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# Airport pricing strategies for ride-hailing services: A game-theoretic analysis

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ABSTRACT

Ride-hailing services (e.g., Uber and DiDi) have significantly transformed airport ground transportation, thereby impacting airport revenues. In the past, airports primarily relied on parking and car rental services to generate stable non-aeronautical revenue. However, as a growing number of passengers have shifted to ride-hailing, these revenue streams have shown a marked decline. In response to this pressure, airports must reconsider their ground transportation pricing strategies. One approach is to directly impose charges on ride-hailing companies to compensate for revenue losses, though such a strategy may suppress related travel demand. Another approach involves making strategic investments to enhance ride-hailing operational efficiency and subsequently imposing reasonable access fees, thereby achieving revenue growth. To systematically evaluate the impacts of different strategies on airport revenues and social welfare, this study develops a two-stage game-theoretic model involving the airport and the ride-hailing company (RHC). The model is used to identify the airport's optimal strategies and to propose corresponding government regulatory policies. The results indicate that when the cost of improving ride-hailing operational efficiency is relatively low, the airport can achieve a "win-win-win" situation for the airport, the RHC, and passengers by enhancing ride-hailing operational efficiency while charging fees. Conversely, when the cost of operational efficiency improvement is high, the airport tends to adopt direct charging strategies to secure revenue streams. In this case, although airport profitability is maintained, overall social welfare may decline. If the government aims to maximize social welfare, fiscal subsidies may be necessary to incentivize airports to adopt the strategy of efficiency improvement combined with reasonable charges.

## 1. Introduction

The COVID-19 pandemic has brought numerous insights to the aviation industry, one of the most significant being the need to improve airport revenue management (Choi, 2021; Wandelt and Wang, 2024). As aviation operations continue to evolve, factors such as government pressure to reduce financial support for airports and unexpected exogenous shocks have made non-aeronautical revenue increasingly critical as a funding source for airports (Huai et al., 2025; Kidokoro and Zhang, 2022; Czerny and Zhang, 2020).

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Compared to traditional aeronautical revenue streams, non-aeronautical revenues are typically more diversified and have higher profit margins (Karanki and Zhang, 2025; Zhang and Zhang, 2010). Before the pandemic, many major airports in Asia and the Middle East with high international passenger volumes derived over 50 % of their total income from non-aeronautical sources (ACI, 2022). These revenues primarily originate from retail concessions, duty-free, parking services, real estate income, food and beverage, among others (Zhang and Zhang, 1997; Czerny et al., 2016; Kidokoro and Zhang, 2018; Zheng et al., 2025). Among these sources, parking revenues stand out for their importance and stability. As shown in Fig. 1, comparing data from 2019 and 2023, while many non-aeronautical revenue streams, such as retail concessions, experienced significant declines, parking revenue remained stable and even became the largest source of non-aeronautical revenue. This stability provided a reliable buffer for airports during the economic downturn.

However, the rise of ride-hailing companies (RHCs), such as Uber and DiDi, is reshaping airport ground transportation and impacting non-aeronautical revenues for airports (Wadud, 2020). Due to the convenience and affordability of ride-hailing services (Contreras and Paz, 2018), they have rapidly become the preferred mode of transportation for many passengers. This shift has led to a decline in the number of passengers driving to airports and utilizing airport parking facilities. For example, a customer survey conducted at San Francisco International Airport (SFO) from 2014 to 2017 revealed that the percentage of air travelers using ride-hailing services to reach the airport increased from 4 % to 23 %, while transactions at public parking facilities decreased by 13 %. This trend has placed downward pressure on airport parking revenues. Mandle and Box (2017) surveyed 58 airports and found that nearly half of the large hub airports reported a decrease in parking revenues. However, the impact of ride-hailing services extends beyond revenue considerations, posing new challenges to the operation and management of airport ground transportation. First, due to the absence of dedicated infrastructure for ride-hailing vehicles, such vehicles often share parking facilities and passenger pick-up/drop-off areas with traditional travel modes. This increases the risk of congestion and reduces overall operational efficiency. Without effective guidance and regulation, the irregularity and spontaneous nature of ride-hailing activities can also lead to traffic disorder. Moreover, while ride-hailing services offer ride-sharing options, in practice they frequently contribute to a shift from shared mobility to private travel, further intensifying traffic pressure at airports (Wang and Yang, 2019).

To address the impact of ride-hailing services' rapid growth on airport sustainable revenue, airports need to reconsider their ground transportation pricing and management strategies. On one hand, some airports focus on traditional ground transportation modes, adopting strategies such as increasing parking and car rental prices. On the other hand, many airports have actively embraced these emerging modes and begun to levy charges directly on RHCs. These fee structures typically include annual permit fees, per-trip fees, activation fees and minimum annual guarantees. For example, at Los Angeles International Airport (LAX), RHCs are required to pay an annual permit fee of $4,000. Additionally, they are charged $5 for each pick-up and drop-off trip, with an extra peak-hour surcharge of approximately $2 per trip during high-demand periods. Furthermore, beyond charging ride-hailing services, some airports actively enhance ride-hailing operational efficiency by establishing designated pick-up/drop-off zones and centralized waiting areas, and introducing intelligent traffic guidance systems. Directly increasing charges for various ground transportation modes can achieve low investment and short-term revenue growth effects, but may potentially suppress related travel demand. While airports' proactive efforts to improve ride-hailing operational efficiency and implement charging require certain upfront investments, they may potentially achieve sustainable revenue growth. This raises a critical question: when the massive influx of ride-hailing services leads to declining parking and rental revenue, should airports compensate for losses by directly increasing parking fees and access charges, or should they pursue sustainable revenue growth by enhancing ride-hailing operational efficiency? What are the impacts of different charging strategies on the welfare of different stakeholders? What policy implications do these effects have for airport administrators and regulators?

To answer the above questions, this study develops a two-stage game-theoretic model to analyze the impact of different airport charging strategies on the airport ground transportation market. We assume that an arriving passenger has three travel options: (1) using a private car or rental car previously parked at the airport; (2) leaving the airport by ride-hailing services; or (3) choosing external low-cost public transportation. For the airport, private cars and rental cars generate parking fees or concession revenues; ride-hailing services produce access fee income; while public transportation contributes no direct revenue. We examine two alternative airport charging strategies: (1) directly imposing charges on ride-hailing services; and (2) investing to improve ride-hailing operational

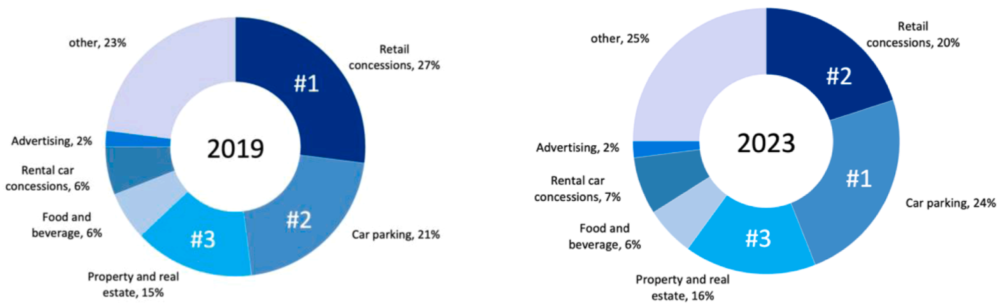


**Fig. 1.** Distribution of non-aeronautical revenue by source (2019 and 2023).
Source: ACI World Airport Economics Database

efficiency while simultaneously charging access fees. By comparing the impacts of these two strategies on passengers' travel choices, we evaluate how each strategy affects the welfare of different stakeholders. The results show that direct charging of RHCs can increase airport profits, but at the expense of reducing both the profits of RHCs and passengers' surplus, ultimately lowering overall social welfare. In contrast, when the cost of operational efficiency improvement is relatively low, the strategy of charging while improving operational efficiency not only raises the airport's profit but also increases the profit of RHC and consumer surplus. Furthermore, we examine the optimal strategies of a profit-maximizing airport and a social welfare-maximizing government under different conditions, and find that the two objectives may not always align. These findings yield important policy implications regarding the design of airport ground transportation pricing and regulatory frameworks.

The contributions of this paper are multi-fold. Methodologically, this paper develops a two-stage game-theoretic model to examine the impact of airports charging RHCs. Previous literature has primarily relied on surveys or empirical data to explore the impact of RHCs entering airports, with limited attention given to the strategic interactions between airports and RHCs, as well as how these interactions affect passengers and social welfare. By constructing this theoretical model, we are able to conduct an in-depth analysis of the game between airports and RHCs, investigate their pricing strategies, and examine the impact on various stakeholders. Practically, our analysis yields clear policy implications that are valuable for both airports and the government. First, regarding airport operational strategies, we reveal the critical role of the cost of improving ride-hailing operational efficiency in decision-making. When the cost of operational efficiency improvement is relatively low, airports have incentives to substantially improve ride-hailing service operational efficiency and achieve profit maximization through charging; conversely, when the cost of operational efficiency improvement is high, airports are more likely to rely on direct charging to increase revenue rather than investing excessively in efficiency improvement. Second, from a governmental perspective, when the cost of operational efficiency improvement is relatively low, the government requirements for airports to enhance ride-hailing service efficiency to a certain level can significantly improve social welfare; when the cost of operational efficiency improvement is high, appropriate fiscal subsidies can serve as an effective instrument to encourage airports to improve ride-hailing service operational efficiency. It is noteworthy that the analytical framework and conclusions of this paper are not only applicable to the specific context of airport-RHC interactions but can also be extended to broader strategic interactions between infrastructure operators and mobility platforms (such as high-speed rail stations and RHCs). This extension enhances the real-world applicability of our research, providing a reference for designing effective infrastructure and pricing policies for transportation hubs.

The rest of this paper is organized as follows. Section 2 reviews relevant literature. In Section 3, we establish a game-theoretical model for the analytical investigations. Section 4 presents our analytical results and the discussions. The policy implications for various stakeholders are presented in Section 5. The last section concludes this study.

## 2. Literature review

This study mainly focuses on the impact of different airport pricing strategies on airport ground transportation. Three main strands of literature are directly relevant to this study. The first strand discusses the impacts of RHCs' entry into airports. The second analyzes the impacts of airport charges, and the last strand focuses on the monopolistic quality supply at the airport.

### *2.1. The impact of RHCs on airports*

A substantial body of research indicates that RHCs have significantly impacted existing transportation services while also introducing broader societal and environmental implications. Some studies examined the substitution and complementary effects of ride-hailing services on other modes of transportation (Zhang and Zhang, 2018; Babar and Burtch, 2020). Another body of literature investigated the impact of RHCs on the environment and traffic congestion (Yu et al., 2017; Li et al., 2016; Erhardt et al., 2019). Our paper, however, focuses more specifically on the impact of ride-hailing services on airports. Existing literature focused on mode replacement (Davol, 2017; Hermawan and Regan, 2017; Dong and Ryerson, 2020), parking demand (Henao, 2018; Wadud, 2020), and congestion issues (Mandle and Box, 2017; Zuniga-Garcia and Machemehl, 2021). Based on extensive ride-hailing data from U.S. airports, Hermawan and Regan (2017) found that ride-hailing services replace the use of shared modes, such as buses, shared vans, and shuttles. Dong and Ryerson (2020) argued that the entry of RHCs into airports has reduced the number of passengers using taxis and private vehicles. Furthermore, Wadud (2020) examined the impact of the entry of RHCs on airport parking transactions and found a statistically significant reduction in the number of cars parked at airports. RHCs also contribute to congestion in airport ground transportation. Zuniga-Garcia and Machemehl (2021) conducted a natural experiment using the unexpected service disruption of RHCs in Austin, Texas, in 2016 to analyze their impact on airport access. They found that when major RHCs resumed operations in the city, the speed within airport access roads decreased. Similarly, Mandle and Box (2017) surveyed the 100 largest airports in the U.S., revealing that 46 % of airports reported increased roadway congestion due to RHC operations. Moreover, research on the impact of RHCs on airport revenue remains limited. Mandle and Box (2016, 2017) indicated that the entry of RHCs into airports has significantly reduced demand for airport parking and car rentals, thereby affecting airport revenue. However, airports have implemented countermeasures, such as charging RHC fees and increasing parking rates. While 98 % of airports permit charging fees to RHCs, airports generally perceive this revenue as insufficient to offset the revenue losses experienced by most airports (Zuniga-Garcia and

Machemehl, 2021). In contrast, Leiner and Adler (2020) argued that the additional revenue generated from charging RHCs could offset, or even surpass, the reductions in parking and car rental income, thereby leading to an overall increase in airport profit. Despite these findings, it remains unclear whether the overall impact of RHCs' entry into the airport ground transportation market is positive or negative. Meanwhile, previous studies have rarely examined the strategic interactions between airports and RHCs, nor have they focused on the implications for passengers and social welfare.

### 2.2. Airport charges

The second strand of literature focuses on airport charges, including aeronautical charges and non-aeronautical charges. There is a growing body of literature that discusses aeronautical charges, focusing on aspects such as regulation (Czerny, 2006; Lu and Pagliari, 2004), cross-subsidization (Ivaldi et al., 2015; Zhang and Zhang, 1997), and revenue sharing (Fu and Zhang, 2010; Saraswati and Hanaoka, 2014). However, there has been limited attention paid to airport charges for non-aeronautical activities. Over the past twenty-five years, the growth rate of non-aeronautical revenue has surpassed that of aeronautical revenue, making it a major source of income for many airports (Yokomi et al., 2017; Fasone et al., 2016). This study primarily focuses on airport charges imposed on RHCs. Currently, airports adopt four main charging models for RHCs: fixed fees, distance- or time-based fees, peak-period fees, and dedicated pickup zone fees (Leiner and Adler, 2020). The methods for determining these fee structures mainly include cost recovery, market-based charging, earmarking RHCs' revenue for specific purposes, and investing in RHCs-related infrastructure. According to Leiner and Adler (2020), cost recovery is the prevailing RHCs fee approach at large-hub airports, while market-based is the approach used by one-third to one-half of large-, medium-, and small-hub airports. A small percentage of airports earmark RHC revenue for specific purposes. Furthermore, airport authorities argue that such charges provide multiple benefits, including reducing traffic congestion, improving air quality, enhancing safety, and encouraging drivers to consider public transportation alternatives. Intuitively, following the implementation of these fees, airports may increase investments in infrastructure or expand staffing to improve the quality of ground transportation services. Overall, existing literature has conducted in-depth discussions on pricing mechanisms between airports and airlines, and some studies have also focused on the pricing of airport non-aeronautical services and their impact on passenger behavior. However, research on emerging ground transportation services (such as ride-hailing services) remains limited. It is worth emphasizing that while these emerging travel modes enhance passenger convenience, they also significantly impact airports' revenue structures. Compared to previous studies that primarily focused on how to enhance airport revenue through non-aeronautical pricing, the charging strategies for ground transportation services are more likely to have profound implications for airports' overall revenue management and coordination among different stakeholders.

### 2.3. Monopolistic quality supply

Furthermore, our research is closely related to the literature on monopolistic quality supply. Early theoretical work, such as Spence (1975) and Mussa and Rosen (1978), indicated that monopolists often have incentives to reduce product quality to strengthen their extraction of consumer surplus. Subsequently, quality supply has also received attention in the fields of operations research, marketing and management (Feichtinger et al., 1994; Jørgensen and Zaccour, 2004; Ouardighi and Kim, 2010). This study focuses specifically on the quality supply problem under monopolistic conditions at airports. Since most cities or regions typically have only one major airport, airports naturally possess considerable market power. They not only have autonomous decision-making authority over pricing levels but can also dominate the configuration of service types and quality standards, such as the differentiated setup of regular and VIP lounges, and various tiers of parking service options. Existing related research has largely concentrated on airport service quality supply for airlines, which has led to discussions on congestion pricing, capacity investment, and other related issues (Oum and Zhang, 1990; Zhang and Zhang, 2003; Huai et al., 2025). In contrast, our work focuses on airport quality supply in ground transportation. Specifically, airports determine the operational efficiency of ride-hailing services by offering a range of supportive measures, such as designating exclusive pick-up and drop-off zones for ride-hailing cars and deploying traffic coordinators.

In addition, our work relates to the literature on platform quality supply. Some studies explored how platforms decide their quality investment in interactions with suppliers. For instance, Tan et al. (2020) emphasized that platforms' direct quality investments can promote bilateral user participation and form complementary relationships with platform pricing structures. Particularly relevant to this paper is Puyang et al. (2025), which examined how platforms choose investment and pricing when platform infrastructure affects common attributes of all differentiated products. The results showed that platform strategic choices may achieve a win-win-win situation for platform profits, supplier profits, and consumer surplus. In our study, the airport can be regarded as a platform that provides complementary service facilities, accommodating both private travels associated with airport operations and third-party ride-hailing services. The fees that airports charge RHCs can be viewed as the "price" for using these complementary service facilities. Within this framework, our study focuses on airport charging strategies for third-party ride-hailing services: whether to potentially suppress their development through direct charging, or to enhance their operational efficiency and generate revenue based on such improvements.

## 3. Base model setting

Currently, travel modes to airports can be categorized into five groups: Private vehicle, RHC/taxicab, rental car, comfortable ground transportation (e.g., shuttle bus, shared van, limousines), and economy ground transportation (e.g., metro, light rail, train) (Leiner and Adler, 2020). Based on the different service providers, we reclassify them into three categories: private travel services provided by airports (e.g., private car, rental car[1]), commercial transportation services provided by RHCs (e.g., ride-hailing services), and public transportation services provided by the government (e.g., metro, light rail, train). Further, we consider that these three travel modes exhibit vertical differentiation in service quality. Travel time is a key component of service quality (Bilotkach et al., 2010; Wan et al., 2016), though other factors such as comfort, cleanliness, and overall convenience also play significant roles in the user experience.

First, we assume that public transportation has the lowest service quality. In cities with constrained transportation resources (such as Tokyo and Hong Kong), subway and other public transit systems offer relatively high accessibility and convenience. However, public transportation has inherent service limitations, including fixed departure schedules, inconvenience for carrying luggage, and limited riding comfort. Meanwhile, public transportation typically adopts relatively low fares to serve a broader passenger base, which to some extent constrains service quality improvements. Therefore, within our study's comparative framework, we define public transportation service quality as the lowest level. Private cars and rental cars are generally considered more direct ground transportation options for airports. Major airports are typically equipped with sufficient parking facilities, allowing passengers to park conveniently near terminals. Additionally, rental car service systems at large airports are relatively well-developed, with passengers able to reserve vehicles in advance through online platforms. Rental service counters are usually located in arrival halls, facilitating quick vehicle pickup upon passenger arrival. Overall, private travel modes provide a "vehicle-waiting-for-passenger" service characteristic, allowing travelers to depart according to their personal schedules, thereby effectively reducing delay risks. Ride-hailing services have developed rapidly in recent years due to their convenient booking methods and advantages, such as eliminating parking concerns. Ride-hailing can provide more flexible travel options with door-to-door service at relatively reasonable pricing. Given the similarities between private travel and ride-hailing services in terms of in-vehicle travel time and ride comfort, this study simultaneously considers the horizontal differentiation between these two travel modes. Considering the preference differences among different consumers, our work establishes two service quality ranking schemes in the subsequent analysis: $S^D > S^R > S^P$ and $S^R > S^D > S^P$.

