A Model of Labeling with Horizontal Differentiation and Cost Variability

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Abstract

We study optimal disclosure of variety by a multi-product firm with random costs. In our model there are two varieties that are horizontally differentiated and differ in overall quality, but buyers cannot distinguish between them without labels. The equilibrium prices for labeled varieties are increasing functions of the absolute value of the cost differential and do not reveal which variety is cheaper to produce. Nondisclosure is most common when there is moderate uncertainty about the relative input cost, not too much idiosyncrasy in consumer valuations, and not too much difference in quality across varieties. Although mandatory disclosure of variety benefits consumers, it decreases expected welfare when relative input cost variability is large and quality asymmetry is small. The cheaper variety tends to be oversupplied (undersupplied) when disclosure is voluntary (mandatory). Competition among multi-product firms that source inputs in the same upstream market may not lead to more disclosure.

Keywords: information, labeling, quality disclosure, product differentiation.

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1. Introduction

Until recently voluntary country-of-origin labeling of food products was relatively uncommon in the U.S. even though the aggregate import share grew to 7% of value and 15% of volume of domestic food consumption in 2005 (Jerardo 2008).[1] In 2009, the mandatory country of origin labeling (MCOOL) regulation contained in the 2002 and 2008 Farm Security and Rural Investment Acts took effect (Federal Register 2009). This labeling regulation requires food retailers to notify their customers of the country of origin of various muscle cuts and ground meats, fish, perishable agricultural commodities (fresh and frozen fruits and vegetables), and nuts. In this paper, we study a model that captures some features of the food and agricultural markets covered by MCOOL, and evaluate the welfare economics of mandatory labeling that provides a cue to consumers about their willingness to pay for a product.

Most of the previous studies of product origin labeling consider producers who cannot credibly signal quality of their products and use geographical indications (GIs) as a means of costly credible certification (e.g., Zago and Pick 2004, Lence et al. 2007, Langinier and Babcock 2008, Moschini, Menapace, and Pick 2008).[2] In such cases labeling regulation (GIs) allows suppliers to transmit information about product attributes to consumers, which they could not do prior to regulation. However, as discussed in Krissoff et al (2004), there is little evidence that consumers systemically lack trust in the country-of-origin information provided by the U.S. food marketing system.[3] When credible *voluntary* product origin labeling is possible, analyzing the effects of MCOOL requires assessing its scope. That is, we need to allow the provision of information about product origin to be endogenously determined, identify conditions under which product

[1] An example of voluntary labeling of food products with their country of origin are lamb imports from Australia and New Zealand (Marette, Clemens and Babcock 2008). Also, there are many examples of the use of geographical origin within the U.S. as a basis for branding commodities such as Main lobster, Kona coffee, Idaho potatoes, Napa Valley wine, Vidalia onions, Washington State apples, Texas Ruby Red grapefruits, and Florida orange juice (Hayes, Lence, and Babcock 2005).

[2] Geographical indications (GIs) such as Protected Designation of Origin or Protected Geographical Indication have long been used by agricultural producers in the European Union. GIs not only indicate origin of the food product but also convey a certain quality and product specification (European Commission 2007).

[3] For example, there were no retailers who participated in the voluntary labeling programs for beef and other products that were offered by USDA before the mandatory policy went into effect (Federal Register 2009, p. 2682).

origin is not revealed in equilibrium, and compare equilibria with and without labeling (Carter, Krissoff, and Zwane 2006). Such an economic analysis involves several modeling decisions that need justification.

First, we abstract from the vertical relations in the industry and consider a retailer (downstream seller) that sources a good from two countries, and can at no cost ascertain products' country of origin and choose whether to label or not label products with their country of origin.[4] Although direct labeling costs can be considerable, unlike GIs, country of origin labeling (by itself) typically does not entail significant changes in production practices other than collecting information and keeping records about product movement (Federal Register 2009).

Second, we assume that products from different countries are differentiated in terms of quality (e.g., safety) and a non-quality characteristic like flavor. In particular, we consider a version of Hotelling model with consumers that are located along the unit interval, interpreted to be the most preferred product characteristic. A good from one country is located at point 0, and a good from the other country is located at point 1. Each country's product is also defined along a second dimension, interpreted to be product quality. We assume that consumers cannot identify the country of origin without labeling, i.e. without labels consumers do not know whether a product belongs to the variety 0 or 1. As discussed in Lusk et al. (2006), consumers may value similar products from different countries differently because of concerns with overall quality and safety as well idiosyncratic preferences. Although the food imported into the U.S. is subjected to the same safety standards as domestically grown food, production methods may still vary across exporting countries (Krissoff et al 2004). Such variability tends to result in unique flavor or nutritional content (and other experience or credence attributes) of food products from different countries (Umberger et al. 2002, Sitz et al. 2005, Feuz et al. 2007).

Third, we assume that the production costs (or wholesale prices) for products from different countries are subject to *country-specific* random shocks that are *not*

[4] So even if products are labeled with their country of origin at a wholesale level, the downstream seller can withhold this information from customers by relabeling final products with an uninformative label. For example, Kay (2008) remarked that even with MCOOL suppliers are able to market a differentiated product as generic by listing several countries on the label. In Section 5, we demonstrate that unlabeled products can be offered in equilibrium with competition among spatially differentiated retailers.

observable to consumers. Most of the commodities covered by the mandatory labeling policy (muscle cuts and ground meats, and fruits and vegetables) are characterized by relatively short shelf-life and seasonal variations in supply. When domestic supply is low or unavailable, and storage is costly, off-season demand is met by imports, and the imported and domestic varieties are typically marketed during different (possibly overlapping) time periods (Huang and Huang 2007).[5]

Note that in the context of labeling what is unknown to consumers is the content (country of origin) of a particular unit of a product. So we assume that consumers know their willingness to pay for variety 0 and variety 1 (which is a sum of common and idiosyncratic components), but cannot distinguish between them without labels. Although throughout our analysis we assume that the overall quality of each variety is fixed, the differences in quality across varieties can be interpreted as *publicly known* shocks to quality. Quality shocks such as food contamination and disease outbreaks tend to be (perhaps with a lag) widely reported in the media, while country-specific input prices and product availability tend to receive less public attention.

When production costs are *constant*, as shown by Wolinsky (1987), a menu of labeled varieties and an unlabeled (unidentified) variety allows the seller to more effectively sort consumers according to their willingness to pay. Buyers who strongly prefer one of the varieties choose the appropriate labeled variety, and indifferent buyers choose a cheaper unlabeled variety. In this paper we analyze an extension of Wolinsky's (1987) model and consider what happens when production costs are subject to variety-specific shocks that are not observable to buyers, and the seller is free to change the variety of the unlabeled product when the relative costs change. In order to avoid "indirect" disclosure of the identity of the least-cost variety to buyers, the seller's pricing strategy must be such that it does not reveal her cost structure. To our knowledge this is the first paper to study labeling of products with variety by a multi-product firm in a

[5] For example, Kay (2008) reported that "…any additional segregation of livestock and finished product will translate into higher wholesale prices and *reduced product availability*, Tyson warns" (italics added). Also, surveys of Belgium consumers found that origin-labeled meat products were perceived as less convenient to purchase due to reduced availability (Verbeke and Roosen 2009).

framework with "universal private information" where consumers privately observe their preferences and the firm privately observes its production costs.[6]

In section 3.1, we characterize equilibrium when quality is symmetric and high relative to the variability in idiosyncratic consumer valuations and production costs. In equilibrium the seller raises prices for *both* labeled varieties when the ex post cost differential increases. As a result the unlabeled product that consists of the cheaper variety is purchased by more consumers who remain in the dark about its true identity. For intermediate levels of ex ante cost variability the seller typically serves many or *all* consumers with an unlabeled variety, and nondisclosure is most common. On the one hand, for small cost variability there is more disclosure, because the seller targets consumers who strongly prefer a particular variety with relatively cheap labeled varieties. On the other hand, there is also more disclosure when ex ante cost variability is large, because the seller has no reason to hide the identity of the ex post least-cost variety when it is very expensive.

