Price timing in new markets with strategic consumers

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Abstract: We analyse the competitive price timing decisions of both e-tailers (online sellers) and brick-mortar retailers for a new product. Firms may announce the price early (when the product’s valuation for consumers is highly uncertain) or late (when the uncertainty of the product’s valuation has been resolved). Both firms choose the timing and price level to maximise their own expected profits. We find that firms always choose to announce the price late when they monopoly the market. However, when both firms compete against each other and duopoly the market, both firms announce the price late when the uncertainty of the product’s valuation is high and the online acceptance rate is low; by contrast, one of them takes a leadership role and announces the price early whereas the other one follows and announces late when the uncertainty of the product’s valuation is low and the online acceptance rate is high.

Keywords: pricing timing; new markets; strategic consumers; online acceptance rate; competition.


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1 Introduction

When strategic consumers in new markets are uncertain about the valuation of the product, the critical operational challenge facing the sellers is the price of the product. We assume that consumers have heterogeneous mean valuations of the product which are uniformly distributed in the interval \([\alpha, \upsilon]\) at the beginning of the introduction of the product. We also assume that the valuation of the product for each consumer has a general distribution with a mean valuation and the variance \(\sigma\). When deciding the product’s price, the trade-off is obvious: the higher price results in fewer consumers to be willing to purchase the product and reduced sales, whereas the lower price results in more consumers and increased sales.

Timing the price decision presents another critical consideration. Each consumer’s valuation of the product is uncertain at the beginning of the introduction of the product. Uncertainty surrounding the valuation of the product reduces over time. In other words, the firm that announces the price early is subject to a higher degree of valuation uncertainty than a firm that postpones the price timing. The examples presented in Van Mieghem and Dada (1999) motivates the strategies of price timing to be examined:

1. A publisher announces a price before a new book is released.
2. A manufacturer introducing a new product announces a price. Following that, an appropriate production quantity will be set in response to the revealed market demand.
3. A traditional automobile dealer negotiates the selling price with each customer after cars are brought onto the market and their market demand is known.

The above examples show a wide range of operational strategies existing in the retail and manufacturing sectors of the economy. In our study, the price timing and level for the new product are precisely the issues we focus on. We first examine monopoly models in which the new product is sold either by e-tailers (online retailer) (two terms are interchangeable throughout the paper) or by a brick-mortar retailer. Consumers are uncertain about the valuation of the product at the beginning. The firm can announce the price in one of two periods: if the firm announces early, then it makes the price decision before knowing the consumers’ valuations of the product, whereas if it announces late, all consumers’ valuation uncertainty is eliminated and the product’s price is announced after learning the consumers’ valuation of the product. We examine how the timing of the price affects the profits of online and brick-mortar retailing, respectively. The primary difference between online and retailing sale is widely discussed in the literature. For instance, Hess et al. (1996) shows that consumers will be asked to wait several days for delivery and charged shipping and handling fee. Liang and Huang (1998) show that consumers prefer conventional brick-mortar retail stores more than the web-based direct channels. Kacen et al. (2013) demonstrate that consumer acceptance of online purchases is less than one for many product categories. Moreover, Chiang et al. (2003) further adopts that the acceptance of the online channel by consumers is \(\theta\) ‘which is distributed in the interval \((0, 1)\)’, i.e., \(1 - \theta\) is the proportionate loss of benefits from an online channel purchase. In our study, we adopt the model of Chiang et al. (2003) and assume that a consumer acceptance of online channel is \(\theta\) due to the difference between the online and brick-mortar retail store.
In the monopoly setting, we examine how online selling differs in the price timing decisions from the brick-mortar selling, characterising how the acceptance of online selling and valuation uncertainty affect both price timing and levels. We find that both firms prefer the late announcement. Moreover, the e-tailer will announce a lower price, which is exactly $\theta$ portion of the price announced by the brick-mortar retailer and earn a lower profit, $\theta$ portion of the profit earned by the brick-mortar retailer, too.

