

Optimal government subsidy strategies for improving charging stations in ride-hailing services

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Abstract: The integration of new energy vehicles into ride-hailing has strengthened the connection between ride-hailing and charging services, with government subsidies being pivotal in expanding charging infrastructure. This paper examines the impact of charging, usage, and building subsidies on the ride-hailing industry through a competitive (cooperative) model that analyses the dynamics between fast and conventional charging services. We find that the charging subsidy and the usage subsidy are mutually substitutive, while the building subsidy plays a positive role. If the building subsidy exceeds a certain threshold, it dominates the other two subsidies. However, the fast-charging service provider cannot always increase profitability with the increase in charging time cost differentiation. Moreover, the marginal building subsidy thresholds that ensure a win-win situation for all entities do not intersect. Additionally, developed regions may focus on implementing usage or charging subsidy strategies, otherwise, the building subsidy strategy is more suitable.

Keywords: government subsidy strategies, ride-hailing platform, charging services, competition, cooperation

1. Introduction

In recent years, governments worldwide have shown a growing interest in promoting new energy vehicles (NEVs) as they are viewed as a pivotal avenue for achieving carbon emissions reduction within the transportation sector (Al-Kanj et al., 2020; Li et al., 2022; Ning et al., 2024). As a critical element of the transportation sector (Jacob and Roet-Green, 2021; Lin et al., 2025), the ride-hailing industry is actively adopting NEVs as a future growth direction, aligning with the current mandates and expectations of governments and platforms. For instance, both Lyft and Uber have made commitments to fully electrify their fleets by 2030^{1,2}, while China's premier ride-hailing platform, DiDi Chuxing, has strategically embarked on expansion into the realm of NEVs and associated ventures³.

When compared to conventional fuel-powered vehicles, employing NEVs as operational vehicles for ride-hailing presents substantial benefits in reducing carbon emissions and operational expenses. Nevertheless, the challenge of charging remains a significant concern (Lv et al., 2024). Therefore, from a psychological standpoint, drivers frequently prioritize the convenience of charging NEVs (Li et al., 2024; Li and Wang, 2023; Yu et al., 2022; Zatsarnaja et al., 2025; Zhang and Dou, 2022). Currently, private charging stations effectively address the inconvenience of charging, but due to high installation costs and constraints like site availability, property regulations, and power infrastructure in urban areas, private charging stations are not the most viable option for ride-hailing drivers. During their operational or idle periods,

¹ <https://www.lyft.com/impact/electric>

² <https://www.theverge.com/2020/9/8/21427196/uber-promise-100-percent-electric-vehicle-ev-2030>

³ <https://www.didiglobal.com/automobile-service/energy>

drivers often select charging service providers because they only need to cover the charging price. However, charging during operations also incurs hidden costs such as travel distance and waiting time, which are factors drivers consider when selecting between fast-charging and conventional charging (slow-charging) services (Anjos et al., 2020; Yang, 2018). The market provides a range of charging options, including fast charging stations like Tesla Superchargers and Evgo, as well as slow-charging stations like CRRC and ChargePoint. The choice of charging service by ride-hailing drivers during their operations impacts both the platform and the charging service providers, with charging efficiency and infrastructure coordination being key determinants of economic performance in such platform-based mobility systems (Goncearuc et al., 2022).

Numerous signs underscore the paramount importance of integrating ride-hailing and charging services. Whether from a sustainability perspective or regarding operational costs, NEVs have emerged as the top choice for ride-hailing services (Hu et al., 2021; Jenn, 2020; Tu et al., 2025). The integration of ride-hailing and charging services allows for better accommodation of passengers' travel needs. Considering the pivotal role of ride-hailing services in urban transportation, the deployment of charging stations should meet the requirements of ride-hailing vehicles. This will encourage more drivers and passengers to embrace NEVs, further promoting their widespread adoption. According to a research report published in China, by the latter half of 2022, NEVs constituted over 50% of the monthly operational mileage in DiDi Chuxing's fleet, surpassing the electrification level of the general vehicle population⁴. This underscores the vital role that ride-hailing plays in advancing charging infrastructure and the adoption of NEVs. The integration of ride-hailing and charging services contributes to the establishment of a more sustainable, environmentally friendly, and economically efficient urban transportation system.

In the integration of ride-hailing and charging services, government subsidy policies have consistently played a pivotal role, providing substantial support both in promoting NEVs and in establishing charging stations. (Jung and Feng, 2020; Yao et al., 2022). Presently, there is a discernible shift in the focus of government subsidies, with an increasing emphasis on charging stations rather than NEVs (Bai et al., 2025; Chen et al., 2023; Shao et al., 2023). China's NEV purchase subsidy policy completed its tapering mechanism by the end of 2022, and its primary focus is now on supporting the improvement of charging stations by providing subsidies to investors or users to alleviate cost burdens or provide incentives. For example, cities like Shanghai and Hainan offer charging subsidies to drivers, while Beijing and Guangdong provide operational subsidies based on the usage of charging stations, and Jiangsu and Chongqing offer one-time building subsidies. Countries worldwide are also committed to enhancing charging infrastructure. The US government intends to

⁴ <https://www.didiglobal.com/news/newsDetail?id=1033&type=news>

allocate \$5 billion to build charging stations, Germany provides subsidies for building charging stations based on the station's power, and the UK offers subsidies and tax incentives for developing public charging networks. Previous research has demonstrated the significant impact of government subsidies on charging stations (Kumar et al., 2021; Yoo et al., 2021; Yu et al., 2022; Zhao et al., 2025). However, existing studies have not yet explored these subsidy policies within the realm of charging services for ride-hailing, nor have they considered the relevant market conditions, such as the economic circumstances of cities or their financial status.

Based on the aforementioned realities and academic observations, we develop a competitive (cooperative) model involving a ride-hailing platform, a conventional charging service provider, and/or a fast-charging service provider. Additionally, we investigate government subsidy strategies that provide charging subsidies for drivers or usage and building subsidies for investors in fast charging stations. Our objective is to address the following three questions:

(1) Under various government subsidy strategies, how do market conditions and government subsidies impact the equilibrium outcomes?

(2) Which subsidy strategy is more effective in promoting the development of both the platform and charging service providers?

(3) How will shifts in the market conditions influence the implementation of government subsidy strategies?

The research findings reveal a substitution relationship between usage and charging subsidies, with building subsidies consistently playing a positive role. Once the level of building subsidies exceeds a certain threshold, they tend to take precedence over usage (charging) subsidies. Moreover, as charging time cost differentiation increases, the adoption of the usage (charging) subsidy strategy becomes more favorable. This extends the applicability of the conclusions drawn by Zhang and Dou (Zhang and Dou, 2022) regarding charging station subsidy selection. When examining both ride-hailing and charging services, the surplus obtained by drivers in ride-hailing services dominates their total surplus. Surprisingly, fast-charging service providers do not always increase profitability with rising charging time cost differentiation, and no threshold crossover exists for the impact of increasing marginal subsidies on achieving win-win scenarios. An increase in unit building subsidy can achieve a win-win situation as long as it ensures that the fast-charging service provider gains more marginal profits, and when the ride-hailing platform (passengers) gains more marginal profits (surplus), it can ensure a win-win situation for all parties in the usage or charging subsidy strategies. These findings underscore the paramount importance of considering the local economic development level when formulating and implementing subsidy strategies. Developed regions tend to lean towards adopting usage (charging) subsidy strategies, while underdeveloped regions may incline towards building subsidy strategies. Regardless of the chosen strategy, ride-hailing platforms are motivated to invest in fast charging stations, particularly in developed urban areas. Finally,

acknowledging the heterogeneity in drivers' sensitivity to charging station availability confirms the robustness of the basic model, emphasizing that drivers' pursuit of charging efficiency promotes the sustainable development of urban transportation and the economy.

The paper is organized as follows: Section 2 reviews relevant literature. Section 3 presents the basic model, parameters, and definitions. Section 4 calculates equilibrium outcomes for all parties under three subsidy strategies and performs sensitivity analysis. Section 5 analyses the optimal subsidy strategy, while Section 6 extends the basic model. Finally, Section 7 concludes the paper.

2. Literature review

2.1 The pricing decision of ride-hailing platforms

A substantial body of research has emerged concerning the pricing decisions of ride-hailing platforms (Castillo et al., 2025; Sheldon and Dua, 2024; Zhong et al., 2024). Song and Jian (2025) propose a context-aware dynamic pricing algorithm with differential privacy protection to address the issue of privacy leakage in ride-hailing platforms. Their approach ensures that while platform revenues are maintained, individual valuation privacy leakage remains controllable when passenger preference distributions are known. Nourinejad & Ramezani (2020) introduce a dynamic non-equilibrium ride-hailing model to address the non-steady-state nature of the taxi market, which tracks the changing numbers of passengers, vacant vehicles, and occupy vehicles over time. Ming et al. (2025), using an empirical research method, investigate the formation mechanisms of the two-sided ride-hailing market and pricing, as well as the value of dynamic pricing. Their findings indicate that although surge pricing enhances passenger and driver welfare and increases platform revenues, it reduces the revenue of the taxi business on the platform. In the context of green mobility, Hong and Liu (2022) consider two types of services in the ride-hailing platform: basic services using fuel-powered vehicles and green services using NEVs. They study the profit-maximizing dynamic pricing mechanism by constructing a model that captures the characteristics of both sides of users. Under regulatory policies managing minimum NEV mileage quotas, Xu et al. (2024) design a two-stage model to elucidate the dynamic interactions among governments, ride-hailing platforms, consumers, and drivers. Their findings reveal that under a laissez-faire policy, platforms tend to charge higher prices for green mobility services. Benjaafar et al. (2022) explore the pricing problem of the ride-hailing platform from the perspective of driver welfare and used a general equilibrium model to explain the interactions between price, wage, labor supply, passenger delay, and demand. In addition to research on the pricing strategies of individual ride-hailing platforms, another common topic is pricing in the context of multi-platform competition (Zhao et al., 2023; Zhou et al., 2022). Cai et al. (2024a) develop a general duopoly evolutionary game model to capture the dynamics of decision-making adjustments and the evolution of market conditions, identifying the existence of stable system states. Bernstein et al. (2021) consider passenger

and driver multi-homing and congestion effects in the dynamic pricing problem of competitive ride-hailing platforms. Yu et al. (2020) investigate pricing issues when the ride-hailing platform competes with taxis under both no government intervention and government regulation policies. With the development of the ride-hailing market, the competition between human drivers and autonomous vehicles also influences platform pricing decisions (Lian and van Ryzin, 2025). In addition to pricing, recent studies highlight the role of consumer information and data-driven strategies in shaping platform business models (Padilla et al., 2022).