In Section 3.2, we consider equilibrium with asymmetric quality across varieties. For small quality asymmetry and cost variability, equilibrium is similar to the case of symmetric quality. However, for large quality asymmetry prices tend to be more informative about relative costs, and the characterization of equilibrium depends on the distribution of cost shocks. We completely characterize equilibrium for different levels of quality asymmetry in a special case with negatively dependent binary cost shocks. When quality asymmetry is sufficiently great and cost variability is not too great, disclosure is "quality-biased" whereas the seller always offers the labeled high-quality variety and an unlabeled product that can consist of either variety. However, if quality asymmetry is not too great and cost variability is sufficiently great, variety is never disclosed in equilibrium.

In Section 4, we analyze the effects of mandatory disclosure on welfare. We find that although it benefits consumers, the overall welfare may increase or decrease. This is because the seller tends to oversupply the cheaper variety under voluntary disclosure but

[6] Daughety and Reinganum (2007) introduce this term to describe an environment in which firms privately observe the quality of their product and consumers privately observe their preferences. They assume that firms make disclosure decisions before they learn their quality. Here we consider a firm that makes disclosure decision after it observes its production costs for varieties that may differ in overall quality.

undersupply it under mandatory disclosure. Suppose that quality is symmetric and high, so that the market is covered (each consumer participates in the market) before and after the policy. Then mandatory disclosure will increase ex post social welfare for small cost differentials but decrease it for large cost differentials. When costs are similar across varieties most consumers should get their preferred variety, and this is what happens under mandatory disclosure. When costs are very different across varieties, most consumers should be served with the cheaper variety, and this is what happens in equilibrium with no disclosure. For moderate differences in costs there are distortions before and after the policy: the seller serves too many (conversely, too few) consumers with the cheaper variety under voluntary (conversely, mandatory) disclosure.

Thus, mandatory disclosure increases *expected* social welfare (i.e. before costs are known to an independent observer) for small cost variability, but decreases it for large cost variability. Mandatory disclosure also tends to decrease welfare when costs are negatively correlated as large cost differentials become more likely. It is worth pointing out that under "large" cost variability production cost may exceed the choke-off demand price. In the context of country of origin labeling, "large" country-specific cost variability can be caused by seasonality in agricultural production whereby product availability fluctuates during the year and varies across exporting countries. However, even with large and negatively correlated cost shocks, mandatory disclosure may increase expected welfare if quality asymmetry is large. This happens when welfare gains from avoiding overconsumption of the cheap low-quality variety, on average, offset welfare losses from underconsumption of the cheap high-quality variety as a result of the policy.

In Section 5, we investigate whether competition among multi-product firms generates more disclosure of variety in equilibrium. We consider spatially differentiated firms that source varieties in the *same* upstream market, and demonstrate that independent firms may also practice nondisclosure. Suppose that only one of the varieties is available in the upstream market, but consumers do not know which one. Then in a non-cooperative equilibrium a firm that expects that the other firm will not disclose its variety, will not achieve higher profits from its own disclosure. On the one hand, if firms are located close to each other and price competition is fierce, the disclosing firm will not be able to raise its price without losing many customers. This is because consumers, who now know which variety is available, will be attracted by the low price at the non-disclosing firm even if it continues to market unlabeled products. On the other hand, if the firms are far apart and price competition is not fierce, the disclosing firm (as well as the non-disclosing firm) will earn a lower profit due to a reduction in sales to consumers who find out that the available variety is not a good match for them.

Our results suggest that, even without accounting for the direct costs of implementing MCOOL, it may decrease social welfare. In particular, this may happen when consumers view products from different countries as close substitutes, and wholesale prices in different countries are volatile and uncorrelated. The model demonstrates that the characteristics of exporting countries such as a history of food safety lapses (vertical quality), production methods (horizontal attributes), and growing seasons (product availability and cost volatility) can play a rather nuanced role in both the scope and the effects of MCOOL on welfare. To the extent that geographic distance between areas where products originate may increase the heterogeneity in consumer preferences and weaken the correlation between wholesale prices, the model predicts a positive relationship between the prevalence of voluntary country of origin labeling and the distances to and among exporting countries during the pre-MCOOL period. Our modeling approach complements the current studies of the effects of MCOOL on welfare that take into account the additional direct costs created by the policy (e.g. Jones, Somwaru, and Whitaker 2009), and suggests that a more complete assessment should include the information effects of the policy on the demand and supply side of the market.

Our findings can also be used to shed light on other issues in the economics of food labeling (Golan, Kuchler, and Mitchell 2000). For example, consumers had little knowledge that relatively cheap soybean oil and corn sweeteners had been replacing saturated fats and sugar in many packaged foods during the 1970s and 1980s (Golan and Unnevehr 2008). The reversion of these trends started with the U.S. Food and Drug Administration regulation requiring disclosure of trans fat content on nutrition labels and increased media attention (Unnevehr and Jagmanaite 2008; Hailu, Cranfield, and Thangaraj 2010). In our model, variety 0 can correspond to a product that contains partially hydrogenated soybean oil, and variety 1 can correspond to a similar product that contains a substitute ingredient such as palm oil. With this interpretation our analysis suggests a signaling explanation of why a large share of products lacked detailed nutrition labeling in spite of the apparent potential for product differentiation before the Nutritional Labeling and Education Act of 1990 went into effect (Caswell 1992).

Related Literature

An early finding in the literature on quality disclosure is that a privately informed seller voluntarily discloses all information if disclosure is costlessly credible (Grossman and Hart 1980, Milgrom and Roberts 1986). The subsequent literature demonstrated that complete unraveling breaks down and some nondisclosure occurs in models with costly disclosure, incomplete product information of the seller, irrational consumers, and competition (see Milgrom 2008 and references therein). The disclosure of product variety generally reveals both public (what is the overall quality of a given product) and private information (how far away is a given product from the buyer's ideal variety) to each potential buyer. Then buyers' private information may play the role of the disclosure "cost" because, all else equal, the seller can extract more surplus from buyers who have *less* private information. The nondisclosure result in the presence of private information is obtained in Sun (2010) who shows that a monopolist may not disclose product characteristics when consumers are uncertain about both vertical quality and horizontal attributes of a product. However, in the existing models of product information disclosure the attributes of a product are exogenous to the seller's problem. A novel feature of our model is that consumer uncertainty about product characteristics is *endogenous* as it is driven by the seller's supply decisions in the presence of input cost variability.[7]

[7] Our model is also related to Levin, Peck, and Ye (2009) who consider costly quality disclosure by a multi-product monopolist as well as competing firms. In their model products are both vertically and horizontally differentiated, and firms privately observe *quality* before making a disclosure decision. Also, Board (2009) and Hotz and Xiao (2010) show that full unraveling does not occur when disclosure is costless with competition among single-product firms. Our result that in equilibrium labeling can be incomplete complements the study by Roe and Sheldon (2007) of the labeling of credence goods and the manner by which quality is communicated in a model of vertical product differentiation.

The firm's incentives to provide buyers with private information about their own valuations for its products are also studied in the literature on informative advertising (Lewis and Sappington (1994), Johnson and Myatt (2006), Anderson and Renault (2006), Saak (2008), and Anderson and Renault 2009). In contrast, following Wolinsky (1987), we focus on consumers' uncertainty about the characteristics of a *particular* product rather than individual match values for a product with known characteristics, and consider a seller that can package different products with different amounts of information.

Also, Ottaviani and Prat (2001) show that the monopolist achieves higher expected profits by *committing* to publicly reveal her private information under affiliation between the seller's and buyers' private signals. In our model there is *no commitment* and the seller decides *which products* to label with variety after she observes her production costs. Moscarini and Ottaviani (2001) consider buyers who are uncertain about their match value for a variety, and show that the sellers' equilibrium profits may fall with the revelation of public information. However, they assume that each seller offers a different variety of a good, and do not consider *multi-product* sellers.