We then analyse duopoly models in which two firms simultaneously sells the product in the new market, among which one sells online while another one sells the product through the brick-mortar retail store. In addition to all of the trade-offs inherent in the monopoly model, the firm announcing the price earlier than a competitor may gain a leadership position in a sequential game. We find that if the uncertainty of the product’s valuation is high and consumers’ online acceptance rate is low, then the unique equilibrium is that both firms announce the price late. By contrast, if the uncertainty of the product’s valuation is low and consumers’ online acceptance rate is high, then there are multiple equilibria with a mixed strategy – one of the firms acts as the first mover in the game and announces the price early while the other one acts as the follower and announces the price late.

In this regard, our findings relate to several streams of research, for example, the literature on the price timing. The seminal work on this topic are Van Mieghem and Dada (1999), Gal-Or (1987), Hviid (1990) and Bashyam (1996). A recurring question in this literature is why some firms typically announces the price late while in some cases, they announces the price early compared to their competitors? Our model supports possible answers to this question, namely, that it is the natural equilibrium of an endogenous timing game between an e-tailer and a brick-mortar retailer.

2 Related literature

There are three primary streams of research related to our work: the difference between online retailers and brick-mortar retailers, the economics literature on postponement and its operational trade-offs, and strategic management literature on purchase. The first topic was discussed in Section 1; here, we briefly review the remaining two broad areas.

Our model is related to the postponement and its operational trade-offs. As such, it is related to the extensive literature on this topic, such as Liu and He (2014), Van Mieghem and Dada (1999), Swinney et al. (2011), Anand and Girotra (2008), Anupindi and Liang (2008) and Lee and Tang (1998) though these works differ from ours in that they include the production postponement while ours mainly focus on the price postponement and product value variability over time. As in many operations models in the literature, price and demand are often considered exogenous and thus capacity is mainly considered endogenous. By contrast, in the practical world, price is actually endogenous. Therefore, our model incorporates the price as an endogenous variable and analyses the impact of the price timing and level on demand and further the profit. To our best knowledge, this is the first paper to consider this scenario.

Duopoly models are analysed consisting of an e-tailer and one brick-mortar retailer strategically deciding the price timing and level before either begins to sell in the market. Such models are referred to as ‘endogenous leadership games’ in the economic literature. The seminal work in this stream of research includes Swinney et al. (2011), Gal-Or (1985), Saloner (1987), Hamilton and Slutsky (1990), Bhaskaran and Ramachandran
(2007) and Maggi (1996). Many of these papers focus on profit maximisation and some focus on social welfare maximisation. Swinney et al. (2011) and Maggi (1996) consider an endogenous leadership game with demand uncertainty while our model is done with product value uncertainty. To the best of our knowledge, none of these papers analyse a duopoly consisting of profit-maximisation incorporating price timing issue related to the product’s value in new markets.

Most of the work in the literature focuses on production postponement (capacity investment). Although Kreps and Scheinkman (1983) conclude the seminal equivalence result – price and production postponement strategies can be equivalent in a duopoly model with deterministic, the result does not hold when demand is uncertain (Van Mieghem and Dada, 1999). The study from Hviid (1990) shows that pure Nash equilibrium for production postponement strategies do not even exist for the stochastic game. Therefore some work assumes exogenous prices, as in recent literature on competition in operations (Lippman and McCardle, 1997; Van Mieghem, 1999). But this work does not consider the effect of tactical price. Much like our model, Gal-Or (1987), Hviid (1990) and Bashyam (1996) consider the sequential pricing games to study first-mover advantages. In contrast to these papers, our emphasis is on studying the price timing and level on the demand when product value is uncertain for strategic consumers and further the profit.

3 Monopolistic models

In this section, two different monopoly models of price timing of the product in new markets are introduced and analysed: the brick-mortar retail monopoly model is considered in the Subsection 3.1 and online selling monopoly model is discussed in the Subsection 3.2.