This study focuses on the departure mode choices of arriving air passengers and incorporates three alternative travel options within the framework of a single origin-destination (O-D) market. To simplify the analysis, we assume that the market includes one private travel operator (i.e., the airport), one RHC, and one public transportation operator. Additionally, it is assumed that all individuals are capable of driving. We further assume that passengers who take ride-hailing do not carpool with other passengers. As a result, RHC charges can be adjusted from a per-vehicle basis to a per-passenger. In order to address the vertical differentiation between private travel, ride-hailing service and public transportation, consider the utility function of a passenger to be

$$U_i^j = \theta S^j - P_i^j \tag{1}$$

where $S$ is the service quality of a travel mode, $\theta$ is the passenger's valuation for service quality, and $P$ is the travel price. We assume $\theta$ is uniformly distributed between 0 and 1 in all scenarios. For private travel, if passengers choose private cars, $P$ represents the parking fees paid by passengers; if they choose car rental, $P$ represents the fees collected by the airport at a certain proportion from the car rental price. In addition, we model the price of public transportation as an exogenous variable, denoted by $P^P$. The superscript $j = D, \quad R, \quad P$ indicates the private travel, the RHC and the public transportation. The superscript $i = 1, \quad 2, \quad 3$ indicates three scenarios.

Within this utility framework, three scenarios are constructed to analyze the pricing interaction between the airport and the ride-hailing company. In the scenario of free competition (i.e., Scenario 1), the airport does not impose any fees or restrictions on ride-hailing services. In this scenario, the airport and the ride-hailing company engage in Bertrand competition, simultaneously determining their respective service prices (i.e., $P_1^D$ and $P_1^R$) in order to maximize their profits. When the airport begins to charge fees (i.e., Scenario 2 and Scenario 3), the airport and ride-hailing company are engaged in a two-stage sequential move game: In the first stage, the airport determines the access fee (i.e., $F_2$ and $F_3$) imposed on the RHC. In the second stage, the airport and the RHC simultaneously determine their respective service prices (i.e., $P_i^D$ and $P_i^R$, $i = 2, 3$) for users in the end market, forming a Nash game. It is worth noting that the price of public transportation is treated as exogenous and remains relatively low, thereby ensuring the fulfillment of basic travel demand.

### 3.1. Baseline model: free competition

We first consider a baseline case with free competition (i.e., Scenario 1). We initially examine the service quality ranking of the three travel modes as follows: $S^D > S^R > S^P$. The marginal consumer who is indifferent between private travel and ride-hailing services is characterized by the incentive condition $U_1^D = U_1^R$, which gives $\theta_1^{DR} = \left(P_1^D - P_1^R\right)/\left(S^D - S^R\right)$. Similarly, the marginal consumer who is indifferent between ride-hailing services and public transportation is characterized by the incentive condition $U_1^R = U_1^P$, which gives $\theta_1^{RP} = \left(P_1^R - P^P\right)/\left(S^R - S^P\right)$. To ensure the non-negativity of utility, the marginal passenger who is indifferent between public

[1] For private car travel, airports need to provide parking facilities, and in this paper, we assume that airport parking lots are operated directly by the airport. For car rental services, although rental services are typically operated directly by rental companies, these companies must pay concession fees or revenue shares to the airport. Based on this economic relationship, we treat the airport as the operator of car rental services.

transportation and the outside option is characterized by $U_1^P = 0$, which gives $\theta_1^{P0} = P^P/S^P$. Thus, passengers with θ between $\theta_1^{DR}$ and 1 choose private travel, passengers with θ between $\theta_1^{RP}$ and $\theta_1^{DR}$ choose ride-hailing services, passengers with θ between $\theta_1^{P0}$ and $\theta_1^{RP}$ choose public transportation, while those with θ below $\theta_1^{P0}$ opt not to travel, as shown in Fig. 2. Using similar logic, we can infer the traffic volumes when $S^R > S^D > S^P$. From this, we obtain the passenger traffic of private travel, ride-hailing service and public transportation, as follows:

$$Q_1^D = \begin{cases} 1 - \dfrac{P_1^D - P_1^R}{S^D - S^R}, \ if\ S^D > S^R > S^P \\ \dfrac{P_1^R - P_1^D}{S^R - S^D} - \dfrac{P_1^D - P^P}{S^D - S^P}, \ if\ S^R > S^D > S^P \end{cases} \tag{2}$$

$$Q_1^R = \begin{cases} \dfrac{P_1^D - P_1^R}{S^D - S^R} - \dfrac{P_1^R - P^P}{S^R - S^P}, \ if\ S^D > S^R > S^P \\ 1 - \dfrac{P_1^R - P_1^D}{S^R - S^D}, \ if\ S^R > S^D > S^P \end{cases} \tag{3}$$

$$Q_1^P = \begin{cases} \dfrac{P_1^R - P^P}{S^R - S^P} - \dfrac{P^P}{S^P}, \ if\ S^D > S^R > S^P \\ \dfrac{P_1^D - P^P}{S^D - S^P} - \dfrac{P^P}{S^P}, \ if\ S^R > S^D > S^P \end{cases} \tag{4}$$

We then use $\pi_1^A$, $\pi_1^R$ and $\pi_1^P$ to denote the profits of the airport, the RHC and the public transportation, respectively. The unit operating costs of the three operators are represented by $C^D$, $C^R$ and $C^P$. Without loss of generality, we normalize $C^D$, $C^R$ and $C^P$ to 0 in the following analysis. The profit functions of the airport, the RHC and public transportation are

$$\pi_1^A = \left(P_1^D - C^D\right)*Q_1^D \tag{5}$$

$$\pi_1^R = \left(P_1^R - C^R\right)*Q_1^R \tag{6}$$

$$\pi_1^P = \left(P^P - C^P\right)*Q_1^P \tag{7}$$

Consumer surplus can reflect the degree of satisfaction after deducting the fare and time paid from the income brought by a transport service. It is the difference between passenger utility and total payment. The consumer surplus in Scenario 1 is expressed as:

$$CS_1 = \begin{cases} \int_{\theta_1^{DR}}^{1} \left(xS^D - P_1^D\right)\mathrm{d}x + \int_{\theta_1^{RP}}^{\theta_1^{DR}} \left(xS^R - P_1^R\right)\mathrm{d}x + \int_{\theta_1^{P0}}^{\theta_1^{RP}} \left(xS^P - P^P\right)\mathrm{d}x, \ if\ S^D > S^R > S^P \\ \int_{\theta_1^{RD}}^{1} \left(xS^R - P_1^R\right)\mathrm{d}x + \int_{\theta_1^{DP}}^{\theta_1^{RD}} \left(xS^D - P_1^D\right)\mathrm{d}x + \int_{\theta_1^{P0}}^{\theta_1^{DP}} \left(xS^P - P^P\right)\mathrm{d}x, \ if\ S^R > S^D > S^P \end{cases} \tag{8}$$

### 3.2. Airport charge

As introduced in the introduction, many airports have begun implementing charges on RHCs to compensate for declining parking revenues. Given airports' monopolistic position, they can directly impose fees on RHCs. We assume that the airport charges a fee $F_2$ for each ride-hailing car entering the airport, and define this situation as Scenario 2. Under this scenario, the traffic volumes for the three travel modes $Q_2^D$, $Q_2^R$, $Q_2^P$and consumer surplus $CS_2$ remain identical to those in Scenario 1. The profit functions of the airport, the RHC and public transportation are

$$\pi_2^A = \left(P_2^D - C^D\right)*Q_2^D + Q_2^R*F_2$$

$$s.t.\ F_2 \le P_2^R \tag{9}$$

$$\pi_2^R = \left(P_2^R - C^R\right)*Q_2^R - Q_2^R*F_2 \tag{10}$$

$$\pi_2^P = \left(P^P - C^P\right)*Q_2^P \tag{11}$$

### 3.3. Airport charge with operational efficiency improvement

In this section, we examine Scenario 3, in which the airport not only charges ride-hailing services but also undertakes measures to

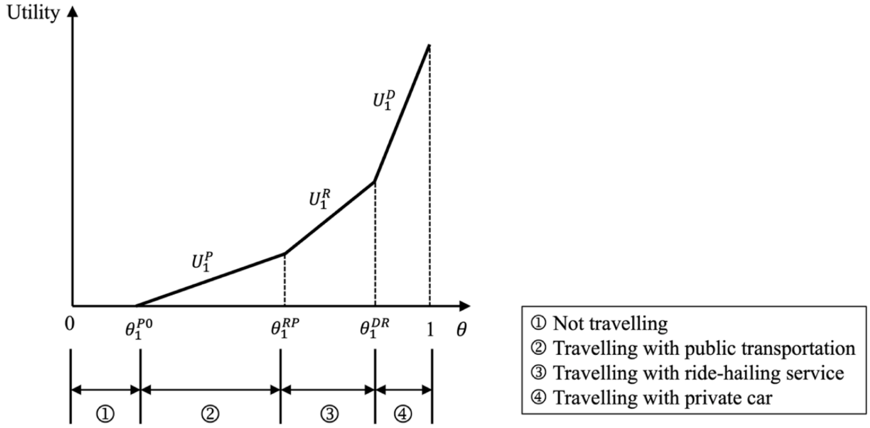


**Fig. 2.** Market division with private car, ride-hailing service and public transportation.

enhance their operational efficiency. Consequently, the overall quality of ride-hailing services depends both on their own service level and on the operational efficiency provided by the airport. Assuming that the airport improves operational efficiency by a parameter $b$[2], the overall quality of ride-hailing services can be expressed as $S^R+b$. Similarly, we need to consider different quality rankings between ride-hailing services and private travel after the enhancement of operational efficiency. Applying the logic from Section 3.1, we obtain the passenger traffic of private travel, ride-hailing service and public transportation, as follows:

$$Q_3^D=\begin{cases}1-\dfrac{P_3^D-P_3^R}{S^D-(S^R+b)},\ if\ S^D>S^R+b>S^P\\ \dfrac{P_3^R-P_3^D}{(S^R+b)-S^D}-\dfrac{P_3^D-P^P}{S^D-S^P},\ if\ S^R+b>S^D>S^P\end{cases} \tag{12}$$

$$Q_3^R=\begin{cases}\dfrac{P_3^D-P_3^R}{S^D-(S^R+b)}-\dfrac{P_3^R-P^P}{(S^R+b)-S^P},\ if\ S^D>S^R+b>S^P\\ 1-\dfrac{P_3^R-P_3^D}{(S^R+b)-S^D},\ if\ S^R+b>S^D>S^P\end{cases} \tag{13}$$

$$Q_3^P=\begin{cases}\dfrac{P_3^R-P^P}{(S^R+b)-S^P}-\dfrac{P^P}{S^P},\ if\ S^D>S^R+b>S^P\\ \dfrac{P_3^D-P^P}{S^D-S^P}-\dfrac{P^P}{S^P},\ if\ S^R+b>S^D>S^P\end{cases} \tag{14}$$

The cost for the airport to improve the operational efficiency of ride-hailing services is given by $\frac{1}{2}kb^2$, where $k\geq 0$ denotes the cost coefficient. A higher value of $k$ indicates a higher cost for the airport to improve the operational efficiency of ride-hailing services. The profit functions of the airport, the RHC and public transportation are

$$\pi_3^A=(P_3^D-C^D)*Q_3^D+Q_3^R*F_3-\frac{1}{2}kb^2$$

$$s.t.\ F_3\leq P_3^R \tag{15}$$

$$\pi_3^R=(P_3^R-C^R)*Q_3^R-Q_3^R*F_3 \tag{16}$$

$$\pi_3^P=(P^P-C^P)*Q_3^P \tag{17}$$

The consumer surplus in Scenario 3 is expressed as:

[2] It should be noted that the airport's improvement of ride-hailing operational efficiency constitutes a long-term investment in infrastructure and management systems that cannot be frequently adjusted. Accordingly, within the short-run pricing game considered in this paper, $b$ is treated as an exogenous parameter representing the pre-determined level of operational efficiency.

$$CS_3 = \begin{cases} \int_{\theta_3^{DR}}^{1} \left(xS^D - P_3^D\right)\mathrm{d}x + \int_{\theta_3^{RP}}^{\theta_3^{DR}} \left(x\left(S^R + b\right) - P_3^R\right)\mathrm{d}x + \int_{\theta_3^{P0}}^{\theta_3^{RP}} \left(xS^P - P^P\right)\mathrm{d}x, \ \text{if } S^D > S^R + b > S^P \\ \int_{\theta_3^{RD}}^{1} \left(x\left(S^R + b\right) - P_3^R\right)\mathrm{d}x + \int_{\theta_3^{DP}}^{\theta_3^{RD}} \left(xS^D - P_3^D\right)\mathrm{d}x + \int_{\theta_3^{P0}}^{\theta_3^{DP}} \left(xS^P - P^P\right)\mathrm{d}x, \ \text{if } S^R + b > S^D > S^P \end{cases} \tag{18}$$

Social welfare is expressed by the sum of consumer surplus and company profits. Therefore, social welfare for the scenario $i$ will be represented as follows:

$$SW_i = \pi_i^A + \pi_i^R + \pi_i^P + CS_i \tag{19}$$

To ensure the non-negativity of passenger traffic, we have the following inequalities:

$$\begin{cases} 0 < \theta_i^{P0} < \theta_i^{RP} < \theta_i^{DR} < 1, \ \text{if } S^D > S^R > S^P \text{or } S^D > S^R + b > S^P \\ 0 < \theta_i^{P0} < \theta_i^{DP} < \theta_i^{RD} < 1, \ \text{if } S^R > S^D > S^P \text{or } S^R + b > S^D > S^P \end{cases} \tag{20}$$

Fares and traffic volumes in each scenario are summarized in Table 1. A glossary of variables with different notation and subscripts can be found in Appendix A. According to the first-order conditions, the Bertrand-Nash equilibrium outputs are obtained. The equilibrium outputs can be found in Appendix B.

## 4. Analytical results and discussions

In this section, we first compare the equilibrium results under the three scenarios to examine the impact of airport charging for ride-hailing services on market equilibrium outcomes (see Section 4.1). Based on the comparison results from Section 4.1, in Section 4.2, we summarize the optimal response strategies for the airport and government regarding ride-hailing entry into airport ground transportation. Finally, in Section 4.3, we use numerical simulations to further discuss the impact of airport improving ride-hailing operational efficiency in Scenario 3.

### *4.1. Comparison of equilibrium outcomes*

We use the superscript * to represent the equilibrium solutions under three scenarios. By comparing the market equilibrium solutions under different scenarios, we can derive the following lemmas and propositions. The comparison results under various scenarios are summarized in Table 2. The proofs of all lemmas and propositions are collated in Appendix C.

**Lemma 1.** *Compared to the free competition baseline, airport charges in Scenario 2 increase the prices of both private travel and ride-hailing services, while reducing their respective traffic volumes (i.e., $P_2^{D*} > P_1^{D*}$, $P_2^{R*} > P_1^{R*}$, $Q_2^{D*} < Q_1^{D*}$, $Q_2^{R*} < Q_1^{R*}$). Moreover, airport charges in Scenario 2 increase the traffic volumes of public transportation (i.e., $Q_2^{P*} > Q_1^{P*}$).*

Lemma 1 shows that the airport's charges on the RHC not only increase the price of ride-hailing services but also raise the price of private travel. An increase in the price of ride-hailing services is expected, as the airport's charges impose additional costs on the RHC. Facing higher costs, the RHC will pass part of the total cost increase through to a higher price for passengers. As the price of ride-hailing services has risen, airports have also taken the opportunity to increase the price of private travel in order to secure higher revenues. This is consistent with the reality that many airports have increased parking rates to make up for the loss of airport revenues since the RHC entered the airports (Bergal, 2017). Due to the increase in prices of both private travel and ride-hailing services while their quality remains unchanged, the demand for both modes decreases. Additionally, public transportation traffic volumes increase. This is because, with the price and service quality of public transportation remaining unchanged, its relative cost-effectiveness increases as the counterpart's price rises, thereby attracting more travelers. This finding aligns with the conclusions of Dong and Ryerson, 2020.

**Proposition 1**. Compared to the free competition baseline, airport charges in Scenario 2 increase the profits of both airport and

**Table 1**
Prices and traffic volumes in each scenario.

| Scenarios | Prices | Traffic volumes | |
|---|---|---|---|
| | | $S^D > S^R > S^P$ | $S^R > S^D > S^P$ |
| Scenario 1 | $P_1^D$ | $Q_1^D = 1 - (P_1^D - P_1^R)/(S^D - S^R)$ | $Q_1^D = (P_1^R - P_1^D)/(S^R - S^D) - (P_1^D - P^P)/(S^D - S^P)$ |
| | $P_1^R$ | $Q_1^R = (P_1^D - P_1^R)/(S^D - S^R) - (P_1^R - P^P)/(S^R - S^P)$ | $Q_1^R = 1 - (P_1^R - P_1^D)/(S^R - S^D)$ |
| | $P^P$ | $Q_1^P = (P_1^R - P^P)/(S^R - S^P) - P^P/S^P$ | $Q_1^P = (P_1^D - P^P)/(S^D - S^P) - P^P/S^P$ |
| Scenario 2 | $P_2^D$ | $Q_2^D = 1 - (P_2^D - P_2^R)/(S^D - S^R)$ | $Q_2^D = (P_2^R - P_2^D)/(S^R - S^D) - (P_2^D - P^P)/(S^D - S^P)$ |
| | $P_2^R$ | $Q_2^R = (P_2^D - P_2^R)/(S^D - S^R) - (P_2^R - P^P)/(S^R - S^P)$ | $Q_2^R = 1 - (P_2^R - P_2^D)/(S^R - S^D)$ |
| | $P^P$ | $Q_2^P = (P_2^R - P^P)/(S^R - S^P) - P^P/S^P$ | $Q_2^P = (P_2^D - P^P)/(S^D - S^P) - P^P/S^P$ |
| | | $S^D > S^R + b > S^P$ | $S^R + b > S^D > S^P$ |
| Scenario 3 | $P_3^D$ | $Q_3^D = 1 - (P_3^D - P_3^R)/(S^D - S^R - b)$ | $Q_3^D = (P_3^R - P_3^D)/(S^R + b - S^D) - (P_3^D - P^P)/(S^D - S^P)$ |
| | $P_3^R$ | $Q_3^R = (P_3^D - P_3^R)/(S^D - S^R - b) - (P_3^R - P^P)/(S^R + b - S^P)$ | $Q_3^R = 1 - (P_3^R - P_3^D)/(S^R + b - S^D)$ |
| | $P^P$ | $Q_3^P = (P_3^R - P^P)/(S^R + b - S^P) - P^P/S^P$ | $Q_3^P = (P_3^D - P^P)/(S^D - S^P) - P^P/S^P$ |

**Table 2**
Equilibrium results comparison.

| | Scenario 2 vs. Scenario 1 | | | Scenario 3 vs. Scenario 1 | | | Scenario 3 vs. Scenario 2 | | |
|---|---|---|---|---|---|---|---|---|---|
| | private travel | ride-hailing services | public transportation | private travel | ride-hailing services | public transportation | private travel | ride-hailing services | public transportation |
| $S^D > S^R > S^P$ | | | | | | | | | |
| $\Delta P$ | $> 0$ | $> 0$ | $= 0$ | $> 0$ | $> 0$ | $= 0$ | $> 0$ or $< 0$ | $> 0$ | $= 0$ |
| $\Delta Q$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ | $> 0$ or $< 0$ | $> 0$ | $> 0$ or $< 0$ | $> 0$ or $< 0$ | $> 0$ |
| $\Delta \pi$ | $> 0$ | $< 0$ | $> 0$ | $> 0$ or $< 0$ | $> 0$ or $< 0$ | $> 0$ | $> 0$ or $< 0$ | $> 0$ or $< 0$ | $> 0$ |
| $\Delta CS$ | $< 0$ | | | $> 0$ or $< 0$ | | | $> 0$ or $< 0$ | | |
| $\Delta SW$ | $< 0$ | | | $> 0$ or $< 0$ | | | $> 0$ or $< 0$ | | |
| $S^R > S^D > S^P$ | | | | | | | | | |
| $\Delta P$ | $> 0$ | $> 0$ | $= 0$ | $> 0$ | $> 0$ | $= 0$ | $> 0$ | $> 0$ | $= 0$ |
| $\Delta Q$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ | $< 0$ | $> 0$ | $< 0$ | $< 0$ | $> 0$ |
| $\Delta \pi$ | $> 0$ | $< 0$ | $> 0$ | $> 0$ or $< 0$ | $> 0$ or $< 0$ | $> 0$ | $> 0$ or $< 0$ | $> 0$ | $> 0$ |
| $\Delta CS$ | $< 0$ | | | $> 0$ or $< 0$ | | | $> 0$ | | |
| $\Delta SW$ | $< 0$ | | | $> 0$ or $< 0$ | | | $> 0$ or $< 0$ | | |

public transportation, but decrease the profit of RHC (i.e., $\pi_2^{A^*} > \pi_1^{A^*}$, $\pi_2^{R^*} < \pi_1^{R^*}$, $\pi_2^{P^*} > \pi_1^{P^*}$). Moreover, the airport charges in Scenario 2 also decrease consumer surplus and social welfare (i.e., $CS_2^* < CS_1^*$, $SW_2^* < SW_1^*$).