2. Model

We consider an extension of Wolinsky's (1987) model of variety labeling (brand names) that allows for random production costs. A risk-neutral monopolist (or seller) offers two product varieties (differentiated by their country of origin or ingredients), 0 and 1, and the unlabeled product n to a continuum of risk-neutral consumers with mass normalized to one. The unit production cost (wholesale price) of variety i is random and is given by σC_i, $i = 0{,}1$. Here $\sigma \geq 0$ is a scale parameter (a measure of the cost variability), and C_0 and C_1 are drawn from the symmetric continuous (unless specified otherwise) distribution function $G(c_0, c_1)$ with density function $g(c_0, c_1)$ on $[0{,}1]\times[0{,}1]$, where $g(c_0, c_1) = g(c_1, c_0)$ for all c_0, c_1. We will use c_i to denote a realization of C_i. Although we assume that C_0 and C_1 have identical marginal distributions, they are not necessarily drawn independently, and may exhibit either positive or negative dependence. For example, positive dependence may better describe the wholesale prices for beef produced in the U.S. and Canada, whereas negative dependence may better describe the wholesale prices for grapes produced in the U.S. and Mexico which are typically not available at the same time.

An important departure from the previous literature is that we assume that the realizations (c_0, c_1) are observable *only* to the monopolist but not to consumers. Typically, consumers do not observe input prices in upstream markets.

Each buyer demands one unit of variety 0 or 1 or none. Consumers differ in their ideal variety x and are uniformly distributed along the interval [0,1]. A consumer whose ideal variety is x is willing to pay $q_0 - tx$ for one unit of variety 0 and $q_1 - t(1-x)$ for one unit of variety 1. Here t is a measure of horizontal differentiation, and q_i is a variety-specific quality shock (i.e. a variety-specific common component of consumer valuations), which is publicly observed by the seller and consumers, $i = 0,1$.

If the identity of the variety offered for sale is not disclosed by the seller (i.e. the product is not labeled with its variety), consumers cannot find out what it is prior to purchase. For example, different varieties of packaged foods, meats, fruits, and vegetables can be similar in appearance but differ in experience and credence attributes such as flavor or nutritional content. We assume that consumers are risk-neutral, and if a consumer at x believes that there is probability h that the unlabeled product is of variety 1 (and, therefore, probability $1-h$ that the unlabeled product is of variety 0), then she is willing to pay $(1-h)(q_0 - tx) + h(q_1 - t(1-x))$ for one unit of the unlabeled product. When deciding which product to buy, a consumer chooses the product that provides the greatest expected utility net of price, or stays out of the market and obtains a reservation utility of zero.

We consider two information regimes: voluntary and mandatory disclosure (labeling) of a product's variety. We assume that, if provided, labeling is truthful. In the voluntary labeling regime, the monopolist decides whether or not to label a product with variety. In the mandatory labeling regime, the monopolist must label each product with its variety. Even though the direct costs of information disclosure including labeling, testing, and keeping records may be significant, they are ignored in the analysis to follow. Accounting for such costs will not change our main findings that full nondisclosure can occur in equilibrium, and that mandatory disclosure can reduce welfare even when all consumers participate in the market before and after the policy is implemented.[8]

Timing of decisions is as follows. First, the buyers and the monopolist observe q_i, each buyer privately observes his ideal variety, x, and the monopolist privately observes her production costs c_i, $i = 0,1$. Second, the monopolist sets the prices for labeled and unlabeled products, $p_i(c_0, c_1)$, $i = 0,1,n$. Third, having seen product prices, buyers update their beliefs about the variety of an unlabeled product (if it is offered for sale) and make their purchasing decisions. Finally, the monopolist produces to satisfy demand.

3. Equilibrium

Consider an equilibrium in which the monopolist offers labeled and unlabeled varieties. Let $s_i(x, p_i) = (1-h_i)(q_0 - tx) + h_i(q_1 - t(1-x)) - p_i$ denote the net utility of a consumer at x who buys product i at price p_i, $i = 0,1,n$, where $h_0 = 0$, $h_1 = 1$, and $h_n \in (0,1)$. A consumer at x buys product i if $s_i(x, p_i) \geq 0$ and $s_i(x, p_i) \geq s_j(x, p_j)$ for all $j \neq i$, $i, j = 0,1,n$, . Because $s_n(x, p_n) - s_0(x, p_0)$ and $s_1(x, p_1) - s_n(x, p_n)$ are increasing in x, for given prices p_i, $i = 0,1,n$, the locations (types) of the marginal consumers who purchase variety i, x_i, and unlabeled product, y_i, are given by

$$s_i(x_i, p_i) = \max[0, s_{-i}(x_i, p_n), s_n(x_i, p_n)], \ i = 0,1, \tag{1a}$$

$$s_n(y_i, p_n) = \max[0, s_i(y_i, p_i)], \ i = 0,1 \tag{1b}$$

where $0 \leq x_0 \leq y_0 \leq y_1 \leq x_1 \leq 1$, $-i = 0$ if $i = 1$ and $-i = 1$ if $i = 0$. In equilibrium in which both labeled and unlabeled products are offered, all consumers with $x \leq x_0$ buy variety 0, all consumers with $y_0 \leq x \leq y_1$ buy an unlabeled variety, and all consumers with $x \geq x_1$ buy variety 1. The case with $h_n = \frac{1}{2}$ for parameter values such that the market is covered is illustrated in Figure 1. For given prices p_0, p_1, p_n, and consumers' beliefs, h_n, the measures of consumers who demand one unit of product 0,1, and *n* are

[8] There is a large literature that studies quality disclosure when credible disclosure is costly (e.g., see Levin, Peck, and Ye (2009) and references therein).

given by $D_0(p_0, p_1, p_n, h_n) = x_0$, $D_1(p_0, p_1, p_n, h_n) = 1 - x_1$, and $D_n(p_0, p_1, p_n, h_n) = y_1 - y_0$, where x_i, y_i, $i = 0,1$, are determined by (1), and therefore depend on p_0, p_1, p_n, and h_n.

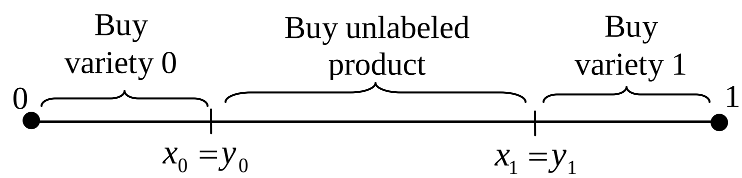

Figure 1. Sub-markets for labeled and unlabeled products

The seller chooses the variety of an unlabeled product based on the realized cost shocks. Thus, unlabeled product consists of variety i if $c_i < c_{-i}$, so that

$$c_n = \min[c_0, c_1]$$

is the unit cost of the unlabeled product. We assume that in the borderline case with $c_0 = c_1$ an unlabeled variety is equally likely to be 0 or 1. Although input costs are not directly observable to consumers, in equilibrium consumers correctly guess what the seller's pricing strategy is, and therefore, they can update their beliefs about an unlabeled variety h_n by observing the prices p_0, p_1, p_n. And so, under voluntary disclosure, h_n is a function of p_0, p_1, p_n, and the seller earns

$$\pi(p_0, p_1, p_n, h_n(p_0, p_1, p_n); c_0, c_1) = \sum_{i=0,1,n} D_i(p_0, p_1, p_n, h_n(p_0, p_1, p_n))(p_i - \sigma c_i). \quad (2)$$

A pure pricing strategy perfect Bayesian equilibrium is defined as follows.

