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Abstract

This paper studies a real options duopoly game between two firms with different time discount rates. I derive the order of investments, investment thresholds, and firm values in equilibrium. With no cost disadvantage, the patient firm enters the market earlier and gains more value than does the impatient opponent. When the patient firm has a cost disadvantage, the order of market entry can depend on the market characteristics. With a weaker first-mover advantage, higher market volatility, and lower market growth rate, the impatient firm is more likely to be the first mover. Notably, the patient firm can earn more than the impatient firm, even though the patient firm enters the market later. These results are consistent with empirical findings on market entry timing.

JEL Classifications Code: C73; G31; L13.

Keywords: real options, time discounting, market entry timing, preemption.

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1 Introduction

Some firms pioneer new markets to gain the first-mover advantage, while other firms enter the market later as followers. What are the determinants of the order of market entry and firm value in this preemptive competition? To answer this question, several studies combine the timing game (cf. Fudenberg and Tirole (1985)) and the real options model (cf. Dixit and Pindyck (1994)) to develop preemption games under market demand uncertainty (see Azevedo and Paxson (2014) for a review). For instance, Huisman (2001), Pawlina and Kort (2006), and Kong and Kwok (2007) show that firms' cost and payoff structures can determine the order of market entry and firm values in duopoly markets. To the best of my knowledge, however, no study investigates the role of discount rates in preemptive competition. This study develops the preemption game in which two firms differ in their discount rates and determines the effects of the discount rates on the market entry order and firm values in equilibrium.

Actually, firms can use different discount rates depending on their characteristics, even if they compete in the same market. As Harrington (1989) explains, more diversified and less financially constrained firms tend to have lower discount rates. He examines the collusion model among firms with different discount rates. Harris and Siebert (2017) show empirically that firms have different discount rates and that merger outcomes depend on the acquirers' discount rates. In addition, from the behavioral viewpoint, many studies show the dispersion of time discounting and preferences (see Frederick, Loewenstein, and O'Donoghue (2002) for a review). In the real options context, Ebert, Wei, and Zhou (2018) investigate the investment timing of a group whose members differ in their discount rates, while Grenadier and Wang (2007) and Luo, Tian, and Yang (2020) examine the effects of time-inconsistent preferences on investment timing.

The present study develops the following preemption game to explore the roles of discount rates in preemptive competition. Two firms with different discount rates consider entering a new market. Throughout the paper, I refer to the firms with the low and high discount rates as firms P and I, respectively, where the notations P and I represent the patient and impatient firms, respectively. The firms can receive stochastic cash flows after they enter the market by paying sunk costs. Cash flows decrease in the number of firms in the market, and hence there is first-mover advantage in that the first entrant can receive monopolistic cash flows until the other firm's entry. The firms have complete information about each other and optimize their market entry timing from strategic considerations. I derive the market entry order, investment thresholds, and firm values endogenously in equilibrium. The results are explained below.

Compared to firm I, firm P has both higher net present value (NPV) and the option value of waiting. Firm P may enter the market earlier because of its higher NPV, while firm P may enter the market later because of its higher value of waiting. When firm P has no cost disadvantage, firm P always enters the market earlier. In other words, the NPV effect dominates the option effect, and hence firm P becomes the first mover. Naturally, firm P has a higher firm value than firm I does.

These results are similar to the standard result that the firm with an advantage in investment costs and/or project payoffs invests earlier and earns more than a disadvantageous opponent does (e.g., Chapter 8 of Huisman (2001) and Pawlina and Kort (2006)). In fact, in the model in this paper, firm P has both the NPV and option value advantages.

Several empirical findings also support the results. For example, Robinson, Fornell, and Sullivan (1992) show that firms with more finance skills tend to enter markets earlier. Clearly, more finance skills relax financial constraints, which leads to lower discount rates. Schoenecker and Cooper (1998) show that larger firms tend to enter markets earlier. Note that larger firms tend to have lower discount rates due to their more diversified project portfolios and less financial constraints (cf. Harrington (1989)). This study can thus potentially explain these observations from the discount rates viewpoint.

I show more notable results when firm P has a higher investment cost than firm I does. With a small cost disadvantage, firm P enters the market earlier and earns more than firm I does, while with a large cost disadvantage, firm P enters the market later and earns less than firm I does. In the intermediate cases, the order of market entry depends on the market characteristics. Indeed, a weaker first-mover advantage, higher volatility, and lower growth rate increase the possibility that firm P becomes the second mover because these parameters increase the option effect relative to the NPV effect. Moreover, firm P can have a higher firm value even when it chooses to be the second mover.

These results contrast with the standard result that regardless of market characteristics, an advantageous firm becomes the leader and earns more than does a disadvantageous opponent (e.g., Chapter 8 of Huisman (2001) and Pawlina and Kort (2006)). On the other hand, Kong and Kwok (2007), Shibata (2016), and Lambrecht (2001) report similar results. For instance, Kong and Kwok (2007) show that in a duopoly market with both cost and cash flow asymmetry, the level of volatility affects the market entry order. Shibata (2016) shows that in a triopoly market with cost asymmetry, the firm with the second lowest cost can be the first mover, especially under higher volatility and a weaker first-mover advantage. Lambrecht (2001), who examines market exit timing in a duopoly market, shows that the exit order can depend on the interest rate and volatility levels. Compared to these studies, I focus on the difference in discount rates and explain the results by the tradeoff between the NPV and option effects.

The results could be also related to several observations in case studies. For instance, Shibata (2016) demonstrates an example in which a smaller and more financially constrained firm moved earlier in the wireless telecommunication market in Japan. Shibata (2016) states that the degree of first-mover advantage in the market is weak, which is consistent with my comparative statics result. Shackleton, Tsekrekos, and Wojakowski (2004) states that Airbus became the first mover in the very large aircrafts market, although compared to its competitor, Boeing, it is smaller and more financially constrained. High uncertainty in the market and lower costs due to subsidies for Airbus are consistent with my comparative statics results.

This paper proceeds as follows. Section 2 introduces the model setup. Section 3 derives the equilibrium solution in the model. In Section 4.1, I explore the case with symmetric investment costs, while in Section 4.2, I explore the case with asymmetric investment costs. Section 5 discusses the empirical implications. Finally, I conclude in Section 6 and describe some potential extensions.

2 Model setup

Consider firms P and I, which intend to enter a new market. Firm P (i.e., the patient firm) has the discount rate ρ_P, while firm I (i.e., the impatient firm) has the discount rate ρ_I, where $0 < \rho_P < \rho_I$. To enter the market, firm $i \in \{P, I\}$ must pay the initial investment cost K_i. When only one of the firms is active in the market, the active firm receives instantaneous cash flows $X(t)$. When both firms are active in the market, each firm receives instantaneous cash flows $DX(t)$, where D is a constant satisfying $0 \leq D \leq 1$, which indicates negative externalities. Following the standard literature (e.g., Dixit and Pindyck (1994)), cash flows $X(t)$ follow a geometric Brownian motion

$$\mathrm{d}X(t) = \mu X(t)\mathrm{d}t + \sigma X(t)\mathrm{d}B(t) \ (t > 0), \quad X(0) = x, \tag{1}$$

where $B(t)$ denotes the standard Brownian motion defined in a filtered probability space $(\Omega, \mathcal{F}, \mathbb{P}, \{\mathcal{F}_t\})$ and $\mu, \sigma(> 0)$ and $x(> 0)$ are constants. For convergence, I assume that $\mu < \rho_P$. The initial value x is sufficiently small that each firm must wait for its entry condition to be met. Each firm maximizes the expected value discounted by its own discount rate and has full information about $X(t), D, \rho_i$, and K_i $(i = P, I)$.

Except the assumption of $\rho_P \neq \rho_I$, the model follows the standard real options duopoly model (e.g., Huisman (2001) and Pawlina and Kort (2006)). In the presence of capital market imperfections and behavioral biases, firms do not necessarily have the same discount rate, even when operating in the same market. Firm characteristics, such as more diversified risks, less financial constraints, more patience, and optimistic biases, tend to lead to lower discount rates. The rationale behind the assumption of $\rho_P \neq \rho_I$ and its implications will be discussed in full detail in Section 5.

3 Model solution

This section derives the equilibrium solution (i.e., the investment thresholds and values of firms P and I) in the real options duopoly game. Following the standard literature (e.g., Chapter 9 of Dixit and Pindyck (1994), Chapters 7 and 8 of Huisman (2001), and Pawlina and Kort (2006)), I solve the game backwards. Suppose that firm $i \in \{P, I\}$ (hereafter, the leader) invested at time s. The remaining firm $j(\neq i)$ (hereafter, the follower) enters the market at the optimal time after s. The follower's value is equal to

$$F_j(X(s)) = \sup_{T_j^F \geq s} \mathbb{E}^{X(s)}[\int_{T_j^F}^{\infty} \mathrm{e}^{-\rho_j(t-s)} DX(t)\mathrm{d}t - \mathrm{e}^{-\rho_j(T_j^F - s)} K_j], \tag{2}$$

where the follower's investment time T_j^F is optimized over all stopping times later than s, and $\mathbb{E}^{X(s)}[\cdot]$ denotes the expectation conditional on $X(s)$.

