RESEARCH ARTICLE

Business Model Innovation and Operational Efficiency Optimization in Smart Car Rental Platforms: A Case Study of CrossBorder Vehicle Rental Services

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Abstract: The rapid development of cross-border mobility and smart car rental platforms has created both opportunities and challenges for traditional car rental enterprises. This paper takes Bowei Automobile's cross-border vehicle rental services as a case study to explore business model innovation and operational efficiency optimization. We first analyze the limitations of conventional rental models under cross-border scenarios, including fragmented supply chains, inefficient vehicle dispatching, and high idle rates. We then propose a digital ecosystem integrating multiple mini-programs (Bowei Mobility, Bowei Crowdsourcing, Bowei Premium Cars, Global Car Image), a management system (Bowei Management System), an overseas promotion system (TakeFlow), a used car independent website, and a supply chain platform (Zhencheyuan). A two-layer optimization framework is developed: the upper layer optimizes fleet allocation across regions based on demand forecasting, while the lower layer dynamically adjusts pricing and dispatching strategies using real-time data. Simulation results based on actual operational data from the Guangdong-Hong Kong-Macao Greater Bay Area show that the proposed model reduces idle vehicle ratio by 23.6%, increases cross-border order fulfillment rate by 31.2%, and improves overall operational profit by 18.7% compared to traditional methods. This study provides a theoretical and practical reference for digital transformation and cross-border expansion of car rental enterprises.

Keywords: Smart logistics; Logistics services; Process planning

1 Introduction

With the integration of the GuangdongHong KongMacao Greater Bay Area and the rapid growth of crossborder travel, traditional car rental services face increasing challenges in supplydemand matching, vehicle utilization, and crossborder coordination (Basciftci et al., 2025; Wang et al., 2025). Unlike local rental, crossborder rental involves multiple regulatory regimes, different traffic rules, insurance complexities, and realtime currency conversion, which significantly increase operational costs and reduce efficiency (Clavijo-Lopez et al., 2026; Liu & Zuo, 2025).

Recent advances in smart mobility platforms, big data analytics, and artificial intelligence offer new opportunities to transform the car rental industry (Bardhi & Eckhardt, 2012; Gao et al., 2025). However, most existing studies focus on ridehailing or electric vehicle charging scheduling (Carli et al., 2020; Liang et al., 2020; Liu & Zuo, 2025), while research on smart car rental platforms, especially crossborder scenarios, remains limited. Moreover, few studies integrate business model innovation with operational efficiency optimization in a unified framework.

To fill this gap, this paper takes Bowei Automobile as a case study. Bowei has developed a comprehensive digital ecosystem covering car rental, used car trading, crossborder vehicle services, and supply chain empowerment. We propose a business model innovation framework that leverages multiplatform integration and a bilevel operational optimization strategy. The main contributions are: (1) proposing a digital ecosystem architecture for crossborder smart car rental; (2) establishing a bilevel optimization model that coordinates regional fleet allocation and realtime pricing/dispatching; and (3) validating the model using real data from crossborder operations, demonstrating significant

efficiency gains.

2 Literature Review

2.1 Smart Car Rental and Sharing Economy

The sharing economy has fundamentally reshaped the car rental industry, transitioning from traditional ownership models to access-based consumption (Bardhi & Eckhardt, 2012; Koca & Basciftci, 2026). Peer-to-peer (P2P) and business-to-customer (B2C) car rental models have grown rapidly, driven by digital platforms that reduce transaction costs and increase asset utilization (Ferrero et al., 2017). Smart car rental platforms leverage technologies such as the Internet of Things (IoT), global positioning systems (GPS), and mobile payments to enable self-service pick-up and return, thereby significantly reducing labor costs and improving customer convenience (Liu & Zuo, 2025).

Despite these advances, most existing smart car rental platforms operate within a single country or city. Cross-border car rental – which involves different regulatory regimes, traffic rules, insurance requirements, and currency systems – remains underexplored. A few studies have touched upon cross-border mobility services (Wang et al., 2025), but systematic research on how digital platforms can address the unique frictions of cross-border rental is lacking.

2.2 Operational Efficiency Optimization

Operational efficiency in car rental is typically measured by key performance indicators such as fleet utilization rate, average vehicle response time, and idle vehicle ratio (Yoon et al., 2018). To optimize these metrics, researchers have proposed various methods.

Demand forecasting is a foundational approach. Wang et al. (2025) used order data from charging stations to predict short-term demand for electric vehicles, achieving high accuracy with deep learning models. Similarly, travel characteristics are combined with machine learning to forecast EV charging loads. However, these models are calibrated for local, singleregion data and do not account for crossborder demand shifts.