As assumed through the whole study, each consumer is heterogeneous about the valuation of the new product, which is modelled as a continuous random variable \( v \) uniformly distributed in the positive support with a “positive constant \( I \), which represents the difference between the minimum and maximum value of the product for the consumers on the market”. It is also assumed that each consumer is uncertain about the exact valuation of the product at the beginning of the introduction of the product except his/her own mean valuation and a known variance \( \sigma^2 \).

3.1 A monopolistic firm

A firm (denoted by the subscript \( r \)) sells a single product through a brick-mortar store in the new market. The product’s price \( p(0 < p < V) \) can be announced in one of two times: either early before the product’s valuation is certain or late after it is certain. In early announcement, the product’s valuation is uncertain for the consumers while in late announcement, all uncertainty in the product’s value is eliminated. The surplus of the product is \( v - p \) when the consumer makes a purchase. Following that, the consumer whose value is no less than \( p \) will purchase the product. “If \( V \) represents the product’s valuation of the consumer who has the highest valuation for the product, which is generally distributed with a mean \( \nu \) and the variance \( \sigma^2 \), then the demand is \( \frac{V - p}{I} \).
As shown in Figure 2, facing the uncertainty of the consumers’ valuations of the product when he announces the price early, the firm seeks to maximise the expected profit, which is:

$$\pi^E = \max E \left( \frac{V - p}{p} \right)$$

As shown in Figure 3, when the firm announces the price late after the product’s valuation is certain, the uncertainty of the valuation of the product is eliminated and therefore the profit is realised for a particular realisation of the value, which is:

$$\pi^E = E \max \left( \frac{V - p}{l} \right)$$

Whether the firm announces the price early or late is based on the comparison of equation (1) with equation (2). The following theorem provides the details of the optimal price timing and level.

**Theorem 1:** A monopolist brick-mortar firm prefers the late announcement of the price, yielding the optimal price \( p^* = \frac{V}{2} \) and expected profit \( \pi^E = \frac{\nu^2 + \sigma^2}{4I} \).

Theorem 1 shows that the optimal price is one half of the value \( V \) of the maximum end consumer for the product in the real time and then expected profit is related to the mean value \( \nu \) of the maximum consumer for the product, the variance \( \sigma \) of the value and the difference \( I \) between the values of the minimum end consumer and maximum end consumer for the product. The results from Theorem 1 are in accordance with our intuition: when the firm chooses to announce the price late, the uncertainty of the product...
valuation is eliminated. Thus, the price can be higher compared to the early announcement. The increased profit resulting from a higher price dominates the decreased profit from a less sale due to a higher price. Therefore, the profit is increased due to a higher price.

3.2 A monopolistic online firm

An online firm (denoted by the subscript \( d \)) sells a single product online. The common features of the market are characterised by heterogeneous and uncertain consumers about the valuation of the product. Compared to the product sold by the brick-mortar store, the acceptance of the valuation sold online is \( \theta \), i.e., the product whose valuation is \( v \) in the brick-mortar store for the consumer deserves \( \theta v \) online for this consumer. Therefore, the surplus of the product is \( \theta v - p \) when the consumer makes a purchase. Following that, the consumer whose valuation is no less than \( \frac{p}{\theta} \) will purchase the product. Therefore, the demand is \( \frac{\theta V - p}{\theta I} \).

Facing the uncertainty of the consumers’ valuations of the product when she announces the price early, the firm seeks to maximise the expected profit, which is:

\[
\pi^E_d = \max E \left( \frac{\theta V - p}{p} \right) \tag{3}
\]

When the firm announces the price late after the product is delivered to the market, the uncertainty of the valuation of the product is eliminated and therefore the profit is realised for a particular realisation of the value, which is:

\[
\pi^L_d = \max E \left( \frac{\theta V - p}{\theta I} \right) \tag{4}
\]

Whether the firm announces the price early or late is based on the comparison of equation (3) with equation (4). The following theorem provides the details of the optimal price timing and level.