In the standard manner (for details, see Dixit and Pindyck (1994)), I can solve the follower's problem (2). Indeed, $F_j(x)$ satisfies the ordinary differential equation

$$(\mu + 0.5\sigma^2)xF_j'(x) + \sigma^2 x^2 F_j''(x) = \rho_j F_j(x). \tag{3}$$

The boundary conditions are the value matching and smooth pasting conditions

$$F_j(x_j^F) = \frac{Dx_j^F}{\rho_j - \mu} - K_j,$$
$$F_j'(x_j^F) = \frac{D}{\rho_j - \mu},$$

where x_j^F denotes the follower's investment threshold, as well as the trivial condition $\lim_{x\to 0} F_j(x) = 0$. By solving (3) with the three boundary conditions, I have the follower's value function:

$$
F_j(X(s)) = \begin{cases} \left(\dfrac{X(s)}{x_j^F}\right)^{\beta_j} \left(\dfrac{DX(s)}{\rho_j - \mu} - K_j\right) & (X(s) < x_j^F), \\ \dfrac{DX(s)}{\rho_j - \mu} - K_j & (X(s) \geq x_j^F), \end{cases} \tag{4}
$$

where β_j is a positive characteristic root defined by

$$
\beta_j = 0.5 - \frac{\mu}{\sigma^2} + \sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho_j}{\sigma^2}} \ (> 1) \tag{5}
$$

and x_j^F is the investment threshold given by

$$
x_j^F = \frac{\beta_j}{\beta_j - 1} \frac{(\rho_j - \mu)K_j}{D}. \tag{6}
$$

The follower's investment time is equal to $T_j^F = \inf\{t \geq s \mid X(s) \geq x_j^F\}$.

Suppose that the follower j enters the market at T_j^F. Then, the leading firm i's investment at time s yields the following expected payoff:

$$
\begin{aligned} L_i(X(s)) &= \mathbb{E}^{X(s)}[\int_s^{T_j^F} \mathrm{e}^{-\rho_i(t-s)} X(t)\mathrm{d}t + \int_{T_j^F}^{\infty} \mathrm{e}^{-\rho_i(t-s)} DX(t)\mathrm{d}t] - K_i \\ &= \frac{X(s)}{\rho_i - \mu} - K_i - \frac{(1-D)x_j^F}{\rho_i - \mu} \left(\frac{X(s)}{\max\{x_j^F, X(s)\}}\right)^{\beta_i}. \end{aligned} \tag{7}
$$

Note that the leader i's instantaneous cash flows are equal to $X(t)$ before time T_j^F and fall to $DX(t)$ after time T_j^F. In the same manner as in the derivation of the follower's investment threshold x_j^F, I can derive the leader i's optimal investment threshold

$$
x_i^L = \frac{\beta_i(\rho_i - \mu)K_i}{\beta_i - 1}. \tag{8}
$$

in the absence of the competitor's preemption.

Finally, I consider the case in which neither firm entered the market. In the region $F_i(X(s)) < L_i(X(s))$, firm i prefers to become the leader, whereas in the region $L_i(X(s)) < F_i(X(s))$, firm i is better off being the follower. For $i = P, I$, firm i's rent equalization threshold x_i^E is

$$
x_i^E = \inf\{x \geq 0 \mid L_i(x) > F_i(x)\}. \tag{9}
$$

Firm i can accelerate investment up to the threshold x_i^E to gain the leader's payoff. For $X(s) = x_i^E < \infty$, firm i is indifferent to whether to be the leader or the follower because the leader's rent is exactly equal to the follower's rent.

Define $i^* = \arg\min_{i=P,I} x_i^E$ and $j^* = \{P, I\} \backslash i^*$.[1] By the standard argument in the timing game (e.g., Fudenberg and Tirole (1985), Chapter 8 of Huisman (2001), and Pawlina

[1] If $x_P^E = x_I^E$ holds, I assume that one of the firms will randomly be firm i^* with probability 1/2.

Table 1: Baseline parameter values.

ρ_P	ρ_I	K_P	K_I	μ	σ	D	x
0.07	0.08	10	10	0.05	0.2	0.5	0.2

and Kort (2006)), I have the equilibrium results below. Firm i^*, which has a stronger incentive to move first, becomes the leader, while firm j^* becomes the follower. Depending on the parameter values, either the preemption or nonstrategic equilibrium arises.

Suppose that firm j^*'s rent equalization threshold $x^E_{j^*}$ is lower than firm i^*'s nonstrategic investment threshold $x^L_{i^*}$. In equilibrium, firm i^* enters the market as the leader at the threshold $x^E_{j^*}$, while firm j^* enters the market as the follower at the threshold $x^F_{j^*}$. Why does firm i^* enter the market at $x^E_{j^*}$ instead of $x^L_{i^*}$? Firm i^* wishes to delay the market entry up to $x^L_{i^*}$, but cannot do so because firm j^* tries to move first for $X(s) > x^E_{j^*}$. Then, in equilibrium, firm i^* accelerates its market entry timing to $x^E_{j^*}$, at which firm j^* has no incentive to move first. Note that I assume that the initial value x is sufficiently small that $x < x^E_{j^*}$. This equilibrium is called the preemption equilibrium. Figure 1 shows an example of a preemption equilibrium using the parameter values set in Table 1. Firm P becomes the leader because $x^E_P = 0.538 < x^E_I = 0.707$. By $x^L_P = 0.953 > x^E_I = 0.707$, the preemption equilibrium arises, where firm P enters the market at $x^E_I = 0.707$ and firm I enters the market at $x^F_I = 2.154$.

Next, suppose that firm j^*'s rent equalization threshold $x^E_{j^*}$ is higher than firm i^*'s nonstrategic investment threshold $x^L_{i^*}$. In this case, firm i^* delays its market entry timing to $x^L_{i^*}$ because firm j^* has no incentive to move first for $X(s) \leq x^L_{i^*}$. Hence, in equilibrium, firm i^* enters the market as the leader at the threshold $x^L_{i^*}$, while firm j^* enters the market as the follower at the threshold $x^F_{j^*}$. Figure 2 shows an example of a nonstrategic equilibrium using the parameter values set in Table 1, except that $\rho_I = 0.1$. Firm P becomes the leader because $x^E_P = 0.496 < x^E_I = 1.059$. By $x^L_P = 0.953 < x^E_I = 1.059$, the nonstrategic equilibrium arises, where firm P enters the market at $x^L_P = 0.953$ and firm I enters the market at $x^F_I = 2.643$.

The next proposition summarizes the investment thresholds and values in equilibrium, denoted by x_i and $V_i(x)$ $(i = P, I)$, respectively. Note that no joint investment occurs in the current model because the joint investment value is not higher than the follower's value.

Proposition 1 *Firm i^* becomes the leader, while firm j^* becomes the follower.*

If $x^E_{j^*} < x^L_{i^*}$ holds, then the investment thresholds and the firm's values are given as follows:

Preemption equilibrium:

$$x_{i^*} = x^E_{j^*}, \ x_{j^*} = x^F_{j^*},$$
$$V_{i^*}(x) = \left(\frac{x}{x^E_{j^*}}\right)^{\beta_{i^*}} L_{i^*}(x^E_{j^*}), \ V_{j^*}(x) = F_{j^*}(x).$$

Otherwise, the investment thresholds and the firm's values are given as follows:

Nonstrategic equilibrium:

$$x_{i^*} = x^L_{i^*}, \ x_{j^*} = x^F_{j^*},$$
$$V_{i^*}(x) = \left(\frac{x}{x^L_{i^*}}\right)^{\beta_{i^*}} L_{i^*}(x^L_{i^*}), \ V_{j^*}(x) = F_{j^*}(x).$$

4 Model analysis

4.1 Symmetric costs

In this subsection, I suppose that both firms have the same investment costs; that is, $K_P = K_I$. For $D = 0$ and 1, I can show the following proposition.