Definition. An equilibrium consists of consumers' beliefs $h_n^*(p_0, p_1, p_n): \Re_+^3 \to [0,1]$ and seller's pure pricing strategies $p_i^*(c_0, c_1): [0,1]^2 \to \Re_+$, $i = 0,1,n$, such that

(i) for each pair of costs $(c_0, c_1) \in [0,1] \times [0,1]$ the pricing strategies are optimal given consumers' belief $h_n^*(p_0, p_1, p_n)$:

$\{p_i^*(c_0, c_1)\}_{i=0,1,n}$ maximize $\pi(p_0, p_1, p_n, h_n^*(p_0, p_1, p_n); c_0, c_1)$; and

(ii) consumers' belief $h_n^*(p_0, p_1, p_n)$ gives the true conditional probability that the unlabeled product consists of variety 1, if the seller employs pricing strategies $\{p_i^*(c_0, c_1)\}_{i=0,1,n}$:

$$h_n^*(p_0, p_1, p_n) = \Pr(C_0 \geq C_1 \mid p_0^*(C_0, C_1) = p_0, p_1^*(C_0, C_1) = p_1, p_n^*(C_0, C_1) = p_n).$$

Although in equilibrium consumers have a common belief that follows the rule of Bayesian updating, there are no restrictions on the *out-of-equilibrium* consumers' beliefs, which may vary across consumers. We will allow for heterogeneous out-of-equilibrium consumers' beliefs, whereas h_n becomes a function of x (as well as the posted prices). At out-of-equilibrium prices demand functions are given by $D_i^o = \int_{x\in\Gamma_i} dx$, where $\Gamma_i = \{x : s_i(x, p_i) \geq 0$ and $s_i(x, p_i) \geq s_j(x, p_j)$ for all $j \neq i$, $i, j = 0,1,n\}$ is the subset of consumers who demand variety i. Also, let $P^* = \{(p_0, p_1, p_n) : p_i^*(c_0, c_1) = p_i, i = 0,1,n$ for some $(c_0, c_1)\}$ denote the set of prices generated by the pricing strategy $p_i^*(c_0, c_1)$, $i = 0,1,n$.

We characterize the perfect Bayesian equilibria in which the seller achieves the greatest expected profit (before the seller observes her production costs), which we refer to as the "best" (for the seller) equilibria. There are several reasons why one may be interested in equilibria that maximize the firm's expected profits. From a positive point of view, a firm that convinces its customers to play a best equilibrium has a higher expected valuation than any other, otherwise identical, firm, and thus is more likely to enter and stay in the market. From a normative point of view, this equilibrium provides a useful benchmark for the analysis of the mandatory disclosure policy as we can focus on the social inefficiency (if any) of the privately optimal disclosure and pricing strategies.

A best equilibrium can be recovered as a solution to the seller's *expected*-profit-maximization problem:

$$\max_{\substack{\vec{p}^*:[0,1]^2\to\Re_+^3,\\ h_n^*:\Re_+^3\to[0,1]}} \int_0^1\int_0^1 \pi(\vec{p}^*(c_0,c_1), h_n^*(\vec{p}^*(c_0,c_1)), c_0, c_1) g(c_0,c_1) dc_0 dc_1 \text{ subject to (i) and (ii)}, \quad (3)$$

where $\vec{p} \equiv \{p_0, p_1, p_n\}$ is the vector of prices posted by the seller. In problem (3) constraint (i) states that the seller finds it optimal ex post (after she observes her production costs) to implement the pricing strategy that was chosen ex ante (before she observes her production costs). Constraint (ii) states that consumers' beliefs are given by the true conditional probabilities along the equilibrium path.

In Section 3.1 we analyze the case with symmetric quality ($q_0 = q_1 = q$), and in Section 3.2 we analyze the case with asymmetric quality ($q_0 \neq q_1$).

3.1. Symmetric Quality

As a starting point, it is useful to consider a socially efficient allocation in which each consumer gets the variety that has the lowest sum of production and disutility costs:

$$i^s(x) = \begin{cases} 0, \text{if } s_0(x, \sigma c_0) \geq \max[0, s_1(x, \sigma c_1)] \\ 1, \text{if } s_1(x, \sigma c_1) \geq \max[0, s_0(x, \sigma c_0)] \\ \text{none, if } \max[s_0(x, \sigma c_0), s_1(x, \sigma c_1)] < 0 \end{cases}, \quad x \in [0,1]. \tag{4}$$

In the socially efficient allocation all consumers are served for all realizations of costs if horizontal differentiation and cost variability are small relative to overall quality, i.e. $\max[s_0(x, \sigma c_0), s_1(x, \sigma c_1)] \geq 0$ for all $x, c_0, c_1 \in [0,1]$ if $q \geq \frac{1}{2}t + \sigma$.[9] We first characterize equilibrium when this condition holds, and there are potentially profitable trades with each consumer for all $c_0, c_1 \in [0,1]$.

The search for a best equilibrium by directly solving (3) is a daunting task because to assure that there are no other equilibria in which the seller achieves a greater expected profit, we need to consider all possible consumers' beliefs that follow the rule of Bayesian updating. However, the search for a best equilibrium is simplified by Lemma 1.

Lemma 1. *Suppose that $q_0 = q_1 = q \geq \frac{1}{2}t + \sigma$. In a perfect Bayesian equilibrium the seller's expected profit is less than* $\int_0^1 \int_{c_0}^1 \left(\frac{\max[t + \sigma(c_0 - c_1), 0]^2}{4t} + 2(q - \frac{1}{2}t - \sigma c_0)\right) g(c_0, c_1) dc_0 dc_1$.

[9] Otherwise, $\max[s_0(\frac{1}{2}, \sigma), s_1(\frac{1}{2}, \sigma)] < 0$, and some consumers are not served in the socially efficient allocation for $(c_0, c_1) = (1,1)$.

To establish this upper bound on equilibrium expected profits we assume that consumers *directly* observe (noisy) signals with the content that would have been revealed had the seller *committed* to her pricing strategy before observing input prices.[10] This yields a two-stage optimization problem whereas the seller chooses (1) the structure of *publicly* observed signals, and (2) prices *conditional* on the public signals. Because we assume that these public signals arrive independently of prices, the seller cannot manipulate consumers' beliefs, and the posted prices, in fact, do not reveal any additional information to consumers.

In the proof of Lemma 1, we first show that in an equilibrium in which the seller achieves the highest expected profit, consumers may know that $(C_0, C_1) \in \{(c_0, c_1), (c_1, c_0)\}$ for some c_0, c_1. The probability that $C_0 \le C_1$ conditional on such signals is just the prior probability because G is symmetric, $\Pr(C_0 \le C_1 \mid (C_0, C_1) \in \{(c_0, c_1), (c_1, c_0)\}) = \frac{1}{2}$. Second, we find the prices that maximize the expected profit conditional on $(C_0, C_1) \in \{(c_0, c_1), (c_1, c_0)\}$:

$$\max_{p_0, p_1, p_n} E[\pi(p_0, p_1, p_n, \tfrac{1}{2}; C_0, C_1) \mid (C_0, C_1) \in \{(c_0, c_1), (c_1, c_0)\}]. \tag{5}$$

If in a candidate equilibrium expected profits reach the upper bound established in Lemma 1, then we know that the candidate equilibrium is, in fact, a best equilibrium. It can also be shown that a best equilibrium is essentially unique (up to the specification of out-of-equilibrium beliefs).

Let us consider the following system of consumers' beliefs:

$$h_n(p_0, p_1, p_n, x) = \begin{cases} \frac{1}{2}, \text{ if } (p_0, p_1, p_n) \in P^* \\ h_n^o(p_0, p_1, p_n, x), \text{ if } (p_0, p_1, p_n) \notin P^* \end{cases}. \tag{6}$$

The out-of-equilibrium consumers' beliefs $h_n^o(p_0, p_1, p_n, x)$ are specified as follows:

[10] Recall that in equilibrium consumers use the posted prices to update their beliefs about the realized input costs. The prices send "noisy" public signals when the same prices are offered for different input costs so that the updated probability distribution is not concentrated on a single point. Note that, as usual in Bayesian games, a plethora of customers' beliefs about what the posted prices might imply about the input costs may constitute a perfect Bayesian equilibrium. To find a system of beliefs that maximizes the seller's expected profits, we use a technical trick that consists of letting the seller directly choose what customers know about the actual input costs. To assure that the information structure chosen by the seller can be supported in equilibrium we require that the prices depend *only* on the public information about costs that is directly revealed by the seller (i.e. are measureable with respect to the public signals).

$$h_n^o(p_0, p_1, p_n, x) = \begin{cases} \frac{1}{2}, \text{if } p_n \geq \max[p_0, p_1] \\ 0, \text{if } p_0 \leq p_n < p_1 \\ 1, \text{if } p_1 \leq p_n < p_0 \\ 1_{x \geq (t - p_0 + p_1)/(2t)}, \text{if } p_n < \min[p_0, p_1] \end{cases}, \tag{7}$$

where $1_{x \geq \hat{x}} = 1$ if $x \geq \hat{x}$ and $1_{x \geq \hat{x}} = 0$ if $x < \hat{x}$.