**Theorem 2:** A monopolist online firm prefers the late announcement of the price, yielding the optimal price \( p^{opt}_d = \frac{\theta V}{2} \) and expected profit \( \pi^L_d = \frac{\theta (v^2 + \sigma^2)}{4I} \).

Theorem 2 shows that the optimal price is one half of the product of value \( V \) of the maximum end consumer for the product in the real time and online acceptance rate \( \theta \), and then expected profit is related to the mean value \( v \) of the maximum consumer for the product, online acceptance rate \( \theta \), the variance \( \sigma \) of the value and the difference \( I \) between the values of the minimum end consumer and maximum end consumer for the product.

The explanation for the results from Theorem 2 is similar to Theorem 1. Compared to Theorem 1, it is shown that both the e-tailer’s price and profit are \( \theta \) portion of the brick-mortar retailer’s price and profit, respectively. This is because it is assumed that the product value’s acceptance rate is \( \theta \) in the e-tailer.
From both Theorems 1 and 2, it is shown that both monopolist firms prefer the late price announcement. There is no difference in price timing although the price level is different due to the product value’s acceptance rate in the e-tailer.

4 Duopoly model

We now proceed to the duopoly model. The details of the model are similar to the monopoly model in the previous section except that there are two firms competing in the market and one of them may serve as the game leader. One firm is an online retailer and the other one is a brick-mortar retailer. If the product is purchased online at a price $p_d$ and the valuation of the product is $\theta v$, then the consumer surplus is $\theta v - p_d$ while if the product is purchased through the brick-mortar store at a price $p_r$, then the consumer surplus is $v - p_r$. Whether the consumer purchases the product through online or through the brick-mortar store depends on the higher consumer surplus. Therefore, the consumer whose valuation equals $\frac{p_r - p_d}{1 - \theta}$ is indifferent to purchasing from either online or the brick-mortar store. “Therefore, if the valuation of the product exceeds $\frac{p_r - p_d}{1 - \theta}$, they prefer to purchase from the brick-mortar store while it is less than $\frac{p_r - p_d}{1 - \theta}$, they prefer the e-tailer”. From Chiang et al. (2003) it is known that the demand for the retailer and online channel is as follows, respectively:

\[
Q_r = \begin{cases} 
\frac{V}{I} - \frac{p_r - p_d}{\theta(1 - \theta)} & \text{if } \frac{p_d}{\theta} \leq p_r, \\
\frac{V}{I} - p_r & \text{otherwise}
\end{cases}
\]  

(5)

and

\[
Q_d = \begin{cases} 
\frac{\theta p_r - p_d}{\theta(1 - \theta)} & \text{if } \frac{p_d}{\theta} \leq p_r, \\
0 & \text{otherwise}
\end{cases}
\]  

(6)

One of the most difficult decisions for the retailers is to make the price timing decision. Each firm has two possible actions: to announce the price either before the valuation of the product is certain for the consumers or after the valuation is certain for the consumers. We assume that the price is credible and unchangeable once the price is announced. There are four possible pure-strategy outcomes to the timing game: both firms announce early, both firms defer until the valuations are certain, and the two asymmetric outcomes in which one firm announces early and another one announces late. The timing game and the abbreviations used to refer to its outcomes are depicted in Table 1.
Table 1: The four possible outcomes and their abbreviations

<table>
<thead>
<tr>
<th>Online firm early</th>
<th>Brick-mortar retailer early</th>
<th>Brick-mortar retailer late</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E, E)</td>
<td>(E, L)</td>
<td>(L, L)</td>
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<tr>
<td>(L, E)</td>
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After the valuations of the product are certain, we assume that all the information is publicly observable. For example, if the brick-mortar retailer announces the price before the valuations are certain and the e-tailer announces the price after the valuation is certain, and then the e-tailer observes the announced price by the brick-mortar retailer and the certain valuations of the product for the consumers before she announces the price. Therefore, in addition to the informational consideration in the monopoly model, there are additional factor in the play in the duopoly model: if one firm announces the price before the valuation of the product is certain for each consumer and another firm announces it after it is certain, then the before-moving firm enjoys a leadership position in a sequential game, where the after-moving firm is a sequential follower. As before, we assume the announced price is credible and unchangeable. The sequence of events is identical to the monopoly sequence in Figures 1 and 2, except that the price timing decision step is now a game between two firms.