Proposition 2 *Assume that D is either 0 or 1. Firm P becomes the leader and firm I becomes the follower. Firm P's value $V_P(x)$ is higher than firm I's value $V_I(x)$ is.*

Proof. First, consider the case when $D = 0$. For $i = P, I$, the follower's value is $F_i(x) = 0$ and the leader's value is $L_i(x) = x/(\rho_i - \mu) - K_i$. Then, I have

$$x^E_P = (\rho_P - \mu)K_P < (\rho_I - \mu)K_P = x^E_I,$$

which implies that firm P is the leader. For $x^E_I < x^L_P$, I have

$$V_P(x) = \left(\frac{x}{x^E_I}\right)^{\beta_P} \left(\frac{x^E_I}{\rho_P - \mu} - K_P\right) > 0 = V_I(x),$$

and for $x^E_I < x^L_P$, I have

$$V_P(x) = \left(\frac{x}{x^L_P}\right)^{\beta_P} \left(\frac{x^L_P}{\rho_P - \mu} - K_P\right) > 0 = V_I(x).$$

Next, consider the case when $D = 1$. For $i = P, I$, I have $L_i(x) \leq F_i(x)$ $(x \geq 0)$, which implies $x^E_i = \infty$. Then, the nonstrategic equilibrium arises. As to the nonstrategic thresholds, I show that $x_P^L < x_I^L$ in Appendix A. Thus, firm P is the leader. In addition,

$$
\begin{aligned}
V_P(x) &= \left(\frac{x}{x_P^L}\right)^{\beta_P}\left(\frac{x_P^L}{\rho_P-\mu}-K_P\right), \\
&\geq \left(\frac{x}{x_I^L}\right)^{\beta_P}\left(\frac{x_I^L}{\rho_P-\mu}-K_P\right) \\
&> \left(\frac{x}{x_I^L}\right)^{\beta_I}\left(\frac{x_I^L}{\rho_I-\mu}-K_P\right) = V_I(x),
\end{aligned} \tag{10}
$$

where (10) follows the optimality of x_P^L. The proof is complete. □

For $D = 0$, firm P enters the market first at the threshold $x_P = \min\{x_I^E, x_P^L\} = \min\{K_I(\rho_I - \mu), K_P(\rho_P - \mu)\beta_P/(\beta_P - 1)\}$ and firm I gives up entering the market. Firm P wins the preemption game because by virtue of the lower discount rate, firm P has a higher NPV than firm I does; that is, $x/(\rho_P - \mu) - K_P > x/(\rho_I - \mu) - K_P$. In other words, for $D = 0$, the NPV effect determines which firm wins the preemption game.

For $D = 1$, firms P and I enter the market at the nonstrategic thresholds x_P^L and x_I^L (see (8)), with no fear of preemption. Firm P's value is higher than firm I's value because the lower discount rate increases both the NPV and option value. Proposition 2 also shows that firm P enters the market earlier than does firm I. This result is not so simple because firm P has the higher value of waiting than firm L does. Indeed, I have $\partial\beta_i/\partial\rho_i > 0$ in (5), which leads to $\beta_P/(\beta_P - 1) > \beta_I/(\beta_I - 1)$ in (8). This option value effect conflicts with the NPV effect; that is, $(\rho_P - \mu)K_P < (\rho_I - \mu)K_P$. The option value effect delays firm P's market entry, while the NPV effect speeds up firm P's market entry. Proposition 2 shows that the NPV effect always dominates the option value effect, and hence firm P enters the market earlier than firm I does. To my knowledge, no prior work in the literature proves this result analytically. From this technical viewpoint, Appendix A contributes to the real options literature.

Unfortunately, for intermediate levels of $D \in (0, 1)$, I cannot analytically prove the results in Proposition 2. However, I suppose that the same relationship holds true for $D \in (0, 1)$ because the option effect is intermediate between the two extreme cases of $D = 0$ (i.e., no option effect) and $D = 1$ (i.e., full option effect). The NPV effect is stronger than the option effect, even for $D = 1$, and it will thus be stronger than the option effect for $D \in (0, 1)$. Below, I numerically verify this hypothesis.

Figure 3 shows the nonstrategic thresholds x_i^L, rent equalization thresholds x_i^E, equilibrium thresholds x_i, and firm value $V_i(x)$ for varying levels of D. The other parameter values are as set in Table 1. In the top-right panel, x_P^E is always lower than x_I^E, which implies that firm P is the leader. Note that $x_I^E = \infty$ holds for $D \geq 0.795$. In the bottom-right panel, $V_P(x)$ is always higher than $V_I(x)$, indicating that the results in Proposition 2 hold true for intermediate levels of $D \in (0,1)$.[2] I have $x_I^E < x_P^L = 0.953$ for $D < 0.745$, which leads to the preemption equilibrium, where $x_P = x_I^E$ increases in D in the bottom-left panel. For $D \geq 0.745$, the nonstrategic equilibrium arises, where $x_P = x_P^L = 0.953$ holds in the bottom-left panel. In other words, a stronger first-mover advantage (i.e., lower D) intensifies preemptive competition. This result is consistent with the standard result (e.g., Chapters 7 and 8 of Huisman (2001) and Pawlina and Kort (2006))).

Notably, the bottom-right panel shows the nonmonotonicity of $V_P(x)$ with respect to D. In fact, $V_P(x)$ decreases in D until $D < 0.103$, after which $V_P(x)$ increases in D, whereas $V_I(x)$ monotonically increases in D. I can explain this nonmonotonicity with the following tradeoff. A higher D weakens preemptive competition and increases x_P (see the bottom-left panel) and cash flows in the duopoly market. This effect increases $V_P(x)$. At the same time, a higher D decreases x_I (see the bottom-left panel) and the duration of the monopoly market. This effect decreases $V_P(x)$. The latter effect dominates the former effect for $D < 0.103$, while the former effect dominates the latter effect for $D \geq 0.103$. In this paper, I do not discuss the sum of the two firm values $V_P(x) + V_I(x)$ because their sum under different discount rates does not make sense.

Figure 4 shows the nonstrategic thresholds x_i^L, rent equalization thresholds x_i^E, equilibrium thresholds x_i, and firm value $V_i(x)$ for varying levels of $\rho_I (> \rho_P = 0.07)$. The other parameter values are as set in Table 1. In the top-right panel, x_P^E is always lower than x_I^E, which implies that firm P is the leader. In the bottom-right panel, $V_P(x)$ is always higher than $V_I(x)$. These panels confirm that firm P becomes the leader and gains the higher payoff. I have $x_I^E < x_P^L = 0.953$ for $\rho_I < 0.095$, which leads to the preemption equilibrium, where $x_P = x_I^E$ increases in ρ_I in the bottom-left panel. For $\rho_I \geq 0.095$, the nonstrategic equilibrium arises, where $x_P = x_P^L = 0.953$ holds in the bottom-left panel. Thus, a higher ρ_I mitigates preemptive competition. Note that in the current model, a higher ρ_I decreases the NPV and value of waiting. The result is similar to the standard result (e.g., Chapter 8 of Huisman (2001) and Pawlina and Kort (2006)) that greater asymmetries in costs and cash flows weaken preemptive competition. I also compute the comparative statics with respect to the growth rate μ and volatility σ. I omit the figures because I did not find a novel result.

In summary, all numerical results show that the results in Proposition 2 hold true for $D \in (0,1)$. Firm P enters the market earlier than firm I does, and firm P's value is higher

[2] I verified the results in all numerical examples with a wide range of parameter values.

than of firm I. Note that by virtue of the lower discount rate, firm P has advantages in terms of NPV and the value of waiting. The results are similar to the standard result that an advantageous firm invests earlier and earns more than does a disadvantageous firm (e.g., Chapter 8 of Huisman (2001) and Pawlina and Kort (2006)). The results are also consistent with those of Luo, Tian, and Yang (2020), who examine the real options duopoly game between time-consistent and time-inconsistent firms. Indeed, they show that that the time-consistent firm enters the market earlier and earns more than its time-inconsistent competitor does. In their model, the time-consistent firm is considered more patient because only the time-inconsistent firm's discount rate can increase over time, where the two firms has the same discount rate at the initial time.

4.2 Asymmetric costs

In the previous subsection, I show that with the same investment costs, firm P enters the market earlier than firm I does because the NPV effect dominates the option effect. Clearly, for $K_P < K_I$, firm P enters the market earlier and earns more than firm I because firm P has advantages in both the discount rate and the investment cost. Now, I suppose that $K_I < K_P$ and examine which firm becomes the leader and which firm gains a higher value. For $D = 0$ and 1, I can show the following proposition, where I define

$$K_I^* = \frac{\rho_P - \mu}{\rho_I - \mu} K_P \ (< K_P), \tag{11}$$

$$K_I^{**} = \frac{\beta_P(\beta_I - 1)}{\beta_I(\beta_P - 1)} \frac{\rho_P - \mu}{\rho_I - \mu} K_P \ (\in (K_I^*, K_P)). \tag{12}$$

Proposition 3

Case of $D = 0$: *For $K_I < K_I^*$, firm I becomes the leader and firm P becomes the follower, where firm I's value $V_I(x)$ is higher than firm P's value $V_P(x)$ is. For $K_I > K_I^*$, firm P becomes the leader, and firm I becomes the follower, where firm P's value $V_P(x)$ is higher than firm I's value $V_I(x)$ is.*

Case of $D = 1$: *For $K_I < K_I^{**}$, firm I becomes the leader and firm P becomes the follower. For $K_I > K_I^{**}$, firm P becomes the leader and firm I becomes the follower. For $K_I > K_I^*$, firm P's value $V_P(x)$ is higher than firm I's value $V_I(x)$ is.*

This proposition shows two interesting results. First, the market entry order depends on the degree of the first-mover advantage (i.e., D). In fact, for $K_I \in (K_I^*, K_I^{**})$, firm P becomes the leader for $D = 0$ and the follower for $D = 1$. This result occurs because the NPV and option effects change with the level of D. For $D = 0$ (i.e., no option effect), firm P becomes the leader when its NPV threshold is lower than that of firm I (i.e., $K_I^{**} < K_I$). On the other hand, for $D = 1$ (i.e., the full option effect), by virtue of the lower discount rate, firm P has a stronger incentive to delay market entry. Then, firm P becomes the follower for $K_I \in (K_I^*, K_I^{**})$.