Proposition 1 indicates that when the airport charges increase the profits of the airport and public transportation, but reduce the profit of RHC and consumer surplus, ultimately leading to a decline in social welfare. The increase in airport profit stems from two factors. One factor is that the airport gains an additional revenue stream by charging fees to the RHC (i.e., $Q_2^{R^*}*F_2^* > 0$). Another factor is that the airport raises the price of private travel, the increase in the price of private travel is higher than the decline in traffic volumes, resulting in increased revenue (i.e., $P_2^{D^*}*Q_2^{D^*} > P_1^{D^*}*Q_1^{D^*}$). However, airport charges reduce the profit of RHC. The RHC is required to pay fees to the airport, which increases its cost, and leads to a reduction in RHC profitability. Additionally, the increased public transit ridership generates higher profits for the public transportation operator.

Airport charges are also detrimental to consumers. As stated in Lemma 1, airport charges increase the prices of both private travel and ride-hailing services, leading to higher travel costs for passengers and a reduction in consumer surplus. Overall, in Scenario 2, only the airport and public transportation benefit, while both the RHC and passengers suffer significant losses due to the airport charges. Furthermore, the magnitude of these losses exceeds the benefits gained by the airport and public transportation, ultimately resulting in a decline in social welfare.

**Lemma 2**. Compared to the free competition baseline, airport charges in Scenario 3 increase the prices of both private travel and ride-hailing services (i.e., $P_3^{D^*} > P_1^{D^*}$, $P_3^{R^*} > P_1^{R^*}$), while reducing the traffic volumes of private travel (i.e., $Q_3^{D^*} < Q_1^{D^*}$). The impact on ride-hailing demand remains uncertain. When $S^D > S^R > S^P$ and $b$ is large enough, airport charges increase the traffic volumes of ride-hailing; when $S^R > S^D > S^P$, airport charges decrease the traffic volumes of ride-hailing ($Q_3^{R^*} > Q_1^{R^*}$ or $Q_3^{R^*} < Q_1^{R^*}$). Moreover, airport charges in Scenario 3 improve the traffic volumes of public transportation (i.e., $Q_3^{P^*} > Q_1^{P^*}$).

Lemma 2 shows that the equilibrium outcomes in Scenario 3 are similar to those in Scenario 2, except for ride-hailing demand. Airport charges lead to higher ride-hailing prices, which naturally reduces demand. However, when $S^D > S^R > S^P$ and $b$ is sufficiently large, the improvement in the operational efficiency of ride-hailing services outweighs the increase in their price, thereby enhancing the cost-effectiveness of ride-hailing services and leading to an increase in demand.

**Proposition 2**. *Compared to the free competition baseline, the impact of airport charges in Scenario 3 is uncertain. When k is relatively small, airport charges increase the airport's profit (i.e., $\pi_3^{A^*} > \pi_1^{A^*}$). When b is relatively large, airport charges also increase the RHC's profit (i.e., $\pi_3^{R^*} > \pi_1^{R^*}$), while public transportation profits always increase (i.e., $\pi_3^{P^*} > \pi_1^{P^*}$). Moreover, when b is sufficiently large, airport charges also lead to increased consumer surplus (i.e., $CS_3^* > CS_1^*$); when b is large and k is small, airport charges result in improved social welfare (i.e., $SW_3^* > SW_1^*$).*

Proposition 2 demonstrates that the impact of airports improving ride-hailing operational efficiency while implementing charges depends on parameters $k$ and $b$. For airports, although enhancing ride-hailing operational efficiency may reduce private travel revenue, the additional revenue from charging RHC can offset this loss ($P_1^{A^*}*Q_1^{A^*} > P_3^{A^*}*Q_3^{A^*}$, $Q_3^{R^*}*F_3^* > P_1^{A^*}*Q_1^{A^*} - P_3^{A^*}*Q_3^{A^*}$). When the cost coefficient $k$ of improving ride-hailing operational efficiency is relatively small, the additional revenue from charging is sufficient to cover the cost increase, ultimately achieving airport profit enhancement. This finding aligns with the empirical observations reported by Leiner and Adler (2020), who noted that the introduction of RHC led to a slight reduction in parking revenue. However, the additional income from fees imposed on RHC could offset or even exceed the reduction in parking revenue, resulting in an overall increase in the airport's profit. For the RHC, when the operational efficiency improvement $b$ is relatively large, the RHC is able to significantly increase prices. Even when traffic volume changes remain uncertain, the substantial price increases ensure profit growth. Simultaneously, increased public transportation ridership also contributes to profit enhancement.

Furthermore, airport charging combined with operational efficiency improvement has dual effects on consumer surplus. On one hand, airport charges drive up prices for both private travel and ride-hailing services, increasing passenger travel costs and reducing consumer surplus. On the other hand, airports' improvement of ride-hailing operational efficiency provides passengers with superior travel experiences, contributing to increased consumer surplus. When operational efficiency improvement $b$ is sufficiently large, the increase in consumer surplus exceeds the decrease, ultimately achieving net growth in consumer surplus. Overall, when operational efficiency improvement $b$ is substantial and cost coefficient $k$ is relatively small, the strategy of airports improving ride-hailing operational efficiency while implementing charges can simultaneously achieve profit growth for the airport, RHC, and public transportation operator, while also enhancing consumer surplus, thereby promoting overall social welfare improvement.

**Lemma 3**. *Compared to Scenario 2, when $S^D > S^R > S^P$ and b is relatively small, private travel in Scenario 3 exhibits a lower price and higher demand (i.e., $P_3^{D^*} < P_2^{D^*}$, $Q_3^{D^*} > Q_2^{D^*}$). Ride-hailing prices in Scenario 3 are consistently higher, with lower demand when b is small (i.e., $P_3^{R^*} > P_2^{R^*}$, $Q_3^{R^*} < Q_2^{R^*}$). When $S^R > S^D > S^P$, both private travel and ride-hailing services in Scenario 3 have higher prices and lower traffic volumes (i.e., $P_3^{R^*} > P_2^{R^*}$, $Q_3^{R^*} < Q_2^{R^*}$, $P_3^{D^*} > P_2^{D^*}$, $Q_3^{D^*} < Q_2^{D^*}$).*

Lemma 3 compares the equilibrium prices and traffic volumes in Scenarios 2 and 3. When $S^D > S^R > S^P$, the relative magnitudes between Scenarios 2 and 3 are influenced by operational efficiency improvement $b$. When $b$ is small, the quality gap between private travel and ride-hailing services narrows, leading to price reductions for high-quality private travel while prices for low-quality ride-hailing services increase. This aligns with classical theory: when product quality converges, consumer substitutability between the two products intensifies, making demand more sensitive to relative prices. Consequently, high-quality products lose some of their pricing power and must reduce prices to maintain demand; low-quality products, benefiting from improved cost performance, can moderately increase prices without losing excessive demand. When $S^R > S^D > S^P$, operational efficiency improvement $b$ only widens the quality gap between the two travel modes. The enhanced quality of ride-hailing services leads to higher product prices, while private travel can also capitalize on this opportunity to raise prices. These price increases result in reduced traffic volumes for both travel modes.

**Proposition 3**. *Compared to Scenario 2, for the airport, when k is relatively small, the airport profit in Scenario 3 is higher (i.e., $\pi_3^{A^*} > \pi_2^{A^*}$). For the RHC's profit, when $S^D > S^R > S^P$ and b is relatively large, the RHC 's profit is higher in Scenario 3. When $S^R > S^D > S^P$, the RHC's profit is consistently higher in Scenario 3 (i.e., $\pi_3^{R^*} > \pi_2^{R^*}$). As for consumer surplus, when $S^D > S^R > S^P$ and b is relatively large, consumer surplus is higher in Scenario 3; when $S^R > S^D > S^P$, consumer surplus is consistently higher in Scenario 3 (i.e., $CS_3^* > CS_2^*$). Regarding social welfare, when k is relatively small, social welfare is higher in Scenario 3 (i.e., $SW_3^* > SW_2^*$).*

Proposition 3 examines the impact of airports enhancing ride-hailing operational efficiency under airport charging scenarios by comparing profits of all parties, consumer surplus, and social welfare between Scenarios 2 and 3. For the airport, regardless of quality ranking, as long as the cost coefficient $k$ of improving ride-hailing operational efficiency is relatively small, the profit obtained from improving ride-hailing operational efficiency while charging exceeds the profit from charging alone. This occurs because in Scenario 3, the airport improves ride-hailing operational efficiency, enabling higher charges for ride-hailing services compared to the simple charging in Scenario 2. As demonstrated in Lemma 3, in most cases, the private travel price is also higher in Scenario 3, contributing to increased private travel profits. Therefore, as long as the cost coefficient $k$ does not exceed a specific threshold, the airport can achieve greater profit in Scenario 3. For the RHC, when $S^D > S^R > S^P$, the RHC's profit depends on the operational efficiency improvement $b$. When $b$ is sufficiently large, the RHC's pricing power strengthens, and revenue growth is sufficient to offset the additional costs caused by airport charges. When $S^R > S^D > S^P$, further improvement of ride-hailing operational efficiency in Scenario 3 leads to substantial price increases. Even with reduced traffic volumes, this can generate revenue growth and subsequently drive profit increases.

The conditions for consumer surplus improvement in Scenario 3 are similar to those for RHC's profit enhancement. When $S^D > S^R > S^P$, only when $b$ is sufficiently large can it offset the decline in the cost-effectiveness of ride-hailing services caused by price increases, thereby achieving an increase in consumer surplus. When $S^R > S^D > S^P$, ride-hailing operational efficiency improvement enables travelers to enjoy a higher-quality travel experience, resulting in consumer surplus growth. Regarding social welfare, it primarily depends on the cost coefficient $k$ of operational efficiency improvement. Airport charging helps increase airport profit, while simultaneously enhancing ride-hailing operational efficiency contributes to improving both RHC's profits and consumer surplus. As long as the cost coefficient $k$ is relatively small, it will inevitably lead to increased social welfare.

### *4.2. Optimal strategies for the airport and government*

By comparing the profits of all parties, consumer surplus, and social welfare under the three scenarios above, we summarize the optimal strategies for the profit-maximizing airport and the welfare-maximizing government.

**Proposition 4**. *When k is relatively small, the airport's optimal strategy is to charge and improve ride-hailing operational efficiency; when k is relatively large, the airport's optimal strategy is to charge directly.*

Proposition 4 demonstrates that the cost coefficient $k$ is a critical factor influencing airport decision-making. When $k$ is relatively small, the airport can charge higher fees by improving ride-hailing operational efficiency without concern for substantial cost increases; therefore, the airport substantially improves ride-hailing operational efficiency while charging fees, and the resulting revenue can compensate for the decline in parking income, thereby increasing airport profits. When $k$ is relatively large, improving ride-hailing operational efficiency increases costs, while the revenue obtained from charging ride-hailing services is insufficient to offset the cost increase, leading to a profit decline; therefore, the optimal strategy for the airport is to leverage its monopolistic position to directly charge the RHC.

Next, we introduce a government that pursues social welfare maximization. We adopt a second-best approach, where the government chooses whether to allow the airport to charge alone or to charge while improving ride-hailing operational efficiency, with the airport and the RHC determining charging prices and travel prices. In reality, the airport and the RHC are typically subject to strict government regulation, but due to their monopolistic positions, they also possess considerable pricing autonomy. Therefore, compared to the first-best analytical approach where the government determines all operational variables, the second-best analytical approach allows the airport and the RHC to autonomously determine prices, providing a more realistic framework. By comparing social welfare under the three scenarios, we obtain Proposition 5.

**Proposition 5**. *When k is relatively small and b is relatively large, allowing the airport to charge fees while requiring it to improve ride-hailing operational efficiency represents the optimal social decision; when k is relatively large, prohibiting airport charges is the optimal social decision.*

Proposition 5 summarizes the socially optimal decision regarding the airport charging for ride-hailing services. When the cost coefficient $k$ is relatively small, allowing the airport to charge fees while enhancing ride-hailing operational efficiency can increase the airport's profits. At the same time, when the operational efficiency improvement $b$ is relatively large, both the profits of RHC and consumer surplus also increase, thereby creating a win-win-win outcome. In contrast, when the cost coefficient $k$ is relatively large, the airport tends to impose fees directly on the RHC without improving operational efficiency, which inevitably reduces social welfare. Therefore, from the government's perspective, prohibiting the airport from charging fees constitutes the preferable strategy.

Comparing Propositions 4 and 5, we find that the optimal strategy of the airport may not align with that of the government. When the cost coefficient $k$ is relatively large, the airport tends to directly charge the RHC; however, the government prefers to prevent such practices, as they would inevitably lead to a reduction in social welfare. In such cases, the government may consider providing financial support to the airport. Many such cases exist in reality. For example, with government financial support, the ground transportation center at Beijing Daxing International Airport specifically established ride-hailing pick-up and drop-off areas on two underground levels, separating them from other private cars and taxi areas, thereby alleviating road congestion and making ride-hailing services more orderly and convenient.

In summary, for airports with relatively low traffic volumes, the cost of improving ride-hailing operational efficiency may be relatively small. The airport may only need to convert part of its parking areas or internal roads into dedicated ride-hailing pick-up and drop-off zones, utilize smart devices to improve passenger-vehicle matching efficiency, and strengthen traffic management personnel. In this case, the airport's optimal decision is to improve ride-hailing operational efficiency while charging for it, with government regulation of the degree of operational efficiency improvement, thereby achieving simultaneous improvement of the airport's profit and social welfare. For airports with relatively high traffic volumes that require massive investments to construct large-scale ground transportation hubs to improve ride-hailing operational efficiency, the government should provide certain financial support to reduce airport investment costs, transforming the airport's optimal strategy from direct charging to improving ride-hailing operational efficiency while charging.

## 4.3. Numerical study

Since the ride-hailing operational efficiency improvement $b$ plays a crucial role in the competition among the three travel modes, we employ numerical simulation to further understand its impact on equilibrium outcomes. We begin by considering the travel time from the city center to the airport, and assign typical values for each mode. Specifically, we set the travel time of private cars at 40 minutes. Since using ride-hailing services at airports typically involves certain waiting, congestion, and transfer times, we average these additional times at 20 minutes. Given that ride-hailing vehicles and private cars have similar driving speeds, the in-vehicle travel time can also be set at 40 minutes, resulting in a total ride-hailing travel time of 60 minutes. By contrast, public transport generally requires significantly longer travel time, which we set at 120 minutes. In our model, we use the inverse of travel time as the indicator of service quality for each travel mode. After normalization, we obtain the following values: $S^D = 3$, $S^R = 2$, and $S^P = 1$. A larger value indicates a higher level of service quality. Furthermore, considering the inherent advantages of ride-hailing services (e.g., passengers do not need to drive and can rest during the trip), their service quality may in some cases surpass that of private travel. Accordingly, we also examine the scenario where $S^R = 3$, $S^D = 2$, and $S^P = 1$. In addition, we set the price of public transportation as $P^P = 0.05$, with cost

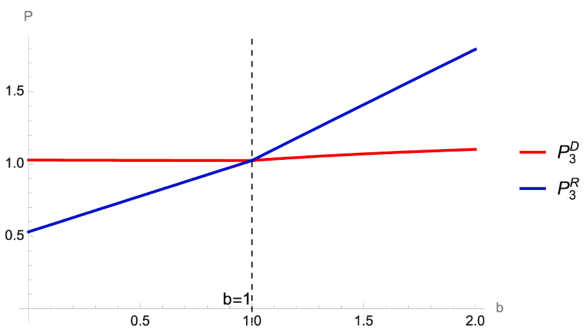


**Fig. 3a.** Changes in price with $b$ when $S^D > S^R > S^P$.

coefficient $k = 0.01$ or 0.05. It is noted that the selected values of parameters for the numerical simulations guarantee that all the non-negative constraints.

We first examine the impact of operational efficiency improvement $b$ on prices and traffic volumes. As shown in Figs. 3a and 3b, under both service quality rankings, parameter $b$ has essentially consistent effects on private travel and ride-hailing prices. As $b$ increases, the price of private travel rises slightly, while the price of ride-hailing service increases significantly, particularly when ride-hailing service quality exceeds that of private travel. This result indicates that a substantial improvement in the operational efficiency of ride-hailing would lead to a relatively rapid increase in their pricing, thereby creating potential benefits for both the airport and the RHC.

The traffic volumes change shown in Figs. 4a and 4b provides some counterintuitive findings. Under both service quality rankings, the improvement of ride-hailing operational efficiency leads to decreased traffic volumes for both private travel and ride-hailing, while public transportation demand increases. For private travel, due to the operational efficiency improvement of its competitor, its relative quality declines, coupled with price increases, demand inevitably decreases. For ride-hailing services, the magnitude of price increase exceeds the extent of operational efficiency improvement, resulting in a decline in cost-effectiveness and consequently reduced traffic volumes. As a result, an increasing number of consumers turn to public transportation, and the traffic volumes of public transportation continue to rise as $b$ increases. Furthermore, Fig. 4a shows that when ride-hailing operational efficiency improvement surpasses the level of private travel, its market share will also exceed that of private travel.

Figs. 5a and 5b reveal the impact of operational efficiency improvement $b$ and cost efficiency $k$ on various operators' profits. When $S^D > S^R > S^P$ and $k$ is relatively small, the profits of the airport and the RHC decrease in, but when the ride-hailing operational efficiency exceeds private travel's quality, profits subsequently increase. When $k$ is relatively large, the profit of the airport consistently decreases in $b$. This indicates that $k$ is crucial for the airport's decision-making. When $S^R > S^D > S^P$, the airport's profit first increases and then decreases as $b$ grows, and as $k$ increases, the peak continuously shifts toward the lower-left. This suggests that, for a profit-maximizing airport, there exists an optimal level of operational efficiency improvement $b$. In addition, the profit of the RHC continuously increases in $b$. Under both service quality rankings, the profit of public transportation exhibits a slight increase in $b$.