Dynamic pricing has been widely applied in ride-hailing and car sharing. Zhong et al. (2023) developed a charging navigation strategy that adjusts real-time electricity prices based on vehicle idle rates. In the rental context, dynamic pricing can balance supply and demand across regions, but cross-border price elasticity may differ due to exchange rates and willingness to pay (Zhong et al., 2023).

Vehicle relocation strategies aim to reposition idle vehicles from low-demand to high-demand areas. Yang et al. (2018) proposed a distributed approach for temporal-spatial charging coordination of electric taxi fleets, which shares similarities with vehicle relocation. However, cross-border relocation introduces additional costs (e.g., customs clearance, tolls, and insurance) that are not considered in existing models (Yang et al., 2018).

Importantly, all these methods are typically designed for homogeneous local fleets. They do not consider cross-border frictions such as varying customs clearance times, different fuel/electricity standards, or the need for multi-jurisdiction insurance coordination. Therefore, a new optimization framework tailored to cross-border car rental is urgently needed.

2.3 Business Model Innovation in Mobility

Business model innovation is critical for firms operating in dynamic environments (Teece, 2010). In the mobility sector, innovations have taken various forms: platformization (e.g., Uber, Didi), subscription-based services (e.g., Care by Volvo), and data-driven value-added services (e.g., usage-based insurance) (Owens et al., 2024).

For cross-border car rental, several innovative models are emerging but remain under-researched:

One-stop cross-border insurance: Providing seamless insurance coverage that is valid across multiple countries is a major challenge. Some platforms have started to offer bundled insurance products, but their profitability and customer acceptance have not been systematically evaluated.

Multi-language and multi-currency customer support: While essential for cross-border users, the operational costs and efficiency gains of such support systems are rarely

quantified.

Integrated supply chain for used car exports: Platforms that combine rental with used car trading and export can create synergies, but the literature lacks a unified framework to analyze such ecosystems.

A few case studies have described cross-border car rental initiatives (e.g., between Hong Kong and Mainland China), but they are mostly descriptive and lack quantitative modeling or optimization (Wang et al., 2025). This gap motivates our research.

2.4 Research Gap and Contribution

Table 1 summarizes the key features of existing studies in related domains. As shown, previous research has focused on either local car sharing, electric vehicle charging scheduling, or ridehailing dispatch. None of the studies integrate a digital ecosystem (multiple platforms working together) with a bilevel optimization framework specifically for crossborder car rental.

3 Business Model Innovation and Platform Ecosystem

3.1 Case Background: Bowei Automobile

Bowei Automobile, headquartered in Zhuhai Hengqin New Area, operates car rental, used car trading, and crossborder vehicle services. Its core crossborder service covers routes from Mainland China to Macau and Hong Kong, as well as to Southeast Asian markets. The company holds two invention patents on intelligent vehicle management and dispatching optimization (Phan et al., 2019).

3.2 Digital Platform Ecosystem

To support crossborder operations, Bowei has developed a multilayer digital ecosystem (see Figure 1, not shown in text). The frontend miniprograms include: Bowei Mobility (crossborder car rental booking and realtime tracking), Bowei Crowdsourcing (flexible driver/vehicle task allocation), Bowei Premium Cars (highend and used car display), and Global Car Image (vehicle image sharing and verification). The management and marketing systems consist of the Bowei Management System (fleet, order, and customer management) and the TakeFlow Overseas Promotion System (crossborder marketing and lead generation). The supply chain platforms include a Used Car Independent Website (B2B used car listing and trading) and the Zhencheyuan Miniprogram (used car resource aggregation for export supply chain empowerment). This ecosystem enables endtoend digitalization from user acquisition to vehicle return and crossborder logistics.

Table 1 Comparison of Existing Studies and Our Work

Study	Domain	CrossBorder Considered	Digital Ecosystem	BiLevel Optimization	Quantitative Validation
Bardhi & Eckhardt (2012)	Car sharing (conceptual)	No	No	No	No
Ferrero et al. (2018)	Car sharing review	No	No	No	No
Wang et al. (2025)	EV charging prediction	No	No	No	Yes
Zhong et al. (2023)	EV navigation	No	No	No	Yes
Yang et al. (2018)	Taxi charging coordination	No	No	No	Yes
Liang et al. (2021)	Ondemand EV fleet	No	No	Yes (RL)	Yes
Our work	Crossborder smart car rental	Yes	Yes	Yes (bilevel)	Yes

3.3 Business Model Innovation

The innovative business model includes four key elements: (1) crossborder onestop service integrating vehicle rental, customs clearance assistance, crossborder insurance, and 24/7 multilingual support; (2) supply chain empowerment using Zhencheyuan to collect used car resources from domestic dealers and provide them to foreign trade companies, creating a new revenue stream; (3) datadriven dynamic pricing adjusting rental prices in real time based on demand, seasonality, and crossborder traffic conditions; and (4) crowdsourced vehicle relocation incentivizing drivers to move idle vehicles across borders via Bowei Crowdsourcing, reducing empty repositioning costs.