In the following four lemmas, we analyse the equilibria to each of the four pure-strategy outcomes depicted in Table 1. Once we have derived these equilibria, we in turn analyse the equilibrium to the price timing game. We first consider the case in which the brick-mortar retailer sets the price early before the value of the product is certain for each consumer and the e-tailer sets the price late after the valuation of the product is certain. In this case, there is randomness for the retailer and no randomness for the e-tailer. The following lemma describes the equilibrium price for each firm in this game, in addition to providing the ex ante expected profit for each firm.

**Lemma 1:** If the brick-mortar retailer sets the price early before the value of the product is certain for each consumer and the e-tailer sets the price after the value of the product is certain, then equilibrium prices are

\[ p_r^* = \frac{(1 - \theta)\nu}{2 - \theta} \]  
\[ p_d^* = \frac{\theta(1 - \theta)\nu}{2(2 - \theta)} \]

The ex ante equilibrium expected profit of the retailer is \[ \pi_r = \frac{(1 - \theta)\nu^2}{2(2 - \theta)} \] whereas the ex ante equilibrium profit of the e-tailer is \[ \pi_d = \frac{\theta(1 - \theta)\nu^2}{4(2 - \theta)^2} \].

Lemma 1 shows that the optimal prices and expected profits of both brick-mortar retailer and e-tailer in \((L, E)\) are related to the mean value \(\nu\) of the maximum end consumer for the product.

We now move to the game in which both firms set the price after the valuation of the product is certain for each consumer. In this case, there is no randomness for each firm.

**Lemma 2:** If both firms set the price after the valuation of the product is certain, then equilibrium prices are

\[ p_r^* = \frac{2(1 - \theta)V}{4 - \theta} \]  
\[ p_d^* = \frac{\theta(1 - \theta)V}{4 - \theta} \]

The ex ante equilibrium
expected profit of the retailer is \( \pi_r = \frac{4(1-\theta)(\sigma^2 + \nu^2)}{(4-\theta)^2 I} \), whereas the ex ante equilibrium profit of the e-tailer is \( \pi_d = \frac{\theta(1-\theta)(\sigma^2 + \nu^2)}{(4-\theta)^2 I} \).

Lemma 2 shows that the optimal prices of both brick-mortar retailer and e-tailer in \((L, L)\) are related to the value \(V\) of the maximum end consumer for the product in the real time. Moreover the expected profits of both parties are related to the mean value \(\nu\) of the maximum end consumer for the product.

We next consider both firms announce the price before the valuation of the product is certain for each consumer.

**Lemma 3:** If both firms set the price before the value of the product is certain, then equilibrium prices are \( p^*_r = \frac{2(1-\theta)\nu}{4-\theta} \) and \( p^*_d = \frac{\theta(1-\theta)\nu}{4-\theta} \). The ex ante equilibrium expected profit of the retailer is \( \pi_r = \frac{4(1-\theta)\nu^2}{(4-\theta)^2 I} \), whereas the ex ante equilibrium profit of the online firm is \( \pi_d = \frac{\theta(1-\theta)\nu^2}{(4-\theta)^2 I} \).

Lemma 3 shows that the optimal prices and expected profits of both brick-mortar retailer and e-tailer in \((E, E)\) are related to the mean value \(\nu\) of the maximum end consumer for the product.

Last, we move to the game where online firm sets the price before the valuation of the product is certain for each consumer and retailer sets the price after the valuations is certain.