Figs. 6a and 6b further analyze the impact of operational efficiency improvement $b$ and cost efficiency $k$ on consumer surplus and social welfare. Under both service quality rankings, consumer surplus increases with $b$. This is intuitive, as ride-hailing operational efficiency improvements enable consumers to enjoy better travel experiences. Social welfare changes are more complex. When $S^D > S^R > S^P$ and $k$ is relatively small, the social welfare decreases in, but when the ride-hailing service quality exceeds private travel's quality, profits subsequently increase. When $k$ is relatively large, the social welfare consistently decreases in $b$. When $S^R > S^D > S^P$, the social welfare first increases and then decreases as $b$ grows, and as $k$ increases, the peak continuously shifts toward the lower-left. Overall, the effect of improving operational efficiency $b$ on social welfare is similar to its effect on airport profit.

## 5. Policy implications

Based on our analytical results in Section 4, we can infer the policy and management implications for various stakeholders. From the airport's perspective, both charging strategies—charging alone and charging while improving ride-hailing operational efficiency—can increase the airport's profit. However, considering the cost of improving ride-hailing operational efficiency, the airport should choose different strategies under different circumstances. Specifically, when the cost of improving operational efficiency is relatively large, the airport tends to implement direct charging; when the cost of improving operational efficiency is relatively small, the airport tends to enhance ride-hailing operational efficiency and charge fees. Additionally, the airport should exercise caution when improving ride-hailing operational efficiency. When $S^D > S^R > S^P$ and cost efficiency $k$ is relatively small, the airport can improve ride-hailing operational efficiency as much as possible to obtain greater profit. When $S^R > S^D > S^P$, there exists an optimal operational efficiency level to achieve profit maximization, and the airport must prevent problems of both insufficient quality provision and excessive quality provision.

Given that the airport may adopt different pricing strategies under varying circumstances, the government should formulate corresponding policy instruments accordingly. Specifically, when the cost of improving operational efficiency is relatively small, the

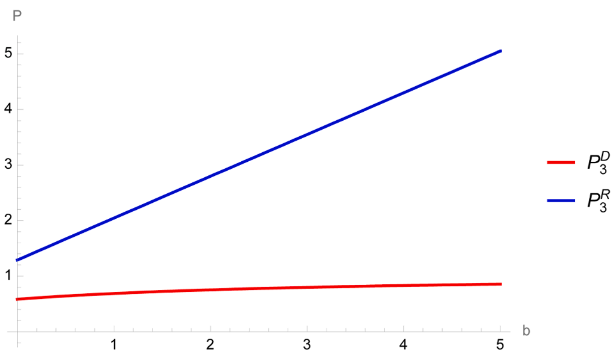


**Fig. 3b.** Changes in price with $b$ when $S^R > S^D > S^P$.

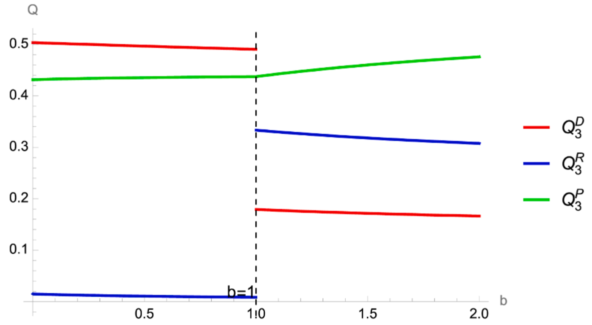


**Fig. 4a.** Changes in traffic volume with $b$ when $S^D > S^R > S^P$.

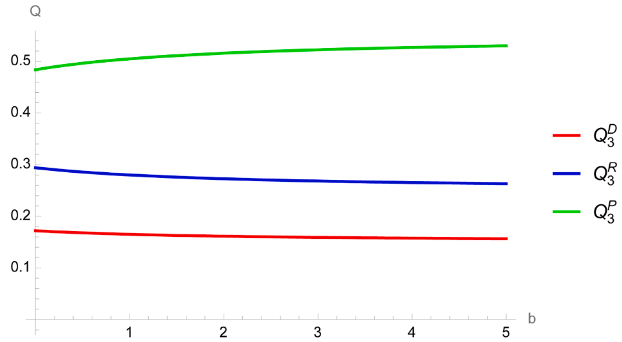


**Fig. 4b.** Changes in traffic volume with $b$ when $S^R > S^D > S^P$.

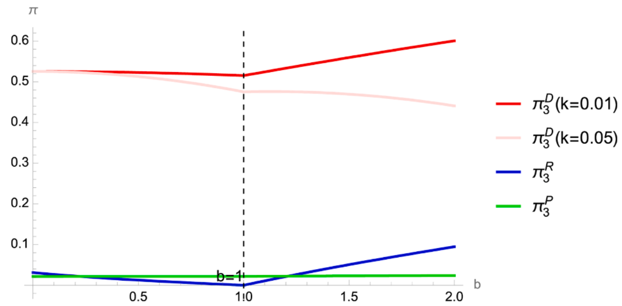


**Fig. 5a.** Changes in profit with $b$ when $S^D > S^R > S^P$.

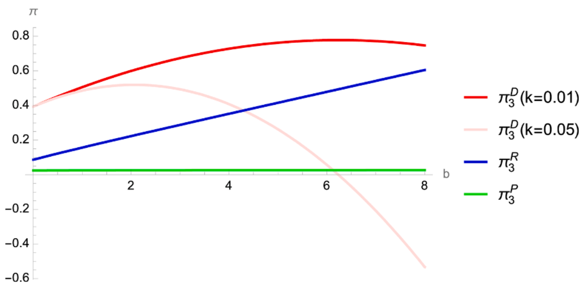


**Fig. 5b.** Changes in profit with $b$ when $S^R > S^D > S^P$.

government should permit airport charging fees, while setting upper limits on charges and supervising operational efficiency improvement to reach a certain level. Such regulation enables the airport's pricing strategy to increase not only its own profit but also that of RHCs, thereby enhancing overall social welfare. When the cost of improving operational efficiency is relatively large, direct charge fees from RHC by the airport will inevitably have adverse effects on RHC, consumers, and social welfare. In this case, the

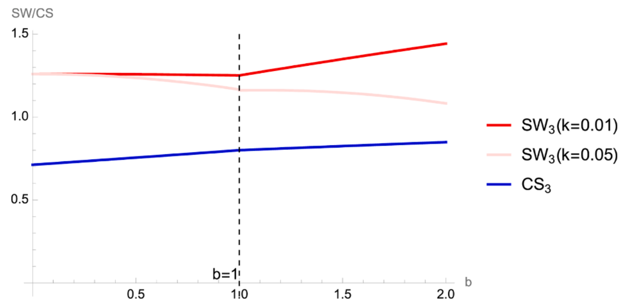


**Fig. 6a.** Changes in social welfare/consumer surplus with $b$ when $S^R > S^D > S^P$.

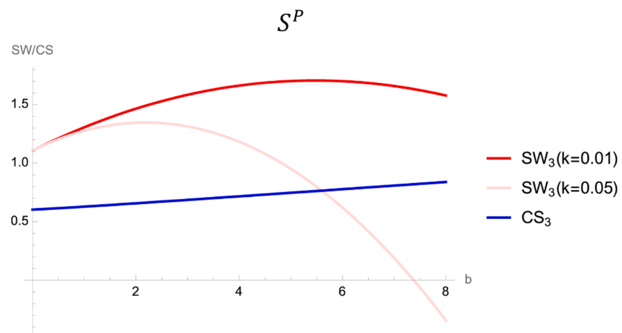


**Fig. 6b.** Changes in social welfare/consumer surplus with $b$ when $S^R > S^D > S^P$.

government can provide subsidies to airports to reduce the cost of improving ride-hailing operational efficiency, thereby encouraging airports to adopt a combined strategy of charging fees while enhancing operational efficiency. For instance, if efficiency improvement relies on fundamental infrastructure investments, such as expanding designated pick-up areas for ride-hailing, the required investment cost may be substantial; therefore, the government could provide fiscal support to alleviate part of the financial burden on airports. Additionally, the government must also prioritize regulatory oversight of operational efficiency improvement. Specifically, the government can mandate that the airport implement service-level agreements (SLAs) or similar mechanisms to link pricing levels to the quality of services offered. For example, the airport and RHC could establish service quality agreements that specify concrete performance targets, such as the waiting times for ride-hailing vehicles entering and exiting the airport or the proximity of pick-up/drop-off areas to the terminal.

## 6. Conclusion

Parking and car rental revenues are critical to airport revenue. However, ride-hailing services have significantly transformed airport ground transportation, particularly by reducing parking and car rental transactions, which affects airport revenue. To balance profitability, the airport has implemented various charging strategies targeting RHCs. These strategies may impact the welfare of stakeholders, thereby influencing overall social welfare. Consequently, it is essential to examine how different airport charging strategies impact the interests of the airport, RHC, and passengers, as well as how the government should formulate policies to enhance social welfare.

This study systematically analyzes the impact of airport charging strategies on the welfare of different stakeholders (i.e., airport, RHC, public transportation, and passengers). First of all, we examine the effects of strategies adopted by profit-maximizing airports on various stakeholders in the market. The findings show that the airport charging fees alone will increase prices for all travel modes while increasing the profit of airport, harming the interests of RHCs and consumers, and ultimately leading to a decline in social welfare. The impact of the strategy, where the airport charges fees and improves ride-hailing operational efficiency, is more nuanced. For the airport, when the cost of improving operational efficiency is relatively small, the optimal strategy is to charge ride-hailing services while enhancing their operational efficiency; when the cost of improving operational efficiency is relatively large, the optimal strategy is direct charging. It is noteworthy that when the cost of operational efficiency improvement is relatively small and operational efficiency improvement is relatively large, the strategy of airport charging combined with ride-hailing operational efficiency improvement can achieve a win-win-win situation for the airport, RHC, and consumers, thereby improving social welfare.

Furthermore, we analyze the regulatory policies of the government aiming to maximize social welfare under various circumstances. When the cost of improving operational efficiency is relatively small, the government should allow airports to charge while requiring the airport to improve ride-hailing operational efficiency above a certain level, which can protect the interests of RHCs and consumers. When the cost of improving operational efficiency is relatively large, the government can prohibit airports from implementing pure charging strategies that harm social welfare. In this case, to improve social welfare, the government can provide financial support to airports to reduce their costs, encouraging airports to adopt the strategy of charging while improving ride-hailing operational efficiency.

This paper has several limitations, which are also potential avenues for future studies. First, the current model does not distinguish between RHCs and traditional taxis, nor does it account for emerging transportation modes such as shared mobility and autonomous vehicles. Incorporating these additional travel modes could make the model more comprehensive and provide passengers with a broader range of travel choices. Secondly, our model only considers static scenarios and does not address dynamic pricing issues. In future research, we can further explore differentiated pricing strategies implemented by airports during peak and off-peak periods, thereby better reflecting real-world demand fluctuations. In addition, the model developed in this study does not account for congestion effects. The majority of measures taken by airports to improve ride-hailing operational efficiency are about alleviating traffic congestion in the pick-up zone, such as capacity expansion. To tackle these issues, a more detailed modeling effort supported by empirical evidence is needed in the future. Lastly, our model has not yet taken into account the potential additional travel demand that may arise from the entry of ride-hailing services into airports. Such a factor could stimulate an expansion of overall travel volume and, in turn, influence the equilibrium outcomes. Despite these limitations, this paper contributes to the literature on RHC entry into airports, analyzes the impact of airport fees on RHC, the airport, and passengers, and provides guidance for airports and governments in charging policy design.

## CRediT authorship contribution statement

**Jianxiu Xiao:** Writing – original draft, Visualization, Software, Investigation, Formal analysis. **Changmin Jiang:** Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Hangjun Yang:** Validation, Supervision, Resources, Project administration, Funding acquisition. **Xiaoqian Sun:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

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## Appendix A Tables

Table A1

**Table A1**
Summary of notations.

| Notation | Meaning |
|---|---|
| $Q_i^D$, $Q_i^R$, $Q_i^P$ | The traffic volumes of private travel, ride-hailing and public transportation |
| $P_i^D$, $P_i^R$, $P^P$ | The prices of private travel, ride-hailing and public transportation |
| $\theta$ | The passenger’s valuation for service quality |
| $F_i$ | Per-passenger fees charged by the airport to RHC |
| $b$ | The operational efficiency improvements provided by the airport to the RHC |
| $k$ | The cost coefficient for the airport to improve ride-hailing service quality |
| $U$ | The collective utility of a representative passenger in the OD market |
| $S^D$, $S^R$, $S^P$ | The service quality of private travel, ride-hailing, and public transportation |
| $C^D$, $C^R$, $C^P$ | The unit operating costs of the airport, RHC, and public transportation (assumption: $C^D = C^R = C^P = 0$) |
| $\pi_i^A$, $\pi_i^R$, $\pi_i^P$ | The profits of the airport, RHC, and public transportation |
| $\mathrm{CS}_i$ | The total consumer surplus |
| $\mathrm{SW}_i$ | The total social welfare |

## Appendix B Model and Solutions

### B.1. Equilibrium in Scenario 1: $S^D > S^R > S^P$

$$P_1^{D*} = \frac{\left(S^D - S^R\right)\left(P^P + 2S^D - 2S^P\right)}{4S^D - S^R - 3S^P} \tag{B1}$$

$$P_1^{R*} = \frac{\left(S^D - S^R\right)\left(2P^P + S^R - S^P\right)}{4S^D - S^R - 3S^P} \tag{B2}$$

$$Q_1^{D*} = \frac{P^P + 2S^D - 2S^P}{4S^D - S^R - 3S^P} \tag{B3}$$

$$Q_1^{R*} = \frac{\left(S^D - S^P\right)\left(2P^P + S^R - S^P\right)}{\left(4S^D - S^R - 3S^P\right)\left(S^R - S^P\right)} \tag{B4}$$

$$Q_1^{P*} = \frac{\frac{\left(S^D - S^R\right)\left(2P^P + S^R - S^P\right)}{4S^D - S^R - 3S^P} - P^P}{S^R - S^P} - \frac{P^P}{S^P} \tag{B5}$$

$$\pi_1^{A*} = \frac{\left(P^P + 2S^D - 2S^P\right)^2\left(S^D - S^R\right)}{\left(3S^P + S^R - 4S^D\right)^2} \tag{B6}$$

$$\pi_1^{R*} = \frac{\left(S^D - S^P\right)\left(S^D - S^R\right)\left(2P^P - S^P + S^R\right)^2}{\left(S^R - S^P\right)\left(3S^P + S^R - 4S^D\right)^2} \tag{B7}$$

$$\pi_1^{P*} = P\left(\frac{\frac{\left(S^D - S^R\right)\left(2P^P + S^R - S^P\right)}{4S^D - S^R - 3S^P} - P^P}{S^R - S^P} - \frac{P^P}{S^P}\right) \tag{B8}$$

$$CS_1^* = \frac{\begin{array}{c} -2P^P\left(S^D - S^R\right)\left(8S^D - S^R - 7S^P\right)\left(S^R - S^P\right)S^P + \\ \left(S^R - S^P\right)S^P\left(4S^{D^3} + S^{D^2}\left(5S^R - S^P\right) - 2S^DS^P\left(9S^R + S^P\right) + S^RS^P\left(S^R + 11S^P\right)\right) + \\ P^{P^2}\left(4S^{D^2}\left(4S^R - 3S^P\right) + S^R\left(S^{R^2} + 5S^RS^P - 2S^{P^2}\right) + S^D\left(11S^{P^2} - 8S^{R^2} - 11S^RS^P\right)\right)\end{array}}{2\left(S^R - S^P\right)S^P\left(S^R + 3S^P - 4S^D\right)^2} \tag{B9}$$

$$SW_1^* = \frac{\begin{array}{c} 8P^P\left(S^D - S^R\right)\left(S^D - S^P\right)\left(S^R - S^P\right)S^P + \\ \left(S^R - S^P\right)S^P\left(12S^{D^3} + S^RS^P\left(3S^R + S^P\right) - S^{D^2}\left(S^R + 19S^P\right) - 2S^D\left(S^{R^2} + S^RS^P - 4S^{P^2}\right)\right) \\ -P^{P^2}\left(4S^{D^2}\left(4S^R - 3S^P\right) + S^R\left(S^{R^2} + 5S^RS^P - 2S^{P^2}\right) + S^D\left(11S^{P^2} - 8S^{R^2} - 11S^RS^P\right)\right)\end{array}}{2\left(S^R - S^P\right)S^P\left(S^R + 3S^P - 4S^D\right)^2} \tag{B10}$$

Let $0 < P^P < \frac{S^DS^RS^P - S^{R^2}S^P - S^DS^{P^2} + S^RS^{P^2}}{4S^DS^R - S^{R^2} - 2S^DS^P - S^RS^P}$ so that the non-negativity condition holds.

**B.2. Equilibrium in Scenario 1: $S^R > S^D > S^P$**

$$P_1^{R*} = \frac{\left(S^R - S^D\right)\left(P^P + 2S^R - 2S^P\right)}{4S^R - S^D - 3S^P} \tag{B11}$$

$$P_1^{D*} = \frac{\left(S^R - S^D\right)\left(2P^P + S^D - S^P\right)}{4S^R - S^D - 3S^P} \tag{B12}$$

$$Q_1^{R*} = \frac{P^P + 2S^R - 2S^P}{4S^R - S^D - 3S^P} \tag{B13}$$

$$Q_1^{D*} = \frac{\left(S^R - S^P\right)\left(2P^P + S^D - S^P\right)}{\left(4S^R - S^D - 3S^P\right)\left(S^D - S^P\right)} \tag{B14}$$

$$Q_1^{P*} = \frac{\frac{\left(S^R - S^D\right)\left(2P^P + S^D - S^P\right)}{4S^R - S^D - 3S^P} - P^P}{S^D - S^P} - \frac{P^P}{S^P} \tag{B15}$$

$$\pi_1^{R*} = \frac{\left(P^P + 2S^R - 2S^P\right)^2\left(S^R - S^D\right)}{\left(3S^P + S^D - 4S^R\right)^2} \tag{B16}$$

$$\pi_1^{A*} = \frac{\left(S^R - S^D\right)\left(S^R - S^P\right)\left(2P^P + S^D - S^P\right)^2}{\left(S^D - S^P\right)\left(S^D + 3S^P - 4S^R\right)^2} \tag{B17}$$

$$\pi_1^{P*} = P^P \left( \frac{\frac{(S^R - S^D)(2P^P + S^D - S^P)}{4S^R - S^D - 3S^P} - P^P}{S^D - S^P} - \frac{P^P}{S^P} \right) \tag{B18}$$

$$CS_1^* = \frac{\begin{array}{c} -2P^P(S^R - S^D)(8S^R - S^D - 7S^P)(S^D - S^P)S^P + \\ (S^D - S^P)S^P\left(4S^{R3} + S^{R2}(5S^D - S^P) - 2S^RS^P(9S^D + S^P) + S^DS^P(S^D + 11S^P)\right) + \\ P^{P2}\left(4S^{R2}(4S^D - 3S^P) + S^D\left(S^{D2} + 5S^DS^P - 2S^{P2}\right) + S^R\left(11S^{P2} - 8S^{D2} - 11S^DS^P\right)\right) \end{array}}{2(S^D - S^P)S^P(S^D + 3S^P - 4S^R)^2} \tag{B19}$$

$$SW_1^* = \frac{\begin{array}{c} 8P^P(S^R - S^D)(S^R - S^P)(S^D - S^P)S^P + \\ (S^D - S^P)S^P\left(12S^{R3} + S^DS^P(3S^D + S^P) - S^{R2}(S^D + 19S^P) - 2S^R\left(S^{D2} + S^DS^P - 4S^{P2}\right)\right) \\ -P^{P2}\left(4S^{R2}(4S^D - 3S^P) + S^D\left(S^{D2} + 5S^DS^P - 2S^{P2}\right) + S^R\left(11S^{P2} - 8S^{D2} - 11S^DS^P\right)\right) \end{array}}{2(S^D - S^P)S^P(S^D + 3S^P - 4S^R)^2} \tag{B20}$$

Let $0 < P^P < \frac{S^RS^DS^P - S^{D2}S^P - S^RS^{P2} + S^DS^{P2}}{4S^RS^D - S^{D2} - 2S^RS^P - S^DS^P}$ so that the non-negativity condition holds.