Second, the firm with the higher value does not always become the leader. Indeed, for $D = 1$ and $K_I \in (K_I^*, K_I^{**})$, firm P becomes the follower, and its value $V_P(x)$ is higher than $V_I(x)$. The option effect explains this phenomenon. Firm P has a higher value to wait than firm I does, and hence firm P prefers to be the follower and earn more value than does firm I.

Next, I numerically examine how the market entry order depends on the key parameter values. Figure 5 shows the market entry order for varying parameter values. The vertical axes represent ρ_I, while the horizontal axes represent K_I, D, μ, and σ. The regions of P and I in each panel represent the regions in which firm P and I, respectively, become the leader. Except the top-right panel, I set firm I's investment cost at $K_I = 8.8(< K_P = 10)$ to present the threshold between the two regions P and I. I set the other parameter values as in Table 1.

In Figure 5, with lower ρ_I and K_I, firm I is more likely to become the leader. This is straightforward because lower values of ρ_I and K_I reduce the discount rate disadvantage and increase the cost advantage, respectively. More notably, the market entry order also depends on the common market factors (i.e., D, μ, and σ). The top-right panel of Figure 5 shows that a higher D increases the likelihood that firm I becomes the leader. As in the argument after Proposition 3, I can explain this result by the tradeoff between the NPV and option effects. Indeed, a higher D increases the option effect, which delays firm P's market entry compared to that of firm I. Then, with a higher D, firm I is more likely to become the leader.

The bottom-left panel of Figure 5 shows that a lower μ increases the likelihood that firm I becomes the leader, whereas the bottom-right panel shows that a higher σ increases the likelihood that firm I becomes the leader. These results also arise because the option effect changes with μ and σ. In fact, a lower μ and higher σ increase the option effect, in which case, firm I is more likely to be the leader.

The effects of the market factors on the market entry order have not been seen in the standard real options model with cost asymmetry (e.g., Section 8 of Huisman (2001) and Pawlina and Kort (2006)), where an advantageous firm enters the market earlier than a disadvantageous firm does, regardless of the market factors. However, my results are similar to those of Kong and Kwok (2007), Shibata (2016), and Lambrecht (2001). For instance, Kong and Kwok (2007) show that in a duopoly market model with both cost and cash flow asymmetry, the level of volatility can change the market entry order. Shibata (2016) shows that in a triopoly market model with cost asymmetry, the market entry order depends on the levels of volatility and first-mover advantage. Lambrecht (2001) shows that the market exit order in a duopoly depends on the common economic factors, such as the interest rate and volatility. Unlike these studies, I examine the difference in discount rates and unveil the tradeoff between the NPV and option effects.

Figure 6 shows the nonstrategic thresholds x_i^L, rent equalization thresholds x_i^E, equilibrium thresholds x_i, and firm value $V_i(x)$ for varying levels of D. I set the parameter values besides those for D and $K_I = 8.8$ as in Table 1. The top-right and bottom-left panels show that the leader changes from firm P to firm I at $D = 0.612$. As explained with the top-right panel of Figure 5, this occurs because with a higher D, the option effect dominates the NPV effect. On the other hand, the bottom-right panel shows that firm P's value $V_P(x)$ remains higher than firm I's value $V_I(x)$. These results imply the notable phenomenon that firm P, which has a higher value, becomes the follower for $D \geq 0.612$. For $D \geq 0.612$, because of the increased value of waiting, firm P prefers to be the follower rather than the leader.

This result contrasts with the standard result that an advantageous firm enters the market earlier and earns more (e.g., Chapter 8 of Huisman (2001) and Pawlina and Kort (2006)). However, Shibata (2016) reports a similar result in an asymmetric real options triopoly game. In fact, he shows that with a weaker first-mover advantage, the firm with the least cost can be the second mover. In contrasted with his result in a triopoly market, my result stems from the tradeoff between the NPV and option effects in a duopoly market. The bottom-right panel of Figure 6 shows the nonmonotonicity of $V_P(x)$ with respect to D. I can explain this nonmonotonicity with the same tradeoff as in the bottom-right panel of Figure 3.

Figure 7 shows the nonstrategic thresholds x_i^L, rent equalization thresholds x_i^E, equilibrium thresholds x_i, and firm value $V_i(x)$ for varying levels of σ, using the parameter values (besides those for σ and $K_I = 8.8$) in Table 1. In the top-right and bottom-left panels, the leader changes from firm P to firm I at $\sigma = 0.227$ for the same reason highlighted with the bottom-right panel of Figure 5 – a higher σ increases the option effect. The bottom-right panel shows that firm P's value $V_P(x)$ is always higher than firm I's value $V_I(x)$. In other words, firm P, which has a higher value, chooses to be the follower for $\sigma \geq 0.227$ due to the higher value of waiting. Shibata (2016) also shows that with a higher volatility, the firm with the least investment cost can be the second mover. Unlike in Shibata (2016), my result holds true in a duopoly market with the tradeoff between the NPV and option effects.

5 Empirical implications

5.1 Empirical predictions

In this subsection, I first explain the determinants of the discount rates, and then explain several implications from the model. As a benchmark, I begin with the capital asset pricing model (CAPM). Let $S(t)$ be the price of a financial portfolio that completely spans the risk of cash flow $X(t)$, where $S(t)$ follows

$$\mathrm{d}S(t) = \alpha S(t)\mathrm{d}t + \sigma S(t)\mathrm{d}B(t),\ S(0) = s. \tag{13}$$

The difference between the rates of return, $\delta = \alpha - \mu$ is positive and is called the convenience yield from the real investment project (see Dixit and Pindyck (1994)). Let ρ be the correlation coefficient between $S(t)$ and the market portfolio price. By the CAPM formula, we have $\alpha = r + \phi\sigma\rho$, where ϕ denotes the market price of risk. Then, the follower's value (4) is

$$F_j(X(s)) = \sup_{T_j^F \geq s} \mathbb{E}^{X(s)}[\int_{T_j^F}^{\infty} \mathrm{e}^{-(r+\phi\sigma)(t-s)} DX(t)\mathrm{d}t - \mathrm{e}^{-r(T_j^F - s)} K_j], \tag{14}$$

$$= \sup_{T_j^F \geq s} \tilde{\mathbb{E}}^{X(s)}[\int_{T_j^F}^{\infty} \mathrm{e}^{-r(t-s)} DX(t)\mathrm{d}t - \mathrm{e}^{-r(T_j^F - s)} K_j], \tag{15}$$

where $\tilde{\mathbb{E}}[\cdot]$ represents the expectation under the risk-neutral measure. Note that under the risk-neutral measure, $X(t)$ follows

$$\mathrm{d}X(t) = (r - \delta)X(t)\mathrm{d}t + \sigma X(t)\mathrm{d}\tilde{B}(t),$$

rather than (1), where $\tilde{B}(t)$ denotes the standard Brownian motion under the risk-neutral measure. Similarly, the leader's value (7) is

$$L_i(X(s)) = \tilde{\mathbb{E}}^{X(s)}[\int_s^{T_j^F} \mathrm{e}^{-r(t-s)} X(t)\mathrm{d}t + \int_{T_j^F}^{\infty} \mathrm{e}^{-r(t-s)} DX(t)\mathrm{d}t] - K_i. \tag{16}$$

Thus, the discount rate (or the risk-neutral measure) is determined only by the project characteristics; namely, the correlation coefficient ρ and the convenience yield δ. In other words, the two firms must have a uniform discount rate for the same project because any risk besides the market risk is diversifiable in CAPM.

In the real world, however, two firms may have different discount rates for the same project because the risk of $X(t)$ may neither be spanned by any combination of financial assets nor be diversifiable. For instance, Harris and Siebert (2017) show empirical evidence that firms differ in their discount factors. Firms with a wide range of businesses may be able to diversify the risk of $X(t)$, which decreases their discount rate. In practice, firms may substitute the weighted average cost of capital (WACC) for the discount rate for simplicity. Then, firms with different WACC have different discount rates. More generally, firms suffer from capital market imperfections such as financing constraints. As Harrington (1989) discusses, more financially constrained firms (e.g., low cash, tight liquidity constraints, etc.) tend to have higher discount rates.

Furthermore, firms (especially entrepreneurs) are not always rational and have behavioral biases (e.g., Frederick, Loewenstein, and O'Donoghue (2002), Grenadier and Wang (2007), and Hackbarth (2009)). Clearly, more patient firms have lower discount rates. In addition, the following model shows that more optimistic firms have lower discount rates. In addition to the baseline model setup in Section 2, I assume that cash flows $X(t)$ disappear by an external shock, which arrives according to an exponential distribution. Suppose that the two firms have the same discount rate ρ, but different estimations of the intensity of the exponential distribution (say $\lambda_H > \lambda_L$). Then, the more optimistic firm, (i.e., the firm with λ_L) discounts $X(t)$ by the rate $\rho + \lambda_L$, which is lower than the other firm's rate $\rho + \lambda_H$.