Suppose that $(p_0, p_1, p_n) \notin P^*$. Then, in accordance with (7), for $p_n \geq \max[p_0, p_1]$, all consumers believe that $h_n = \frac{1}{2}$. At such prices and beliefs, we have $s_n(x, p_n) < \max[s_0(x, p_0), s_1(x, p_1)]$ for all $x \in [0,1]$ (possibly with the exception of $x = \frac{1}{2}$), and there is no demand for the unlabeled product at positive prices. If $p_n < \max[p_0, p_1]$, then there are three possibilities that need to be considered. For $p_0 \leq p_n < p_1$ (or $p_1 \leq p_n < p_0$), by (7), we have $s_n(x, p_n) \leq s_0(x, p_0)$ (or $s_n(x, p_n) \leq s_1(x, p_1)$) for all $x \in [0,1]$, because all consumers believe that the variety of unlabeled product is 0 (or 1). Hence, there is no demand for the unlabeled product because the labeled product 0 (or 1) is cheaper. Finally, for $p_n < \min[p_0, p_1]$, all consumers for whom $s_0(x, p_0) \geq (<) s_1(x, p_1)$ believe that the variety of the unlabeled product is 0 (1). Hence, $s_n(x, p_n) > \max[s_0(x, p_0),\ s_1(x, p_1)]$ for all $x \in [0,1]$, and there is no demand for labeled products of either variety.

Thus, the out-of-equilibrium beliefs in (7) are such that by setting prices $(p_0, p_1, p_n) \notin P^*$ with $p_n < \min[p_0, p_1]$, the seller earns at most $\min[p_n, q - \frac{1}{2}t] - \sigma c_n$, and by setting prices $(p_0, p_1, p_n) \notin P^*$ with $p_n \geq \min[p_0, p_1]$, the seller earns at most

$$\pi_L(c_0, c_1) = \max_{p_0, p_1 \leq q} \sum_{i=0,1} D_i^L(p_0, p_1)(p_i - \sigma c_i), \tag{8}$$

where $D_i^L(p_0, p_1) = \min[\frac{1}{2} + \frac{1}{2t}(p_{-i} - p_i),\ \frac{1}{t}(q - p_i)]$ is demand for variety i, and $\pi_L(c_0, c_1)$ is the highest profits that the seller can achieve under full disclosure.

Our main result is the following characterization of the best perfect Bayesian equilibrium that is supported by consumers' beliefs in (6).[11]

[11] All proofs are collected in the Appendix.

Proposition 1 (Symmetric quality). *Suppose that* $q_0 = q_1 = q \geq \frac{1}{2}t + \sigma$. *In the best equilibrium for each* $(c_0, c_1) \in [0,1] \times [0,1]$

1. *consumers do not learn which variety is cheaper for the retailer;*
2. *prices are given by*

$$p_i^*(c_0, c_1) = q - \tfrac{1}{4}\max[t - \sigma \,|\, c_0 - c_1 \,|, 0], \; i = 0,1, \textit{ and } \; p_n^*(c_0, c_1) = q - \tfrac{1}{2}t; \qquad (9)$$

3. *the market shares of each labeled and an unlabeled variety are*

$$x_0^*(c_0, c_1) = 1 - x_1^*(c_0, c_1) = \tfrac{1}{4}\max[1 - \tfrac{\sigma}{t} \,|\, c_0 - c_1 \,|, 0], \textit{ and} \qquad (10)$$

$$x_1^*(c_0, c_1) - x_0^*(c_0, c_1) = 1 - \tfrac{1}{2}\max[1 - \tfrac{\sigma}{t} \,|\, c_0 - c_1 \,|, 0].$$

Even though the market shares of labeled varieties and the unlabeled product depend on the cost differential, consumers never learn which variety is cheaper. The seller offers both labeled and unlabeled products (or just an unlabeled product) when the cost differential is less (greater) than horizontal differentiation, $| c_0 - c_1 | < (\geq) \frac{t}{\sigma}$. The unlabeled product has a dominant market share for all realizations of costs (it is purchased by all consumers in the interval between $x_0^*(c_0, c_1)$ and $x_1^*(c_0, c_1)$).

Were buyers not updating their beliefs, the seller would charge a higher (lower) price for a more expensive (cheaper) variety. However, in equilibrium labeled products are priced similarly in order to hide the identity of the cheaper variety from consumers. The price of labeled products is an increasing piece-wise linear function of the absolute value of the cost differential. Recall that the prices in (9) solve (5), and equate the marginal *conditional expected* profits across the three segments served with products $i = 0,1,n$. Conditional expected profit in (5) can be written as

$$E[\pi(p_0, p_1, p_n, \tfrac{1}{2}; C_0, C_1) \,|\, (C_0, C_1) \in \{(c_0, c_1), (c_1, c_0)\}] \qquad (11)$$

$$= \sum_{i=0,1} D_i(p_0, p_1, p_n, \tfrac{1}{2})(p_i - \tfrac{\sigma}{2}(c_0 + c_1)) + D_n(p_0, p_1, p_n, \tfrac{1}{2})(p_n - \sigma \min[c_0, c_1])$$

$$= \sum_{i=0,1} D_i(p_0, p_1, p_n, \tfrac{1}{2})(p_i - p_n - \tfrac{\sigma}{2} \,|\, c_0 - c_1 \,|) + p_n - \sigma \min[c_0, c_1] \quad ,$$

where $D_i(p_0, p_1, p_n, \frac{1}{2}) = \frac{1}{2} + \frac{p_n - p_i}{t}$, $D_n(p_0, p_1, p_n, \frac{1}{2}) = 1 - \sum_{i=0,1} D_i(p_0, p_1, p_n, \frac{1}{2})$, $i = 0,1$.

The first equality follows because the seller charges the same prices for $(C_0, C_1) = (c_0, c_1)$

and $(C_0, C_1) = (c_1, c_0)$. The second equality follows because the seller can substitute the cheaper variety for the more expensive variety when producing an unlabeled product, but he cannot do that when producing the labeled products. As a result, an increase in the relative cost $\sigma | c_0 - c_1 |$ calls for an expansion of the submarket for an unlabeled variety that becomes relatively cheaper to produce, and contraction of the submarkets for the labeled varieties that, *on average*, become relatively more expensive to produce.

If $\frac{1}{2}t < q < \sigma + \frac{1}{2}t$, such a pricing strategy may no longer be optimal for some input costs. In this case, if both varieties are too expensive, the seller may achieve higher profits by offering labeled varieties at different prices and revealing the identity of the cheaper variety. The following example illustrates.