**B.3. Equilibrium in Scenario 2: $S^D > S^R > S^P$**

$$P_2^{D*} = \frac{1}{2}\left(S^D - S^P + \frac{P^P(10S^D - S^R - 9S^P)}{8S^D + S^R - 9S^P}\right) \tag{B21}$$

$$P_2^{R*} = \frac{1}{2}\left(S^R - S^P + \frac{P^P\left(12S^{D2} - S^{R2} + 4S^RS^P + 9S^{P2} - 2S^D(S^R + 11S^P)\right)}{(8S^D + S^R - 9S^P)(S^D - S^P)}\right) \tag{B22}$$

$$Q_2^{D*} = \frac{1}{2}\left(1 + \frac{P^P(2S^D + S^R - 3S^P)}{(8S^D + S^R - 9S^P)(S^D - S^P)}\right) \tag{B23}$$

$$Q_2^{R*} = \frac{P^P(2S^D + S^R - 3S^P)}{(8S^D + S^R - 9S^P)(S^R - S^P)} \tag{B24}$$

$$Q_2^{P*} = \frac{\begin{array}{c} P^P\left(4S^{D2}(4S^R - 3S^P) - S^P\left(S^{R2} - 14S^RS^P + 9S^{P2}\right) + 2S^D\left(S^{R2} - 16S^RS^P + 11S^{P2}\right)\right) \\ -\left((8S^D + S^R - 9S^P)(S^D - S^P)(S^R - S^P)S^P\right) \end{array}}{2S^P(S^P - S^D)(S^P - S^R)(9S^P - 8S^D - S^R)} \tag{B25}$$

$$\pi_2^{A*} = \frac{1}{4}\left(2P^P + S^D - S^P + \frac{P^{P2}(2S^D + S^R - 3S^P)^2}{(8S^D + S^R - 9S^P)(S^D - S^P)(S^R - S^P)}\right) \tag{B26}$$

$$\pi_2^{R*} = \frac{P^{P2}(S^D - S^R)(2S^D + S^R - 3S^P)^2}{(8S^D + S^R - 9S^P)^2(S^D - S^P)(S^R - S^P)} \tag{B27}$$

$$\pi_2^{P*} = \frac{\begin{array}{c} P^P(-((8S^D + S^R - 9S^P)(S^D - S^P)(S^R - S^P)S^P) + \\ P^P\left(4S^{D2}(4S^R - 3S^P) - S^P\left(S^{R2} - 14S^RS^P + 9S^{P2}\right) + 2S^D\left(S^{R2} - 16S^RS^P + 11S^{P2}\right)\right)) \end{array}}{2S^P(S^P - S^D)(S^P - S^R)(9S^P - 8S^D - S^R)} \tag{B28}$$

$$CS_2^* = \frac{\begin{array}{c} (8S^D + S^R - 9S^P)^2(S^R - S^P)S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right) + \\ 2P^P(S^D - S^P)S^P(S^P - S^R)\left(208S^{D2} + 34S^DS^R + S^{R2} - 450S^DS^P - 36S^RS^P + 243S^{P2}\right) + \\ P^{P2}(16S^{D3}(16S^R - 15S^P) + S^{D2}\left(64S^{R2} - 860S^RS^P + 748S^{P2}\right) + \\ 4S^D\left(S^{R3} - 29S^{R2}S^P + 229S^RS^{P2} - 189S^{P3}\right) + S^P\left(S^{R3} + 37S^{R2}S^P - 297S^RS^{P2} + 243S^{P3}\right)) \end{array}}{8(8S^D + S^R - 9S^P)^2(S^D - S^P)(S^R - S^P)S^P} \tag{B29}$$

$$SW_2^* = \frac{3S^D + \frac{6P^P\left(2S^D + S^R - 3S^P\right)}{8S^D + S^R - 9S^P} + S^P - \left(P^{P^2}\left(16S^{D^3}\left(16S^R - 15S^P\right) + S^{D^2}\left(64S^{R^2} - 860S^RS^P + 748S^{P^2}\right) + 4S^D\left(S^{R^3} - 29S^{R^2}S^P + 229S^RS^{P^2} - 189S^{P^3}\right) + S^P\left(S^{R^3} + 37S^{R^2}S^P - 297S^RS^{P^2} + 243S^{P^3}\right)\right)\right)}{8\left(8S^D + S^R - 9S^P\right)^2\left(S^D - S^P\right)\left(S^R - S^P\right)S^P} \tag{B30}$$

Let $0 < P^P < \frac{8S^{D^2}S^RS^P + S^DS^{R^2}S^P - 8S^{D^2}S^{P^2} - 18S^DS^RS^{P^2} - S^{R^2}S^{P^2} + 17S^DS^{P^3} + 10S^RS^{P^3} - 9S^{P^4}}{16S^{D^2}S^R + 2S^DS^{R^2} - 12S^{D^2}S^P - 32S^DS^RS^P - S^{R^2}S^P + 22S^DS^{P^2} + 14S^RS^{P^2} - 9S^{P^3}}$ so that the non-negativity condition holds.

### B.4. Equilibrium in Scenario 2: $S^R > S^D > S^P$

$$P_2^{R^*} = \frac{12S^{R^2} - S^{D^2} + P^P\left(8S^R + S^D - 9S^P\right) + 4S^DS^P + 9S^{P^2} - 2S^R\left(S^D + 11S^P\right)}{2\left(8S^R + S^D - 9S^P\right)} \tag{B31}$$

$$P_2^{D^*} = \frac{1}{2}\left(P^P + \frac{\left(10S^R - S^D - 9S^P\right)\left(S^D - S^P\right)}{8S^R + S^D - 9S^P}\right) \tag{B32}$$

$$Q_2^{R^*} = \frac{2S^R + S^D - 3S^P}{8S^R + S^D - 9S^P} \tag{B33}$$

$$Q_2^{D^*} = \frac{1}{2}\left(\frac{2S^R + S^D - 3S^P}{8S^R + S^D - 9S^P} + \frac{P^P}{S^D - S^P}\right) \tag{B34}$$

$$Q_2^{P^*} = \frac{\left(10S^R - S^D - 9S^P\right)\left(S^D - S^P\right)S^P - P^P\left(8S^R + S^D - 9S^P\right)\left(2S^D - S^P\right)}{2S^P\left(S^P - S^D\right)\left(9S^P - 8S^R - S^D\right)} \tag{B35}$$

$$\pi_2^{R^*} = \frac{\left(S^R - S^D\right)\left(2S^R + S^D - 3S^P\right)^2}{\left(8S^R + S^D - 9S^P\right)^2} \tag{B36}$$

$$\pi_2^{A^*} = \frac{1}{4}\left(2P^P + \frac{\left(2S^R + S^D - 3S^P\right)^2}{8S^R + S^D - 9S^P} + \frac{P^{P^2}}{S^D - S^P}\right) \tag{B37}$$

$$\pi_2^{P^*} = \frac{P^P\left(\left(10S^R - S^D - 9S^P\right)\left(S^D - S^P\right)S^P - P^P\left(8S^R + S^D - 9S^P\right)\left(2S^D - S^P\right)\right)}{2S^P\left(S^P - S^D\right)\left(9S^P - 8S^R - S^D\right)} \tag{B38}$$

$$CS_2^* = \frac{1}{8}\left(\frac{P^{P^2}\left(4S^D - 3S^P\right)}{\left(S^D - S^P\right)S^P} + \frac{16S^{R^3} + 5S^{D^3} - 35S^{D^2}S^P + 27S^DS^{P^2} + 243S^{P^3} + 4S^{R^2}\left(9S^D + 43S^P\right) + 8S^R\left(3S^{D^2} - 7S^DS^P - 54S^{P^2}\right)}{\left(8S^R + S^D - 9S^P\right)^2} - \frac{2P^P\left(26S^R + S^D - 27S^P\right)}{8S^R + S^D - 9S^P}\right) \tag{B39}$$

$$SW_2^* = \frac{1}{8}\left(\frac{2P^P\left(10S^R - S^D - 9S^P\right)}{8S^R + S^D - 9S^P} - \frac{P^{P^2}\left(4S^D - 3S^P\right)}{\left(S^D - S^P\right)S^P} + \frac{112S^{R^3} - S^{D^3} + 4S^{R^2}\left(27S^D - 47S^P\right) + 8S^RS^D\left(3S^D - 25S^P\right) - 17S^{D^2}S^P + 81S^DS^{P^2} + 81S^{P^3}}{\left(8S^R + S^D - 9S^P\right)^2}\right) \tag{B40}$$

Let $0 < P^P < \frac{10S^RS^DS^P - S^{D^2}S^P - 10S^RS^{P^2} - 8S^DS^{P^2} + 9S^{P^3}}{16S^RS^D + 2S^{D^2} - 8S^RS^P - 19S^DS^P + 9S^{P^2}}$ so that the non-negativity condition holds.

### B.5. Equilibrium in Scenario 3: $S^D > S^R + b > S^P$

$$P_3^{D^*} = \frac{P^P\left(10S^D - S^R - 9S^P\right) + \left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right) - b\left(P^P - S^D + S^P\right)}{2\left(b + 8S^D + S^R - 9S^P\right)} \tag{B41}$$

$$P_3^{R^*} = \frac{2b\left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right) - 2bP^P\left(S^D + S^R - 2S^P\right) + \left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(S^R - S^P\right) - b^2\left(P^P - S^D + S^P\right) + P^P\left(12S^{D^2} - S^{R^2} + 4S^RS^P + 9S^{P^2} - 2S^D\left(S^R + 11S^P\right)\right)}{2\left(b + 8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)} \tag{B42}$$

$$Q_3^{D^*} = \frac{P^P\left(2S^D + S^R - 3S^P\right) + \left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right) + b\left(P^P + S^D - S^P\right)}{2\left(b + 8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)} \tag{B43}$$

$$Q_3^{R*} = \frac{P^P\left(b + 2S^D + S^R - 3S^P\right)}{\left(b + 8S^D + S^R - 9S^P\right)\left(b + S^R - S^P\right)} \tag{B44}$$

$$Q_3^{P*} = \frac{\begin{array}{c} 2b\left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right)S^P + \left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(S^R - S^P\right)S^P + \\ b^2\left(\left(S^D - S^P\right)S^P + P^P\left(S^P - 2S^D\right)\right) - 2bP^P\left(8S^{D2} + 2S^D\left(S^R - 8S^P\right) + S^P\left(7S^P - S^R\right)\right) + \\ P^P\left(S^P\left(S^{R2} - 14S^RS^P + 9S^{P2}\right) - 4S^{D2}\left(4S^R - 3S^P\right) - 2S^D\left(S^{R2} - 16S^RS^P + 11S^{P2}\right)\right) \end{array}}{2\left(b + 8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(b + S^R - S^P\right)S^P} \tag{B45}$$

$$\pi_3^{A*} = \frac{\begin{array}{c} 2b\left(P^{P2}\left(2S^D + S^R - 3S^P\right) + 2P^P\left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right) + \left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right)^2\right) + \\ P^{P2}\left(2S^D + S^R - 3S^P\right)^2 - 8b^3k\left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right) + 2P^P\left(8S^D + S^R - 9S^P\right) \\ \left(S^D - S^P\right)\left(S^R - S^P\right) + \left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)^2\left(S^R - S^P\right) + 4b^4k\left(S^P - S^D\right) + \\ b^2\left(P^{P2} + 2P^P\left(S^D - S^P\right) + \left(S^D - S^P\right)\left(S^D - 32kS^D\left(S^R - S^P\right) - S^P - 4k\left(S^{R2} - 10S^RS^P + 9S^{P2}\right)\right)\right) \end{array}}{4\left(b + 8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(b + S^R - S^P\right)} \tag{B46}$$

$$\pi_3^{R*} = -\frac{P^{P2}\left(b - S^D + S^R\right)\left(b + 2S^D + S^R - 3S^P\right)^2}{\left(b + 8S^D + S^R - 9S^P\right)^2\left(S^D - S^P\right)\left(b + S^R - S^P\right)} \tag{B47}$$

$$\pi_3^{P*} = \frac{\begin{array}{c} P^P(4P^PS^{D2}\left(4S^R - 3S^P\right) - 2b\left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right)S^P - \left(8S^D + S^R - 9S^P\right) \\ \left(S^D - S^P\right)\left(S^R - S^P\right)S^P + b^2\left(2P^PS^D - P^PS^P - S^DS^P + S^{P2}\right) - P^PS^P\left(S^{R2} - 14S^RS^P + 9S^{P2}\right) \\ +2P^PS^D\left(S^{R2} - 16S^RS^P + 11S^{P2}\right) + 2bP^P\left(8S^{D2} + 2S^D\left(S^R - 8S^P\right) + S^P\left(7S^P - S^R\right)\right) \end{array}}{-2\left(b + 8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(b + S^R - S^P\right)S^P)} \tag{B48}$$

$$CS_3^* = \frac{\begin{array}{c} \left(8S^D + S^R - 9S^P\right)^2\left(S^R - S^P\right)S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right) + 2P^P\left(S^D - S^P\right)S^P\left(S^P - S^R\right) \\ \left(208S^{D2} + 34S^DS^R + S^{R2} - 450S^DS^P - 36S^RS^P + 243S^{P2}\right) + b^3(2P^PS^P\left(S^P - S^D\right) + \\ P^{P2}\left(4S^D + S^P\right) + S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right)\Big) + P^{P2}\Big(16S^{D3}\left(16S^R - 15S^P\right) + S^{D2} \\ \left(64S^{R2} - 860S^RS^P + 748S^{P2}\right) + 4S^D\left(S^{R3} - 29S^{R2}S^P + 229S^RS^{P2} - 189S^{P3}\right) + S^P \\ \left(S^{R3} + 37S^{R2}S^P - 297S^RS^{P2} + 243S^{P3}\right)\Big)\Big) + b^2(-2P(34S^D + 3S^R - 37S^P)\left(S^D - S^P\right)S^P \\ +\left(16S^D + 3S^R - 19S^P\right)S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right) + P^{P2}(64S^{D2} + 4S^D\left(3S^R - 29S^P\right) \\ +S^P\left(3S^R + 37S^P\right))) + b(S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right)(64S^{D2} + 3S^{R2} + 32S^D\left(S^R - 5S^P\right) \\ -38S^RS^P + 99S^{P2}) - 2P^P\left(S^D - S^P\right)S^P(208S^{D2} + 68S^DS^R + 3S^{R2} - 484S^DS^P - \\ 74S^RS^P + 279S^{P2}) + P^{P2}\Big(256S^{D3} + 4S^{D2}\left(32S^R - 215S^P\right) + S^P\Big(3S^{R2} + 74S^RS^P \\ -297S^P) + 4S^D\left(3S^{R2} - 58S^RS^P + 229S^{P2}\right))) \end{array}}{8\left(b + 8S^D + S^R - 9S^P\right)^2\left(S^D - S^P\right)\left(b + S^R - S^P\right)S^P} \tag{B49}$$

$$SW_3^* = \frac{\begin{array}{c} 8b^4k\left(16S^D + 3S^R - 19S^P\right)\left(S^D - S^P\right)S^P - 8b^5kS^P\left(S^P - S^D\right) - \left(8S^D + S^R - 9S^P\right)^2\left(S^R - S^P\right) \\ S^P\left(3S^{D2} - 2S^DS^P - S^{P2}\right) + 6P^P\left(S^D - S^P\right)S^P\left(S^P - S^R\right)(16S^{D2} + 10S^DS^R + S^{R2} - 42S^DS^P \\ -12S^RS^P + 27S^{P2}\Big) + P^{P2}\Big(16S^{D3}\left(16S^R - 15S^P\right) + S^{D2}\left(64S^{R2} - 860S^RS^P + 748S^{P2}\right) + \\ 4S^D\left(S^{R3} - 29S^{R2}S^P + 229S^RS^{P2} - 189S^{P3}\right) + S^P\left(S^{R3} + 37S^{R2}S^P - 297S^RS^{P2} + 243S^{P3}\right)\Big) \\ +b^3\Big(6P^PS^P\left(S^P - S^D\right) + P^{P2}\left(4S^D + S^P\right) + \left(S^D - S^P\right)S^P\Big(512kS^{D2} + S^D\left(-3 + 256k\left(S^R - 5S^P\right)\right) \\ -S^P + 8k\left(3S^{R2} - 38S^RS^P + 99S^{P2}\right)\Big)\Big) + b(-6P^P\left(S^D - S^P\right)S^P(16S^{D2} + 20S^DS^R + 3S^{R2} \\ -52S^DS^P - 26S^RS^P + 39S^{P2}\Big) + S^P\left(2S^DS^P + S^{P2} - 3S^{D2}\right)\Big(64S^{D2} + 3S^{R2} + 32S^D\left(S^R - 5S^P\right) \\ -38S^RS^P + 99S^{P2}\Big) + P^{P2}\Big(256S^{D3} + 4S^{D2}\left(32S^R - 215S^P\right) + S^P\left(3S^{R2} + 74S^RS^P - 297S^{P2}\right) + \\ 4S^D\left(3S^{R2} - 58S^RS^P + 229S^{P2}\right))) + b^2(-6P^P\left(10S^D + 3S^R - 13S^P\right)\left(S^D - S^P\right)S^P + \\ P^{P2}\left(64S^{D2} + 4S^D\left(3S^R - 29S^P\right) + S^P\left(3S^R + 37S^P\right)\right) + \left(S^D - S^P\right)S^P(16S^{D2}(-3 + 32k\left(S^R - S^P\right)) \\ +8k\left(S^R - 9S^P\right)^2\left(S^R - S^P\right) + S^P\left(19S^P - 3S^R\right) + S^D(128kS^{R2} + S^P\left(41 + 1152kS^P\right) \\ -S^R\left(9 + 1280kS^P\right)))) \end{array}}{-8\left(b + 8S^D + S^R - 9S^P\right)^2\left(S^D - S^P\right)\left(b + S^R - S^P\right)S^P} \tag{B50}$$

$$F_3^* = \frac{\begin{gathered} b^2\left(P^P + S^D - S^P\right) + \left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(S^R - S^P\right) + 2b(4{S^D}^2 + P^P S^R + \\ S^D\left(S^R - 9S^P\right) - P^P S^P - S^R S^P + 5{S^P}^2) + P^P\left(8{S^D}^2 + {S^R}^2 - 16S^D S^P - 2S^R S^P + 9{S^P}^2\right) \end{gathered}}{2\left(b + 8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)} \tag{B51}$$

Let $0 < P^P < \frac{10S^R S^D S^P - {S^D}^2 S^P - 10S^R {S^P}^2 - 8S^D {S^P}^2 + 9{S^P}^3}{16S^R S^D + 2{S^D}^2 - 8S^R S^P - 19S^D S^P + 9{S^P}^2}$ so that the non-negativity condition holds.