To summarize, in the presence of capital market imperfections or behavioral biases, discount rates depend on firm characteristics. More diversified, less financially constrained, more patient, and more optimistic firms tend to have lower discount rates, and I thus refer to them as firm P in this model. Larger, older, and more successful firms can be regarded as firm P because they have these characteristics. Section 4.1 shows that with no cost disadvantage, firm P enters the market earlier and earns more. Section 4.2 shows that with a cost disadvantage, firm I can be the first mover, especially in a market with a weak first-mover advantage, high volatility, and low growth rate. It also predicts that firm P can earn more than firm I can, even if firm P enters the market later.

5.2 Empirical findings

Although no study investigates the effects of discount rates on market entry timing empirically, I find several results related to my predictions in Section 5.1. Schoenecker and Cooper (1998) show that larger firms tend to enter markets earlier. This finding is consistent with my result. Although Schoenecker and Cooper (1998) explain their finding by the conventional theory of Schumpeter (1950) – larger firms have capability advantages (e.g., lower investment cost), my study complements this argument. Indeed, even in the absence of capability advantages, larger firms can enter markets earlier by virtue of lower discount rates.

Robinson, Fornell, and Sullivan (1992) show that firms with more finance skills tend to enter markets earlier, which is also consistent with my result. More finance skills decrease financing costs and relax financial constraints, which leads to lower discount rates. Thus, my result can potentially explain their finding – with no cost disadvantage, firm P enters the market first.

Although the above observations show that larger and less financially constrained firms tend to enter markets earlier, many case studies show that smaller and younger firms (especially IT venture businesses) can enter new markets earlier than larger and older competitors. Many researchers argue that these first movers beat their opponents by virtue of lower cost and faster decision-making. Section 4.2 shows that with a cost advantage, firm I can enter the market earlier; nevertheless, firm P can gain a higher value than firm I can. This result points to the possibility that larger and older firms may not be losers in competition, but be more successful, even if they enter markets later.

Shibata (2016) illustrates an example in which a smaller and more financially constrained firm invested earlier in the wireless telecommunication market in Japan. In fact, in 1999, KDDI Corporation started providing wireless telecommunication services, which were called "2.5G" technology services, earlier than its larger competitor, NTT DOCOMO. According to Shibata (2016), the first-mover advantage in the market is weak. This example is therefore consistent with the result that firm I is more likely to be the leader in a market with a weaker first-mover advantage.

Shackleton, Tsekrekos, and Wojakowski (2004) studies the competition between Boeing and Airbus. Boeing is a larger and less financially constrained firm than Airbus is, but Airbus became the leader by launching the A380 in the very large aircrafts market. Airbus receives large amounts of subsidies, which decrease investment costs compared to Boeing. The very large aircraft market has high uncertainty. Thus, this example is also consistent with my result that firm I, which has a larger cost advantage, is more likely to be the leader in a market with higher volatility.

6 Conclusion

This study investigates preemptive competition between firms P and I, which have different discount rates. I derive the market entry order, investment thresholds, and firm values in equilibrium. The results are summarized below. With no cost disadvantage, firm P enters the market earlier and gains more value than does firm I. With a cost disadvantage, firm P can be the follower in the market, especially with a weak first-mover advantage, high volatility, and low growth rate. Notably, firm P can earn more than firm I can, even when firm P becomes the follower. These results can potentially account for several empirical findings on market entry.

Lastly, I explain some potential directions for future research. Similar results to those I report here hold true in a model of two firms with different growth rate parameters (say $\mu_H > \mu_L$). Indeed, the firm with μ_H has both higher NPV and option value, and hence corresponds to firm P in the model in this study. With the same investment cost, the firm with μ_H enters the market first because the NPV effect dominates the option effect. When the firm has a higher investment cost, the market entry order can change with market characteristics, and the firm with the higher value can become the follower. However, the assumptions of different growth rate parameters may not be plausible because firms can update their parameters by observing $X(t)$. One interesting issue for future research would be to investigate the dynamic learning effects on the preemption game (cf. Décamps, Mariotti, and Villeneuve (2005)).

Another limitation is the assumption that firms have complete information about each other (especially, discount rates). It could actually be difficult to precisely know another firm's discount rate. However, as I explained in Section 5.1, observable factors (e.g., business diversification, financial constraints, size, age, etc.) are related to discount rates, so firms can estimate each other's discount rates to a certain degree. One important future direction is to study such incomplete information rigorously (cf. Lambrecht and Perraudin (2003)).

An increasing number of studies examine the interactions between investment and debt financing (e.g., Sundaresan, Wang, and Yang (2015) and Shibata and Nishihara (2018)). Although these studies use the risk-free interest rate under the risk-neutral measure, it would be interesting to examine the roles of the discount rate in the preemption game with debt financing (cf. Nishihara and Shibata (2010) and Nishihara and Shibata (2014)).

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A Proof of $x_P^L < x_I^L$

Define

$$f(\rho) = \frac{\beta(\rho)(\rho - \mu)}{\beta(\rho) - 1} \quad (\rho > \mu),$$

where

$$\beta(\rho) = 0.5 - \frac{\mu}{\sigma^2} + \sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}} \ (> 1).$$

I can prove $f'(\rho) > 0$ as follows.

$$\begin{aligned}
f'(\rho) &= \frac{1}{\beta(\rho)-1}\left(\beta(\rho) - \frac{\rho-\mu}{\beta(\rho)-1}\beta'(\rho)\right) \\
&= \frac{1}{\beta(\rho)-1}\left(0.5 - \frac{\mu}{\sigma^2} + \sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}}\right. \\
&\left. - \frac{\rho-\mu}{-0.5 - \frac{\mu}{\sigma^2} + \sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}}} \frac{1}{\sigma^2\sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}}}\right) \\
&= \frac{1}{\beta(\rho)-1}\left(0.5 - \frac{\mu}{\sigma^2} + \sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}}\right. \\
&\left. - \frac{\sigma^2\left(0.5 + \frac{\mu}{\sigma^2} + \sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}}\right)}{2} \frac{1}{\sigma^2\sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}}}\right) \\
&= \frac{1}{\beta(\rho)-1}\left(-\frac{\mu}{\sigma^2} + \sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}} - \frac{0.5 + \frac{\mu}{\sigma^2}}{2\sqrt{\left(0.5 - \frac{\mu}{\sigma^2}\right)^2 + \frac{2\rho}{\sigma^2}}}\right) \\
&= \frac{1}{\beta(\rho)-1}\left(-\frac{\mu}{\sigma^2} + \sqrt{\left(0.5 + \frac{\mu}{\sigma^2}\right)^2 + \frac{2(\rho-\mu)}{\sigma^2}} - \frac{0.5 + \frac{\mu}{\sigma^2}}{2\sqrt{\left(0.5 + \frac{\mu}{\sigma^2}\right)^2 + \frac{2(\rho-\mu)}{\sigma^2}}}\right) \\
&> \frac{1}{\beta(\rho)-1}\left(-\frac{\mu}{\sigma^2} + \sqrt{\left(0.5 + \frac{\mu}{\sigma^2}\right)^2 + \frac{2(\rho-\mu)}{\sigma^2}} - 0.5\right) &\quad (17) \\
&> 0, &\quad (18)
\end{aligned}$$

