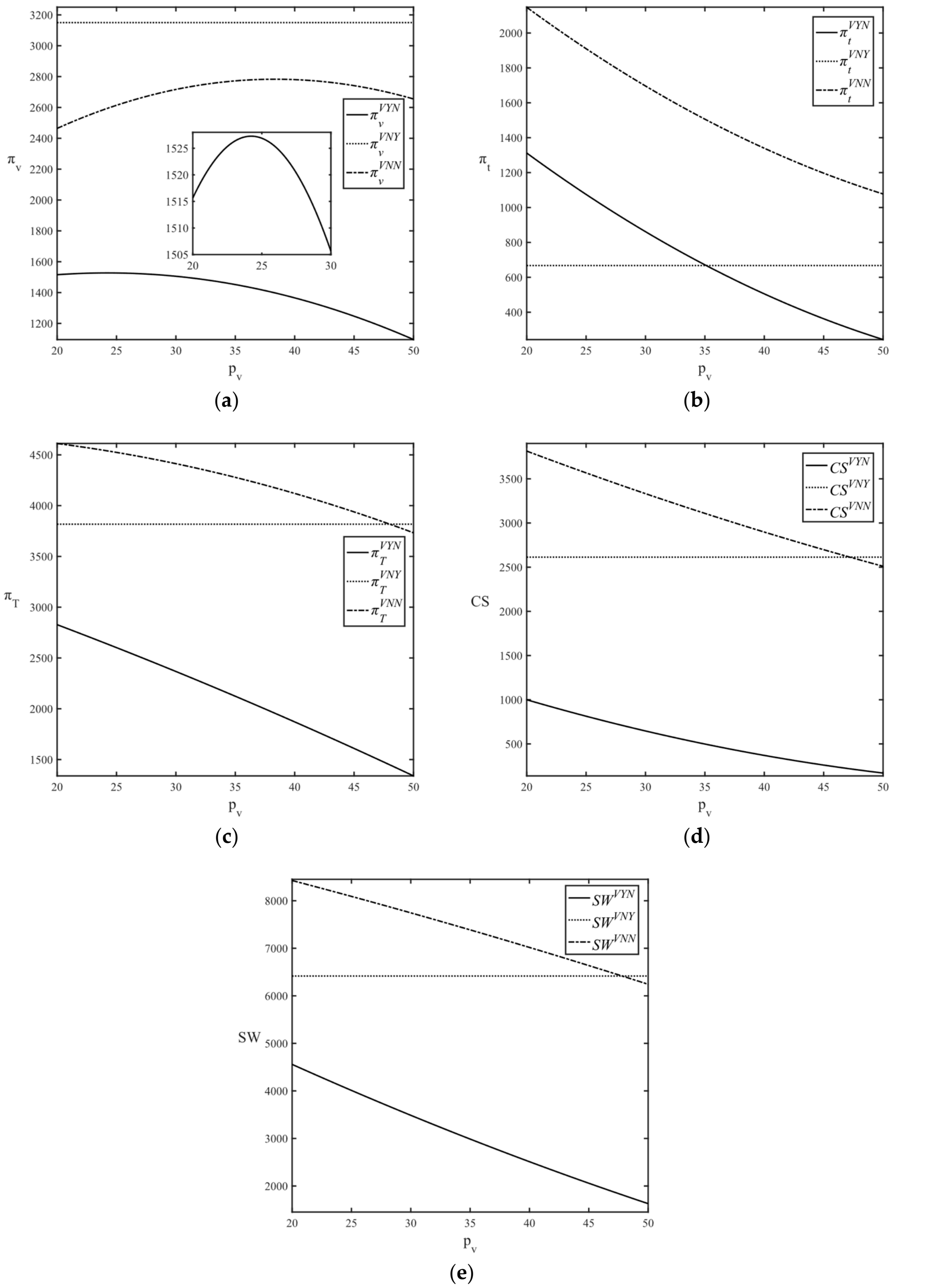


Figure 3. The influence of p_v in low θ. (**a**) The influence of p_v on π_v. (**b**) The influence of p_v on π_t. (**c**) The influence of p_v on π_T. (**d**) The influence of θ on CS. (**e**) The influence of θ on SW.

(2) High swapping price sensitivity.

This subsection examines the case in which consumers are highly sensitive to swapping prices, i.e., $\theta = 0.8$.