### B.6. Equilibrium in Scenario 3: $S^R + b > S^D > S^P$

$$P_3^{R*} = \frac{12b^2 + 12{S^R}^2 - 2S^R S^D - {S^D}^2 + b\left(8P^P + 24S^R - 2S^D - 22S^P\right) + P^P\left(8S^R + S^D - 9S^P\right) - 22S^R S^P + 4S^D S^P + 9{S^P}^2}{2\left(8b + 8S^R + S^D - 9S^P\right)} \tag{B52}$$

$$P_3^{D*} = \frac{P^P\left(8S^R + S^D - 9S^P\right) + 2b\left(4P^P + 5S^D - 5S^P\right) + \left(10S^R - S^D - 9S^P\right)\left(S^D - S^P\right)}{2\left(8b + 8S^R + S^D - 9S^P\right)} \tag{B53}$$

$$Q_3^{R*} = \frac{2b + 2S^R + S^D - 3S^P}{8b + 8S^R + S^D - 9S^P} \tag{B54}$$

$$Q_3^{D*} = \frac{P^P\left(8S^R + S^D - 9S^P\right) + \left(2S^R + S^D - 3S^P\right)\left(S^D - S^P\right) + 2b\left(4P^P + S^D - S^P\right)}{2\left(8b + 8S^R + S^D - 9S^P\right)\left(S^D - S^P\right)} \tag{B55}$$

$$Q_3^{P*} = \frac{-P^P\left(8S^R + S^D - 9S^P\right)\left(2S^D - S^P\right) + \left(10S^R - S^D - 9S^P\right)\left(S^D - S^P\right)S^P - 2b\left(P^P\left(8S^D - 4S^P\right) + 5S^P\left(S^P - S^D\right)\right)}{2\left(8b + 8S^R + S^D - 9S^P\right)\left(S^D - S^P\right)S^P} \tag{B56}$$

$$\pi_3^{R*} = \frac{\left(b + S^R - S^D\right)\left(2b + 2S^R + S^D - 3S^P\right)^2}{\left(8b + 8S^R + S^D - 9S^P\right)^2} \tag{B57}$$

$$\pi_3^{A*} = \frac{\begin{gathered} 4b\left(2{P^P}^2 + 4P\left(S^D - S^P\right) + \left(2S^R + S^D - 3S^P\right)\left(S^D - S^P\right)\right) + {P^P}^2\left(8S^R + S^D - 9S^P\right) - 32b^3k\left(S^D - S^P\right) \\ -4b^2\left(-1 + k\left(8S^R + S^D - 9S^P\right)\right)\left(S^D - S^P\right) + 2P^P\left(8S^R + S^D - 9S^P\right)\left(S^D - S^P\right) + \left(2S^R + S^D - 3S^P\right)^2\left(S^D - S^P\right) \end{gathered}}{4\left(8b + 8S^R + S^D - 9S^P\right)\left(S^D - S^P\right)} \tag{B58}$$

$$\pi_3^{P*} = \frac{P^P\left(P^P\left(8S^R + S^D - 9S^P\right)\left(2S^D - S^P\right) - \left(10S^R - S^D - 9S^P\right)\left(S^D - S^P\right)S^P + 2b\left(P^P\left(8S^D - 4S^P\right) + 5S^P\left(S^P - S^D\right)\right)\right)}{2\left(8b + 8S^R + S^D - 9S^P\right)S^P\left(S^P - S^D\right)} \tag{B59}$$

$$CS_3^* = \frac{\begin{gathered} 16b^3\left(S^D - S^P\right)S^P - 2P^P\left(S^D - S^P\right)S^P\left(208{S^R}^2 + 34S^R S^D + {S^D}^2 - 450S^R S^P - 36S^D S^P + 243{S^P}^2\right) + \\ 4b^2\left(16{P^P}^2\left(4S^D - 3S^P\right) - 104P^P\left(S^D - S^P\right)S^P + \left(S^D - S^P\right)S^P\left(12S^R + 9S^D + 43S^P\right)\right) + \left(S^D - S^P\right)S^P \\ \left(16{S^R}^3 + 5{S^D}^3 - 35{S^D}^2 S^P + 27S^D {S^P}^2 + 243{S^P}^3 + 4{S^R}^2\left(9S^D + 43S^P\right) + 8S^R\left(3{S^D}^2 - 7S^D S^P - 54{S^P}^2\right)\right) \\ 4b\left(4{P^P}^2\left(8S^R + S^D - 9S^P\right)\left(4S^D - 3S^P\right) - P^P\left(208S^R + 17S^D - 225S^P\right)\left(S^D - S^P\right)S^P + \right. \\ \left. 2\left(S^D - S^P\right)S^P\left(6{S^R}^2 + 9S^R S^D + 3{S^D}^2 + 43S^R S^P - 7S^D S^P - 54{S^P}^2\right)\right) + {P^P}^2\left(8S^R + S^D - 9S^P\right)^2\left(4S^D - 3S^P\right) \end{gathered}}{8\left(8b + 8S^R + S^D - 9S^P\right)^2\left(S^D - S^P\right)S^P} \tag{B60}$$

$$SW_3^* = \frac{\begin{gathered} {P^P}^2\left(8S^R + S^D - 9S^P\right)^2\left(4S^D - 3S^P\right) + 512b^4k\left(S^D - S^P\right)S^P + \\ 16b^3\left(8k\left(8S^R + S^D - 9S^P\right) - 7\right)\left(S^D - S^P\right)S^P + 2P^P\left(S^D - S^P\right)S^P\left({S^D}^2 - 80{S^R}^2 - 2S^R\left(S^D - 81S^P\right) - 81{S^P}^2\right) + \\ \left(S^D - S^P\right)S^P\left({S^D}^3 - 112{S^R}^3 - 4{S^R}^2\left(27S^D - 47S^P\right) - 8S^R S^D\left(3S^D - 25S^P\right) + 17{S^D}^2 S^P - 81S^D {S^P}^2 - 81{S^P}^3\right) - \\ 4b\left(-4{P^P}^2\left(8S^R + S^D - 9S^P\right)\left(4S^D - 3S^P\right) + P^P\left(80S^R + S^D - 81S^P\right)\left(S^D - S^P\right)S^P + 2\left(S^D - S^P\right)S^P\right. \\ \left.\left(42{S^R}^2 + 27S^R S^D + 3{S^D}^2 - 47S^R S^P - 25S^D S^P\right)\right) + 4b^2\left(16{P^P}^2\left(4S^D - 3S^P\right) - 40P^P\left(S^D - S^P\right)S^P + \left(S^D - S^P\right)S^P\right. \\ \left.\left(128k{S^R}^2 + 2k{S^D}^2 + 4S^R\left(-21 + 8k\left(S^D - 9S^P\right)\right) - 9S^D\left(3 + 4kS^P\right) + S^P\left(47 + 162kS^P\right)\right)\right) \end{gathered}}{-8\left(8b + 8S^R + S^D - 9S^P\right)^2\left(S^D - S^P\right)S^P} \tag{B61}$$

$$F_3^* = \frac{8b^2 + 8{S^R}^2 + {S^D}^2 + P^P\left(8S^R + S^D - 9S^P\right) + 8b\left(P^P + 2S^R - 2S^P\right) - 16S^R S^P - 2S^D S^P + 9{S^P}^2}{2\left(8b + 8S^R + S^D - 9S^P\right)} \tag{B62}$$

Let $0 < P^P < \frac{10bS^DS^P+10S^RS^DS^P-S^{D2}S^P-10bS^{P2}-10S^RS^{P2}-8S^DS^{P2}+9S^{P3}}{16bS^D+16S^RS^D+2S^{D2}-8bS^P-8S^RS^P-19S^DS^P+9S^{P2}}$ so that the non-negativity condition holds.

## Appendix C Proofs

**Proof of Lemma 1.**

$S^D > S^R > S^P$

$$P_2^{D*} - P_1^{D*} = \frac{1}{2}\left(S^D - S^P + \frac{P^P\left(10S^D - S^R - 9S^P\right)}{8S^D + S^R - 9S^P} - \frac{2\left(S^D - S^R\right)\left(P^P + 2S^D - 2S^P\right)}{4S^D - S^R - 3S^P}\right) > 0$$

$$P_2^{R*} - P_1^{R*} = \frac{1}{2}\left(S^R - S^P + \frac{P^P\left(12S^{D2} - S^{R2} + 4S^RS^P + 9S^{P2} - 2S^D\left(S^R + 11S^P\right)\right)}{\left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)} - \frac{2\left(S^D - S^R\right)\left(2P^P + S^R - S^P\right)}{4S^D - S^R - 3S^P}\right) > 0$$

$$Q_2^{D*} - Q_1^{D*} = \frac{1}{2}\left(1 - \frac{2\left(P^P + 2S^D - 2S^P\right)}{4S^D - S^R - 3S^P} + \frac{P^P\left(2S^D + S^R - 3S^P\right)}{\left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)}\right) < 0$$

$$Q_2^{R*} - Q_1^{R*} = \frac{\frac{P^P\left(2S^D+S^R-3S^P\right)}{8S^D+S^R-9S^P} + \frac{\left(S^D-S^P\right)\left(S^P-2P-S^R\right)}{4S^D-S^R-3S^P}}{S^R - S^P} < 0$$

$$Q_2^{P*} - Q_1^{P*} = \frac{\left(2S^D + S^R - 3S^P\right)\left(\left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(S^R - S^P\right) + P^P\left(8S^{D2} + S^{R2} - 16S^DS^P - 2S^RS^P + 9S^{P2}\right)\right)}{2\left(8S^D + S^R - 9S^P\right)\left(4S^D - S^R - 3S^P\right)\left(S^D - S^P\right)\left(S^R - S^P\right)} > 0$$

$S^R > S^D > S^P$

$$P_2^{D*} - P_1^{D*} = \frac{1}{2}\left(P^P + \frac{\left(10S^R - S^D - 9S^P\right)\left(S^D - S^P\right)}{8S^R + S^D - 9S^P} - \frac{2\left(S^R - S^D\right)\left(2P^P + S^D - S^P\right)}{4S^R - S^D - 3S^P}\right) > 0$$

$$P_2^{R*} - P_1^{R*} = \frac{\left(2S^R + S^D - 3S^P\right)\left(8S^{R2} + S^{D2} + P^P\left(8S^R + S^D - 9S^P\right) - 16S^RS^P - 2S^DS^P + 9S^{P2}\right)}{2\left(8S^R + S^D - 9S^P\right)\left(4S^R - S^D - 3S^P\right)} > 0$$

$$Q_2^{D*} - Q_1^{D*} = -\frac{8S^{R2} + S^{D2} + P^P\left(8S^R + S^D - 9S^P\right) - 16S^RS^P - 2S^DS^P + 9S^{P2}}{2\left(8S^R + S^D - 9S^P\right)\left(4S^R - S^D - 3S^P\right)} < 0$$

$$Q_2^{R*} - Q_1^{R*} = \frac{2S^R + S^D - 3S^P}{8S^R + S^D - 9S^P} - \frac{P^P + 2S^R - 2S^P}{4S^R - S^D - 3S^P} < 0$$

$$Q_2^{P*} - Q_1^{P*} = \frac{3\left(8S^{R2} + S^{D2} + P^P\left(8S^R + S^D - 9S^P\right) - 16S^RS^P - 2S^DS^P + 9S^{P2}\right)}{2\left(8S^R + S^D - 9S^P\right)\left(4S^R - S^D - 3S^P\right)} > 0$$

So we have $P_2^{D*} > P_1^{D*}$, $P_2^{R*} > P_1^{R*}$, $Q_2^{D*} < Q_1^{D*}$, $Q_2^{R*} < Q_1^{R*}$ and $Q_2^{P*} > Q_1^{P*}$. ■

**Proof of Proposition 1.**

$S^D > S^R > S^P$

$$\pi_2^{A*} - \pi_1^{A*} = \frac{1}{4}\left(2P^P + S^D - S^P + \frac{P^{P2}\left(2S^D + S^R - 3S^P\right)^2}{\left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(S^R - S^P\right)} - \frac{4\left(S^D - S^R\right)\left(P^P + 2S^D - 2S^P\right)^2}{\left(S^R + 3S^P - 4S^D\right)^2}\right) > 0$$

$$\pi_2^{R*} - \pi_1^{R*} = \frac{\left(S^D - S^R\right)\left(\frac{P^{P2}\left(2S^D+S^R-3S^P\right)^2}{\left(8S^D+S^R-9S^P\right)^2} - \frac{\left(S^D-S^P\right)^2\left(2P^P+S^R-S^P\right)^2}{\left(S^R+3S^P-4S^D\right)^2}\right)}{\left(S^D - S^P\right)\left(S^R - S^P\right)} < 0$$

$$\pi_2^{P*}-\pi_1^{P*}=\frac{P^P\left(2S^D+S^R-3S^P\right)\left(\left(8S^D+S^R-9S^P\right)\left(S^D-S^P\right)\left(S^R-S^P\right)+P^P\left(8S^{D2}+S^{R2}-16S^DS^P-2S^RS^P+9S^{P2}\right)\right)}{2\left(8S^D+S^R-9S^P\right)\left(4S^D-S^R-3S^P\right)\left(S^D-S^P\right)\left(S^R-S^P\right)}>0$$

$$CS_2^*-CS_1^*=\frac{\begin{array}{c}-2P^P\left(S^D-S^R\right)\left(8S^D-S^R-7S^P\right)\left(S^R-S^P\right)S^P+\left(S^R-S^P\right)S^P(4S^{D3}+S^{D2}\\ \left(5S^R-S^P\right)-2S^DS^P\left(9S^R+S^P\right)+S^RS^P\left(S^R+11S^P\right)\big)+P^{P2}\left(4S^{D2}\left(4S^R-3S^P\right)\right.\\ \left.+S^R\left(S^{R2}+5S^RS^P-2S^{P2}\right)+S^D\left(11S^{P2}-8S^{R2}-11S^RS^P\right)\right))\end{array}}{-2\left(S^R-S^P\right)S^P\left(3S^P-4S^D+S^R\right)^2}$$
$$+\frac{\begin{array}{c}\left(8S^D+S^R-9S^P\right)^2\left(S^R-S^P\right)S^P\left(S^{D2}+2S^DS^P-3S^{P2}\right)+2P^P\left(S^D-S^P\right)S^P\left(S^P-S^R\right)\\ \left(208S^{D2}+34S^DS^R+S^{R2}-450S^DS^P-36S^RS^P+243S^{P2}\right)+P^{P2}(16S^{D3}\left(16S^R-15S^P\right)+\\ +S^{D2}\left(64S^{R2}-860S^RS^P+748S^{P2}\right)+4S^D\left(S^{R3}-29S^{R2}S^P+229S^RS^{P2}-189S^{P3}\right)\\ +S^P\left(S^{R3}+37S^{R2}S^P-297S^RS^{P2}+243S^{P3}\right))\end{array}}{8\left(8S^D+S^R-9S^P\right)^2\left(S^D-S^P\right)\left(S^R-S^P\right)S^P}<0$$

$$SW_2^*-SW_1^*=\frac{1}{8}(3S^D+S^P+\frac{6P^P\left(2S^D+S^R-3S^P\right)}{8S^D+S^R-9S^P}$$
$$-\frac{\begin{array}{c}P^{P2}\left(16S^{D3}\left(16S^R-15S^P\right)+S^{D2}\left(64S^{R2}-860S^RS^P+748S^{P2}\right)+4S^D\left(S^{R3}-\right.\right.\\ \left.\left.29S^{R2}S^P+229S^RS^{P2}-189S^{P3}\right)+S^P\left(S^{R3}+37S^{R2}S^P-297S^RS^{P2}+243S^{P3}\right)\right)\end{array}}{\left(8S^D+S^R-9S^P\right)^2\left(S^D-S^P\right)\left(S^R-S^P\right)S^P}$$
$$-\frac{\begin{array}{c}4(8P^P\left(S^D-S^R\right)\left(S^D-S^P\right)\left(S^R-S^P\right)S^P+\left(S^R-S^P\right)S^P(12S^{D3}+S^RS^P\left(3S^R+S^P\right)\\ -S^{D2}\left(S^R+19S^P\right)-2S^D\left(S^{R2}+S^RS^P-4S^{P2}\right)\big)-P^{P2}\left(4S^{D2}\left(4S^R-3S^P\right)\right.\\ \left.+S^R\left(S^{R2}+5S^RS^P-2S^{P2}\right)+S^D\left(11S^{P2}-8S^{R2}-11S^RS^P\right)\right)))\end{array}}{\left(S^R-S^P\right)S^P\left(3S^P-4S^D+S^R\right)^2}<0$$

$S^R>S^D>S^P$

$$\pi_2^{A*}-\pi_1^{A*}=\frac{\left(8S^{R2}+S^{D2}+P^P\left(8S^R+S^D-9S^P\right)-16S^RS^P-2S^DS^P+9S^{P2}\right)^2}{4\left(8S^R+S^D-9S^P\right)\left(S^D+3S^P-4S^R\right)^2}>0$$

$$\pi_2^{R*}-\pi_1^{R*}=\left(S^R-S^D\right)\left(\frac{\left(2S^R+S^D-3S^P\right)^2}{\left(8S^R+S^D-9S^P\right)^2}-\frac{\left(P^P+2S^R-2S^P\right)^2}{\left(S^D+3S^P-4S^R\right)^2}\right)<0$$

$$\pi_2^{P*}-\pi_1^{P*}=\frac{3P^P\left(8S^{R2}+S^{D2}+P^P\left(8S^R+S^D-9S^P\right)-16S^RS^P-2S^RS^P+9S^{P2}\right)}{2\left(8S^R+S^D-9S^P\right)\left(4S^R-S^D-3S^P\right)}>0$$

$$CS_2^*-CS_1^*=\frac{1}{8}\left(\frac{P^{P2}\left(4S^D-3S^P\right)}{\left(S^D-S^P\right)S^P}-\frac{2P^P\left(26S^R+S^D-27S^P\right)}{8S^R+S^D-9S^P}+\frac{\begin{array}{c}16S^{R3}+5S^{D3}-35S^{D2}S^P+27S^DS^{P2}+243S^{P3}+\\ 4S^{R2}\left(9S^D+43S^P\right)+8S^R\left(3S^{D2}-7S^DS^P-54S^{P2}\right)\end{array}}{\left(8S^R+S^D-9S^P\right)^2}\right.$$
$$\left.-\frac{\begin{array}{c}4(-2P^P\left(S^R-S^D\right)\left(8S^R-S^D-7S^P\right)\left(S^D-S^P\right)S^P+\left(S^D-S^P\right)S^P(4S^{R3}+S^{R2}\left(5S^D-S^P\right)-2S^RS^P\left(9S^D+S^P\right)+S^DS^P\\ \left(S^D+11S^P\right)\big)+P^{P2}\left(4S^{R2}\left(4S^D-3S^P\right)+S^D\left(S^{D2}+5S^DS^P-2S^{P2}\right)+S^R\left(11S^{P2}-8S^{D2}-11S^DS^P\right)\right))\end{array}}{\left(S^D-S^P\right)S^P\left(S^D+3S^P-4S^R\right)^2}\right)<0$$

$$SW_2^* - SW_1^* = \frac{1}{8}\left(\frac{2P^P(10S^R - S^D - 9S^P)}{8S^R + S^D - 9S^P} - \frac{P^{P2}(4S^D - 3S^P)}{(S^D - S^P)S^P} + \frac{112S^{R3} - S^{D3} + 4S^{R2}(27S^D - 47S^P) + 8S^RS^D(3S^D - 25S^P) - 17S^{D2}S^P + 81S^DS^{P2} + 81S^{P3}}{(8S^R + S^D - 9S^P)^2} - \frac{4\left(8P^P(S^R - S^D)(S^R - S^P)(S^D - S^P)S^P + (S^D - S^P)S^P(12S^{R3} + S^DS^P(3S^D + S^P) - S^{R2}(S^D + 19S^P) - 2S^R\left(S^{D2} + S^DS^P - 4S^{P2}\right)\right) - P^{P2}\left(4S^{R2}(4S^D - 3S^P) + S^D\left(S^{D2} + 5S^DS^P - 2S^{P2}\right) + S^R\left(11S^{P2} - 8S^{D2} - 11S^DS^P\right)\right)\right)}{(S^D - S^P)S^P(S^D + 3S^P - 4S^R)^2}\right) < 0$$