where (17) and (18) follow from $\rho > \mu$. The proof is complete. $\square$

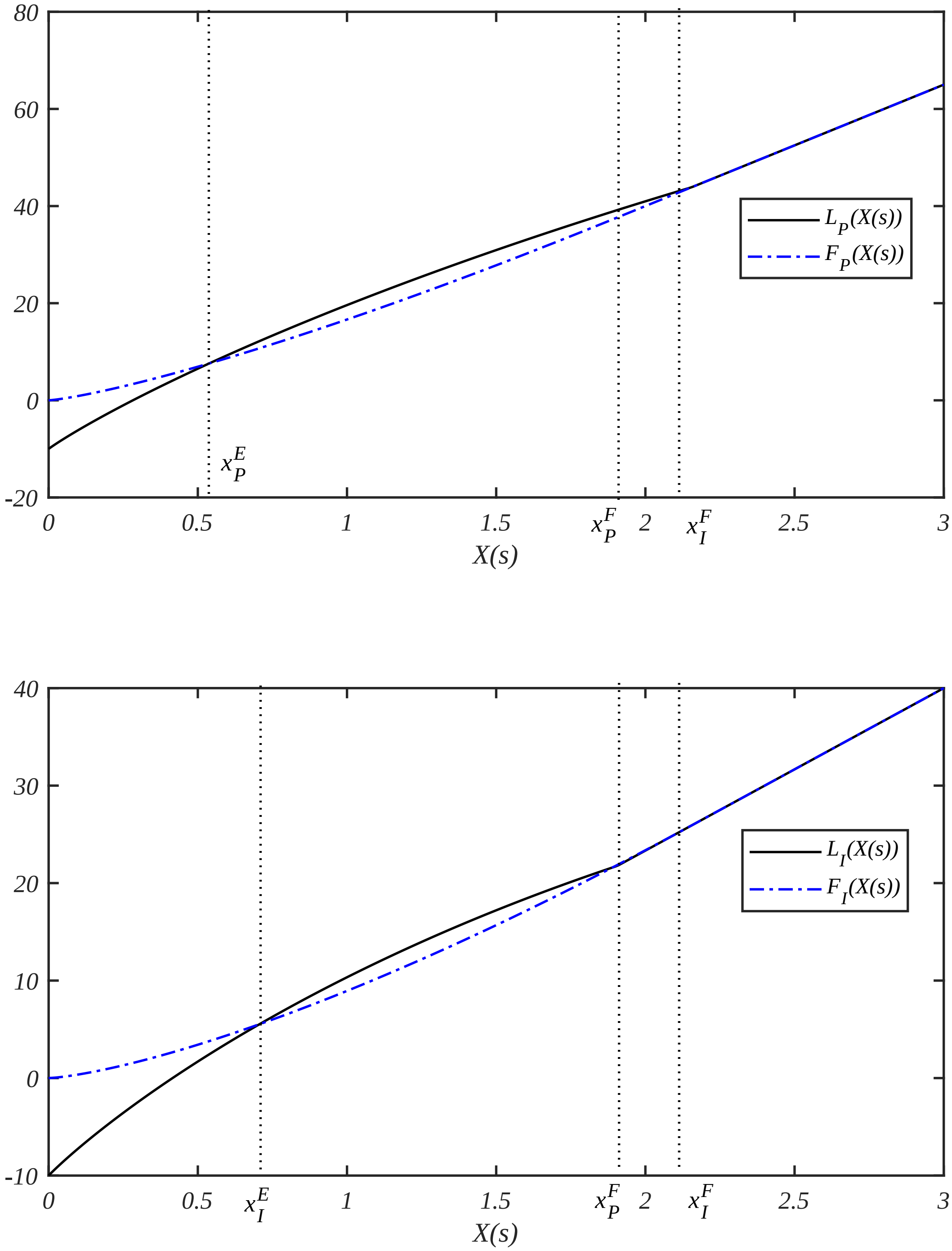

Figure 1: $L_i(X(s))$ and $F_i(X(s))$. The parameter values are those in Table 1. The preemption equilibrium arises because $x_P^L = 0.953$ is higher than $x_I^E = 0.707$.

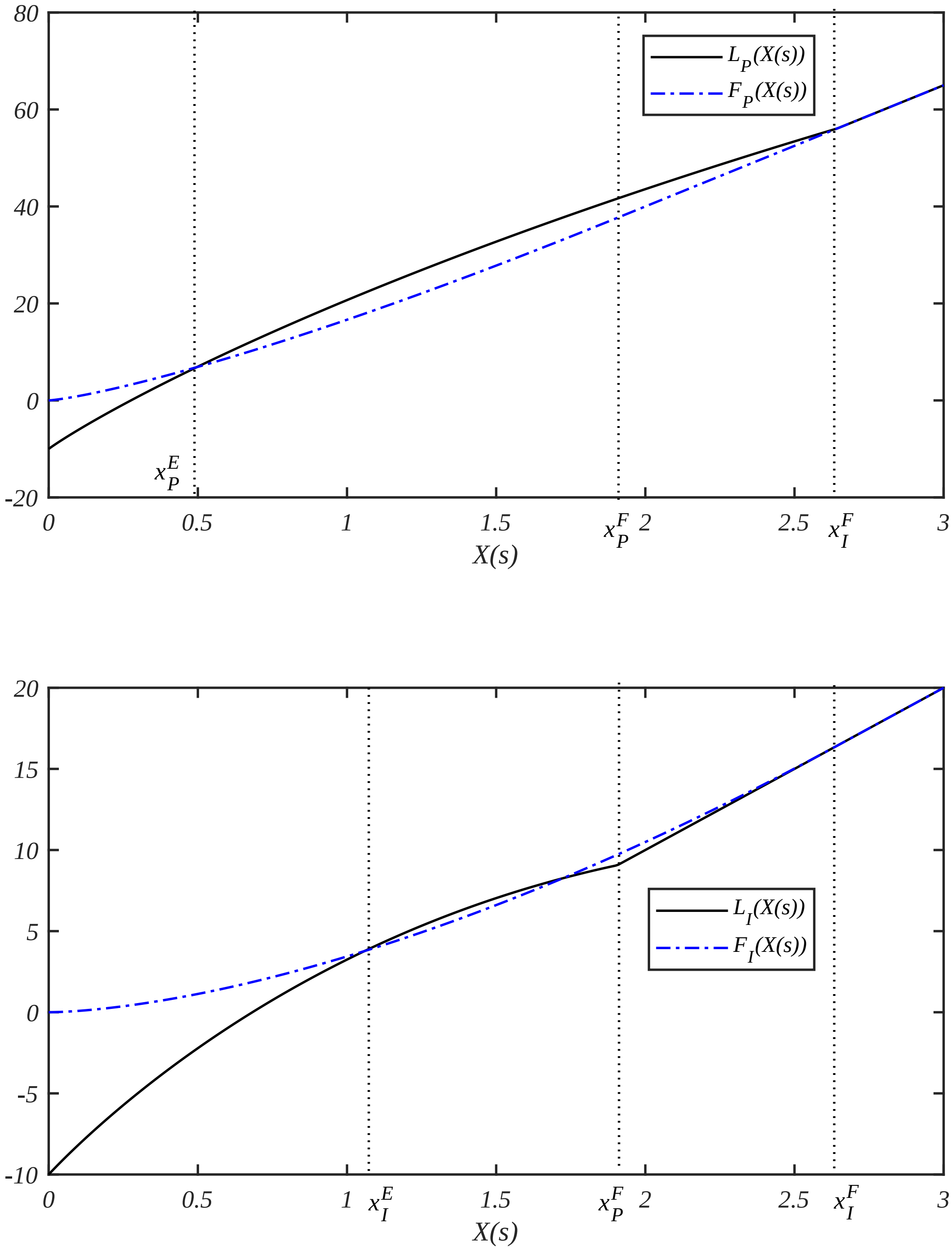

Figure 2: $L_i(X(s))$ and $F_i(X(s))$. The parameter values are those in Table 1, except $\rho_I = 0.1$. The nonstrategic equilibrium arises because $x_P^L = 0.953$ is lower than $x_I^E = 1.059$.

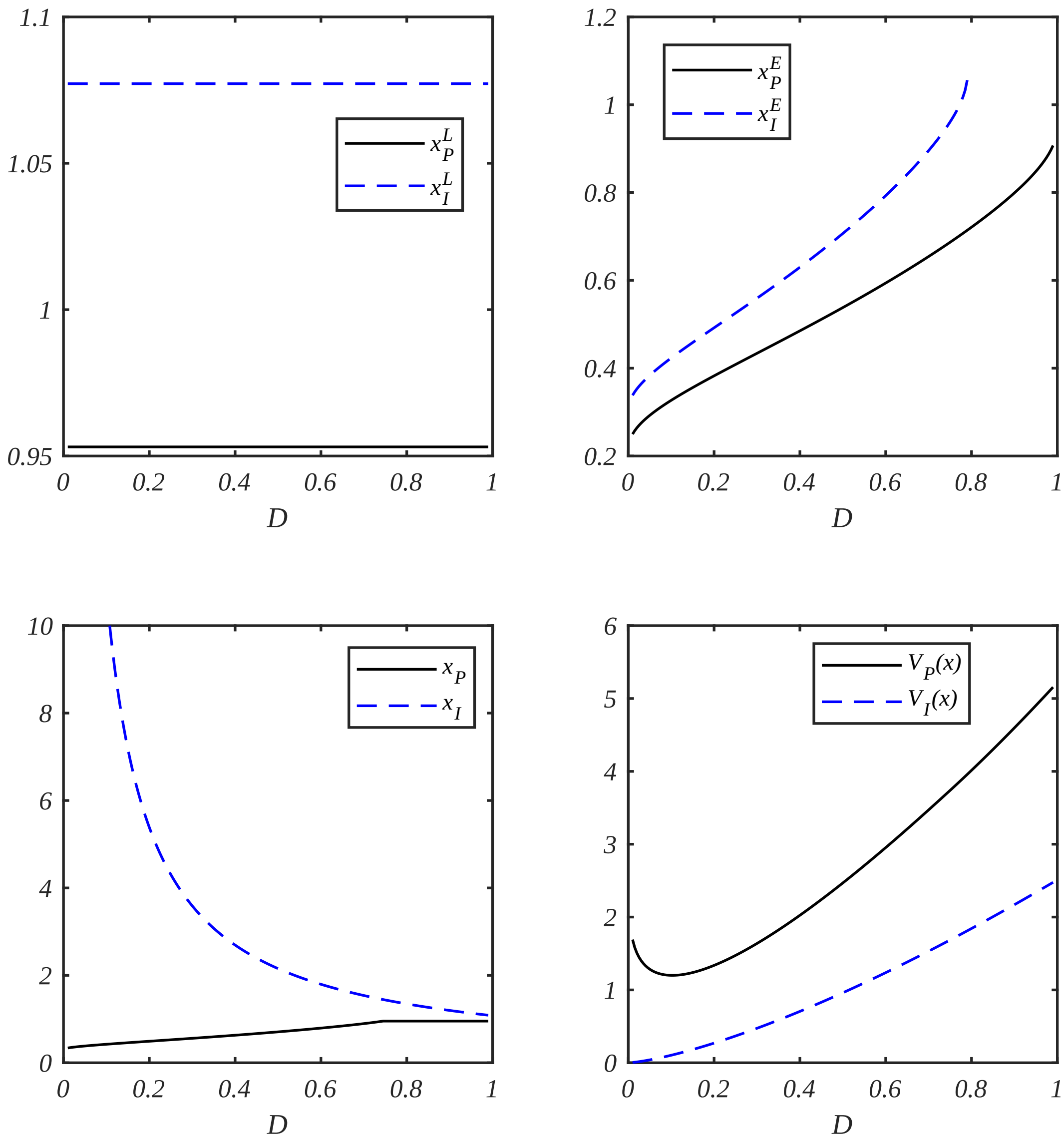

Figure 3: Comparative statics with respect to D. This figure shows the nonstrategic thresholds x_i^L, rent equalization thresholds x_i^E, equilibrium thresholds x_i, and firm value $V_i(x)$. The other parameter values are those in Table 1. The preemption equilibrium arises for $D < 0.745$, while the nonstrategic equilibrium arises for $D \geq 0.745$.