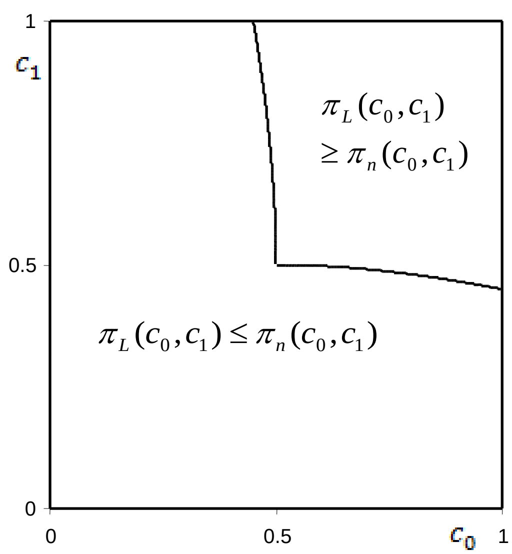

Figure 2. Variety disclosure and input costs with low symmetric quality

Example 1. (Equilibrium with partial and pure labeling) Let $q = t = \sigma = 1$ ($\frac{1}{2}t < q < \sigma + \frac{1}{2}t$ holds). The total profit (sum over the three commodities) from charging not revealing prices in (9) is given by

$$\pi_n(c_0, c_1) = \tfrac{1}{8}(1 - | c_0 - c_1 |)^2 + \tfrac{1}{2} - \min[c_0, c_1]. \tag{12}$$

However, there is another pricing strategy that may generate higher profits. By offering only labeled varieties at "revealing" prices $p_i^L(c_0,c_1) = \frac{1+c_i}{2}$, $i = 0,1$, that maximize (8), the seller earns

$$\pi_L(c_0,c_1) = \tfrac{1}{4}\sum_{i=0,1}(1-c_i)^2 . \tag{13}$$

By comparing (12) and (13), we see that the seller achieves higher profits by offering only labeled products if both varieties are sufficiently expensive, i.e. $\pi_L(c_0,c_1) \geq \pi_n(c_0,c_1)$ if $\min[c_0,c_1] \geq \sqrt{4\max[c_0,c_1]+2} - \max[c_0,c_1] - 1$ (see Figure 2). Note that with symmetric quality the seller is *equally likely* to achieve higher profits by posting "revealing" prices $p_i(c_0,c_1) = \frac{1+c_i}{2}$, $i = 0,1$ when $C_0 > C_1$ or $C_0 < C_1$. Therefore, the buyers do not learn any new information when the seller posts "non-revealing" prices in (9). ■

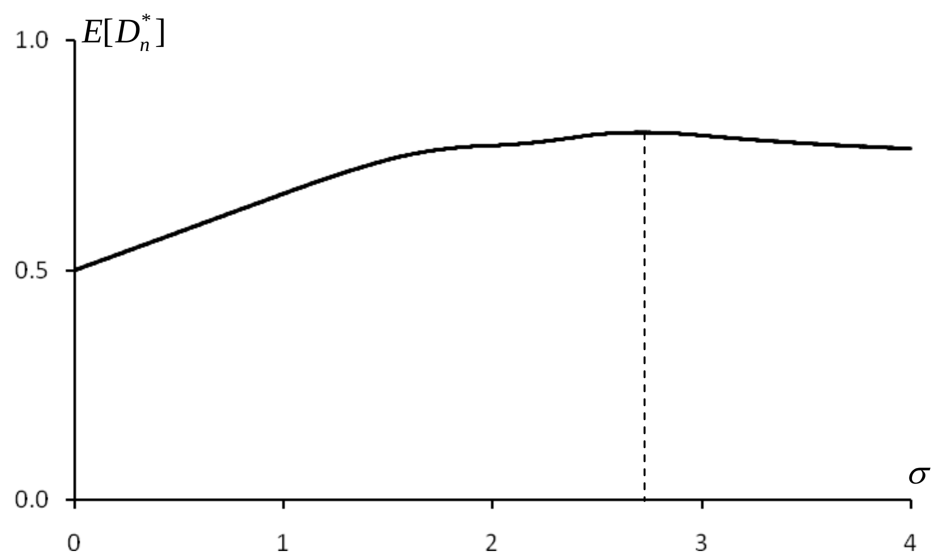

Figure 3. Expected market share of unlabeled products and cost variability

Next we investigate whether an increase in cost variability increases or decreases the supply of an unlabeled variety, $D_n^* = x_1^*(c_0,c_1) - x_0^*(c_0,c_1)$. For $\sigma \in [0, q - \frac{1}{2}t)$, as can be seen from (10), a small increase in σ has a positive effect on D_n^*. However, as Example 1 demonstrates, for $\sigma \geq q - \frac{1}{2}t$ there is no market for unlabeled products at all, if both c_0 and c_1 are sufficiently close to 1. And so, assuming that C_0, C_1 are independently drawn from a uniform distribution, the effect of σ on the *expected* market share of an unlabeled product, $\int_0^1\int_0^1 (x_1^*(c_0,c_1) - x_0^*(c_0,c_1))dc_0 dc_1$, is non-monotone as shown in Figure 3, where $q = 2$ and $t = 1$.

Finally, if $q \le \frac{1}{2}t$, the seller never offers unlabeled products in equilibrium. If the idiosyncratic component of consumer valuations (horizontal differentiation) is too large, uncertainty about the variety of the unlabeled product eliminates demand for it.

3.2. Asymmetric Quality

We now suppose that varieties 0 and 1 differ in overall quality, and assume that $\Delta = q_0 - q_1 > 0$.[12] When the quality differential and cost variability are small relative to the horizontal differentiation, $\Delta + \sigma \le t$, and the average quality is high relative to the cost variability and horizontal differentiation, $\frac{1}{2}(q_0 + q_1) = q \ge \sigma + \frac{1}{2}t$, in the best equilibrium consumers do not glean any new information from prices about the relative input costs. As in the case with symmetric quality, in equilibrium prices maximize expected profit conditional on $(C_0, C_1) \in \{(c_0,c_1),(c_1,c_0)\}$ for some c_0, c_1 (see (5)):

$$\max_{p_0 \le q_0,\, p_1 \le q_1,\, p_n \le q - \frac{1}{2}t} E[\pi(p_0, p_1, p_n, \tfrac{1}{2}; C_0, C_1) \,|\, (C_0,C_1) \in \{(c_0,c_1),(c_1,c_0)\}] \qquad (14)$$

where $D_i(p_0, p_1, p_n, \frac{1}{2}) = \frac{1}{2} + \frac{1}{t}((\frac{1}{2} - i)\Delta + p_n - p_i)$, $D_n(p_0, p_1, p_n, \frac{1}{2}) = \frac{1}{t}(p_0 + p_1 - 2p_n)$, $i = 0{,}1$. It is easy to verify that the prices at which (14) achieves its maximum are given by:

$$p_i^*(c_0,c_1) = q + \tfrac{1}{2}(\tfrac{1}{2} - i)\Delta - \tfrac{1}{4}(t - \sigma\,|\,c_1 - c_0\,|),\ i = 0{,}1, \text{ and } p_n^*(c_0,c_1) = q - \tfrac{1}{2}t. \qquad (15)$$

Using arguments that are similar to the ones used to establish Proposition 1 it can be shown that constraint (i) in problem (3) is satisfied for all c_0, c_1, when the system of consumers' beliefs is given by (6) but with the set of equilibrium prices P^* that is generated by the pricing strategy in (15), and the out-of-equilibrium consumers' beliefs that are specified as follows

[12] The case with $\Delta < 0$ is analogous.

$$h_n^o(p_0, p_1, p_n, x) = \begin{cases} \frac{1}{2}, \text{if } p_n \geq \max[p_0, p_1] \\ 0, \text{if } p_0 \leq p_n < p_1 \\ 1, \text{if } p_1 \leq p_n < p_0 \\ 1_{x \geq (\Delta + t - p_0 + p_1)/(2t)}, \text{if } p_n < \min[p_0, p_1] \end{cases} . \tag{16}$$

(16) assures that the seller does not gain from deviating from the announced pricing strategy in (15) for any c_0, c_1. Thus, the pricing strategy in (15) combined with this system of consumers' beliefs constitute an equilibrium. The variation in equilibrium prices for labeled varieties in (15) only reflects the difference in overall quality but reveals nothing about the identity of the cheaper variety. Although the seller offers the labeled high-quality and low-quality varieties and an unlabeled variety, the market share of the labeled high-quality variety is greater than that of the low-quality variety.

When the quality differential and cost variability are large relative to the horizontal differentiation, $\sigma + \Delta > t$, or the average quality is low relative to cost variability and horizontal differentiation, $q < \sigma + \frac{1}{2}t$**,** in the best equilibrium consumers may learn from prices about which variety is likely to be cheaper. A characterization of the best equilibrium will now depend on the distribution of costs, G. To investigate the effect of quality asymmetry on the equilibrium pricing strategy and the patterns of disclosure, we consider a special case when input costs take only two values and exhibit perfect negative dependence with $\Pr((C_0, C_1) = (1,0)) = \Pr((C_0, C_1) = (0,1)) = \frac{1}{2}$.