According to Figure 4, the effect of the vehicle's base price on equilibrium outcomes under high swapping price sensitivity is comparable to that under low sensitivity (Figure 3).

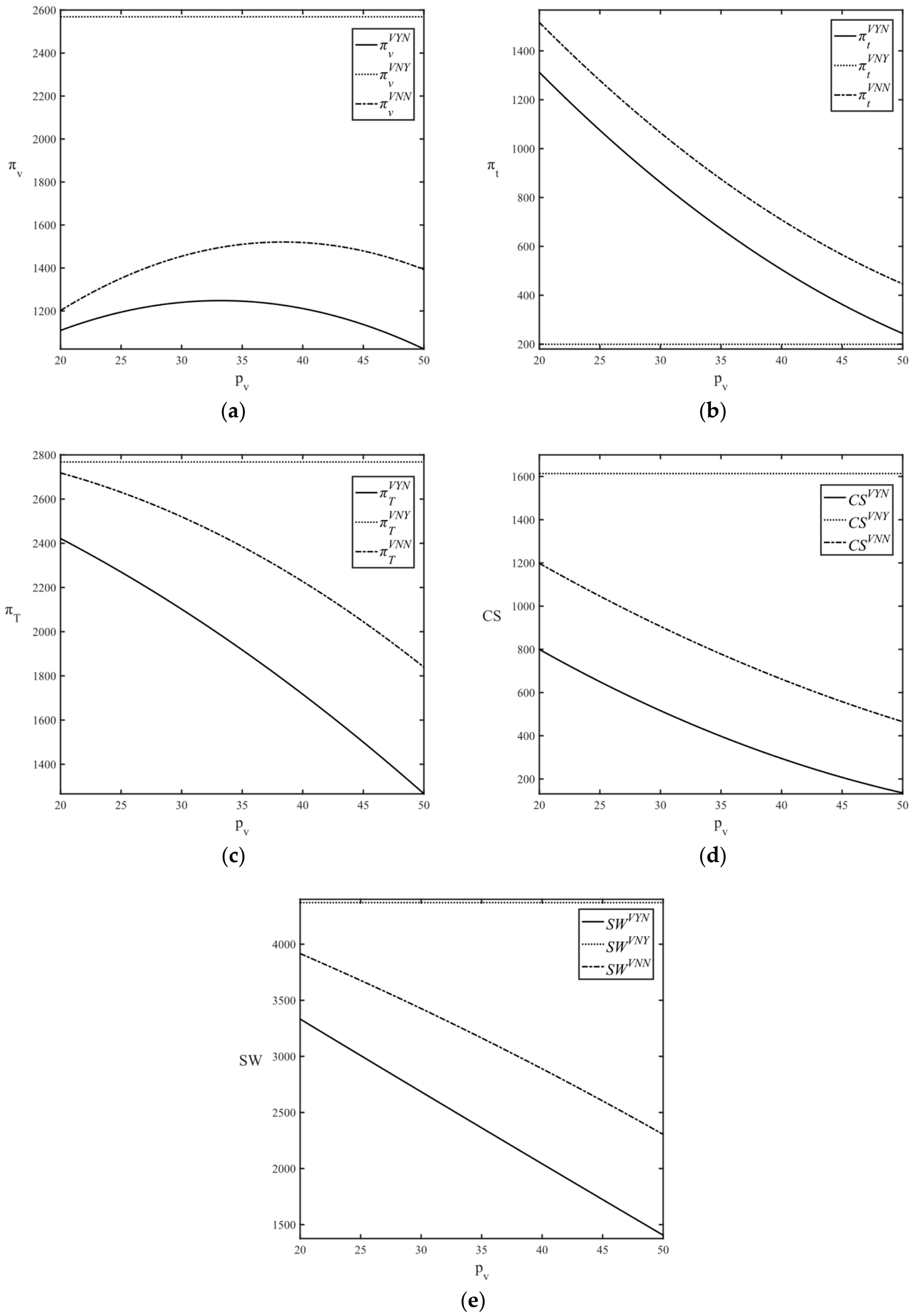


Figure 4. The influence of p_v in high θ. (**a**) The influence of p_v on π_v. (**b**) The influence of p_v on π_t. (**c**) The influence of p_v on π_T. (**d**) The influence of θ on CS. (**e**) The influence of θ on SW.