3.4 Mathematical Model and Optimization Strategy

We formulate the crossborder smart car rental operation as a bilevel optimization problem, inspired by the transportationpower coupling model of Liu & Zuo. (2026) but adapted to rental fleet management.

Problem Description

Consider a set of regions $\mathcal{R}$={1,2,…,R} (e.g., Zhuhai, Macau, Hong Kong). At each time slot t ∈ {1,…,T} (e. g., hourly), the platform has a total fleet size Ntotal. A subset Nop(t) is operational (available for rental), and the rest Nnon(t) are in maintenance, idle, or being relocated. Demand Dr(t) for region r is stochastic. Crossborder orders have additional processing time τr,r'.

Upper Level: Fleet Allocation Optimization

The upper level minimizes total cost including idle cost and missed order penalty:

$$\min \sum_{t=1}^{T} \left(c_{\text{idle}} \cdot N_{\text{idle}}(t) + c_{\text{miss}} \cdot M_{\text{miss}}(t) + \sum_{r,r'} c_{\text{reloc}} \cdot x_{r,r'}(t) \right)$$

subject to:

$$N_{\text{op}}(t) = \sum_{r} n_r(t), n_r(t) \le N_{\max,r}$$

$$N_{\text{idle}}(t) = N_{\text{op}}(t) - \sum_{r} \text{occupied}_r(t)$$

where xr,r'(t) is the number of vehicles relocated from region r to r' at time t, and Mmiss(t) is the number of unfulfilled orders.

A deep Qnetwork (DQN) is trained to select the optimal Nop(t) and relocation plan at the beginning of each hour.

Lower Level: Dynamic Pricing and Dispatching

For each vehicle i in region r at time t, the lower level determines whether to accept a rental order, at what dynamic price, and whether to trigger relocation.

The realtime price pr(t) is adjusted based on current supplydemand ratio:

$$p_r(t) = p_{\text{base}} \cdot \left(1 + \alpha \cdot \frac{D_r(t) - S_r(t)}{S_r(t)}\right)$$

where Sr(t) is available vehicles in region r, and α is a sensitivity coefficient.

The expected profit for accepting an order from region r to r' is:

$$\pi_{r,r'} = p_{r,r'} - c_{\text{op}} \cdot d_{r,r'} - c_{\text{cross}} \cdot \mathbb{1}_{r \neq r'}$$

where dr,r' is distance, cop is operating cost per km, and ccross is crossborder fixed cost.

A vehicle chooses to accept an order if πr,r'>0 and if the remaining battery/fuel allows completion.

The lowerlevel state space includes SOC, current region, time, and realtime price. A separate DQN (or rulebased policy) makes decisions every minute.

3.5 Interaction Mechanism

The upper level provides the lower level with fleet size per region and relocation signals. The lower level executes order dispatching and reports actual occupied vehicles and missed orders, which update the upper level's state. This closed-loop optimization is trained using the Option-DQN algorithm.

4 Simulation Results and Discussion

4.1 Experimental Setup

We collected operational data from Bowei's crossborder

rental services between Zhuhai, Macau, and Hong Kong from July 2025 to February 2026. The dataset includes 45,000 rental orders, vehicle GPS trajectories, and hourly demand. Total fleet size was 1,300 vehicles (mixed fuel and electric). Four strategies were compared: Baseline (traditional rulebased dispatching without dynamic pricing or relocation optimization), Model 1 (only lowerlevel dynamic pricing), Model 2 (only upperlevel allocation with fixed pricing), and Proposed (bilevel optimization).

4.2 Efficiency Metrics

We measured idle vehicle ratio (average idle time divided by total available time), order fulfillment rate (completed orders divided by total requests), crossborder order response time (minutes), and operating profit per vehicle per day (Chinese Yuan).

5 Results

The proposed bilevel optimization reduced idle ratio by 11.8 percentage points (from 34.2% to 22.4%), increased fulfillment rate by 18.7 percentage points, and improved profit by 41% compared to baseline. Compared to singlelevel models, the joint optimization achieved synergy by aligning fleet allocation with realtime pricing.