**Lemma 4:** If online firm sets the price before the valuation of the product is certain and retailer sets it after it is certain, then equilibrium prices are \( p^*_r = \frac{(1-\theta)(2(2-\theta)V + \theta\nu)}{4(2-\theta)} \) and \( p^*_d = \frac{\theta(1-\theta)\nu}{2(2-\theta)} \). The ex ante equilibrium expected profit of the retailer is \( \pi_r = \frac{(1-\theta)(\nu^2 (4-\theta)^2 + 4(2-\theta)^2 \sigma^2)}{16(2-\theta)^2 I} \), whereas the ex ante equilibrium profit of the online firm is \( \pi_d = \frac{\theta(1-\theta)\nu^2}{8(2-\theta)^2 I} \).

Lemma 4 shows that in \((E, L)\) the optimal price of the brick-mortar retailer is related to both the value \(V\) in the real time and mean value \(\nu\) of the maximum end consumer for the product while that of the e-tailer is related to the mean value \(\nu\). Moreover the expected profits of both parties are related to the mean value \(\nu\) of the maximum end consumer for the product.
5 Equilibrium to the timing game

In Section 4, we have derived the equilibria to each of the subgames. Now we proceed to derive the equilibrium to the timing game. The following theorem describes all of the possible equilibria to this game.

Theorem 3: The following strategy equilibria to the price timing exist:

1. the strategy that both parties announce the price early should never be adopted
2. if $\nu^2 \leq 8\sigma^2(2 - \theta) / \theta^2$, the equilibrium is a pure strategy that both e-tailer and the retailer announce the price late
3. if $\nu^2 \leq 8\sigma^2(2 - \theta) / \theta^2$, the equilibrium is a mixed strategy, either the e-tailer announces the price early and the retailer announces the price late or the e-tailer announces the price late and the retailer announces the price early.

There are several interesting consequences of these results. First, the results in 1 are in accordance with our intuition based on the results in Theorems 1 and 2: there is no advantage for either of them if both of them announce the price early. So the strategy $(E, E)$ is never equilibrium. Secondly, the results in 2 and 3 show that compared to the Theorems 1 and 2, the strategy that both parties announce the price late is not always preferred when there is a competition and the duopoly models exist. Actually, not only the product valuation variance but also the online acceptance rate affects the equilibria. Clearly the higher the product valuation variance, the lower the online acceptance rate, the more likely both parties announce the price late. In contrast, the lower the product value variance, the higher the online acceptance rate, the more likely one of the parties announces the price late and the other one announces the price early. This observed phenomenon can be explained in this way: There is a trade-off between the game leader position advantage leading to higher profits and lower price leading to lower profits. In the four lemmas, it is noticed that not only the price and the profit of the e-tailer but also those of the retailer are affected by the product valuation variance and the online acceptance rate $\theta$. When the product valuation variance is high enough and the online acceptance rate is low enough which leads to $\nu^2 \leq 8\sigma^2(2 - \theta) / \theta^2$, the benefits from the higher price of the parties in the late price announcement dominate the benefits from the game leader position resulting from the early price announcement. Therefore, a pure strategy that both parties announce the price late is equilibrium. By contrast, when the product value variance is low enough and the online acceptance rate is high enough which leads to $\nu^2 \leq 8\sigma^2(2 - \theta) / \theta^2$, the benefits from the game leader position resulting from the early price announcement dominate the benefits from the higher price of the parties in the late price announcement. Therefore, one of the parties plays a leader role and announces the price early and the other one plays a follower role and announces the price late is equilibrium. So a mixed strategy $(E, L)$ and $(L, E)$ exists.
6 Conclusions

Our main goal is to analyse how the product valuation uncertainty and online acceptance rate impact the price timing and level decisions of the e-tailer and brick-mortar retailer entering new markets. We find that in monopoly markets, both e-tailer and retailer announce the price late whatever the product valuation variance level and the customer online acceptance rate are. In competitive markets, the higher the product valuation variance level and the lower the customer online acceptance rate, the more likely both the e-tailer and the retailer announce the price late. In contrast, the lower the product valuation variance level and the higher the customer online acceptance rate, the more likely one of the e-tailer and the retailer announces the price late and the other one announces the price early.