However, previous research often overlooks the application and operational characteristics of NEVs in ride-hailing. With government policies and platform reforms, NEVs are poised to significantly impact the industry. Our study distinguishes itself by not only examining pricing decisions of ride-hailing platforms but also focusing on the decision-making processes related to charging station construction, positioning NEVs as the central link.

2.2 Operational management of charging stations

Our research also closely aligns with the literature on the operational management of charging stations (Zavvos et al., 2021; Zhang et al., 2020a). From a practical perspective, the construction of charging stations is crucial for advancing new energy development (Zhao et al., 2025). However, the operation of charging stations is often fraught with competition. Sun et al. (2020) develop a network equilibrium model to capture the interactions among NEV routing choices, charging plans, and electricity prices. Bulawa et al. (2024) examined market reference behaviors among enterprises in constructing charging infrastructure, revealing that the layout and efficiency of charging networks are significantly influenced by competitors' decisions, while reasonable market reference mechanisms can enhance both the economic benefits and market competitiveness of charging infrastructure. Zhang et al. (2020b) consider single monopoly and duopoly charging markets, which provide fast and slow charging services. Zavvos et al. (2021) consider competition factors and driver queuing in charging station layout, using game theory to help charging service providers determine the capacity, location, power output, and fees of charging stations. Currently, there is limited research on competition among charging service providers. Nevertheless, studies related to competition in supply chain operations have offered valuable insights that have informed the construction of our game-theoretic model. For example, Wu et al., (2022) develop a game theory model consisting of one contract manufacturer and two asymmetric brand firms to study whether weak brand firms should use brand spillover as a marketing strategy. Jena and Meena (2019) focus on the sensitivity of tourists to pricing and services in a tourism supply chain with two competing tour operators. Mandal and Jain (2021) strongly emphasize the differentiation of product quality within the framework of competition both upstream and downstream in the supply chain. Additionally, the presence of NEVs operating on ride-hailing platforms generates substantial business opportunities for charging service providers, which should be factored into charging station development (Lai and Li, 2024). Cai et al.

(2024b) propose a shared charging solution for ride-hailing services, and numerical analysis highlighted the role of shared charging services in promoting the sustainable development of the ride-hailing market. Chen et al. (2024) explore the impact of charging costs, including electricity costs and waiting times during charging, on the demand and supply of ride-hailing services. Zhao et al. (2025) explore three potential business relationships between ride-hailing platforms and charging service providers. Unlike existing research on operational management of charging stations, we account for the interdependence between the ride-hailing platform and heterogeneous charging providers. We model a two-stage driver choice: first, drivers decide whether to become active, then they select a charging provider. Additionally, we analyze how market conditions affect the equilibrium outcomes for both providers.

2.3 Government subsidies for building charging stations

Government subsidies have greatly promoted the improvement of charging infrastructure (Feng et al., 2025; Tang et al., 2024; Yu et al., 2022). This is consistent with the view that different policy instruments may create synergistic effects in shaping firms' technological and operational decisions (Wu et al., 2025). Zhang and Dou (2022) study how the government designs subsidy policies to promote the adoption of NEVs when there is a mismatch between charging supply and demand. Kumar et al. (2021) explore four different charging infrastructure construction modes in the context of the entire vehicle supply chain, based on whether charging stations are constructed by NEV manufacturers or the government and whether the government provides vehicle purchase subsidies to consumers. Similarly, Feng et al. (2024) examine how government subsidies, including purchase subsidies, station construction subsidies, and a combination of both, affect NEV demand and charging station scale. Pi et al. (2024) investigate how these subsidies influence manufacturers' decisions to enter the NEV market and exit the traditional fuel vehicle market. However, as government policy subsidies transition, charging infrastructure is poised to become the focal point of future subsidy efforts. Yoo et al. (2021) discuss the issue of constructing charging stations without providing vehicle purchase subsidies in the future by considering the different focus of government subsidies between the current and future and the sensitivity of drivers to service costs. Li et al. (2025) compare two government subsidy policies for charging station construction, namely unit subsidies and percentage subsidies, and find that when the government prioritizes social welfare, the two policies yield comparable effects. Shi et al. (2022) consider the inconvenience of charging in studying the optimal subsidy structure of the government. They find that the government can encourage NEV adoption by providing vehicle purchase subsidies or reducing charging inconvenience through charging station subsidies. Chen et al. (2023) establish a game model to explore the impact of government investment and usage subsidies on the adoption of new technologies represented by charging infrastructure. Distinct from existing literature, we focus on the growing ride-hailing sector within the sharing economy and analyze how government strategies for charging infrastructure affect both ride-hailing platforms and charging service

providers. We examine and compare three common subsidy strategies—charging, usage, and building subsidies—providing valuable insights for government decision-making.

3. Model preliminaries

This study constructs a competitive (cooperative) model integrating ride-hailing and charging services, consisting of a ride-hailing platform (referred to as “platform”), a conventional charging service provider (referred to as “provider-c”), and/or a fast-charging service provider (referred to as “provider-f”). The platform recruits drivers with NEVs to provide ride-hailing services for passengers. In the basic model, the platform refrains from engaging in building charging stations, and drivers have the option to select between fast charging or conventional charging services. The government provides corresponding subsidies to drivers or charging service providers to improve charging infrastructure. Without loss of generality, we assume that the subsidies provided by the government to provider-c are normalized to 0. Therefore, the subsidy strategies in the basic model include charging subsidies for drivers using fast charging stations (NC strategy), usage subsidies for provider-f (NU strategy), or building subsidies for provider-f (NB strategy). The relationships among the various entities in the basic model are depicted in Fig.1, and the notations and definitions are presented in Table 1.

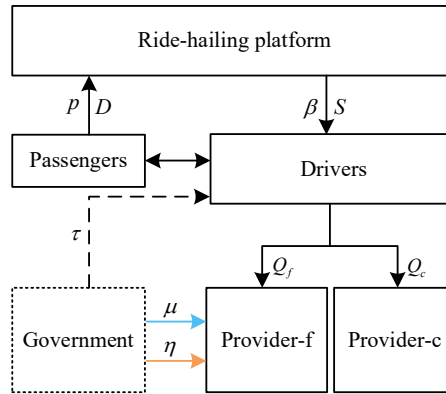


Fig.1. Relationships among Entities

Table 1. Definitions of Notations

Notations	Definitions	Notations	Definitions
Exogenous variable		τ	Government subsidy for drivers using fast charging services
s	The driver's service rate	μ	Government subsidy provided to provider-f based on charging station usage
β	The commission rate that drivers receive per order	η	Government subsidy provided to provider-f based on the number of charging stations built
k	The building cost coefficient of fast charging stations	Decision variables	
α	The network externality coefficient of passengers on driver supply	p	The ride price charged by the platform per order
ρ	The sensitivity coefficient of drivers to the	n_c	The number of charging stations built by provider-

	number of charging stations		c
e_0	Charging price paid by the driver to provider-c	n_f	The number of charging stations built by provider-f
ε	Driver's reservation wage	e	The additional fare that drivers need to pay for selecting fast charging services.
θ	The initial perceived value of the platform by passengers	Endogenous variable	
x	The driving distance for the driver from their current location to the provider-f	U^d	The utility of drivers
$v_i, i \in \{f, c\}$	The initial perceived value of the provider-f or provider-c by the driver	$U_i^d, i \in \{f, c\}$	The utility of drivers from the provider-f or provider-c
$t_i, i \in \{f, c\}$	The time it takes for NEVs to complete charging at fast or conventional charging stations, $t_f < t_c$	U^p	The utility of passengers
r	The driver's unit time cost	S	The number of active drivers
m	The driver's unit distance cost from the current location to the charging stations	$Q_i, i \in \{f, c\}$	The charging demand of provider-f or provider-c
λ	The potential number of passengers on the platform	D	The demand for the platform

(1) Driver side

To begin with, registered drivers on the platform make the initial decision of whether to become active drivers providing services for passengers based on income, charging convenience, and reservation wage. Charging convenience depends on the scale of charging stations within the market (Feng et al., 2025; Yoo et al., 2021; Yu et al., 2022). Additionally, existing empirical research indicates that driver satisfaction with income levels is the most crucial factor for drivers (Fielbaum and Tirachini, 2021). Therefore, the utility for drivers engaging in ride-hailing is given by $U^d = s\beta p + \rho(n_f + n_c) - \varepsilon$. s represents the driver's service rate, which is the average number of services provided to passengers per unit time, and a higher service rate reflects better economic development in the city. $\varepsilon \sim U[0, 1]$ represents the driver's reservation wage (Bai et al., 2019; Lin et al., 2021; Zhao et al., 2025). Assuming the number of registered drivers is normalized to 1, drivers will only be willing to provide service if their utility is positive. Thus, the number of active drivers is given by $S = \int_0^{\varepsilon_1} 1 d\varepsilon = s\beta p + \rho(n_f + n_c)$, where $\varepsilon_1 = s\beta p + \rho(n_f + n_c)$. The driver surplus in the ride-hailing service is calculated as $DS_r = \int_0^{\varepsilon_1} U^d d\varepsilon = \frac{s^2}{2}$.