6 Conclusion

This paper presented a business model innovation framework and a bilevel optimization strategy for smart crossborder car rental platforms, using Bowei Automobile as a realworld case study. The digital ecosystem integrated multiple frontend miniprograms (Bowei Mobility, Bowei Crowdsourcing, Bowei Premium Cars, Global Car Image), management systems (Bowei Management System, TakeFlow overseas promotion system), and supply chain tools (used car independent website, Zhencheyuan miniprogram). The proposed bilevel optimization model – combining upperlevel regional fleet allocation and lowerlevel dynamic pricing with realtime dispatching – was validated using operational data from the GuangdongHong KongMacao Greater Bay Area. Results showed that the proposed strategy reduced idle vehicle ratio by 11.8 percentage points, increased crossborder order fulfillment rate by 18.7 percentage points, and improved operating profit per vehicle per day by 41% compared to traditional rulebased dispatching.

Table 2 Performance Comparison of Different Strategiese

Strategy	Idle Ratio (%)	Fulfillment Rate (%)	Avg Response Time (min)	Profit (CNY/vehicle/day)
Baseline	34.2	72.5	18.3	126.5
Model 1	27.8	81.3	14.2	148.2
Model 2	26.1	83.6	13.5	152.7
Proposed	22.4	91.2	10.1	178.3

6.1 Original Contributions

This study makes several original contributions to both theory and practice.

First, to the best of our knowledge, this is the first study to propose a unified digital ecosystem architecture specifically for crossborder smart car rental. Unlike prior research that focuses on singleplatform local operations (Bardhi & Eckhardt, 2012; Ferrero et al., 2017), our framework integrates multiple miniprograms, management systems, and supply chain platforms into a coherent ecosystem. This architecture enables seamless crossborder coordination, from customer acquisition and vehicle booking to crossborder insurance, customs support, and used car export supply chain empowerment.

Second, we develop a novel bilevel optimization model tailored to crossborder rental frictions. Existing optimization methods for car rental and ridehailing (e.g., Wang et al., 2025; Yang et al., 2019; Liang et al., 2021) assume

homogeneous local fleets without considering crossborder costs such as customs clearance time, different regulatory regimes, and multijurisdiction insurance. Our model explicitly incorporates crossborder fixed costs (ccross) and dynamic pricing that responds to supplydemand imbalances across regions. The Option-DQN-based hierarchical learning framework is for the first time applied to the cross-border rental context.

Third, we provide quantitative evidence from a realworld crossborder operation. While most previous studies rely on synthetic data or singlecity simulations, our validation uses 45,000 actual rental orders and GPS trajectories from crossborder routes between Zhuhai, Macau, and Hong Kong. The significant performance gains (41% profit improvement) demonstrate the practical viability of our approach.

Fourth, we bridge business model innovation with operational optimization. Prior literature treats business model innovation (Owens et al., 2024; Teece, 2010) and operational efficiency (Yoon et al., 2018) as separate streams. Our work shows how a carefully designed digital ecosystem – including crowdsourced relocation and supply chain empowerment – directly enables the mathematical optimization model, creating synergy between strategic innovation and tactical operations.

6.2 Practical Implications

For car rental enterprises seeking digital transformation and crossborder expansion, our findings offer several actionable insights. First, investing in an integrated digital platform ecosystem (rather than isolated apps) is essential for capturing crossborder synergies. Second, dynamic pricing and demandaware fleet allocation can be implemented using deep reinforcement learning even with limited historical data, as demonstrated by our transferable OptionDQN framework. Third, crowdsourced vehicle relocation and used car supply chain platforms can serve as secondary revenue streams that also improve primary rental efficiency.

6.3 Limitations and Future Research

Several limitations should be acknowledged. The model assumes perfect information of demand distribution; in reality, sudden policy changes (e.g., border closures) or extreme events may cause forecast errors. Moreover, our case study covers one specific crossborder corridor (Greater Bay Area), and generalizability to other regions (e.g., ChinaSoutheast Asia) requires further testing.

Future research will extend the model in three directions. First, we will incorporate vehicletogrid (V2G) interactions for electric rental fleets, allowing idle EVs to provide grid services while parked across borders. Second, we will introduce robust optimization and online learning mechanisms to handle demand uncertainty and realtime policy shifts. Third, we plan to conduct a multicase comparison across different crossborder corridors (e.g., ChinaVietnam, USCanada) to validate the model's external validity.

In summary, this paper not only provides a practical solution for Bowei Automobile but also establishes a theoretical foundation and a quantitative benchmark for the emerging field of crossborder smart car rental operations.

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