Furthermore, under all three strategies, the VNY strategy remains optimal for vehicle manufacturers; however, its adoption significantly erodes the profitability of third-party operators. Conversely, the VNN strategy maximizes third-party operators' profits but proves detrimental to both vehicle manufacturers and overall supply chain performance.

In summary, Figures 2–4 reveal a divergence in optimal operational strategies among supply chain members. Vehicle manufacturers consistently prefer VNY, whereas third-

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party operators favor VNN. The optimal strategy for system-wide performance is contingent on the levels of swapping price sensitivity and the vehicle's base price.

6.3. The Influence of Other Parameters

This section further analyzes the impact of other parameters, such as battery rental time and battery cost, on the optimal decisions of firms, as shown in Table 9.

Table 9. Robustness test of the model.

Parameters	Value Range	Unit of Analysis Type	Optimal Strategy
a	$[80,140]$	π_v	VNY
		π_t	VNN
		π_T	VNY
μ	$[0,1]$	π_v	VNY
		π_t	VNN
		π_T	VNY
c_b	$[0,7]$	π_v	VNY
		π_t	VNN
		π_T	VNY
t_s	$[6,15]$	π_v	VNY
		π_t	VNN
		π_T	VNY
t_b	$[6,10]$	π_v	VNY
		π_t	VNN
		π_T	VNY
ω	$[0,0.6]$	π_v	VNY
		π_t	VNN
		π_T	VNY

Table 9 shows that within the feasible ranges of parameters such as a, μ, and other parameters, VNY is optimal for vehicle manufacturers and the supply chain, whereas VNN is optimal for the third-party operators. These results indicate that the optimal strategies at both the firm and supply chain levels are relatively stable within this feasible parameter range.

7. Conclusions

This paper considers a battery swapping supply chain with a vehicle manufacturer and a third-party operator under the VBS model, which offers BLS services. Based on the automaker's external provision of these services, three strategies are defined: provision of swapping only (VYN strategy), provision of leasing only (VNY strategy), and full outsourcing of both (VNN strategy). The main results are presented below.

(1) Numerical analysis reveals that VNY is optimal for the vehicle manufacturer, whereas the third-party operator prefers to cooperate with a manufacturer adopting VNN. The strategy that maximizes total supply chain profit depends on swapping price sensitivity and the vehicle's base price: VNN is optimal when both are low; otherwise, VNY is optimal.

(2) To promote the adoption of battery-swappable vehicles, vehicle manufacturers should outsource swapping services (i.e., adopt VNY or VNN). The choice between these two strategies is contingent on consumer sensitivity to swapping fees, the vehicle's base price, and battery cost.

(3) To facilitate the expansion of battery swapping services, automakers should outsource leasing services (i.e., adopt VYN or VNN). The optimal selection is influenced by the sensitivity of swapping price, the vehicle's base price, and the cost of swapping operation.

These findings yield the following managerial implications.

(1) From a supply chain perspective, the optimal service operation strategy depends on the price sensitivity of swapping and the vehicle's base price. When both are low, VNN is recommended; otherwise, VNY is more effective in improving overall supply chain performance.
(2) The results further reveal an incentive misalignment between the two parties: the vehicle manufacturer's optimal strategy may reduce the third-party operator's profit, and vice versa.
(3) To accelerate the adoption of battery-swappable vehicles, vehicle manufacturers should consider outsourcing swapping services, thereby allowing them to focus on vehicle manufacturing.
(4) To facilitate the widespread adoption of battery swapping services, vehicle manufacturers should consider outsourcing leasing services. Transferring leasing operations to third-party operators reduces operational and financial burdens; this enables more efficient leasing services and further accelerates the development of the battery swapping ecosystem.

This study examines operation outsourcing strategies under the VBS model from the automaker's perspective, without considering competitive interactions among multiple manufacturers—a factor that may significantly influence outsourcing decisions and market performance. Beyond this competitive dimension, several other modeling simplifications also warrant future exploration. First, the vehicle body price is treated as exogenous to maintain focus on the core operational pricing of BLS services; a natural extension would be to endogenize and examine joint pricing decisions. Second, our current model adopts a deterministic demand specification, which does not capture market uncertainty. A natural extension would be to incorporate stochastic demand to test the robustness of our findings. Third, our analysis is confined to a single-period horizon; extending it to a multi-period or infinite-horizon framework would capture dynamic aspects such as battery degradation. These extensions together offer a coherent agenda for future research.