Furthermore, active drivers, while operational, make their selection of charging services based on factors such as the charging price, waiting time cost for charging, and distance cost. The charging price for drivers to select provider-c is denoted as e_0 , which is exogenously given. However, when drivers select provider-f, they need to pay an additional fare e . For example, in bustling urban areas, drivers are more inclined to expedite their charging processes to swiftly return to providing ride-hailing services. Nevertheless, these prime urban locations entail higher investment costs for fast-charging service providers. Consequently, the operation of fast charging stations can incur considerable service fares. Suppose under the same electricity consumption, a NEV takes t_f time to complete charging at a fast-charging station and t_c time

at a conventional charging station, with $t_f < t_c$. It means that drivers need to wait for t_f or t_c time, respectively, and the driver's unit time cost is r . In the model, the provider-f is located at position 0, while the provider-c is at position 1. The distance from the current location of the driver to the provider-f is denoted as x , and the distance to the provider-c is $1 - x$. Active drivers are uniformly distributed between the two charging service providers: $x \sim U[0, 1]$, and the driver's unit distance cost is denoted as m . Hence, the utility of drivers from the provider-f is given by $U_f^d = v_f - (e_0 + e) + \tau - rt_f - mx$, and the utility of drivers from the provider-c is given by $U_c^d = v_c - e_0 - rt_c - m(1 - x)$. Here, τ represents the government subsidy for drivers using fast charging services, i.e., charging subsidy. For simplicity, we assume that the initial perceived value of drivers from the provider-f and the provider-c are equal, i.e., $v_f = v_c = v$. We define $\bar{x}$ as the indifference point where the driver is equally indifferent between selecting the two services, and we obtain $\bar{x} = \frac{1}{2} + \frac{\tau - e + r(t_c - t_f)}{2m}$. Define $\Delta = r(t_c - t_f)$ as the charging time cost differentiation for drivers between fast charging service and conventional charging service, i.e., $\bar{x} = \frac{m + \Delta - e + \tau}{2m}$. Consequently, the charging demand for the provider-f is $Q_f = TS\bar{x}$, and the charging demand for the provider-c is $Q_c = TS(1 - \bar{x})$, where T represents the average number of times a NEV charges in unit time and can be normalized to 1 without loss of generality. Finally, we can calculate the driver surplus for selecting fast charging services as $DS_f = S \int_0^{\bar{x}} U_f^d dx = \frac{S(m - e + \Delta + \tau)(4v - 3e - 4e_0 - \Delta - 4rt_f - m - \tau)}{8m}$, and the driver surplus for selecting conventional charging services as $DS_c = S \int_{\bar{x}}^1 U_c^d dx = \frac{S(m + e - \Delta - \tau)(4v - e - 4e_0 - 3\Delta - 4rt_f - m + \tau)}{8m}$. Therefore, the total driver surplus is $DS = DS_r + DS_f + DS_c$.

(2) Passenger side

Assuming the potential number of passengers on the platform denoted by λ , the utility of passengers is determined by the ride price and the number of active drivers on the platform. Referring to relevant studies (Parker and Van Alstyne, 2005; Zhang et al., 2022; Zhao et al., 2025), the utility of passengers can be represented as $U^p = \theta - p + \alpha S$, where θ is the initial perceived value of passengers for the platform and follows a uniform distribution on the interval $[0, 1]$. Thus, the demand for the platform can be calculated as $D = \int_{\theta_1}^1 \lambda d\theta = \lambda(1 - p + \alpha S)$, where $\theta_1 = p - \alpha S$. The passenger surplus is given by $CS = \lambda \int_{\theta_1}^1 U^p d\theta = \frac{\lambda}{2}(1 - p + \alpha S)^2 = \frac{D^2}{2\lambda}$.

(3) Charging service providers

Charging service providers generate revenue from their charging operations, but they must initially make significant investments in building charging stations. Previous research has indicated that the investment cost for building charging stations exhibits an increasing and convex relationship with the number of charging stations (Kumar et al., 2021; Yoo et al., 2021; Yu et al., 2022). This form of quadratic growth in investment costs has been verified in empirical research

(Hartman et al., 1997). Therefore, the profit function of the provider-f is given by $\pi_f = Q_f(e_0 + e + \mu) - kn_f^2 + \eta n_f$, and the profit function of the provider-c is $\pi_c = Q_c e_0 - n_c^2$. Here, μ represents the usage subsidy, and η represents the building subsidy. Drawing inspiration from the studies by (Kim et al., 2021; Mandal and Jain, 2021), we normalize the building cost coefficient for conventional charging stations to 1, and the building cost coefficient of fast charging stations, denoted as k , is higher than 1 to capture the cost differential. The magnitude of “ k ” reflects the pricing levels within the local city. For example, the cost of installing a 7kW AC charging station is approximately \$6,000, whereas installing a high-power DC charging station may require tens of thousands of dollars⁵.

(4) The platform

In the basic model, considering that the platform does not invest in building fast charging stations, the platform’s profit is derived from the commission taken from the drivers’ orders. It is assumed that the platform will meet all the generated demands to enhance the passenger’s travel experience, thus we have $D \leq sS$ (Bernstein et al., 2021; Lin et al., 2021). Therefore, the profit function of the platform is given by $\pi_r = (1 - \beta)pD$.

(5) Decision sequence

In the game model proposed in this paper, we identify the ride price p , the number of charging stations built n_c and n_f , and the additional fare e as decision variables due to their significant impact on the profits and core business of the involved entities. The specific sequence of decisions is as follows: firstly, provider-f makes decisions regarding the additional fare e and the number of fast charging stations built n_f , while provider-c decides on the number of conventional charging stations built n_c . Subsequently, the platform determines the ride price p .

4. Basic model

In the basic model, equilibrium decisions and outcomes for each entity under the NC, NU, and NB strategies are initially calculated separately. Then, the impact of the users preferences on the platform and charging time cost differentiation on the relevant outcomes of the platform and charging service providers is examined.

4.1 NC strategy

Under the NC strategy, the government provides charging subsidies for drivers using fast charging services, with $\mu = \eta = 0$ in this scenario. The equilibrium decisions and outcomes can be determined through backward induction, as illustrated in Table 2. For a detailed calculation procedure, please refer to Appendix B.

⁵ <https://evse.com.au/blog/evchargercost/>

Table 2. Equilibrium decisions and outcomes in the NC strategy

NC strategy		
$e^{NC*} = \frac{1}{2}(m + \tau + \Delta - e_0)$	$n_f^{NC*} = \frac{\rho(2 - s\alpha\beta)(m + \Phi_1)^2}{32km(1 - s\alpha\beta)}$	$n_c^{NC*} = \frac{e_0\rho(2 - s\alpha\beta)(3m - \Phi_1)}{16m(1 - s\alpha\beta)}$
$p^{NC*} = \frac{1}{2(1 - s\alpha\beta)} + \frac{\alpha\rho^2(2 - s\alpha\beta)(2ke_0(3m - \Phi_1) + (m + \Phi_1)^2)}{64km(1 - s\alpha\beta)^2}$	$D^{NC*} = \lambda \left(\frac{1}{2} + \frac{\alpha\rho^2(2 - s\alpha\beta)((m + \Phi_1)^2 + 2ke_0(3m - \Phi_1))}{64km(1 - s\alpha\beta)} \right)$	
$S^{NC*} = \frac{\rho^2(2 - s\alpha\beta)^2((m + \Phi_1)^2 + 2ke_0(3m - \Phi_1))}{64km(1 - s\alpha\beta)^2} + \frac{s\beta}{2(1 - s\alpha\beta)}$	$Q_c^{NC*} = \frac{(3m - \Phi_1)S^{NC*}}{4m}$	$Q_f^{NC*} = \frac{(m + \Phi_1)S^{NC*}}{4m}$
$\pi_c^{NC*} = e_0(3m - \Phi_1) \left(\frac{\rho^2(2 - s\alpha\beta)^2(ke_0(3m - \Phi_1) + (m + \Phi_1)^2)}{256km^2(1 - s\alpha\beta)^2} + \frac{ks\beta}{8m(1 - s\alpha\beta)} \right)$	$\pi_f^{NC*} = (m + \Phi_1)^2 \left(\frac{\rho^2(2 - s\alpha\beta)^2((m + \Phi_1)^2 + 4ke_0(3m - \Phi_1))}{1024km^2(1 - s\alpha\beta)^2} + \frac{s\beta}{16m(1 - s\alpha\beta)} \right)$	
$\pi_r^{NC*} = \frac{(1 - \beta)\lambda \left(\frac{\alpha\rho^2(2 - s\alpha\beta)((m + \Phi_1)^2 + 2ke_0(3m - \Phi_1))}{+32km(1 - s\alpha\beta)} \right)^2}{4096k^2m^2(1 - s\alpha\beta)^3}$	$CS^{NC*} = \frac{\lambda}{2}(D^{NC*})^2$	$DS^{NC*} = DS_r^{NC*} + DS_f^{NC*} + DS_c^{NC*}$

Here, $\Phi_1 = e_0 + \tau + \Delta$, represents the economic cost borne by drivers when selecting conventional charging services, encompassing explicit charging costs, subsidy losses from not selecting fast charging services, and implicit costs such as time. To guarantee the positivity of the Hessian matrix, as well as all equilibrium decisions and outcomes, it is essential to fulfil the conditions $m + \Delta - e_0 + \tau > 0$ and $3m - \Phi_1 > 0$.

4.2 NU strategy

Under the NU strategy, the government offers usage subsidies to provider-f based on the utilization of charging stations, with $\tau = \eta = 0$ in this scenario. The calculation process for the NU strategy mirrors that of the NC strategy, and equilibrium decisions and outcomes can be obtained as illustrated in Table 3.