For this distribution of costs, in a pure pricing strategy equilibrium, prices necessarily convey either null or full information about the actual costs. To see why, suppose that in equilibrium the seller offers an unlabeled variety for $(c_0, c_1) = (0,1)$ and $h_n \in (0,1)$. Then the seller must (ex post) set the same prices for $(c_0, c_1) = (1,0)$ as well. Otherwise, with only two possible outcomes (either $(C_0, C_1) = (1,0)$ or $(C_0, C_1) = (0,1)$) consumers, who know the seller's pricing strategy, will easily infer from the posted prices which variety is cheaper.

And so, if in the best equilibrium the seller offers an unlabeled variety, then the equilibrium is given by the solution to the following problem:

$$\max_{p_0 \leq q_0,\, p_1 \leq q_1,\, p_n \leq q - \frac{1}{2}t} \sum_{(c_0, c_1) \in \{(1,0),(0,1)\}} \tfrac{1}{2}\pi(p_0, p_1, p_n, \tfrac{1}{2}, c_0, c_1) \text{ subject to} \tag{17a}$$

$$\pi(p_0, p_1, p_n, \tfrac{1}{2}, c_0, c_1) \geq \pi_L(c_0, c_1) \text{ for } (c_0, c_1) \in \{(1,0),\{0,1)\}, \qquad (17b)$$

where $\pi_L(c_0, c_1) = \max_{p_i \leq q_i, i=0,1} \sum_{i=0,1} D_i(p_0, p_1)(p_i - \sigma c_i)$, $D_i(p_0, p_1) = \min[\tfrac{1}{2} + \tfrac{1}{2t}(p_{-i} - p_i)$ $+2(\tfrac{1}{2} - i)\Delta, \tfrac{1}{t}(q_i - p_i)]$ is demand for variety i if the seller deviates from the non-revealing prices. If there exist no prices p_0, p_1, p_n such that the "implementation" constraints (17b) *simultaneously* hold, then in the best equilibrium the seller offers only labeled varieties and earns $\sum_{(c_0,c_1)\in\{(1,0),(0,1)\}} \tfrac{1}{2}\pi_L(c_0, c_1)$.

By solving (17) we obtain the following characterization of the best equilibrium that is supported by the consumers' beliefs in (6) and the out-of-equilibrium beliefs in (16).

Proposition 2 (Asymmetric quality). *Suppose that* $\Pr((C_0, C_1) = (1,0)) = \Pr((C_0, C_1) = (0,1)) = \tfrac{1}{2}$, $\tfrac{1}{2}(q_0 + q_1) = t = 1$, *and* $\Delta \in [0,1]$. *In the best equilibrium the seller offers for each* $(c_0, c_1) \in \{(1,0), (0,1)\}$

I. all three products at $p_0 = \frac{3+\Delta+\sigma}{4}$, $p_1 = \frac{3-\Delta+\sigma}{4}$, *and* $p_n = \tfrac{1}{2}$, *if* $\sigma \leq 1 - \Delta$;

II. the labeled high-quality and an unlabeled variety at $p_0 = \frac{3+\Delta+\sigma}{4}$ *and* $p_n = \tfrac{1}{2}$ *if* $1 - \Delta < \sigma < 1 + \Delta$ *and* $\Delta \leq 2(\sqrt{2} - 1)$, *or* $1 - \Delta < \sigma \leq 1 + \tfrac{1}{2}\Delta$ *and* $\Delta > 2(\sqrt{2} - 1)$;

III. the labeled high-quality and an unlabeled variety at $p_0 = \frac{3+\Delta+\sqrt{(5-2\Delta)}}{4}$ *and* $p_n = \tfrac{1}{2}$, *if* $1 + \tfrac{1}{2}\Delta < \sigma \leq \frac{2\Delta}{(1+\Delta-\sqrt{5-2\Delta})}$ *and* $\Delta > 2(\sqrt{2} - 1)$;

IV. only an unlabeled variety at $p_n = \tfrac{1}{2}$, *if* $\sigma \geq 1 + \Delta$ *and* $\Delta \leq 2(\sqrt{2} - 1)$;

V. only the labeled high-quality variety at $p_0 = \tfrac{1}{2}(1 + \tfrac{1}{2}\Delta)$ *for* $(c_0, c_1) = (0,1)$ *or only the labeled low-quality variety at* $p_1 = \tfrac{1}{2}(1 - \tfrac{1}{2}\Delta)$ *for* $(c_0, c_1) = (1,0)$, *if* $\sigma > \frac{2\Delta}{(1+\Delta-\sqrt{5-2\Delta})}$ *and* $\Delta > 2(\sqrt{2} - 1)$.

Figure 4 depicts the combinations of quality differentials and cost volatilities for which different types of pricing strategies are employed in equilibrium. The seller may offer labeled high-quality and low-quality and an unlabeled variety (area I), only labeled high-quality and an unlabeled variety (areas II and III), only an unlabeled variety (area IV), or only labeled varieties (area V).

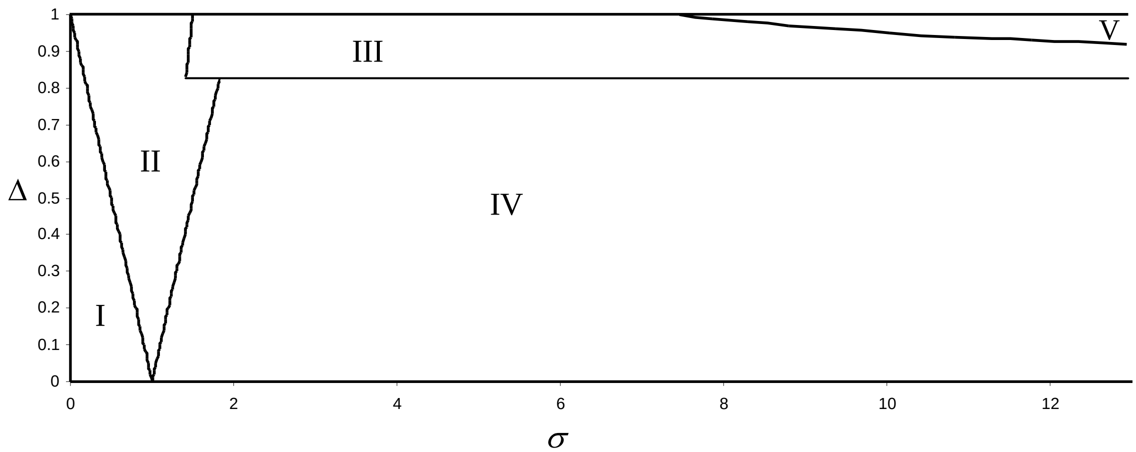

Figure 4. Variety disclosure, pricing strategy, asymmetric quality, and cost variability

If $\sigma \leq 1-\Delta$ (area I), the seller offers all three products (this is a special case of the pricing strategy in (15)). The price premium for the high-quality variety (and its market share) increases with the quality differential. As in the case with symmetric quality, the prices of both labeled varieties increase and their market shares fall when cost variability is greater.

If cost variability is in some intermediate range, $1-\Delta < \sigma < 1+\Delta$ and $\Delta \leq 2(\sqrt{2}-1)$, or $1-\Delta < \sigma \leq 1+\frac{1}{2}\Delta$ and $\Delta > 2(\sqrt{2}-1)$, the seller only labels the high-quality variety and expands the share of the market served with an unlabeled variety (area II). In this case, the low-quality variety is unattractive even for consumers whose ideal variety is close to 1, and the seller does not create a niche market for that variety.