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Appendix A

The first-order condition for the third-party operator's profit function in Equation (2) is given as $\frac{\partial \pi_t(p_r)}{\partial p_r} = \frac{t_s(t_s \omega p_v - 2p_r t_s t_b + a t_b + \mu t_b - p_v t_b)}{t_b}$. The second derivative is $-2t_s^2$. Since the second-order derivative is negative, there exists a unique optimal solution p_r

that maximizes the profit function π_t. Let $\frac{\partial \pi_t(p_r)}{\partial p_r}=0$, then we obtain $p_r=\frac{t_s\omega p_v+at_b+\mu c_s t_b-p_v t_b}{2t_s t_b}$. Substituting the optimal decision p_r of the third-party operator into Equation (1), the first-order derivative of $\pi_v(p_s)$ over p_s is obtained as $\frac{\partial \pi_v(p_s)}{\partial p_s}=\frac{-2\mu\theta c_s t_b-\mu c_s t_b-\omega p_v t_s+2\theta c_s t_b-4\theta p_s t_b+at_b-p_v t_b}{2t_b}$. The second derivative of Equation (1) is -2θ. This guarantees the uniqueness of the optimal solution p_s that maximizes the objective function π_v. Let $\frac{\partial \pi_v(p_s)}{\partial p_s}=0$, then we obtain $p_s=\frac{-2\mu\theta c_s t_b-t_s\omega p_v+2\theta c_s t_b+at_b-\mu c_s t_b-p_v t_b}{4t_b\theta}$. By substituting this result into p_r, the optimal leasing price can be obtained. Subsequently, substituting the optimal service prices into the demand functions, yields the corresponding optimal demands $D_v^{\text{VYN}}=\frac{at_b-t_s\omega p_v-\mu c_s t_b-p_v t_b}{2t_b}$ and $D_s^{\text{VYN}}=\frac{2\mu\theta c_s t_b-t_s\omega p_v-2\theta c_s t_b+at_b-\mu c_s t_b-p_v t_b}{4t_b}$. Finally, substituting the optimal prices and demand into Equations (1) and (2) yields the equilibrium profits, represented by

$$\pi_v^{\text{VYN}}=\frac{\left\{\begin{array}{l}2X_2(4\theta c_b X_1-c_s t_b(6\mu\theta-\mu-2\theta)+at_b(4\theta-1))p_v\\-X_2^2(8\theta-1)p_v^2+t_b\left(\begin{array}{l}t_b\left(2\theta c_s(\mu-1)+a-\mu c_s\right)^2\\-8\theta X_1(a-\mu c_s)c_b\end{array}\right)\end{array}\right\}}{16\theta t_b^2}$$

and

$$\pi_t^{\text{VYN}}=\frac{X_2^2 p_v^2-t_b X_2(2a-\mu c_s)p_v+t_b^2\left(2\mu\theta c_s^2(1-\mu)+a^2-a\mu c_s\right)}{4t_b^2}$$, respectively.

Appendix B

The first-order condition of p_s for the third-party operator's profit function in Equation (10) is given by $\frac{\partial \pi_t(p_s)}{\partial p_s}=a-\theta p_s-t_s p_r-p_v-\left(p_s-c_s(1-\mu)-h\right)\theta$, and the corresponding second-order derivative is -2θ. Given the negativity of the second-order derivative, there exists a unique optimal solution p_s that maximizes the profit function π_t. Solving $\frac{\partial \pi_t(p_s)}{\partial p_s}=0$ yields $p_s=\frac{h\theta-\mu\theta c_s+\theta c_s-t_s p_r+a-p_v}{2\theta}$. Substituting p_s into Equation (9), we derive the first-order partial derivatives of $\pi_v(p_r,h)$ with respect to p_r and h as $\frac{\partial \pi_v(p_r,h)}{\partial p_r}=\frac{t_s\left(2\lambda c_b t_b-4t_s p_r t_b+2at_b-ht_b+\mu t_b+2t_s c_b-4p_v t_b\right)}{2t_b}$, $\frac{\partial \pi_v(p_r,h)}{\partial h}=\frac{1}{2}\mu\theta+\frac{1}{2}\mu\theta c_s-h\theta-\frac{1}{2}\theta c_s-\frac{1}{2}t_s p_r+\frac{1}{2}a-\frac{1}{2}p_v$. The associated Hessian matrix is $H=\begin{bmatrix}-2t_s^2 & -1/2t_s\\ -1/2t_s & -\theta\end{bmatrix}$. For H to be negative definite, the condition $8\theta-1>0$ must be satisfied. Consequently, π_v is jointly concave in p_r and h, which guarantees the existence of a unique pair of optimal solutions. Solving the first-order conditions