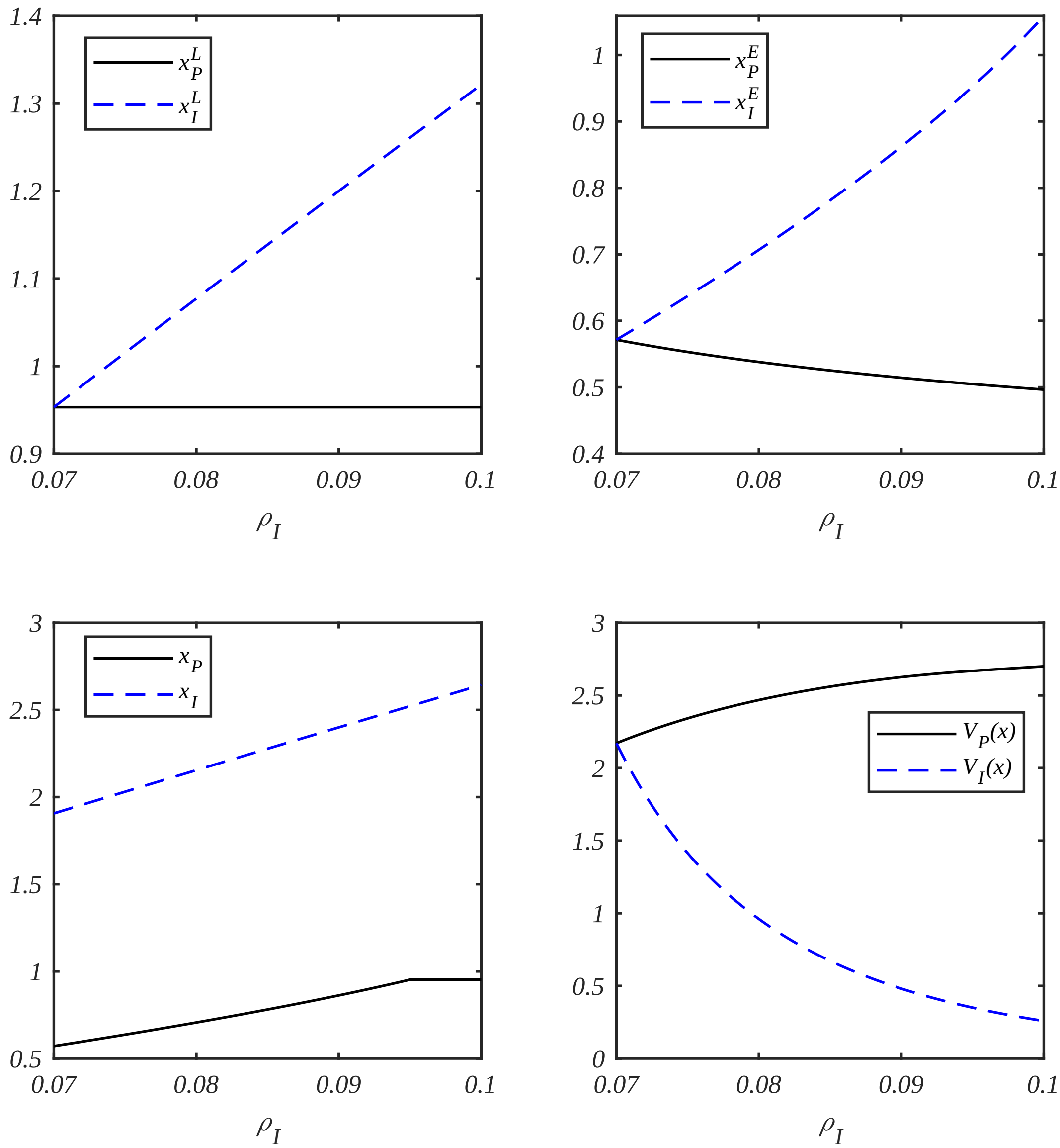

Figure 4: Comparative statics with respect to ρ_I. This figure shows the nonstrategic thresholds x_i^L, rent equalization thresholds x_i^E, equilibrium thresholds x_i, and firm value $V_i(x)$. The other parameter values are those in Table 1. The preemption equilibrium arises for $\rho_I < 0.095$, while the nonstrategic equilibrium arises for $\rho_I \geq 0.095$.

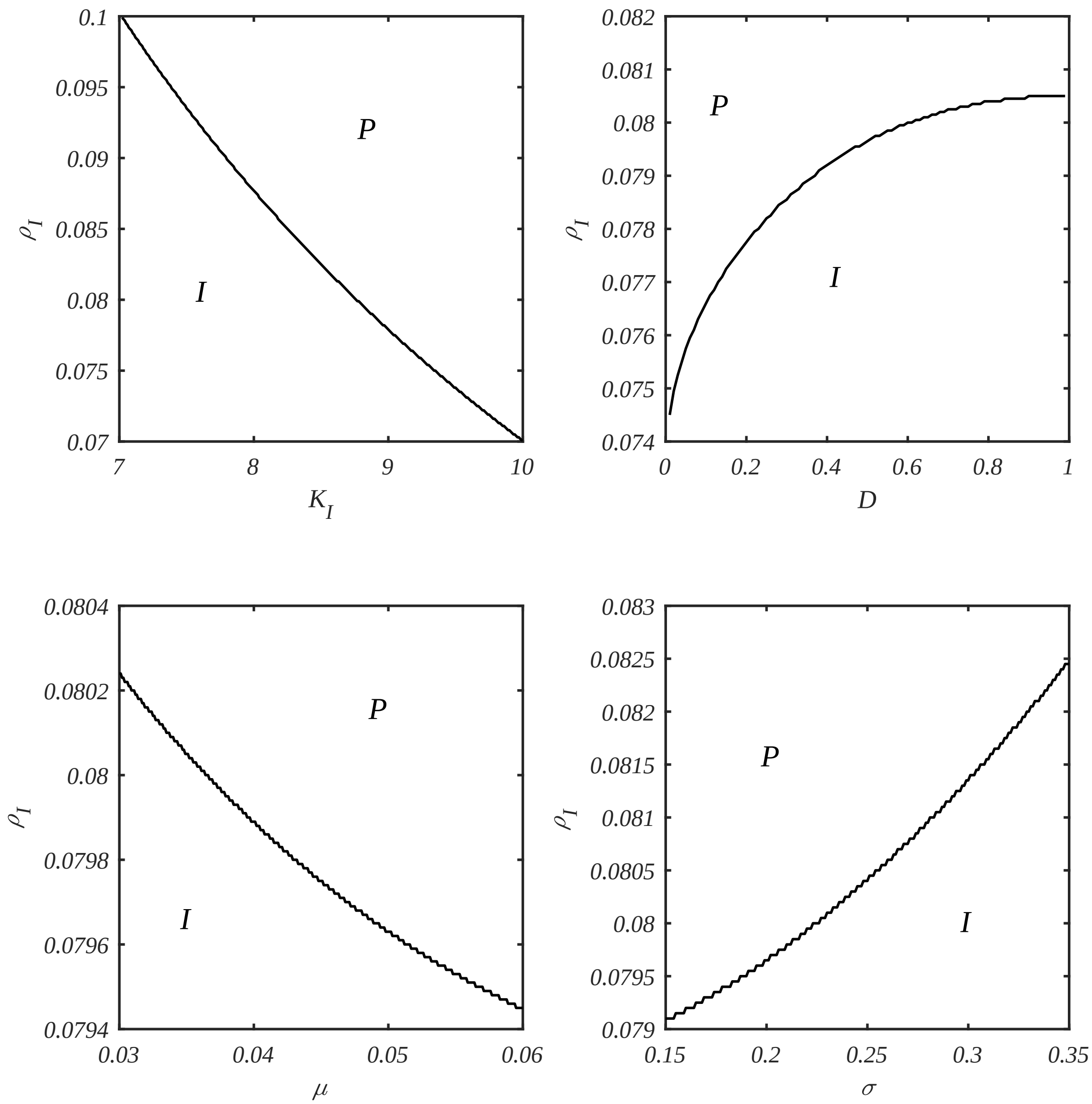

Figure 5: The market entry order in equilibrium. The notations P and I in the figure represent the regions in which firms P and I become the leader, respectively. Except the top-right panel, firm I's investment cost is set at $K_I = 8.8$. The other parameter values are those in Table 1.