Table 3. Equilibrium decisions and outcomes in the NU Strategy

NU strategy		
$e^{NU*} = \frac{1}{2}(m + \Delta - e_0 - \mu)$	$n_f^{NU*} = \frac{\rho(2 - s\alpha\beta)(m + \Phi_2)^2}{32km(1 - s\alpha\beta)}$	$n_c^{NU*} = \frac{e_0\rho(2 - s\alpha\beta)(3m - \Phi_2)}{16m(1 - s\alpha\beta)}$
$p^{NU*} = \frac{1}{2(1 - s\alpha\beta)} + \frac{\alpha\rho^2(2 - s\alpha\beta)(2ke_0(3m - \Phi_2) + (m + \Phi_2)^2)}{64km(1 - s\alpha\beta)^2}$	$D^{NU*} = \lambda \left(\frac{1}{2} + \frac{\alpha\rho^2(2 - s\alpha\beta)((m + \Phi_2)^2 + 2ke_0(3m - \Phi_2))}{64km(1 - s\alpha\beta)} \right)$	
$S^{NU*} = \frac{\rho^2(2 - s\alpha\beta)^2((m + \Phi_2)^2 + 2ke_0(3m - \Phi_2))}{64km(1 - s\alpha\beta)^2} + \frac{s\beta}{2(1 - s\alpha\beta)}$	$Q_c^{NU*} = \frac{(3m - \Phi_2)S^{NU*}}{4m}$	$Q_f^{NU*} = \frac{(m + \Phi_2)S^{NU*}}{4m}$
$\pi_c^{NU*} = e_0(3m - \Phi_2) \left(\frac{\rho^2(2 - s\alpha\beta)^2(ke_0(3m - \Phi_2) + (m + \Phi_2)^2)}{256km^2(1 - s\alpha\beta)^2} + \frac{ks\beta}{8m(1 - s\alpha\beta)} \right)$	$\pi_f^{NU*} = (m + \Phi_2)^2 \left(\frac{\rho^2(2 - s\alpha\beta)^2((m + \Phi_2)^2 + 4ke_0(3m - \Phi_2))}{1024km^2(1 - s\alpha\beta)^2} + \frac{s\beta}{16m(1 - s\alpha\beta)} \right)$	
$\pi_r^{NU*} = \frac{(1 - \beta)\lambda \left(\frac{\alpha\rho^2(2 - s\alpha\beta)((m + \Phi_2)^2 + 2ke_0(3m - \Phi_2))}{+32km(1 - s\alpha\beta)} \right)^2}{4096k^2m^2(1 - s\alpha\beta)^3}$	$CS^{NU*} = \frac{\lambda}{2}(D^{NU*})^2$	$DS^{NU*} = DS_r^{NU*} + DS_f^{NU*} + DS_c^{NU*}$

Here, $\Phi_2 = e_0 + \mu + \Delta$ similarly represents the economic cost borne by drivers when charging at conventional

charging stations. To guarantee the positivity of the Hessian matrix and all equilibrium decisions and outcomes, it is crucial to satisfy the conditions $m + \Delta - e_0 - \mu > 0$ and $3m - \Phi_2 > 0$.

4.3 NB strategy

Under the NB strategy, the government offers building subsidies to provider-f based on the number of charging stations built, with $\tau = \mu = 0$ in this scenario. The equilibrium decisions and outcomes are presented in Table 4.

Table 4. Equilibrium decisions and outcomes in the NB strategy

NB strategy		
$e^{NB*} = \frac{1}{2}(m + \Delta - e_0)$	$n_f^{NB*} = \frac{\rho(2 - s\alpha\beta)(m + \Phi_3)^2}{32km(1 - s\alpha\beta)} + \frac{\eta}{2k}$	$n_c^{NB*} = \frac{e_0\rho(2 - s\alpha\beta)(3m - \Phi_3)}{16m(1 - s\alpha\beta)}$
$p^{NB*} = \frac{k + \alpha\rho\eta}{2k(1 - s\alpha\beta)} + \frac{\alpha\rho^2(2 - s\alpha\beta)(2ke_0(3m - \Phi_3) + (m + \Phi_3)^2)}{64km(1 - s\alpha\beta)^2}$	$D^{NB*} = \lambda \left(\frac{\alpha\rho^2(2 - s\alpha\beta)((m + \Phi_3)^2 + 2ke_0(3m - \Phi_3))}{64km(1 - s\alpha\beta)} + \frac{1}{2} + \frac{\alpha\rho\eta}{4k} \right)$	
$S^{NB*} = \frac{\rho^2(2 - s\alpha\beta)^2((m + \Phi_3)^2 + 2ke_0(3m - \Phi_3))}{64km(1 - s\alpha\beta)^2} + \frac{2ks\beta + (2 - s\alpha\beta)\rho\eta}{4k(1 - s\alpha\beta)}$	$Q_c^{NB*} = \frac{(3m - \Phi_3)S^{NB*}}{4m}$	$Q_f^{NB*} = \frac{(m + \Phi_3)S^{NB*}}{4m}$
$\pi_c^{NC*} = e_0(3m - \Phi_3) \left(\frac{((2 - s\alpha\beta)^2\rho^2((m + \Phi_3)^2 + ke_0(3m - \Phi_3)))}{256km^2(1 - s\alpha\beta)^2} + \frac{2ks\beta + \eta\rho(2 - s\alpha\beta)}{16km(1 - s\alpha\beta)} \right)$	$\pi_f^{NB*} = \frac{\left((16m\eta(1 - s\alpha\beta) + (2 - s\alpha\beta)\rho(m + \Phi_3)^2) + 2(m + \Phi_3)^2 \left(2k \left(\frac{e_0\rho^2(2 - s\alpha\beta)^2(3m - \Phi_3)}{16ms\beta(1 - s\alpha\beta)} \right) \right) \right)}{1024km^2(1 - s\alpha\beta)^2}$	
$\pi_r^{NB*} = \frac{\lambda(1 - \beta) \left(\frac{16(1 - s\alpha\beta)\alpha\rho m\eta + 32km(1 - s\alpha\beta)}{+ \alpha\rho^2(2 - s\alpha\beta)((m + \Phi_3)^2 + 2ke_0(3m - \Phi_3))} \right)^2}{4096k^2m^2(1 - s\alpha\beta)^3}$	$CS^{NB*} = \frac{\lambda}{2}(D^{NB*})^2$	$DS^{NB*} = DS_r^{NB*} + DS_f^{NB*} + DS_c^{NB*}$

Here, $\Phi_3 = \Delta + e_0$, this economic cost does not include the related costs introduced by government subsidies in comparison to Φ_1 or Φ_2 . To ensure the positivity of the Hessian matrix and all equilibrium decisions and outcomes, it is necessary to fulfil the conditions $m + \Delta - e_0 > 0$ and $3m - \Phi_3 > 0$.

4.4 Sensitivity analysis

This subsection analyses the separate impacts of psychological preferences of bilateral users on the platform, and charging time cost differentiation on the platform and charging service providers. For a detailed proof of all propositions, please refer to Appendix B.

Proposition 1. Under the three subsidy strategies, an increase in the network externality coefficient α for passengers and the sensitivity coefficient ρ for drivers collectively fosters the growth of the user base and enhances the profitability of both the platform and charging service providers.

Proposition 1 indicates that when the psychological preferences of bilateral users are captured, stronger preferences will drive both the platform and charging service providers to make more aggressive decisions. For passengers, an increase in the network externality coefficient α results in the expansion of the driver supply on the platform, gradually leading

to more passengers selecting the platform. Furthermore, higher ride prices can attract more drivers to become active drivers, which amplifies the demand for charging service providers, incentivizing them to expand the scale of charging stations. Such an outcome not only acts as a compelling motivator for drivers to cater to passengers but also establishes a positive feedback loop. Drivers, who place a premium on the convenience of charging for electric vehicles, play an instrumental role in advocating for the development of robust charging infrastructure and stimulating increased charging demand. Therefore, a higher degree of psychological preference among bilateral users on the platform proves advantageous in advancing charging infrastructure, expanding the user base, and ultimately augmenting profits for both the platform and charging service providers.

Proposition 2. Under the three subsidy strategies, as the charging time cost differentiation Δ increases: (1) The equilibrium decisions of the provider-f become progressively more aggressive, while the equilibrium decision of the provider-c becomes increasingly conservative; (2) Changes in demand and profits for both provider-f and provider-c are correlated with the range of Δ and k ; (3) The changes in equilibrium decisions, driver supply, passenger demand, and profits of the platform are correlated with the range of Δ .

Proposition 2 demonstrates the consistent impact of charging time cost differentiation Δ across the three subsidy strategies. Firstly, as Δ increases, it signifies a heightened competitive advantage for fast charging stations. This motivates provider-f to raise the additional fare and expand the scale of charging stations. In contrast, provider-c tends to adopt a conservative approach by scaling down the construction scale. Secondly, the market demand and profits of the two charging service providers change with the variation of Δ and are correlated with the magnitudes of Δ and k . Take provider-f as an example. Surprisingly, provider-f cannot always increase profitability with the increase in Δ . The market demand for provider-f decreases when both Δ and k surpass a certain threshold value. This is due to a high k indicating a smaller construction scale for fast charging stations, resulting in a low rate of increase in the construction scale with Δ . The inability to balance the decrease in the construction scale of conventional charging stations with the increase in Δ leads to an overall reduction in market charging station capacity. In alternative scenarios, an increase in Δ enhances market demand and profitability for provider-f. However, market demand and profitability for provider-c generally follow an opposite trend to those of provider-f. Lastly, the impact of Δ on the platform, encompassing ride prices, driver supply, passenger demand, and profits, is linked to the range of Δ . Essentially, this impact reflects how Δ affects the construction scale of fast charging stations versus conventional charging stations. A large Δ , indicating a higher rate of expansion in the scale of fast charging stations compared to the reduction in the scale of conventional charging stations, leads to an overall increase in market charging station capacity. This, in turn, results in an increase in active drivers and favourable changes in the ride-hailing market. Therefore, for the healthy and balanced development of the

ride-hailing and charging markets, provider-f should not blindly pursue the competitive advantage stemming from the difference in fast charging time but should effectively manage the charging speed according to the market environment.

5. Optimal subsidy strategy analysis

In this section, we will initially investigate the impact of the three subsidy strategies on the equilibrium decisions and related outcomes. Subsequently, through a comparative analysis of the equilibrium outcomes under each subsidy strategy and the changes in marginal profits and surplus caused by increasing unit subsidies, we delve into the specific conditions under which each subsidy strategy is applicable.