$\frac{\partial \pi_v(p_r,h)}{\partial p_r}=0$ and $\frac{\partial \pi_v(p_r,h)}{\partial h}=0$ simultaneously yields $p_r^{\mathrm{VNY}}=\frac{4\lambda\theta c_b t_b+4a\theta t_b+4\theta c_b t_s+\theta c_s t_b-8\theta p_v t_b-at_b+p_v t_b}{t_b t_s(8\theta-1)}$ and $h^{\mathrm{VNY}}=\frac{4\theta c_s t_b(2\mu-1)-2\lambda c_b t_b-\mu c_s t_b+2at_b-2c_b t_s}{t_b(8\theta-1)}$. Applying backward substitution, we insert p_r and h into p_s, thereby obtaining $p_s^{\mathrm{VNY}}=\frac{2\theta c_s t_b-3\lambda c_b t_b+3at_b-3c_b t_s-c_s t_b}{t_b(8\theta-1)}$, which in turn gives the corresponding optimal demands $D_v^{\mathrm{VNY}}=\frac{\theta(4at_b-4\lambda c_b t_b-4c_b t_s-c_s t_b)}{t_b(8\theta-1)}$ and $D_s^{\mathrm{VNY}}=\frac{\theta(at_b-\lambda c_b t_b-2\theta c_s t_b-c_b t_s)}{t_b(8\theta-1)}$. Finally, substituting all optimal prices and demands into Equations (9) and (10) yields the equilibrium profits, denoted by $\pi_v^{\mathrm{VNY}}=\frac{\left(2X_1^2c_b^2-t_bX_1(4a-c_s)c_b+t_b^2\left(\theta c_s^2+2a^2-ac_s\right)\right)\theta}{(8\theta-1)t_b^2}$ and $\pi_t^{\mathrm{VNY}}=\frac{\theta(at_b-\lambda c_b t_b-2\theta c_s t_b-c_b t_s)^2}{t_b^2(8\theta-1)^2}$, respectively.

Appendix C

The first derivative of the third-party operator's profit $\pi_t(p_r,p_s)$ in Equation (19) with respect to p_r and p_s is: $\frac{\partial \pi_t(p_r,p_s)}{\partial p_r}=\frac{t_s(t_s\omega p_v-2t_s p_r t_b+at_b+t_b h+t_b c_s-t_b p_s-p_v t_b)}{t_b}$ and $\frac{\partial \pi_t(p_r,p_s)}{\partial p_s}=a-\theta p_s-t_s p_r-p_v-(p_s-c_s-h)\theta$. The corresponding Hessian matrix is $H=\begin{bmatrix}-2t_s^2 & -t_s\\ -t_s & -2\theta\end{bmatrix}$. For this Hessian to be negative definite, the condition $4\theta-1>0$ must be satisfied. Under this condition, π_t is jointly concave in p_s and p_r. Solving the simultaneous first-order conditions $\frac{\partial \pi_t(p_r,p_s)}{\partial p_r}=0$ and $\frac{\partial \pi_t(p_r,p_s)}{\partial p_s}=0$ yields the unique optimal solutions $p_r^{\mathrm{VNN}}=\frac{2\omega\theta p_v t_s+2a\theta t_b+h\theta t_b+\theta c_s t_b-2\theta p_v t_b-at_b+p_v t_b}{t_b t_s(4\theta-1)}$ and $p_s^{\mathrm{VNN}}=\frac{2h\theta t_b-t_s\omega p_v+2\theta c_s t_b+at_b-t_b h-t_b c_s-p_v t_b}{t_b(4\theta-1)}$. Turning to the vehicle manufacturer's problem, differentiating the profit function in Equation (18) with respect to h yields the first-order condition $h=\frac{\theta(\lambda c_b t_b-4h\theta t_b-2t_s\omega p_v-2\theta c_s t_b+at_b+c_b t_s-2p_v t_b)}{t_b(4\theta-1)}$. The second-order derivative is strictly negative $-\frac{4\theta^2}{4\theta-1}$ which guarantees the existence of a unique optimal solution that maximizes π_v. Let $\frac{\partial \pi_v(h)}{\partial h}=0$, we can get $h=\frac{\lambda c_b t_b-2t_s\omega p_v-2\theta c_s t_b+at_b+c_b t_s-2p_v t_b}{4\theta t_b}$. By substituting this result into p_r and p_s, we derive $p_r^{\mathrm{VNN}}=\frac{2X_3(\omega t_s-t_b)p_v+8a\theta t_b+\lambda c_b t_b+2\theta c_s t_b-3at_b+c_b t_s}{4t_b t_s X_3}$ and