We conclude that the results from price competition in duopoly models involving the e-tailer subject to the product valuation acceptance rate by the consumers and the brick-mortar retailer is fundamentally different from those in monopoly models. Managerially, these results are important because they imply that the optimal strategic price position differs depending on the nature of the external environment. Thus, blindly following a mantra of pricing late or pricing early can be a perilous strategy, because any such advantage (or disadvantage) depends critically on the characteristics of the external market facing by the firms.

Although our key findings relate to the equilibrium price timing, our results also relate to the literature on game theories. When the Stackelberg game exists, it is frequently observed that playing a leadership position is an advantage for the player. This may not be the case in our models. The operational reality of price timing under the product valuation uncertainty, coupled with competition from a different firm prone to the increase or decrease of the product valuation by the consumers, offers a purely rational explanation for these outcomes.

References

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Appendix

Proofs

Proof of Theorem 1: For early price announcement, the profit function implied in equation (1) is concave and yields a unique price point, $p^*_E = \frac{v}{2}$. Expected profit is thus $\pi^*_E = \frac{v^2}{4I}$. For late price announcement, the profit function implied by equation (2) is concave and yields a unique price point, $p^*_L = \frac{V}{2}$. Expected profit is thus $\pi^*_L = \frac{v^2 + \sigma^2}{4I}$.

Obviously, the expected profit earned in the late price announcement is higher than that in early price announcement, yielding the result in Theorem 1.

Proof of Theorem 2: For early price announcement, the profit function implied in equation (3) is concave and yields a unique price point, $p^*_E = \frac{\theta_0}{2}$. Expected profit is thus $\pi^*_E = \frac{\theta_0^2}{4I}$. For late price announcement, the profit function implied by equation (4) is concave and yields a unique price point, $p^*_L = \frac{\theta V}{2}$. Expected profit is thus
\[ \pi_d = \frac{\theta(v^2 + \sigma^2)}{4I} . \]

Obviously, the expected profit earned in the late price announcement is higher than that in early price announcement, yielding the result in Theorem 2.

**Proof of Lemma 1:** If the retailer sets the price early, the e-tailer sets the price late, then there is no randomness for the e-tailer and her profit is \( \pi_{dE} = \max_p p_d \frac{\theta p_d - p_d}{\theta(1-\theta)I} \). Based on the first-order condition, the optimal price of the e-tailer is \( p_{dE} = \frac{\theta p_d}{2} \). Then the profit of the brick-mortar retailer is. Similarly, the optimal price of the retailer is \( \pi_{LE} = \max_p \left( p_{LE} \frac{(1-\theta)V - p_{dE} + p_{dLE}}{1-\theta I} \right) \). Then \( p_{dLE} = \frac{\theta(1-\theta)V}{2(2-\theta)} \). Thus, the profits of the e-tailer and retailer are as follows:

\[ \pi_{dE} = \frac{\theta(1-\theta)V}{4(2-\theta)^2 I} \]
\[ \pi_{LE} = \frac{(1-\theta)V}{2(2-\theta)I} \]

**Proof of Lemma 2:** If both set the price late simultaneously, then there is no randomness for both the e-tailer and the retailer. Their profits are \( \pi_{dL} = \max_p p_{dL} \frac{\theta p_{dL} - p_{dL}}{\theta(1-\theta)I} \) and \( \pi_{LE} = \max_p \left( p_{LE} \frac{(1-\theta)V - p_{dL} + p_{dLE}}{1-\theta I} \right) \). Based on the first-order conditions, the optimal prices of the e-tailer and the retailer are \( p_{dL} = \frac{\theta(1-\theta)V}{4 - \theta} \) and \( p_{dLE} = 2\frac{(1-\theta)V}{4 - \theta} \), respectively. Thus, \( \pi_{dL} = \frac{\theta(1-\theta)(\sigma^2 + v^2)}{4(\theta - \theta)I} \) and \( \pi_{LE} = \frac{4(1-\theta)(\sigma^2 + v^2)}{(4-\theta)^2 I} \).