To begin, Proposition 3 and Proposition 4 respectively examine the impact of the three subsidy strategies on various aspects such as equilibrium decisions, driver supply, demand, profits, and surplus. Please consult Appendix A for abbreviations of thresholds used in the subsequent discussions.

Proposition 3. The impact of increasing subsidy values on the equilibrium decisions, driver supply, passenger demand, and charging demand is shown in Table 5.

Table 5. Impact of subsidy increase on equilibrium decisions and outcomes

	e^*	n_f^*	n_c^*	$p^*/S^*/D^*$	Q_f^*	Q_c^*
τ	$\uparrow$	$\uparrow$	$\downarrow$	If $\tau > \tau_1$, $\uparrow$; otherwise, $\downarrow$	If $\tau \leq \tau_2$ or $\tau > \tau_2$ and $k < k_1$, $\uparrow$; otherwise, $\downarrow$	If $\tau \geq \tau_3$ or $\tau < \tau_3$ and $k > k_2$, $\downarrow$; otherwise, $\uparrow$
μ	$\downarrow$	$\uparrow$	$\downarrow$	If $\mu > \mu_1$, $\uparrow$; otherwise, $\downarrow$	If $\mu \leq \mu_2$ or $\mu > \mu_2$ and $k < k_3$, $\uparrow$; otherwise, $\downarrow$	If $\mu \geq \mu_3$ or $\mu < \mu_3$ and $k > k_4$, $\downarrow$; otherwise, $\uparrow$
η	-	$\uparrow$	-	$\uparrow$	$\uparrow$	$\uparrow$

Proposition 4. The impact of increasing subsidy values on the optimal profits as well as the impact on passenger and driver surplus is shown in Table 6.

Table 6. Impact of subsidy increase on optimal profits and surplus

	π_f^*	π_c^*	π_r^*/CS^*	DS^*
τ	If $\tau \leq \tau_4$ or $\tau > \tau_4$ and $k < k_5$, $\uparrow$; otherwise, $\downarrow$	If $\tau \geq \tau_3$ or $\tau < \tau_3$ and $k > k_6$, $\downarrow$; otherwise, $\uparrow$	If $\tau > \tau_1$, $\uparrow$; otherwise, $\downarrow$	If $\tau > \tau_1$, $\uparrow$; if $\tau < \tau_5$, $\downarrow$
μ	If $\mu \leq \mu_4$ or $\mu > \mu_4$ and $k < k_7$, $\uparrow$; otherwise, $\downarrow$	If $\mu \geq \mu_3$ or $\mu < \mu_3$ and $k > k_8$, $\downarrow$; otherwise, $\uparrow$	If $\mu > \mu_1$, $\uparrow$; otherwise, $\downarrow$	If $\mu > \mu_1$, $\uparrow$; if $\mu < \mu_5$, $\downarrow$
η	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$

Based on Proposition 3 and Proposition 4, it is evident that an increase in charging subsidy τ prompts provider-f to raise the additional fare. Conversely, when the government provides usage subsidies to provider-f, an increase in μ will gradually reduce the additional fare. Charging subsidies and usage subsidies consistently manifest the same impact on other equilibrium outcomes. Both forms of subsidies shape the competitive dynamics between the two charging service providers by impacting the additional fare in the driver utility function. As a result, the impact of both subsidies on

equilibrium outcomes mirrors the effects of charging time cost differentiation Δ . Additionally, we analyze the impact of subsidies on passenger surplus and driver surplus, using the usage subsidy as an example. The effect of the usage subsidy on passenger surplus aligns with its influence on passenger demand, given that passengers only gain surplus in ride-hailing services. However, drivers receive a surplus in both charging services and ride-hailing services, resulting in a more intricate composition of their surplus. Notably, the surplus drivers gain from ride-hailing services plays a dominant role in their overall surplus. When usage subsidy is relatively large, an increase in μ attracts more drivers to become active, allowing drivers to gain more surplus irrespective of changes in charging demand. In contrast, when the usage subsidy is very small, an increase in μ leads to a decrease in the number of active drivers due to the impact of the downsizing of charging stations. This results in a lower surplus obtained by drivers in the ride-hailing service and the total surplus, even though the surplus in the charging service may increase. Compared to the charging subsidy and usage subsidy, the building subsidy directly stimulates provider-f to expand the construction scale of charging stations, enabling provider-c and the platform to increase economic benefits and user surplus by free-riding, without affecting the additional fare and the construction scale of conventional charging stations. Hence, we can conclude that the widespread adoption of the building subsidy strategy by local governments is based on the understanding that building subsidies can yield positive impacts without necessitating an exhaustive analysis of the current market environment. On the other hand, the success of the usage subsidy strategy and charging subsidy strategy hinges more on the interplay between various entities in the market, and these strategies may not attain the desired outcomes even with government subsidy support, potentially leading to economic losses.

To provide a more intuitive comparison of the impact of the three subsidies on the outcomes of both the platform and charging service providers, we present Proposition 5 and Proposition 6.

Proposition 5. (1) $e^{NC*} > e^{NB*} > e^{NU*}$; (2) Usage subsidies and charging subsidies exhibit similar impacts on various aspects, including the scale of conventional charging stations and fast charging stations, ride price, supply and demand on the platform, as well as the demand for charging services; (3) $n_c^{NU*} < n_c^{NB*}$; (4) If $\eta > \eta_1$, $n_f^{NB*} > n_f^{NU*}$; otherwise, $n_f^{NB*} \leq n_f^{NU*}$; (5) If $\eta > \eta_2$, $p^{NB*} > p^{NU*}$, $S^{NB*} > S^{NU*}$, $D^{NB*} > D^{NU*}$; otherwise, $p^{NB*} \leq p^{NU*}$, $S^{NB*} \leq S^{NU*}$, $D^{NB*} \leq D^{NU*}$; (6) If $\eta > \eta_3$, $Q_c^{NB*} > Q_c^{NU*}$; otherwise, $Q_c^{NB*} \leq Q_c^{NU*}$; (7) If $\eta > \eta_4$, $Q_f^{NB*} > Q_f^{NU*}$; otherwise, $Q_f^{NB*} \leq Q_f^{NU*}$.

Proposition 6. (1) Charging subsidies and usage subsidies exhibit a substitution relationship in the optimal profits of each entity; (2) If $\eta > \eta_5$, $\pi_c^{NB*} > \pi_c^{NU*}$; otherwise, $\pi_c^{NB*} \leq \pi_c^{NU*}$; (3) If $\eta > \eta_6$, $\pi_f^{NB*} > \pi_f^{NU*}$; otherwise, $\pi_f^{NB*} \leq \pi_f^{NU*}$; (4) If $\eta > \eta_2$, $\pi_r^{NB*} > \pi_r^{NU*}$; otherwise, $\pi_r^{NB*} \leq \pi_r^{NU*}$.

According to Proposition 5 and Proposition 6, we conducted a comprehensive analysis. Firstly, under the NC strategy,

the additional fare is the highest, while under the NU strategy, the additional fare is the lowest, and the building subsidy has no impact on the additional fare. Secondly, both charging subsidies and usage subsidies have substitutive effects on the scale of conventional charging stations and fast charging stations, ride price, platform supply and demand, demand from charging service providers, and the profits of different entities. These findings align with the conclusions drawn in Proposition 3 and Proposition 4. Furthermore, we compare the NU strategy with the NB strategy as an example. Given that usage subsidies are unfavorable for the construction scale of conventional charging stations, a factor unaffected by building subsidies, the NB strategy yields a larger scale of conventional charging stations. As per Proposition 3 and Proposition 4, building subsidies consistently stimulate the expansion of the fast-charging station's scale and facilitate the development of the platform and charging service providers. Therefore, when the government provides substantial building subsidies to provider-f, the NB strategy proves more effective than the NU strategy in promoting the construction of fast charging stations, thereby encouraging more drivers to become active (as $\eta_1 > \eta_2$). This, in turn, generates more demand for the platform and charging service providers. Conversely, if the building subsidies are minimal, the NU strategy will have a more pronounced effect on expanding the market scale for the platform and charging service providers.

Proposition 6 elucidates the comparative results of profits for different entities under the NU (NC) strategy and the NB strategy. Irrespective of whether viewed from the standpoint of provider-c, provider-f, or the platform, it holds that when the building subsidy η surpasses a certain threshold, the subsidy strategy prevails over the NU (NC) strategy, resulting in augmented profits for all entities. The variation lies in the threshold for comparing profits under the two subsidy strategies. Therefore, when the government provides a substantial building subsidy to provider-f, i.e., $\eta > \max\{\eta_2, \eta_5, \eta_6\}$, it will create a mutually beneficial scenario for the platform, provider-f, and provider-c. This result reinforces the conclusion that increasing the building subsidy η consistently proves advantageous for enhancing the interests of all entities. As the value of the building subsidy reaches a certain level, the NB strategy is assured to deliver higher economic benefits than the other two subsidy strategies.