$p_s^{\text{VNN}} = \frac{(2\theta-1)X_1c_b - 2X_3X_2p_v + t_b\left(4\theta^2c_s + 6a\theta - 2\theta c_s - a\right)}{4\theta t_b X_3}$. Consequently, the corresponding demands are obtained as $D_v^{\text{VNN}} = \frac{8a\theta t_b - 2X_3X_2p_v - 2\theta c_s t_b - at_b - X_1c_b}{4t_bX_3}$ and $D_s^{\text{VNN}} = \frac{\theta\left(at_b - \lambda c_b t_b - 2\theta c_s t_b - c_b t_s\right)}{2t_bX_3}$. Finally, substituting the prices, as well as the demands into Equations (18) and (19) yields $\pi_v^{\text{VNN}} = \frac{\left\{\begin{array}{l}4X_3X_2\left(\lambda c_b t_b + at_b + c_b t_s\right)p_v - 4X_2^2X_3p_v^2 + X_1^2 \\ -2t_bX_1\left(8a\theta - 2\theta c_s - a\right) + t_b^2\left(a - 2\theta c_s\right)^2\end{array}\right\}}{8t_b^2X_3}$ and $\pi_t^{\text{VNN}} = \frac{\left\{\begin{array}{l}4X_2^2X_3p_v^2 - 8at_bX_3X_2p_v + X_1^2c_b^2 - 2t_bX_1\left(a - 2\theta c_s\right)c_b \\ +t_b^2\left(4\theta^2c_s^2 + 16a^2\theta - 4a\theta c_s - 3a^2\right)\end{array}\right\}}{16t_b^2X_3}$, respectively.

Appendix D

$$p_s^{\text{VYN}} - p_s^{\text{VNY}} = -\frac{\left\{\begin{array}{l}(8\theta-1)\left(\omega t_s + t_b\right)p_v + c_s t_b(2\theta+1)(8\theta-1)\mu \\ +4\theta\left(at_b - 3\lambda c_b t_b - 2\theta c_s t_b - 3c_b t_s\right) - 2\theta c_s t_b + at_b\end{array}\right\}}{4t_b\theta(8\theta-1)} \tag{A1}$$

$$p_s^{\text{VYN}} - p_s^{\text{VNN}} = -\frac{\left\{\begin{array}{l}2\theta t_b\left(a - 2\theta c_s\right) - (4\theta-1)\left(\omega t_s + t_b\right)p_v \\ +t_b c_s(2\theta+1)(4\theta-1)\mu + 2(\theta - 1/2)\left(\lambda t_b + t_s\right)c_b\end{array}\right\}}{4t_b\theta(4\theta-1)} \tag{A2}$$

The numerator of Equation (A1) is the sum of three positive terms, from which the sign of the equation directly follows. Therefore, Equation (A1) is negative.

The sign of Equation (A2) turns on the sign of its numerator $f\left(p_v^2\right)$, and we can obtain $p_v^2 = \left(t_b c_s(2\theta+1)(4\theta-1)\mu + 2\theta\left(\lambda c_b t_b + at_b + c_b t_s\right) - 4\theta^2c_s t_b - \lambda c_b t_b - c_b t_s\right)/\left((4\theta-1)\left(\omega t_b + t_s\right)\right)$. Furthermore, the sign of p_v^2 lies in its numerator $f(\mu)$ which can be derived $\mu = -\frac{2\lambda\theta c_b t_b - 4\theta^2c_s t_b + 2a\theta t_b - \lambda c_b t_b + 2\theta c_b t_s - c_b t_s}{t_b c_s(2\theta+1)(4\theta-1)} < 0$. Therefore, we obtain $p_v^2 > 0$.