So we have $\pi_2^{A*} > \pi_1^{A*}$, $\pi_2^{R*} < \pi_1^{R*}$, $\pi_2^{P*} > \pi_1^{P*}$, $CS_2^* < CS_1^*$ and $SW_2^* < SW_1^*$. ■

**Proof of Lemma 2.**

$S^D > S^R > S^P$

$$P_3^{D*} - P_1^{D*} = \frac{P^P(10S^D - S^R - 9S^P) + (8S^D + S^R - 9S^P)(S^D - S^P) - b(P^P - S^D + S^P)}{2(b + 8S^D + S^R - 9S^P)} - \frac{(S^D - S^R)(P^P + 2S^D - 2S^P)}{4S^D - S^R - 3S^P} > 0$$

$$P_3^{R*} - P_1^{R*} = \frac{2b(4S^D + S^R - 5S^P)(S^D - S^P) - 2bP^P(S^D + S^R - 2S^P) + (8S^D + S^R - 9S^P)(S^D - S^P)(S^R - S^P) - b^2(P^P - S^D + S^P) + P^P\left(12S^{D2} - S^{R2} + 4S^RS^P + 9S^{P2} - 2S^D(S^R + 11S^P)\right)}{2(b + 8S^D + S^R - 9S^P)(S^D - S^P)} - \frac{(S^D - S^R)(2P^P + S^R - S^P)}{4S^D - S^R - 3S^P} > 0$$

$$Q_3^{D*} - Q_1^{D*} = \frac{P^P(2S^D + S^R - 3S^P) + (8S^D + S^R - 9S^P)(S^D - S^P) + b(P^P + S^D - S^P)}{2(b + 8S^D + S^R - 9S^P)(S^D - S^P)} - \frac{P^P + 2S^D - 2S^P}{4S^D - S^R - 3S^P} < 0$$

$Q_3^{R*} - Q_1^{R*} = \frac{2b + S^D + 2S^R - 3S^P}{8b + S^D + 8S^R - 9S^P} + \frac{(S^D - S^P)(S^P - 2P^P - S^R)}{(4S^D - S^R - 3S^P)(S^R - S^P)} > 0$ when $b$ exceeds a certain threshold.

$$Q_3^{P*} - Q_1^{P*} = \frac{2b(4S^D + S^R - 5S^P)(S^D - S^P)S^P + (8S^D + S^R - 9S^P)(S^D - S^P)(S^R - S^P)S^P + b^2\left((S^D - S^P)S^P + P^P(S^P - 2S^D)\right) - 2bP^P\left(8S^{D2} + 2S^D(S^R - 8S^P) + S^P(7S^P - S^R)\right) + P^P\left(S^P\left(S^{R2} - 14S^RS^P + 9S^{P2}\right) - 4S^{D2}(4S^R - 3S^P) - 2S^D\left(S^{R2} - 16S^RS^P + 11S^{P2}\right)\right)}{2(b + 8S^D + S^R - 9S^P)(S^D - S^P)(b + S^R - S^P)S^P} + \frac{P^P}{S^P} - \frac{\frac{(S^D - S^R)(2P^P + S^R - S^P)}{4S^D - S^R - 3S^P} - P}{S^R - S^P} > 0$$

$S^R > S^D > S^P$

$$P_3^{D*} - P_1^{D*} = \frac{3(S^D - S^P)(8S^{R2} + S^{D2} + P^P(8S^R + S^D - 9S^P) + 2b(4P^P + 4S^R + S^D - 5S^P) - 16S^RS^P - 2S^DS^P + 9S^{P2})}{2(8b + 8S^R + S^D - 9S^P)(4S^R - S^D - 3S^P)} > 0$$

$$P_3^{R*} - P_1^{R*} = \frac{12b^2 + 12S^{R2} - 2S^RS^D - S^{D2} + b(8P^P + 24S^R - 2S^D - 22S^P) + P^P(8S^R + S^D - 9S^P) - 22S^RS^P + 4S^DS^P + 9S^{P2}}{2(8b + 8S^R + S^D - 9S^P)} - \frac{(S^R - S^D)(P^P + 2S^R - 2S^P)}{4S^R - S^D - 3S^P} > 0$$

$$Q_3^{D*} - Q_1^{D*} = \frac{8S^{R2} + S^{D2} + P^P(8S^R + S^D - 9S^P) + 2b(4P^P + 4S^R + S^D - 5S^P) - 16S^RS^P - 2S^DS^P + 9S^{P2}}{-2(8b + 8S^R + S^D - 9S^P)(4S^R - S^D - 3S^P)} < 0$$

$$Q_3^{R*} - Q_1^{R*} = \frac{2b + S^D + 2S^R - 3S^P}{8b + S^D + 8S^R - 9S^P} + \frac{(S^D - S^P)(S^P - 2P^P - S^R)}{(4S^D - S^R - 3S^P)(S^R - S^P)} < 0$$

$$Q_3^{P^*} - Q_1^{P^*} = \frac{3\left(8S^{R2} + S^{D2} + P^P\left(8S^R + S^D - 9S^P\right) + 2b\left(4P^P + 4S^R + S^D - 5S^P\right) - 16S^RS^P - 2S^DS^P + 9S^{P2}\right)}{2\left(8b + 8S^R + S^D - 9S^P\right)\left(4S^R - S^D - 3S^P\right)} > 0$$

So we have $P_3^{D^*} > P_1^{D^*}$, $P_3^{R^*} > P_1^{R^*}$, $Q_3^{D^*} < Q_1^{D^*}$, $Q_3^{R^*} < Q_1^{R^*}$ or $Q_3^{R^*} > Q_1^{R^*}$, and $Q_3^{P^*} > Q_1^{P^*}$. ■

**Proof of Proposition 2.**

$$S^D > S^R > S^P$$

$$\pi_3^{A^*} - \pi_1^{A^*} = \frac{\begin{gathered}2b\Big(P^{P2}\left(2S^D + S^R - 3S^P\right) + 2P^P\left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right) + \left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right)^2\Big) + \\ P^{P2}\left(2S^D + S^R - 3S^P\right)^2 - 8b^3k\left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right) + 2P^P\left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(S^R - S^P\right) + \\ \left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)^2\left(S^R - S^P\right) + 4b^4k\left(S^P - S^D\right) + b^2(P^{P2} + 2P^P\left(S^D - S^P\right) + \left(S^D - S^P\right) \\ \left(S^D - 32kS^D\left(S^R - S^P\right) - S^P - 4k\left(S^{R2} - 10S^RS^P + 9S^{P2}\right)\right)\Big)\end{gathered}}{4\left(b + 8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(b + S^R - S^P\right)}$$

$$-\frac{\left(S^D - S^R\right)\left(P^P + 2S^D - 2S^P\right)^2}{\left(3S^P - 4S^D + S^R\right)^2} > 0$$

when $k$ falls below a certain threshold.

$$\pi_3^{R^*} - \pi_1^{R^*} = \frac{-P^{P2}\left(b - S^D + S^R\right)\left(b + 2S^D + S^R - 3S^P\right)^2}{\left(b + 8S^D + S^R - 9S^P\right)^2\left(S^D - S^P\right)\left(b + S^R - S^P\right)} - \frac{\left(S^D - S^R\right)\left(S^D - S^P\right)\left(2P^P + S^R - S^P\right)^2}{\left(S^R - S^P\right)\left(S^R + 3S^P - 4S^D\right)^2} > 0$$

when $b$ exceeds a certain threshold.

$$\pi_3^{P^*} - \pi_1^{P^*} = P^P\left(\frac{P^P}{S^P} - \frac{\dfrac{\left(S^D - S^R\right)\left(2P^P + S^R - S^P\right)}{4S^D - S^R - 3S^P} - P^P}{S^R - S^P}\right)$$

$$-\frac{\begin{gathered}P^P(4P^PS^{D2}\left(4S^R - 3S^P\right) - 2b\left(4S^D + S^R - 5S^P\right)\left(S^D - S^P\right)S^P - \left(8S^D + S^R - 9S^P\right)\left(S^D - S^P\right) \\ \left(S^R - S^P\right)S^P + b^2\left(2P^PS^D - P^PS^P - S^DS^P + S^{P2}\right) - P^PS^P\left(S^{R2} - 14S^RS^P + 9S^{P2}\right) + \\ 2P^PS^D\left(S^{R2} - 16S^RS^P + 11S^{P2}\right) + 2bP^P\left(8S^{D2} + 2S^D\left(S^R - 8S^P\right) + S^P\left(7S^P - S^R\right)\right))\end{gathered}}{2\left(b + 8S^D + S^R - 9S^P\right)\left(S^D - S^P\right)\left(b + S^R - S^P\right)S^P} > 0$$

$$CS_3^* - CS_1^* = \frac{\begin{gathered}-4(-2P^P\left(S^D - S^R\right)\left(8S^D - S^R - 7S^P\right)\left(S^R - S^P\right)S^P + \\ \left(S^R - S^P\right)S^P\left(4S^{D3} + S^{D2}\left(5S^R - S^P\right) - 2S^DS^P\left(9S^R + S^P\right) + S^RS^P\left(S^R + 11S^P\right)\right) + \\ P^{P2}\left(4S^{D2}\left(4S^R - 3S^P\right) + S^R\left(S^{R2} + 5S^RS^P - 2S^{P2}\right) + S^D\left(11S^{P2} - 8S^{R2} - 11S^RS^P\right)\right))\end{gathered}}{8S^P\left(S^R - S^P\right)\left(S^R + 3S^P - 4S^D\right)^2} +$$

$$\frac{\begin{gathered}\left(8S^D + S^R - 9S^P\right)^2\left(S^R - S^P\right)S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right) + 2P^P\left(S^D - S^P\right)S^P\left(S^P - S^R\right)(208S^{D2} + 34S^DS^R + S^{R2} \\ -450S^DS^P - 36S^RS^P + 243S^{P2}) + b^3\left(2P^PS^P\left(S^P - S^D\right) + P^{P2}\left(4S^D + S^P\right) + S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right)\right) + \\ P^{P2}(16S^{D3}\left(16S^R - 15S^P\right) + S^{D2}\left(64S^{R2} - 860S^RS^P + 748S^{P2}\right) + 4S^D\left(S^{R3} - 29S^{R2}S^P + 229S^RS^{P2} - 189S^{P3}\right) \\ +S^P\left(S^{R3} + 37S^{R2}S^P - 297S^RS^{P2} + 243S^{P3}\right)) + b^2(-2P^P\left(34S^D + 3S^R - 37S^P\right)\left(S^D - S^P\right)S^P + \left(16S^D + 3S^R - 19S^P\right) \\ S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right) + P^{P2}\left(64S^{D2} + 4S^D\left(3S^R - 29S^P\right) + S^P\left(3S^R + 37S^P\right)\right)) + b(S^P\left(S^{D2} + 2S^DS^P - 3S^{P2}\right) \\ \left(64S^{D2} + 3S^{R2} + 32S^D\left(S^R - 5S^P\right) - 38S^RS^P + 99S^{P2}\right) - 2P^P\left(S^D - S^P\right)S^P(208S^{D2} + 68S^DS^R + 3S^{R2} - 484S^DS^P \\ -74S^RS^P + 279S^{P2}) + P^{P2}\left(256S^{D3} + 4S^{D2}\left(32S^R - 215S^P\right) + S^P\left(3S^{R2} + 74S^RS^P - 297S^{P2}\right) \right. \\ \left. +4S^D\left(3S^{R2} - 58S^RS^P + 229S^{P2}\right)\right))\end{gathered}}{8S^P\left(b + 8S^D + S^R - 9S^P\right)^2\left(S^D - S^P\right)\left(b + S^R - S^P\right)} > 0$$

when $b$ exceeds a certain threshold.

$$SW_3^* - SW_1^* = -\frac{1}{8S^P}\Bigg(\frac{\begin{gathered}8b^4k(16S^D+3S^R-19S^P)(S^D-S^P)S^P - 8b^5kS^P(S^P-S^D) - (8S^D+S^R-9S^P)^2(S^R-S^P)S^P \\ (3S^{D2}-2S^DS^P-S^{P2}) + 6P^P(S^D-S^P)S^P(S^P-S^R)(16S^{D2}+10S^DS^R+S^{R2}-42S^DS^P-12S^RS^P+ \\ 27S^{P2})+P^{P2}\left(16S^{D3}(16S^R-15S^P)+S^{D2}(64S^{R2}-860S^RS^P+748S^{P2})+4S^D(S^{R3}-29S^{R2}S^P+\right. \\ 229S^RS^{P2}-189S^{P3})+S^P(S^{R3}+37S^{R2}S^P-297S^RS^{P2}+243S^{P3})) + b^3(6P^PS^P(S^P-S^D)+ \\ P^{P2}(4S^D+S^P)+(S^D-S^P)S^P(512kS^{D2}+S^D(-3+256k(S^R-5S^P))-S^P+8k(3S^{R2}-38S^RS^P+ \\ 99S^{P2}))) + b(-6P^P(S^D-S^P)S^P(16S^{D2}+20S^DS^R+3S^{R2}-52S^DS^P-26S^RS^P+39S^{P2})+ \\ S^P(S^{P2}-3S^{D2}+2S^DS^P)(64S^{D2}+3S^{R2}+32S^D(S^R-5S^P)-38S^RS^P+99S^{P2})+P^{P2}(256S^{D3}+ \\ 4S^{D2}(32S^R-215S^P)+S^P(3S^{R2}+74S^RS^P-297S^{P2})+4S^D(3S^{R2}-58S^RS^P+229S^{P2})))+ \\ b^2(-6P^P(10S^D+3S^R-13S^P)(S^D-S^P)S^P+P^{P2}(64S^{D2}+4S^D(3S^R-29S^P)+S^P(3S^R+37S^P)) \\ +(S^D-S^P)S^P(16S^{D2}(-3+32k(S^R-S^P))+8k(S^R-9S^P)^2(S^R-S^P)+ \\ S^P(19S^P-3S^R)+S^D(128kS^{R2}+S^P(41+1152kS^P)-S^R(9+1280kS^P))))\end{gathered}}{(b+8S^D+S^R-9S^P)^2(S^D-S^P)(b+S^R-S^P)} + \frac{\begin{gathered}4(8P^P(S^D-S^R)(S^D-S^P)(S^R-S^P)S^P+(S^R-S^P)S^P(12S^{D3}+S^RS^P(3S^R+S^P)-S^{D2}(S^R+19S^P)- \\ 2S^D(S^{R2}+S^RS^P-4S^{P2}))-P^{P2}(4S^{D2}(4S^R-3S^P)+S^R(S^{R2}+5S^RS^P-2S^{P2})+S^D(11S^{P2}-8S^{R2}-11S^RS^P)))\end{gathered}}{(S^R-S^P)(3S^P-4S^D+S^R)^2}\Bigg) < 0$$

when $b$ exceeds a certain threshold and $k$ falls below a certain threshold.

$S^R > S^D > S^P$

$$\pi_3^{A*} - \pi_1^{A*} = \frac{1}{4(S^D-S^P)}\left(\frac{\begin{gathered}4b(2P^{P2}+4P^P(S^D-S^P)+(2S^R+S^D-3S^P)(S^D-S^P))+P^{P2}(8S^R+S^D \\ -9S^P)-32b^3k(S^D-S^P)-4b^2(-1+k(8S^R+S^D-9S^P))(S^D-S^P) \\ +2P^P(8S^R+S^D-9S^P)(S^D-S^P)+(2S^R+S^D-3S^P)^2(S^D-S^P)\end{gathered}}{8b+8S^R+S^D-9S^P} - -\frac{4(S^R-S^D)(S^R-S^P)(2P^P+S^D-S^P)^2}{(S^D+3S^P-4S^R)^2}\right) > 0$$

when $k$ falls below a certain threshold.