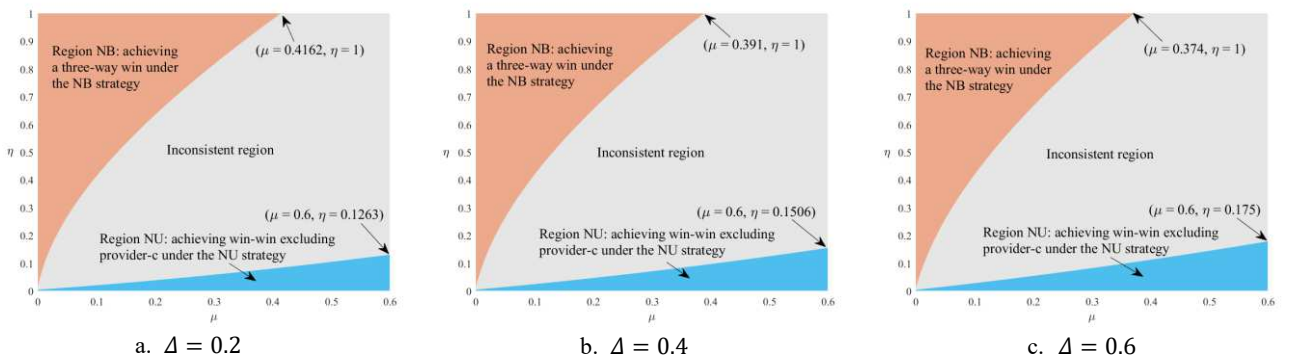


Fig.2. The impact of Δ on the government implementation of subsidy strategies

Note. $s = 2$, $\alpha = 0.2$, $\beta = 0.75$, $\rho = 0.4$, $m = 0.6$, $k = 1.2$, $e_0 = 0.3$, $\lambda = 1.2$

Fig. 2 depicts the impact of the charging time cost differentiation Δ on the government implementation of subsidy strategies. Given the substitutive relationship between NU and NC strategies, our analysis compares the NU strategy with the NB strategy. Examining Fig. 2 reveals that, under the NB strategy, provider-c consistently achieves higher profits, reflecting the threshold $\eta_5 < 0$ mentioned in Proposition 6. This is attributed to the endogenization of the additional fare, with provider-f shifting the usage subsidy to the additional fare. Consequently, the NU strategy exhibits a lower free-rider effect for provider-c compared to the NB strategy. Furthermore, an increase in Δ results in a contraction of the three-way win region for the platform, provider-f, and provider-c under the NB strategy, while expanding the win-win region (excluding provider-c) under the NU strategy. This suggests that, with advancements in charging technology and a diminishing competitive gap between provider-c and provider-f, the government can adopt NB strategy to safeguard the market's overall economic benefits.

Proposition 7 conducts a comparative analysis of the alterations in marginal profits and overall surplus for each entity to gain a deeper comprehension of the contributions of the three subsidy strategies.

Proposition 7. (1) Apart from driver surplus, charging subsidies and usage subsidies exhibit a substitutive relationship in the interests of the other entities; (2) For the platform and passengers surplus (provider-f), building subsidies prove more effective than usage subsidies when η is greater than the threshold value $\bar{\eta}$ ($\hat{\eta}$); (3) Building subsidies consistently outperform usage subsidies for provider-c; (4) Concerning driver surplus, building subsidies exhibit greater effectiveness than usage subsidies when η is greater than the threshold value $\tilde{\eta}$.

Proposition 7 compares three subsidy strategies from the perspective of how marginal subsidies improve the benefits of each entity. Firstly, concerning profits and passenger surplus, the substitutability relationship between the NC and NU strategy remains valid. However, given the intricate nature of the marginal impact of charging subsidies and usage subsidies on driver surplus, a comprehensive understanding emerges through a blend of theoretical analysis and numerical simulation results (as shown in Fig. B.1 in Appendix B). Surprisingly, we find that, in terms of driver surplus, the NU strategy may outperform the NC strategy. Furthermore, consistent with the discoveries in Proposition 6, achieving a win-win scenario for all entities necessitates higher building subsidies.

As shown in Fig. 3, contrary to initial expectations, there is no overlapping region evident in the simulation graph. On one hand, by ensuring that an increase in unit building subsidy translates to higher marginal profits for the provider-f, the other entities stand to achieve elevated marginal profits or surplus. The direct impact of building subsidies on provider-f proves more invigorating than that of usage subsidies, allowing other entities to garner increased profits from the expanded scale of fast-charging stations. On the other hand, higher marginal usage subsidies, ensuring that the platform (and passengers) accrue greater marginal profits (or surplus), also result in added benefits for the remaining

entities excluding provider-c. Additionally, as the building cost coefficient increases, the region where a win-win scenario is realized under both subsidy strategies gradually contracts. This implies that, to enhance the marginal benefits for each entity by increasing unit subsidies within a specific subsidy strategy, a higher level of subsidy coverage is requisite to counterbalance the escalating building costs and achieve a mutually beneficial outcome.

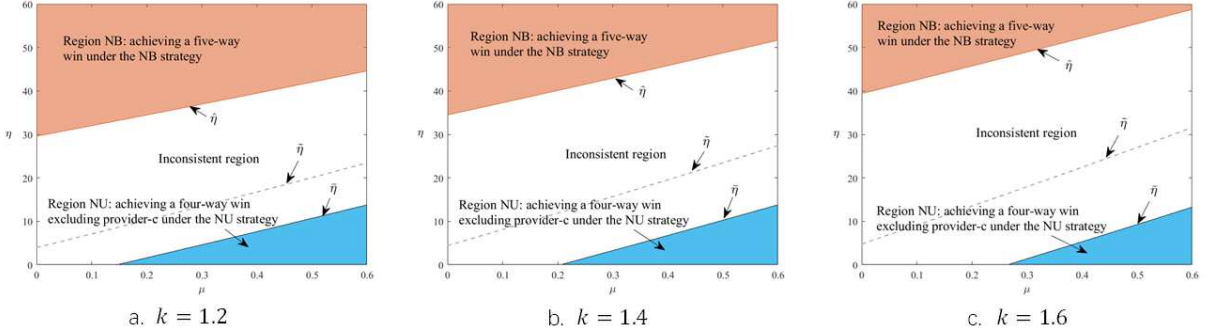


Fig.3. The distribution of win-win areas for each entity under the NU strategy and the NB

Note. $s = 6$, $\alpha = 0.2$, $\beta = 0.75$, $\rho = 0.4$, $m = 0.6$, $\Delta = 0.4$, $e_0 = 0.3$, $v = 1.5$, $r = 0.4$, $t_f = 0.5$

6. Extension

For a comprehensive analysis of the government's optimal subsidy strategy, we consider three scenarios: the platform invests in fast charging stations through equity cooperative shareholding and heterogeneity in drivers' sensitivity to the number of charging stations. In the extended model, we compare only the usage subsidy and building subsidy strategies, given the substitutability between usage and charging subsidies.

6.1 The platform invests in fast charging stations through cooperative shareholding

Platforms often partner with fast-charging providers to penetrate the charging market efficiently. For instance, Didi Chuxing collaborates with Teld, and Uber with BP to expand NEV ride-hailing services. In this section, we examine the platform's cooperative shareholding with provider-f for fast-charging stations, while Appendix D covers scenarios where the platform holds a controlling stake. We refer to the usage subsidy strategy as the "CU strategy" and the building subsidy strategy as the "CB strategy".

Under the CU strategy, the profit functions are as follows:

$$\pi_r^{CU} = (1 - \beta)pD + \delta(Q_f(e_0 + e + \mu) - kn_f^2) \quad (1)$$

$$\pi_f^{CU} = (1 - \delta)(Q_f(e_0 + e + \mu) - kn_f^2) \quad (2)$$

$$\pi_c^{CU} = Q_c e_0 - n_c^2 \quad (3)$$

Under the CB strategy, the profit functions are as follows:

$$\pi_r^{CB} = (1 - \beta)pD + \delta(Q_f(e_0 + e) - kn_f^2 + \eta n_f) \quad (4)$$

$$\pi_f^{CB} = (1 - \delta)(Q_f(e_0 + e) - kn_f^2 + \eta n_f) \quad (5)$$

$$\pi_c^{CB} = Q_c e_0 - n_c^2 \quad (6)$$

Assuming $\delta < 0.5$ represents the platform's shareholding ratio in cooperation with provider-f, indicating it lacks decision-making authority over charging station construction. To simplify the model, we treat the additional fare e as exogenous, allowing the platform and provider-f to focus on charging station scale. This is reasonable, as drivers prioritize charging efficiency over costs. Equilibrium decisions are detailed in Appendix C. Through numerical simulations, we compare interests under both subsidy strategies, identifying market conditions favoring the CU and CB strategies, leading to Claim 1.

Claim 1. (1) A five-way win can only be achieved under the CB strategy, whereas the CU strategy can achieve a four-way win excluding passengers; (2) With an increase in s or δ , the region for achieving a four-way win expands under the CU strategy, while the region for achieving a five-way win shrinks under the CB strategy. However, an increase in k diminishes the region of achieving a win-win situation under both strategies.

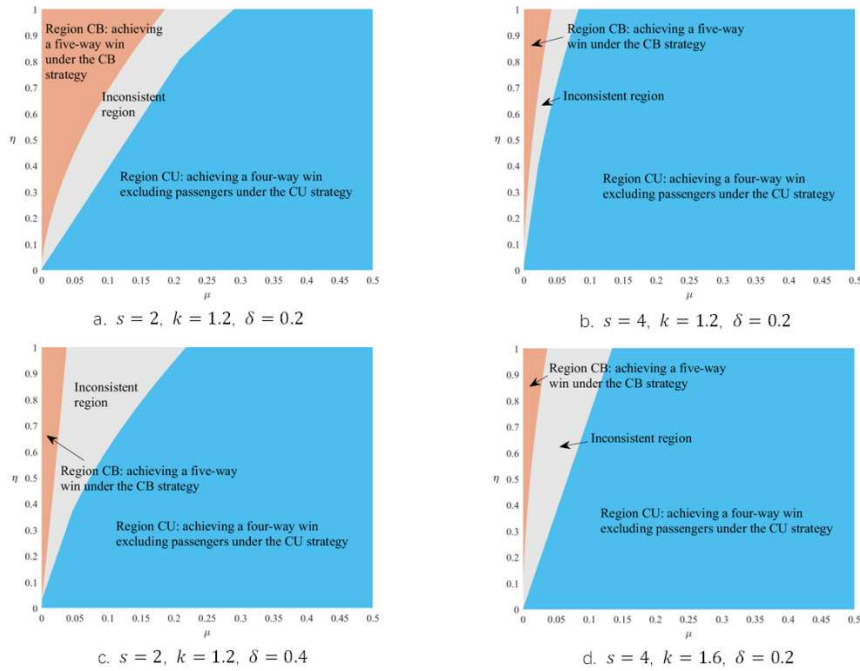


Fig.4. The impact of market environment on government implementation of subsidy

Note. $\beta = 0.75, \alpha = 0.2, \rho = 0.4, m = 0.6, \Delta = 0.4, e_0 = 0.3, \lambda = 1.2, e = 0.2, v = 1.5, r = 0.4, t_f = 0.5$