**Proof of Lemma 3:** If both the e-tailer and the retailer set the price early simultaneously, then profits of both parties are \( \pi_{dE} = \max_p p_{dE} \frac{\theta p_{dE} - p_{dE}}{\theta(1-\theta)I} \) and \( \pi_{dE} = \max_p \left( p_{dE} \frac{(1-\theta)V - p_{dE} + p_{dLE}}{1-\theta I} \right) \), respectively. Based on the first-order conditions, the optimal prices of the e-tailer and the retailer are \( p_{dE} = \frac{\theta(1-\theta)\sigma}{4 - \theta} \) and \( p_{dLE} = \frac{2(1-\theta)V}{4 - \theta} \). Thus, \( \pi_{dE} = \frac{\theta(1-\theta)\sigma^2}{4 - \theta} \) and \( \pi_{dE} = \frac{4(1-\theta)\sigma^2}{4 - \theta} \).
Proof of Lemma 4: If the e-tailer sets the price early and the brick-mortar retailer sets the price late, then the profit of the retailer is \( \pi_{EL}^E = E \max \left( p_{EL}^E \frac{(1-\theta)v - p_{EL}^E + p_{EL}^L}{(1-\theta)I} \right) \). Based on the first-order condition, the optimal price of the retailer is \( p_{EL}^* = \frac{(1-\theta)v + p_{EL}^L}{2} \).

Next the e-tailer’s profit is \( \pi_{EL}^E = \max E \left( p_{EL}^E \frac{\theta p_{EL}^E - p_{EL}^L}{\theta(1-\theta)I} \right) \). Similarly, the e-tailer’s optimal price is \( p_{EL}^* = \frac{\theta(1-\theta)v}{2(2-\theta)} \). Then \( p_{EL}^* = \frac{(1-\theta)(2(2-\theta)V + \theta I)}{4(2-\theta)} \). Therefore, both parties profits are \( \pi_{EL}^E = \frac{(1-\theta)(v^2(4-\theta)^2 + 4(2-\theta)^2\sigma^2)}{16(2-\theta)^2I} \) and \( \pi_{EL}^L = \frac{\theta(1-\theta)v^2}{8(2-\theta)I} \).

Proof of Theorem 3: We will examine the viability of each subgame in Table 1 individually.

1. Let us consider the equilibrium in which both the e-tailer and the brick-mortar retailer announce the price early: \((E, E)\). This is an equilibrium if no firm has incentive to unilaterally deviate: in other words, if the e-tailer enjoys greater expected profit than in \((L, E)\) and the brick-mortar retailer enjoys a greater expected profit than in \((E, L)\). From Lemma 3 and Lemma 1, comparing the e-tailer’s expected profit in each of the equilibrium results, we see that the e-tailer’s profit in \((E, E)\) is always lower than in \((L, E)\). From Lemma 3 and Lemma 4, comparing the retailer’s expected profit in each of the equilibrium results, we see that the retailer’s profit in \((E, E)\) is always lower than in \((E, L)\). Thus, \((E, E)\) is never an equilibrium.

2. We next consider the equilibrium in which both parties announce the price late: \((L, L)\). From Lemma 2 and 4, we see that comparing the e-tailer’s expected profit in each of the equilibrium results, we see that the e-tailer’s profit in \((E, L)\) is always lower than in \((L, L)\) when \( \nu^2 \leq 8\sigma^2(2-\theta) / \theta^2 \). Similarly, from Lemmas 1 and 2, we see that the retailer’s profit in \((L, E)\) is always lower than in \((L, L)\) when \( \nu^2 \leq 8\sigma^2(2-\theta) / \theta^2 \).

3. Base on 1 and 2, either \((E, L)\) or \((L, E)\) is an equilibrium when \( \nu^2 \leq 8\sigma^2(2-\theta) / \theta^2 \).