In conclusion, when $p_v < p_v^2$, $p_s^{\text{VYN}} < \left\{p_s^{\text{VNY}}, p_s^{\text{VNN}}\right\}$; when $p_v \geq p_v^2$, $p_s^{\text{VNN}} < \left\{p_s^{\text{VYN}}, p_s^{\text{VNY}}\right\}$.

Appendix E

$$D_v^{\text{VYN}} - D_v^{\text{VNN}} = -\frac{8\mu\theta c_s t_b - \lambda c_b t_b - 2\mu c_s t_b - 2\theta c_s t_b + at_b - c_b t_s}{4t_b(4\theta-1)} \tag{A3}$$

$$D_v^{\text{VNY}} - D_v^{\text{VNN}} = -\frac{\left\{\begin{array}{l}\left(64\theta^2 - 24\theta + 1\right)\left(\lambda t_b + t_s\right)c_b - 2\theta c_s t_b + at_b \\ -2(8\theta-1)(4\theta-1)\left(\omega t_s + t_b\right)p_v\end{array}\right\}}{4t_b(8\theta-1)(4\theta-1)} \tag{A4}$$

According to the decision variables and the non-negativity constraints on parameters, Equation (A3) is negative. The numerator $f\left(c_b^1\right)$ dictates the sign of Equation (A4), and we obtain $c_b^{\,1} = -\left(at_b - 2\theta c_s t_b - 2(8\theta-1)(4\theta-1)(\omega t_s + t_b)\,p_v\right)\Big/\left(\left(64\theta^2 - 24\theta + 1\right)(\lambda t_b + t_s)\right)$. By considering the numerator of $c_b^{\,1}$ as $f\left(p_v^{\,1}\right)$, we can obtain $p_v^{\,1} = \left(t_b\,(a - 2\theta c_s)\right)\Big/\left(2(8\theta-1)(4\theta-1)(\omega t_s + t_b)\right) > 0$. Similarly, by considering the denominator of $c_b^{\,1}$ as $f\left(\theta^1\right)$, we can obtain $\theta^1 = \left(3+\sqrt{5}\right)\Big/16$.

Therefore, Corollary 3 follows from the relationships among θ^1, $p_v^{\,1}$, and $c_b^{\,1}$.

Appendix F

$$D_s^{\mathrm{VYN}} - D_s^{\mathrm{VNN}} = \frac{\begin{Bmatrix} t_b\,(2\theta-1)(4\mu\theta-\mu-2\theta)\,c_s - (4\theta-1)(\omega t_s + t_b)\,p_v \\ +2\lambda\theta c_b t_b + 2a\theta t_b + 2\theta c_b t_s - a t_b \end{Bmatrix}}{4t_b\,(4\theta-1)} \tag{A5}$$

$$D_s^{\mathrm{VNY}} - D_s^{\mathrm{VNN}} = -\frac{\theta\left(at_b - \lambda c_b t_b - 2\theta c_s t_b - c_b t_s\right)}{2t_b\,(8\theta-1)(4\theta-1)} \tag{A6}$$

The numerator $f\left(c_s^{\,1}\right)$ of Equation (A5) determines its sign and $c_s^{\,1} = -\left(2\lambda\theta c_b t_b + 2a\theta t_b + 2\theta c_b t_s - at_b - (4\theta-1)(\omega t_s + t_b)\,p_v\right)\Big/\left(t_b\,(2\theta-1)(4\mu\theta-\mu-2\theta)\right)$. Furthermore, by analyzing the sign of the numerator $f\left(p_v^{\,3}\right)$ of $c_s^{\,1}$, we obtain $p_v^{\,3} = \left(2\lambda\theta c_b t_b + 2a\theta t_b + 2\theta c_b t_s - at_b\right)\Big/\left((4\theta-1)(\omega t_s + t_b)\right)$. Furthermore, the denominator of $c_s^{\,1}$ is related to $\theta = 1/2$. Therefore, based on the relationship between $\theta = 1/2$, $p_v^{\,3}$ and $c_s^{\,1}$, the sign of Equation (A5) can be obtained. Given the decision variables and the non-negativity constraints on parameters, Equation (A6) is negative. Thus, Corollary 4 can be derived.

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