As shown in Fig. 4a, passengers consistently gain more surplus under the CB strategy, and a five-way win is possible only when the building subsidy is large enough for provider-c to benefit from free-riding against provider-f. Therefore, the five-way win region exists only under the CB strategy. However, as the service rate increases (as depicted in Fig. 4a and 4b), drivers are more likely to gain surplus under the CU strategy, causing the CB strategy to lose dominance when the usage subsidy is high. A five-way win under the CU strategy requires an extremely high usage subsidy, but in reality, driver subsidies cannot exceed their charging fare (i.e., $\mu \leq e_0 + e$), limiting the CU strategy to a four-way win without

passengers. A five-way win under the CB strategy requires it to be significantly more intense than the CU strategy, providing higher profits for provider-f and greater benefits for others through station construction. As the shareholding ratio increases (as observed in Fig. 4a and 4c), the platform shares more profits from fast charging but raises ride prices to attract drivers, benefiting both the platform and providers. This shift strengthens the CU strategy, leading to a four-way win excluding passengers. The higher shareholding ratio reduces the five-way win under the CB strategy, as only larger building subsidies can offset provider-f's lost profit. Finally, higher building costs (Fig. 4b, 4d) mean that only substantial building or usage subsidies can ease the financial burden, reducing the win-win region for both strategies.

6.2 Heterogeneity in drivers' sensitivity to the number of charging stations

In real-world scenarios, differences in charging time and cost between fast charging and conventional charging, introduce varying sensitivities among drivers when deciding whether to enter the ride-hailing market. As a result, we account for this heterogeneity in drivers' sensitivity to the number of charging stations, where their utility in deciding to become an active driver is given by $U^d = s\beta p + \rho_1 n_f + \rho_2 n_c - \varepsilon$. ρ_1 and ρ_2 denote drivers' sensitivity to the number of fast charging stations and conventional charging stations, respectively. Further, the number of active drivers can be expressed as $S = s\beta p + \rho_1 n_f + \rho_2 n_c$. In this extension, the usage subsidy strategy and the building subsidy strategy are referred to as “ NU_ρ strategy” and “ NB_ρ strategy”, respectively, with all equilibrium decisions outlined in Appendix C.

The equilibrium outcomes show that drivers' sensitivity to the number of fast and conventional charging stations affects the equilibrium results through their construction scales. As in the basic model, an increase in ρ_1 or ρ_2 boosts user scale and improves profits for the platform and charging providers. Using the control variable method, we analyze the impact of ρ_1 and ρ_2 on government subsidy strategies for mutually beneficial outcomes (as shown in Fig. 5). Firstly, under the NB_ρ strategy, all entities can achieve a win-win, while the NU_ρ strategy results in only four entities winning, as provider-c consistently profits more under NB_ρ strategy, confirming the basic model's stability. Furthermore, as ρ_1 increases, reflecting drivers' focus on fast charging stations, the multi-win region expands for both strategies. However, higher ρ_2 reduces the multi-win region under NU_ρ strategy. This is because drivers' emphasis on fast charging stations stimulates provider-f to expand the construction scale, thereby reducing the government's subsidy burden for fast charging stations. In other words, at higher levels of ρ_1 , the same level of subsidies enables each entity to gain more benefits. Conversely, drivers' attention to conventional charging stations necessitates more government subsidies for fast charging stations, particularly in the NU_ρ strategy. From the perspective of the ride-hailing industry, drivers' pursuit of charging efficiency contributes to the enhancement of charging infrastructure, fostering the economic and sustainable development of urban transportation.

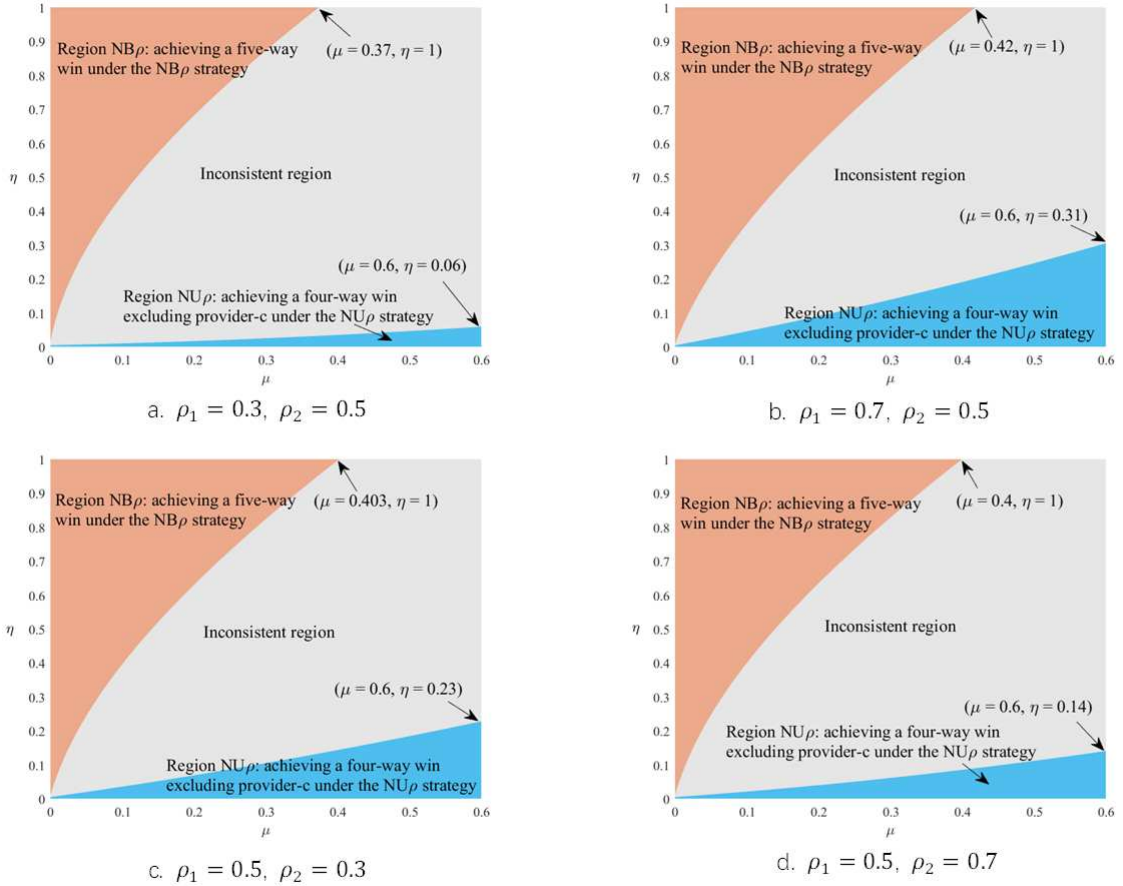


Fig.5. The impact of ρ_1 and ρ_2 on government implementation of subsidy

Note. $s = 2, \beta = 0.75, \alpha = 0.2, m = 0.6, \Delta = 0.4, e_0 = 0.3, \lambda = 1.2, k = 1.2, v = 1.5, r = 0.4, t_f = 0.5$

7. Conclusions

The application of NEVs in ride-hailing services has intricately linked the efficiency of ride-hailing and the adequacy of charging infrastructure. The development of charging infrastructure is a competitive process heavily reliant on government subsidies. In light of this context, a competitive (cooperative) model involving a ride-hailing platform and charging service providers is developed to analyze the impact of user preferences and charging time cost differentiation. To assess these dynamics, a comparative analysis of charging, usage, and building subsidies is conducted under scenarios where the platform either avoids building charging stations or invests in fast charging stations through cooperation.

Our research has yielded the following conclusions. (1) The increase of users' psychological preferences consistently contributes to market development, while an increase in the building cost coefficient has a negative effect. Additionally, the increase in charging time cost differentiation and (charging) subsidies does not always lead to an improvement in the profitability of the fast-charging service provider, and the impact of those factors on the interests of various entities is also correlated with the building cost coefficient while building subsidies have a positive impact on the equilibrium outcomes. (2) In scenarios where the ride-hailing platform abstains from participating in building charging stations, charging

subsidies and usage subsidies exhibit a substitution relationship. Once building subsidies exceed a certain threshold, this strategy dominates the usage (charging) subsidy strategy, benefiting the ride-hailing platform and charging service providers. Moreover, an increase in charging time cost differentiations diminishes the advantage of the building subsidy strategy. When concentrating on enhancing marginal benefits through an increase in the unit subsidy, the marginal building subsidy thresholds that ensure a win-win situation for all entities do not intersect, and a rise in the building cost coefficient reduces the effectiveness of subsidy strategies. (3) When the ride-hailing platform cooperates with provider-f, the increase in the shareholding ratio results in a reduction in the five-way win region under the building subsidy strategy, while enhancing the advantage of the usage subsidy strategy. (4) The scenario involving heterogeneity in drivers' sensitivity to the number of charging stations validates the stability of the basic model. Moreover, drivers' heightened focus on the scale of fast charging stations is more conducive to a multi-way win situation in the subsidy strategy.

Based on our research conclusions, we provide the following insights for the government authorities and managers in the ride-hailing market: Whether ride-hailing platforms select to invest in building fast charging stations or not, if the government aims to optimize the interests of various entities under a designated subsidy strategy, it should intensify efforts in that specific subsidy strategy, clearly favoring it over other subsidy policies. Moreover, when implementing subsidy policies, the government should pay particular attention to the local economic conditions. Developed regions can lean towards implementing the usage subsidy strategy, while underdeveloped regions should favor the building subsidy strategy. Additionally, managers of ride-hailing platforms should consider investing in fast charging stations to enhance service efficiency, and the investment outcomes are likely to be more significant in economically developed cities. For fast-charging service providers, efficiently managing charging speeds contributes to the balanced development of both ride-hailing services and the charging market.