$\pi_3^{R*} - \pi_1^{R*} = \frac{(b+S^R-S^D)(2b+2S^R+S^D-3S^P)^2}{(8b+8S^R+S^D-9S^P)^2} - \frac{(S^R-S^D)(P^P+2S^R-2S^P)^2}{(S^D+3S^P-4S^R)^2} > 0$ when $b$ exceeds a certain threshold.

$$\pi_3^{P*} - \pi_1^{P*} = \frac{3P^P\left(8S^{R2}+S^{D2}+P^P(8S^R+S^D-9S^P)+2b(4P^P+4S^R+S^D-5S^P)-16S^RS^P-2S^DS^P+9S^{P2}\right)}{2(8b+8S^R+S^D-9S^P)(4S^R-S^D-3S^P)} > 0$$

$$16b^3(S^D - S^P)S^P - 2P^P(S^D - S^P)S^P\left(208S^{R^2} + 34S^RS^D + S^{D^2} - 450S^RS^P - 36S^DS^P + 243S^{P^2}\right) +$$

$$4b^2\left(16P^2(4S^D - 3S^P) - 104P^P(S^D - S^P)S^P + (S^D - S^P)S^P(12S^R + 9S^D + 43S^P)\right) + (S^D - S^P)S^P$$

$$\left(16S^{R^3} + 5S^{D^3} - 35S^{D^2}S^P + 27S^DS^{P^2} + 243S^{P^3} + 4S^{R^2}(9S^D + 43S^P) + 8S^R\left(3S^{D^2} - 7S^DS^P - 54S^{P^2}\right)\right)$$

$$4b\left(4P^{P^2}(8S^R + S^D - 9S^P)(4S^D - 3S^P) - P^P(208S^R + 17S^D - 225S^P)(S^D - S^P)S^P + \right.$$

$$CS_3^* - CS_1^* = \frac{\left.2(S^D - S^P)S^P\left(6S^{R^2} + 9S^RS^D + 3S^{D^2} + 43S^RS^P - 7S^DS^P - 54S^{P^2}\right)\right) + P^{P^2}(8S^R + S^D - 9S^P)^2(4S^D - 3S^P)}{8(8b + 8S^R + S^D - 9S^P)^2(S^D - S^P)S^P}$$

$$-\frac{\begin{array}{c}-2P^P(S^R - S^D)(8S^R - S^D - 7S^P)(S^D - S^P)S^P + \\ (S^D - S^P)S^P\left(4S^{R^3} + S^{R^2}(5S^D - S^P) - 2S^RS^P(9S^D + S^P) + S^DS^P(S^D + 11S^P)\right) + \\ P^{P^2}\left(4S^{R^2}(4S^D - 3S^P) + S^D\left(S^{D^2} + 5S^DS^P - 2S^{P^2}\right) + S^R\left(11S^{P^2} - 8S^{D^2} - 11S^DS^P\right)\right)\end{array}}{2(S^D - S^P)S^P(S^D + 3S^P - 4S^R)^2} > 0$$

when $b$ exceeds a certain threshold.

$$SW_3^* - SW_1^* = \frac{\begin{array}{c}P^{P2}(8S^R + S^D - 9S^P)^2(4S^D - 3S^P) + 512b^4k(S^D - S^P)S^P + \\ 16b^3\left(-7 + 8k(8S^R + S^D - 9S^P)\right)(S^D - S^P)S^P + 2P^P(S^D - S^P)S^P\left(-80S^{R^2} + S^{D^2} - 2S^R(S^D - 81S^P) - 81S^{P^2}\right) + \\ (S^D - S^P)S^P\left(-112S^{R^3} + S^{D^3} - 4S^{R^2}(27S^D - 47S^P) - 8S^RS^D(3S^D - 25S^P) + 17S^{D^2}S^P - 81S^DS^{P^2} - 81S^{P^3}\right) - \\ 4b\left(-4P^{P^2}(8S^R + S^D - 9S^P)(4S^D - 3S^P) + P^P(80S^R + S^D - 81S^P)(S^D - S^P)S^P + 2(S^D - S^P)S^P\right. \\ \left.\left(42S^{R^2} + 27S^RS^D + 3S^{D^2} - 47S^RS^P - 25S^DS^P\right)\right) + 4b^2\left(16P^{P^2}(4S^D - 3S^P) - 40P^P(S^D - S^P)S^P + (S^D - S^P)S^P\right. \\ \left.\left(128kS^{R^2} + 2kS^{D^2} + 4S^R\left(-21 + 8k(S^D - 9S^P)\right) - 9S^D(3 + 4kS^P) + S^P(47 + 162kS^P)\right)\right)\end{array}}{-8(8b + 8S^R + S^D - 9S^P)^2(S^D - S^P)S^P}$$

$$-\frac{\begin{array}{c}8P^P(S^R - S^D)(S^R - S^P)(S^D - S^P)S^P + \\ (S^D - S^P)S^P\left(12S^{R^3} + S^DS^P(3S^D + S^P) - S^{R^2}(S^D + 19S^P) - 2S^R\left(S^{D^2} + S^DS^P - 4S^{P^2}\right)\right) \\ -P^{P^2}\left(4S^{R^2}(4S^D - 3S^P) + S^D\left(S^{D^2} + 5S^DS^P - 2S^{P^2}\right) + S^R\left(11S^{P^2} - 8S^{D^2} - 11S^DS^P\right)\right)\end{array}}{2(S^D - S^P)S^P(S^D + 3S^P - 4S^R)^2} > 0$$

when $b$ exceeds a certain threshold and $k$ falls below a certain threshold.

So we have $\pi_3^{A^*} > \pi_1^{A^*}$, $\pi_3^{R^*} < \pi_1^{R^*}$ or $\pi_3^{R^*} > \pi_1^{R^*}$, $\pi_3^{P^*} > \pi_1^{P^*}$, $CS_3^* > CS_1^*$ or $CS_3^* < CS_1^*$, and $SW_3^* > SW_1^*$ or $SW_3^* < SW_1^*$. ■

**Proof of Lemma 3.**

$S^D > S^R > S^P$

$P_3^{D^*} - P_2^{D^*} = \frac{b\left(-8P^P(S^D - S^R) + (8S^D + S^R - 9S^P)(S^D - S^P)\right) - (S^D - S^R)\left(P^P(S^D + 8S^R - 9S^P) + (8S^D + S^R - 9S^P)(S^D - S^P)\right)}{(8S^D + S^R - 9S^P)(8b + S^D + 8S^R - 9S^P)} > 0$ when $b$ exceeds a certain threshold.

$$P_3^{R^*} - P_2^{R^*} = \frac{\begin{array}{c}b\left(-(8S^D + S^R - 9S^P)^2(S^D - S^P) + b(8S^D + S^R - 9S^P)(P^P - S^D + S^P)\right. \\ \left.+P^P\left(28S^{D^2} + S^{R^2} + 8S^D(2S^R - 9S^P) - 18S^RS^P + 45S^{P^2}\right)\right)\end{array}}{-2(8S^D + S^R - 9S^P)(b + 8S^D + S^R - 9S^P)(S^D - S^P)} > 0$$

$Q_3^{D^*} - Q_2^{D^*} = \frac{3bP^P}{(8S^D + S^R - 9S^P)(b + 8S^D + S^R - 9S^P)} > 0$ when $b$ falls below a certain threshold.

$Q_3^{R^*} - Q_2^{R^*} = \frac{2b + S^D + 2S^R - 3S^P}{8b + S^D + 8S^R - 9S^P} - \frac{P^P(2S^D + S^R - 3S^P)}{(8S^D + S^R - 9S^P)(S^R - S^P)} > 0$ when $b$ exceeds a certain threshold.

$$Q_3^{P^*} - Q_2^{P^*} = \frac{2bP^P\left(8S^{D^2} + b(S^D - S^R) - S^{R^2} + 2S^D(S^R - 9S^P) + 9S^{P^2}\right)}{(8S^D + S^R - 9S^P)(b + 8S^D + S^R - 9S^P)(S^R - S^P)(b + S^R - S^P)} > 0$$

$S^R > S^D > S^P$

$$P_3^{D*} - P_2^{D*} = \frac{9b\left(S^D - S^P\right)^2}{\left(8S^R + S^D - 9S^P\right)\left(8b + 8S^R + S^D - 9S^P\right)} > 0$$

$$P_3^{R*} - P_2^{R*} = \frac{3b\left(16S^{R^2} + S^{D^2} + 4S^R\left(S^D - 9S^P\right) + 2b\left(8S^R + S^D - 9S^P\right) - 6S^DS^P + 21S^{P^2}\right)}{\left(8S^R + S^D - 9S^P\right)\left(8b + 8S^R + S^D - 9S^P\right)} > 0$$

$$Q_3^{D*} - Q_2^{D*} = -\frac{3b\left(S^D - S^P\right)}{\left(8S^R + S^D - 9S^P\right)\left(8b + 8S^R + S^D - 9S^P\right)} < 0$$

$$Q_3^{R*} - Q_2^{R*} = \frac{2b + S^D + 2S^R - 3S^P}{8b + S^D + 8S^R - 9S^P} - \frac{P^P\left(2S^D + S^R - 3S^P\right)}{\left(8S^D + S^R - 9S^P\right)\left(S^R - S^P\right)} < 0$$

$$Q_3^{P*} - Q_2^{P*} = \frac{9b\left(S^D - S^P\right)}{\left(8S^R + S^D - 9S^P\right)\left(8b + 8S^R + S^D - 9S^P\right)} > 0$$

So we have $P_3^{D*} > P_2^{D*}$ or $P_3^{D*} < P_2^{D*}$, $P_3^{R*} > P_2^{R*}$, $Q_3^{D*} < Q_2^{D*}$, $Q_3^{R*} > Q_2^{R*}$ or $Q_3^{R*} < Q_2^{R*}$, and $Q_3^{P*} > Q_2^{P*}$. ■

**Proof of Proposition 3.**

$S^D > S^R > S^P$

$$\pi_3^{A*} - \pi_2^{A*} = -\frac{\begin{array}{c} b(b\left(P^{P^2}\left(S^D - S^R\right) + k\left(8S^D + S^R - 9S^P\right)^2\left(S^R - S^P\right)^2\right) + b^3k\left(8S^D + S^R - 9S^P\right)\left(S^R - S^P\right) + P^{P^2}(8S^{D^2} - S^{R^2} \\ +2S^D\left(S^R - 9S^P\right) + 9S^{P^2}\right) + 2b^2k\left(S^R - S^P\right)\left(32S^{D^2} + 12S^DS^R + S^{R^2} - 76S^DS^P - 14S^RS^P + 45S^{P^2}\right)\big)\end{array}}{\left(8S^D + S^R - 9S^P\right)\left(b + 8S^D + S^R - 9S^P\right)\left(S^R - S^P\right)\left(b + S^R - S^P\right)} > 0$$

when $k$ falls below a certain threshold.

$$\pi_3^{R*} - \pi_2^{R*} = \frac{\left(bS^R - S^D\right)\left(2b + S^D + 2S^R - 3S^P\right)^2}{\left(8b + S^D + 8S^R - 9S^P\right)^2} - \frac{P^{P^2}\left(S^D - S^R\right)\left(2S^D + S^R - 3S^P\right)^2}{\left(8S^D + S^R - 9S^P\right)^2\left(S^D - S^P\right)\left(S^R - S^P\right)} > 0$$

when $b$ exceeds a certain threshold.

$$\pi_3^{P*} - \pi_2^{P*} = \frac{2bP^{P^2}\left(8S^{D^2} + b\left(S^D - S^R\right) - S^{R^2} + 2S^D\left(S^R - 9S^P\right) + 9S^{P^2}\right)}{\left(8S^D + S^R - 9S^P\right)\left(b + 8S^D + S^R - 9S^P\right)\left(S^R - S^P\right)\left(b + S^R - S^P\right)} > 0$$

$S^R > S^D > S^P$

$$\pi_3^{A*} - \pi_2^{A*} = \frac{\begin{array}{c} b\left(S^{D^2} - 8S^{R^2} - 2S^R\left(S^D - 9S^P\right) + 8b^2k\left(8S^R + S^D - 9S^P\right) \\ +b\left(-1 + k\left(8S^R + S^D - 9S^P\right)\right)\left(8S^R + S^D - 9S^P\right) - 9S^{P^2}\right)\end{array}}{-\left(8S^R + S^D - 9S^P\right)\left(8b + 8S^R + S^D - 9S^P\right)} > 0$$

when $k$ falls below a certain threshold.

$$\pi_3^{R*} - \pi_2^{R*} = \frac{\left(b + S^R - S^D\right)\left(2b + 2S^R + S^D - 3S^P\right)^2}{\left(8b + 8S^R + S^D - 9S^P\right)^2} - \frac{\left(S^R - S^D\right)\left(2S^R + S^D - 3S^P\right)^2}{\left(8S^R + S^D - 9S^P\right)^2} > 0$$

$$\pi_3^{P*} - \pi_2^{P*} = \frac{9bP^P\left(S^D - S^P\right)}{\left(8S^R + S^D - 9S^P\right)\left(8b + 8S^R + S^D - 9S^P\right)} > 0$$

So we have $\pi_3^{A*} > \pi_2^{A*}$ or $\pi_3^{A*} < \pi_2^{A*}$, $\pi_3^{R*} > \pi_2^{R*}$ or $\pi_3^{R*} < \pi_2^{R*}$, and $\pi_3^{P*} > \pi_2^{P*}$. ■

**Proof of Proposition 4.**

$S^D > S^R > S^P$

$$CS_3^* - CS_2^* = \frac{\begin{array}{c} bP^P( - ((8S^D + S^R - 9S^P)( - 9(8S^D + S^R - 9S^P)(S^D - S^P)(S^R - S^P)^2 + 2P^P(S^D - S^R) \\ \left(16S^{D2} + 22S^DS^R + 7S^{R2} - 54S^DS^P - 36S^RS^P + 45S^{P2}\right))) + b^2(9(8S^D + S^R - 9S^P) \\ (S^D - S^P)(S^R - S^P) + P^P\left(71S^DS^R - 4S^{D2} + 14S^{R2} - 63S^DS^P - 99S^RS^P + 81S^{P2}\right)) + \\ b\left(18(S^D - S^P)(S^R - S^P)\left(32S^{D2} + 12S^DS^R + S^{R2} - 76S^DS^P - 14S^RS^P + 45S^{P2}\right) + \right. \\ P^P(28S^{R3} - 64S^{D3} + 12S^{D2}(19S^R - 3S^P) - 297S^{R2}S^P + \\ 738S^RS^{P2} - 405S^{P3} + 3S^D\left(71S^{R2} - 294S^RS^P + 159S^{P2}\right)))) \end{array}}{2(8S^D + S^R - 9S^P)^2(b + 8S^D + S^R - 9S^P)^2(S^R - S^P)(b + S^R - S^P)} > 0$$

when $b$ exceeds a certain threshold.

$$SW_3^* - SW_2^* = \frac{1}{8}( - 3S^D - S^P - \frac{6P^P(2S^D + S^R - 3S^P)}{8S^D + S^R - 9S^P}$$

$$- \frac{\begin{array}{c} 8b^4k(16S^D + 3S^R - 19S^P)(S^D - S^P)S^P - 8b^5kS^P(S^P - S^D) \\ -(8S^D + S^R - 9S^P)^2(S^R - S^P)S^P\left(3S^{D2} - 2S^DS^P - S^{P2}\right) + 6P^P(S^D - S^P) \\ S^P(S^P - S^R)\left(16S^{D2} + 10S^DS^R + S^{R2} - 42S^DS^P - 12S^RS^P + 27S^{P2}\right) \\ +P^{P2}(16S^{D3}(16S^R - 15S^P) + S^{D2}\left(64S^{R2} - 860S^RS^P + 748S^{P2}\right) + 4S^D \\ \left(S^{R3} - 29S^{R2}S^P + 229S^RS^{P2} - 189S^{P3}\right) + S^P\left(S^{R3} + 37S^{R2}S^P - 297S^RS^{P2} + 243S^{P3}\right)) + \\ b^3\left(6P^PS^P(S^P - S^D) + P^{P2}(4S^D + S^P) + (S^D - S^P)S^P\left(512kS^{D2} + S^D( - 3 + 256k(S^R - 5S^P))\right.\right. \\ \left.\left. -S^P + 8k\left(3S^{R2} - 38S^RS^P + 99S^{P2}\right)\right)\right) + b( - 6P^P(S^D - S^P)S^P(16S^{D2} + 20S^DS^R + 3S^{R2} - \\ 52S^DS^P - 26S^RS^P + 39S^{P2}) + S^P\left(2S^DS^P + S^{P2} - 3S^{D2}\right)\left(64S^{D2} + 3S^{R2} + 32S^D(S^R - 5S^P)\right. \\ \left. -38S^RS^P + 99S^{P2}\right) + P^{P2}\left(256S^{D3} + 4S^{D2}(32S^R - 215S^P) + S^P\left(3S^{R2} + 74S^RS^P - 297S^{P2}\right)\right. \\ \left. +4S^D\left(3S^{R2} - 58S^RS^P + 229S^{P2}\right)\right)) + b^2( - 6P^P(10S^D + 3S^R - 13S^P)(S^D - S^P)S^P + P^{P2} \\ \left(64S^{D2} + 4S^D(3S^R - 29S^P) + S^P(3S^R + 37S^P)\right) + (S^D - S^P)S^P(16S^{D2}( - 3 + 32k(S^R - S^P)) \\ +8k(S^R - 9S^P)^2(S^R - S^P) + S^P(19S^P - 3S^R) + S^D(128kS^{R2} + S^P(41 + 1152kS^P) \\ -S^R(9 + 1280kS^P)))) \end{array}}{(b + 8S^D + S^R - 9S^P)^2(S^D - S^P)(b + S^R - S^P)S^P}$$

$$+ + \frac{\begin{array}{c} P^{P2}\left(16S^{D3}(16S^R - 15S^P) + S^{D2}\left(64S^{R2} - 860S^RS^P + 748S^{P2}\right) + 4S^D\left(S^{R3} - \right.\right. \\ \left.\left. 29S^{R2}S^P + 229S^RS^{P2} - 189S^{P3}\right) + S^P\left(S^{R3} + 37S^{R2}S^P - 297S^RS^{P2} + 243S^{P3}\right)\right) \end{array}}{(8S^D + S^R - 9S^P)^2(S^D - S^P)(S^R - S^P)S^P}) > 0$$

when $k$ falls below a certain threshold.

$S^R > S^D > S^P$

$$CS_3^* - CS_2^* = \frac{\begin{array}{c} b(4b^2(8S^R + S^D - 9S^P)^2 + b(512S^{R3} - 71S^{D3} + 192S^{R2}(S^D - 9S^P) + 441S^{D2}S^P - 477S^DS^{P2} - 405S^{P3} \\ -12S^R\left(19S^{D2} + 48P^P(S^D - S^P) - 6S^DS^P - 141S^{P2}\right) - 72P^P\left(S^{D2} - 10S^DS^P + 9S^{P2}\right)) + (8S^R + S^D - 9S^P) \\ \left(32S^{R3} + 12S^{R2}(S^D - 9S^P) - 9P^P\left(S^{D2} - 10S^DS^P + 9S^{P2}\right) - 2S^D\left(7S^{D2} - 36S^DS^P + 45S^{P2}\right)\right. \\ \left. +S^R\left( - 30S^{D2} - 72P(S^D - S^P) + 36S^DS^P + 90S^{P2}\right)\right)) \end{array}}{2(8S^R + S^D - 9S^P)^2(8b + 8S^R + S^D - 9S^P)^2} > 0$$

$$SW_3^* - SW_2^* = \frac{\begin{array}{c} b\left(128b^3k(8S^R + S^D - 9S^P)^2 + 4b^2( - 7 + 8k(8S^R + S^D - 9S^P))(8S^R + S^D - 9S^P)^2 - (8S^R + S^D - 9S^P)\right. \\ \left(224S^{R3} + 84S^{R2}(S^D - 9S^P) + 9P^P\left(S^{D2} - 10S^DS^P + 9S^{P2}\right) + 6S^R\left(S^{D2} + 12P^P(S^D - S^P) - 30S^DS^P + 141S^{P2}\right)\right. \\ \left. +2\left(5S^{D3} - 18S^{D2}S^P + 63S^DS^{P2} - 162S^{P3}\right)\right) + b(8192kS^{R4} - 72PS^{D2} - 43S^{D3} + 2kS^{D4} + 512S^{R3} \\ ( - 7 + 8k(S^D - 9S^P)) + 192S^{R2}( - 7 + 4k(S^D - 9S^P))(S^D - 9S^P) + 720P^PS^DS^P + 261S^{D2}S^P - 72kS^{D3}S^P \\ -648P^PS^{P2} - 1737S^DS^{P2} + 972kS^{D2}S^{P2} + 5103S^{P3} - 5832kS^DS^{P3} + 13122kS^{P4} - 4\ S^R \\ \left.\left( - 16kS^{D3} + 144P^P(S^D - S^P) - 18S^DS^P(41 + 216kS^P) + S^{D2}(33 + 432kS^P) + 9S^{P2}(377 + 1296kS^P)\right)\right)\Big) \end{array}}{-2(8S^R + S^D - 9S^P)^2(8b + 8S^R + S^D - 9S^P)^2} > 0$$

when $k$ falls below a certain threshold.

## Data availability

No data was used for the research described in the article.

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