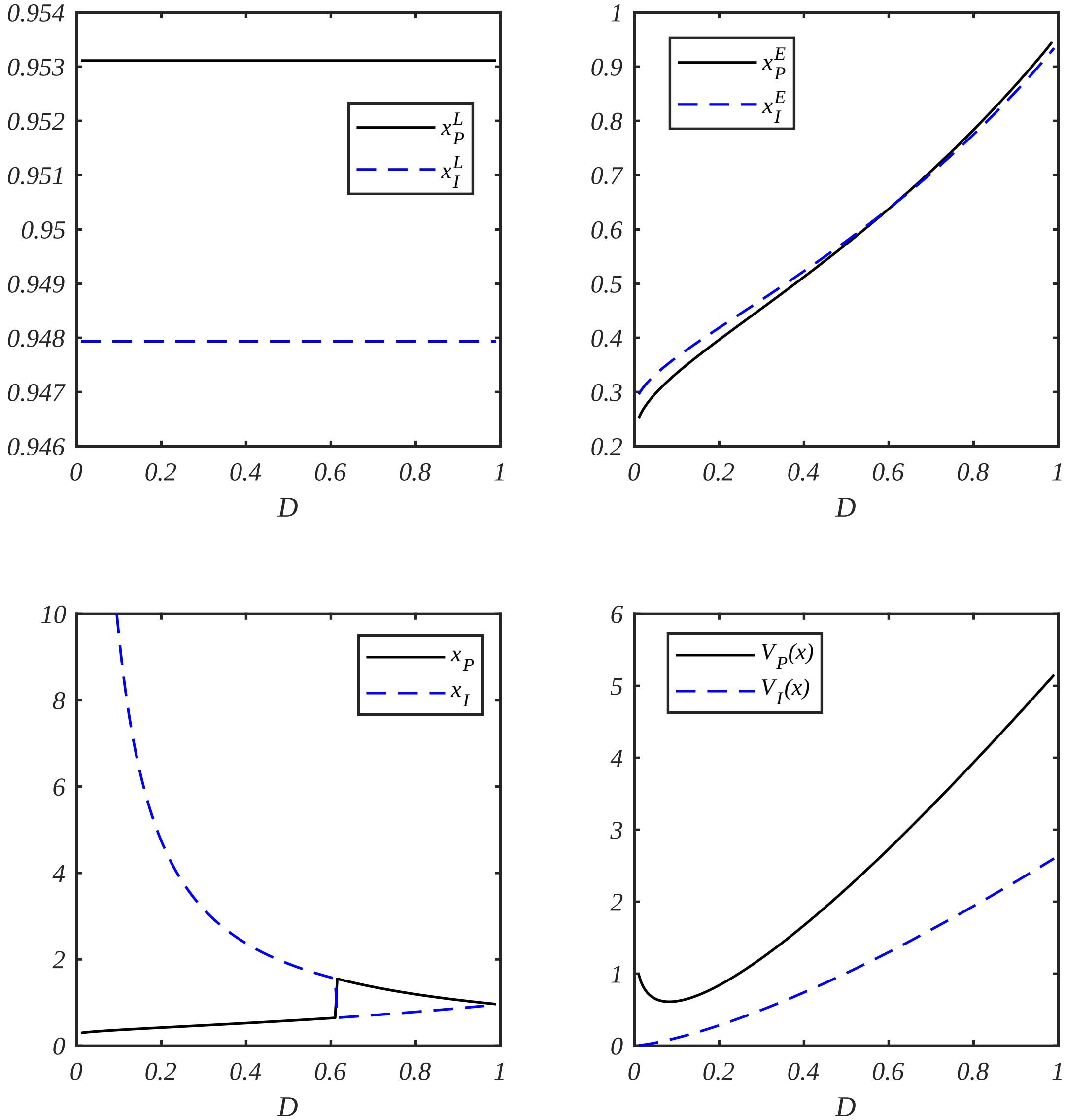

Figure 6: Comparative statics with respect to D. This figure shows the nonstrategic thresholds x_i^L, rent equalization thresholds x_i^E, equilibrium thresholds x_i, and firm value $V_i(x)$. Firm I's investment cost is set at $K_I = 8.8$. The other parameter values are those in Table 1. Firm P becomes the leader for $D < 0.612$, while firm I becomes the leader for $D \geq 0.612$. The preemption equilibrium arises for any $D < 1$.

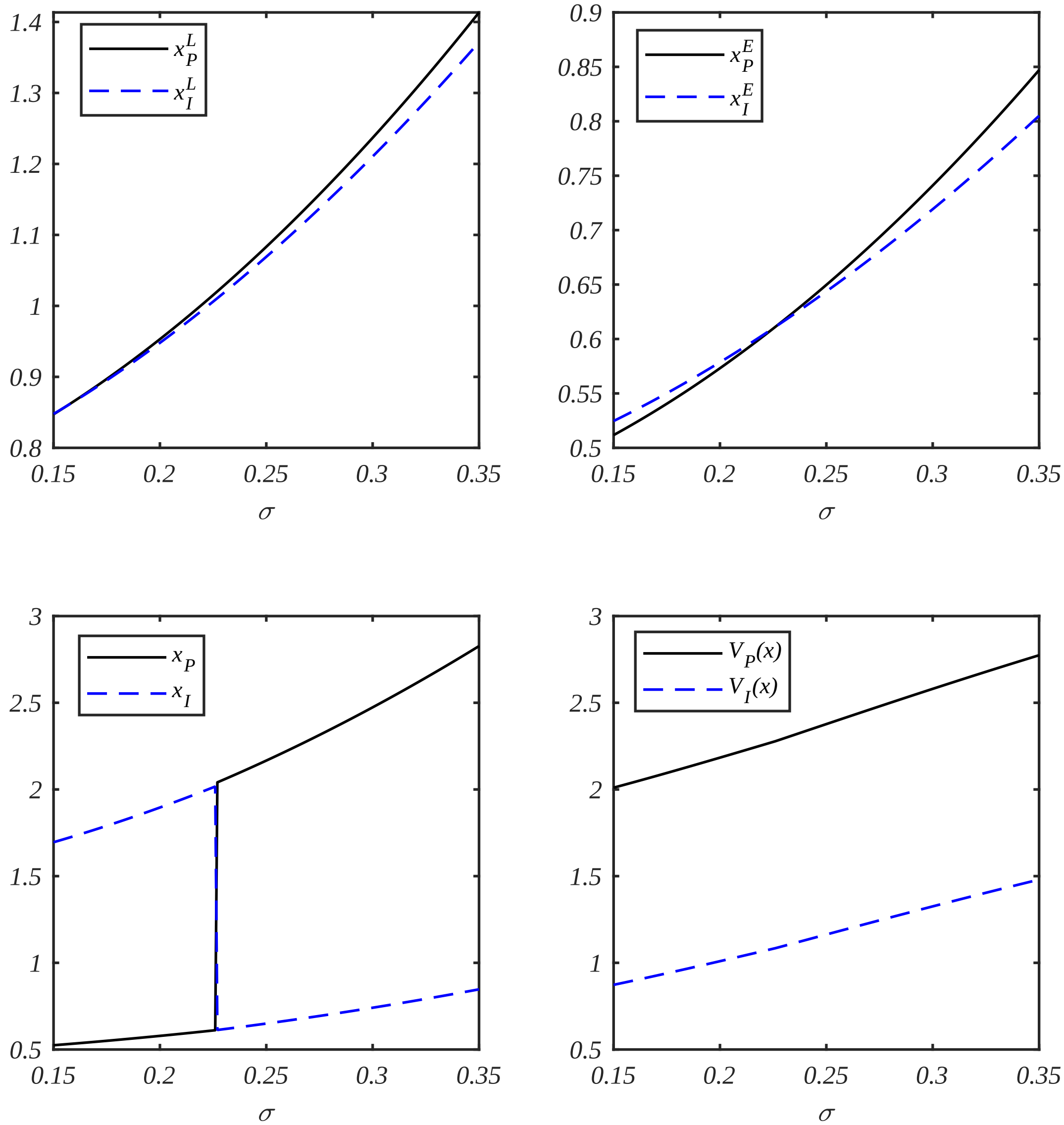

Figure 7: Comparative statics with respect to σ. This figure shows the nonstrategic thresholds x_i^L, rent equalization thresholds x_i^E, equilibrium thresholds x_i, and firm value $V_i(x)$. Firm I's investment cost is set at $K_I = 8.8$. The other parameter values are those in Table 1. Firm P becomes the leader for $\sigma < 0.227$, while firm I becomes the leader for $\sigma \geq 0.227$. The preemption equilibrium arises for the full range.