There are still some limitations in this study. Firstly, we did not consider vehicles outside the ride-hailing platform in the model. In reality, privately owned NEVs that do not provide ride-hailing services are also important customers for charging service providers. In future studies, it may be worth considering the impact of such customers on platform decisions regarding the construction of charging stations. Secondly, the three-way competition between the charging services in ride-hailing platforms, fast charging services, and conventional charging services is quite common in the market. How to depict the differences between them in the model is a focus of future research.

Appendix A. Summary of Thresholds

The thresholds used in the paper and their detailed expressions are shown in Table 7.

Table 7. Summary of thresholds used

$\tau_1 = \mu_1 = (k-1)e_0 - m - \Delta$	$\tau_2 = \mu_2 = \frac{8ms\beta(1-s\alpha\beta)}{e_0\rho^2(2-s\alpha\beta)^2} + m - \Delta - e_0$	$\tau_3 = \mu_3 = \frac{5m}{3} - \Delta - e_0$	$\tau_4 = \mu_4 = \frac{32ms\beta(1-s\alpha\beta)}{3e_0\rho^2(2-s\alpha\beta)^2} + \frac{5m}{3} - e_0 - \Delta$
$\tau_5 = \frac{m(2-s\alpha\beta)^2\rho^2(e_0(k-1)-m-\Delta)-4k(1-s\alpha\beta)^2(\Delta+e_0-m)}{m(2-s\alpha\beta)^2\rho^2+16k(1-s\alpha\beta)^2}$	$\mu_5 = \frac{m(2-s\alpha\beta)^2\rho^2(e_0(k-1)-m-\Delta)-4k(1-s\alpha\beta)^2(\Delta+e_0-m)}{m(2-s\alpha\beta)^2\rho^2+4k(1-s\alpha\beta)^2}$		
$k_1 = \frac{-3\rho^2(2-s\alpha\beta)^2(m+\Delta+e_0+\tau)^2}{4(e_0\rho^2(2-s\alpha\beta)^2(m-(e_0+\Delta+\tau))+8ms\beta(1-s\alpha\beta))}$	$k_2 = \frac{\rho^2(2-s\alpha\beta)^2(m+\Delta+e_0+\tau)(5m-3(\Delta+e_0+\tau))}{4(e_0\rho^2(2-s\alpha\beta)^2(3m-(e_0+\Delta+\tau))+8ms\beta(1-s\alpha\beta))}$		
$k_3 = \frac{-3\rho^2(2-s\alpha\beta)^2(m+\Delta+e_0+\mu)^2}{4(e_0\rho^2(2-s\alpha\beta)^2(m-(\Delta+e_0+\mu))+8ms\beta(1-s\alpha\beta))}$	$k_4 = \frac{\rho^2(2-s\alpha\beta)^2(m+\Delta+e_0+\mu)(5m-3(e_0+\mu+\Delta))}{4(e_0\rho^2(2-s\alpha\beta)^2(3m-(\Delta+e_0+\mu))+8ms\beta(1-s\alpha\beta))}$		
$k_5 = \frac{-\rho^2(2-s\alpha\beta)^2(m+\Delta+e_0+\tau)^2}{e_0\rho^2(2-s\alpha\beta)^2(5m-3(\Delta+e_0+\tau))+32ms\beta(1-s\alpha\beta)}$	$k_6 = \frac{\rho^2(2-s\alpha\beta)^2(m+\Delta+e_0+\tau)(5m-3(\Delta+e_0+\tau))}{2(e_0\rho^2(2-s\alpha\beta)^2(3m-(\Delta+e_0+\tau))+16ms\beta(1-s\alpha\beta))}$		
$k_7 = \frac{-\rho^2(2-s\alpha\beta)^2(m+\Delta+e_0+\mu)^2}{e_0\rho^2(2-s\alpha\beta)^2(5m-3(\Delta+e_0+\mu))+32ms\beta(1-s\alpha\beta)}$	$k_8 = \frac{\rho^2(2-s\alpha\beta)^2(m+\Delta+e_0+\mu)(5m-3(\Delta+e_0+\mu))}{2e_0\rho^2(2-s\alpha\beta)^2(3m-(\Delta+e_0+\mu))+32ms\beta(1-s\alpha\beta)}$		
$\eta_1 = \frac{\mu\rho(2-s\alpha\beta)(2(m+\Delta+e_0)+\mu)}{16m(1-s\alpha\beta)}$	$\eta_2 = \frac{\mu\rho(2-s\alpha\beta)(2(m+\Delta-e_0(k-1))+\mu)}{16m(1-s\alpha\beta)}$		
$\eta_3 = \frac{\mu(\rho^2(2-s\alpha\beta)^2((3m-\Delta-e_0)(2(m+\Delta+e_0)+\mu)-(m+\Delta+e_0+\mu)^2)-2k(16ms\beta(1-s\alpha\beta)+e_0\rho^2(2-s\alpha\beta)^2(2(3m-\Delta-e_0)-\mu)))}{16mp(2-s\alpha\beta)(1-s\alpha\beta)(3m-\Delta-e_0)}$			
$\eta_4 = \frac{\mu(\rho^2(2-s\alpha\beta)^2(m(4ke_0+3(m+\mu+2e_0+2\Delta))+e_0(e_0(3-4k)+(3-2k)(\mu+2\Delta))+\mu^2+3\Delta(\mu+\Delta))+32mks\beta(1-s\alpha\beta))}{16mp(1-s\alpha\beta)(2-s\alpha\beta)(m+\Delta+e_0)}$			
$\eta_5 = \frac{\mu(\rho^2(2-s\alpha\beta)^2((3m-e_0-\Delta)(2(m+\Delta+e_0)+\mu)-(m+\mu+\Delta+e_0)^2)-k(32ms\beta(1-s\alpha\beta)+e_0\rho^2(2-s\alpha\beta)^2(2(3m-\Delta-e_0)-\mu)))}{16mp(2-s\alpha\beta)(1-s\alpha\beta)(3m-\Delta-e_0)}$			
$\eta_6 = \frac{1}{16m(1-s\alpha\beta)} \left(\frac{-\rho(2-s\alpha\beta)(m+\Delta+e_0)^2 + \sqrt{\rho^2(2-s\alpha\beta)^2((e_0^2+(m+\mu+\Delta)^2)+4e_0(m+\mu+\Delta)(e_0(m+\mu+\Delta+e_0)+(m+\mu+\Delta)^2))+4\mu k(e_0\rho^2(2-s\alpha\beta)^2(e_0(2m-3\mu-6\Delta-3e_0)+m(5m+4\mu+2\Delta)-(\mu^2+3\mu\Delta+3\Delta^2))+16ms\beta(1-s\alpha\beta)(2(m+e_0+\Delta)+\mu))}}{4\mu k(e_0\rho^2(2-s\alpha\beta)^2(e_0(2m-3\mu-6\Delta-3e_0)+m(5m+4\mu+2\Delta)-(\mu^2+3\mu\Delta+3\Delta^2))+16ms\beta(1-s\alpha\beta)(2(m+e_0+\Delta)+\mu))}} \right)$			
$\bar{\eta} = \frac{\left(\rho(2-s\alpha\beta)(m+\Delta+\mu-e_0(k-1)) \left(\alpha(2-s\alpha\beta)\rho^2(m+\Delta+e_0+\mu)^2+2k(16m(1-s\alpha\beta)+\alpha e_0\rho^2(2-s\alpha\beta)(3m-(\Delta+e_0+\mu))) \right) - (8m\alpha(2-s\alpha\beta)(1-s\alpha\beta)\rho^2(m+\Delta+e_0)^2+16km(1-s\alpha\beta)(16m(1-s\alpha\beta)+\alpha e_0\rho^2(2-s\alpha\beta)(3m-(\Delta+e_0+\mu))) \right) \right)}{128\alpha\rho m^2(1-s\alpha\beta)^2}$			
$\hat{\eta} = \frac{(m+\Delta+e_0+\mu) \left((2-s\alpha\beta)^2\rho^2(m+\Delta+e_0+\mu)^2+k(e_0\rho^2(2-s\alpha\beta)^2(5m-3(\Delta+e_0+\mu))+32ms\beta(1-s\alpha\beta)) \right)}{128m^2(1-s\alpha\beta)^2}$			
$\tilde{\eta} = \frac{\frac{\rho(2-s\alpha\beta)(m+\Delta+e_0)^2}{16m(1-s\alpha\beta)} \left(\frac{\left(\left(16k(1-s\alpha\beta)^2(e_0+\mu+\Delta-m)+4\rho^2(2-s\alpha\beta)^2(m+\mu+\Delta-e_0(k-1)) \right) \left(\rho^2(2-s\alpha\beta)^2(e_0+m+\mu+\Delta)^2+2k(16ms\beta(1-s\alpha\beta)+e_0\rho^2(2-s\alpha\beta)^2(3m-e_0-\mu-\Delta)) \right) + 2\rho^2(2-s\alpha\beta)^2(m+\mu+\Delta-e_0(k-1)) \right) \left(8k(1-s\alpha\beta)^2(4m(4(v-rt_f)-3(m+e_0+\mu+\Delta)-2m+\mu)+(m-e_0-\mu-\Delta)^2) \right)}{512\rho^2m^3(1-s\alpha\beta)^2(2-s\alpha\beta)^2} - \frac{k(1-s\alpha\beta)}{4\rho m(2-s\alpha\beta)} (4m(4(v-rt_f)-3(m+e_0+\Delta)+m)+(m-e_0-\Delta)^2) - \frac{\rho(2-s\alpha\beta)}{16m(1-s\alpha\beta)} (2ke_0(3m-(e_0+\Delta))+(e_0+\Delta+m)^2) - \frac{2ks\beta}{\rho(2-s\alpha\beta)} \right)}{128m^2(1-s\alpha\beta)^2}$			

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Declaration of interest statement:

The authors confirm that the data supporting the findings of this study are available within the paper.

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