If the quality differential is sufficiently large, $\Delta > 2(\sqrt{2}-1)$, and the cost variability is large (but not too large), $1+\frac{1}{2}\Delta < \sigma \leq \frac{2\Delta}{(1+\Delta-\sqrt{5-2\Delta})}$, the implementation constraint (17b) binds when the high-quality variety is cheap (area III). Then in equilibrium with $(c_0, c_1) = (0,1)$ the seller is indifferent between offering (a) a menu of the labeled high-quality and an unlabeled variety, and (b) posting revealing prices and offering just the labeled high-quality variety at a lower price. The loss in profits for

$(c_0, c_1) = (0,1)$ due to such a reduction in the price of the high-quality variety is offset by the gain in profits for $(c_0, c_1) = (1,0)$ when the seller can keep it a secret that the unlabeled product consists of the low-quality variety.

If the quality differential is not too large, $\Delta \le 2(\sqrt{2} - 1)$, and the cost variability is sufficiently large, $\sigma \ge 1 + \Delta$, the seller offers *only* an unlabeled variety (area IV). Even when the high-quality variety is cheaper, the seller serves the entire market with an unlabeled product because lowering the price for the labeled high-quality variety will reveal to consumers the identity of the unlabeled product. The seller achieves higher expected profits from offering a single product of an unknown variety (complete nondisclosure) than being forced to offer the labeled high-quality variety when it is expensive.

Finally, if both the quality differential and the cost variability are sufficiently large, $\Delta > 2(\sqrt{2} - 1)$ and $\sigma > \frac{2\Delta}{(1+\Delta-\sqrt{5-2\Delta})}$, the seller achieves the highest expected profits by adjusting prices in response to the changes in costs, and offers only the labeled varieties (area V).

Unlike in the case with symmetric quality, the "pricing strategy implementation" constraint for $(c_0, c_1) = (0,1)$ in (17b) binds when the quality differential is large. Because non-revealing prices maximize the seller's *expected* profits, were consumers unable to learn from the posted prices, the seller would prefer to lower the price of the labeled high-quality variety when its actual cost is low. If the gain in profits from serving a larger share of the market with the labeled high-quality variety is sufficiently great, the seller, in fact, prefers to post revealing prices. Of course, this would be anticipated by consumers and ruin the seller's ability to offer an unlabeled variety when the high-quality variety is expensive, $(c_0, c_1) = (1,0)$.

4. Mandatory Disclosure

In this section we consider the effect of mandatory labeling of products with their variety on welfare. We begin with the case when quality is symmetric and sufficiently high, $q_0 = q_1 = q \ge t + \sigma$. Then under both voluntary and mandatory labeling the market is covered (each consumer trades with the seller) for any realization of costs. As a result, mandatory labeling only affects the allocation of varieties across consumers but not the number of consumers who participate in the market.

Under mandatory labeling the equilibrium prices maximize (8), and are given by (see the proof of Proposition 1) $p_i^L(c_0,c_1) = q - \frac{1}{2}t - \frac{1}{4}\sigma(c_{-i} - c_i) \leq p_i^*(c_0,c_1)$, $i = 0,1$, for all c_0, c_1, where the inequality follows by (9). And so, each consumer gains under mandatory labeling. Consumers who used to purchase the labeled varieties under voluntary labeling are better off because their prices decrease. Consumers who used to purchase an unlabeled variety do not lose anything from not being offered an unlabeled product, but gain from the reduction in prices for the labeled varieties.[13]

Next we consider the effect of mandatory labeling on social welfare. Let us compare the monopolist's solution under voluntary and mandatory labeling with the socially efficient allocation. Suppose that variety 0 is cheaper to produce than variety 1, $c_0 \leq c_1$ (the case with $c_0 \geq c_1$ is analogous). Then under voluntary labeling in the market supplied by the monopolist all consumers with $x \leq x_1^*(c_0,c_1) = \min[\frac{3}{4} + \frac{\sigma}{4t}(c_1 - c_0),1]$ consume variety 0 (this includes all consumers who buy labeled variety 0 and the unlabeled product, i.e. $D_0 + D_n$ evaluated at equilibrium prices), and the rest consume variety 1. Under mandatory labeling all consumers with $x \leq x_1^M(c_0,c_1) = \min[\frac{1}{2} + \frac{\sigma}{4t}(c_1 - c_0),1]$ consume variety 0 (this includes all consumers who derive a non-negative surplus from purchasing variety 0 at $p_0^L(c_0,c_1)$), and the rest consume variety 1. In the socially efficient allocation, by (4), all consumers with $x \leq x_1^s(c_0,c_1) = \min[\frac{1}{2} + \frac{\sigma}{2t}(c_1 - c_0),1]$ consume variety 0 (i.e. all consumers for whom $s_0(x,\sigma c_0) \geq s_1(x,\sigma c_1)$), and the rest consume variety 1.

[13] Note that the monopolist extracts the entire expected surplus from the buyers of an unlabeled variety. If consumers' valuations for varieties 0 and 1 are drawn independently both across varieties and across consumers (see Perloff and Salop 1985), consumers with high and similar valuations for both varieties will enjoy some surplus from purchasing an unlabeled variety. Under a more general specification of preferences, it is possible that consumers are worse off under mandatory labeling.

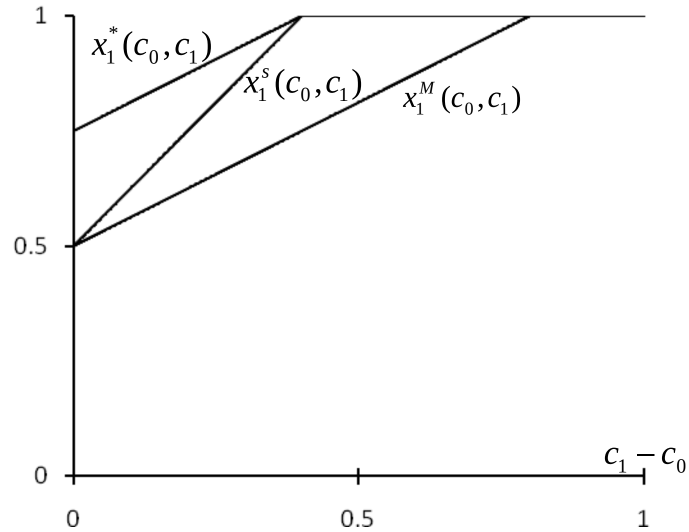

Figure 5. Supply of the cheap variety and cost differential

Therefore, the seller *oversupplies* (*undersupplies*) the cheaper variety under voluntary (mandatory) labeling provided that the input cost differential is not too great: $x_1^M(c_0,c_1) < x_1^s(c_0,c_1) < x_1^*(c_0,c_1)$, if $c_1 - c_0 \in (0, \frac{t}{\sigma})$ and $x_1^M(c_0,c_1) < x_1^s(c_0,c_1) = x^*(c_0,c_1) = 1$, if $c_1 - c_0 \in [\frac{t}{\sigma}, 2\frac{t}{\sigma})$. For very large cost differentials the monopolist's and socially efficient allocation coincide: all consumers are served with the cheaper variety if $c_1 - c_0 \geq 2\frac{t}{\sigma}$. Figure 5 depicts the shares of consumers who get variety 0 in the socially efficient allocation and in monopoly under voluntary and mandatory labeling with $\sigma = \frac{5}{2}, t = 1$. And so, mandatory policy reduces (conversely, increases) the distortion in the relative supply of each variety for small (conversely, large) cost differentials.

Now we can easily determine the effect of mandatory labeling on welfare. Let $W^*(c_0,c_1) = W(x_1^*(c_0,c_1), c_0, c_1)$ and $W^M(c_0,c_1) = W(x^M(c_0,c_1), c_0, c_1)$ denote social welfare (the sum of consumers' surplus and seller's profits) in equilibrium under voluntary and mandatory labeling for given c_0, c_1, where $W(\hat{x}, c_0, c_1) = \int_0^{\hat{x}} (q - tx - \sigma c_0)dx + \int_{\hat{x}}^1 (q - t(1-x) - \sigma c_1)dx$ is social welfare when all consumers with $x \leq \hat{x}$ ($x > \hat{x}$) are served with variety 0 (1).

Proposition 3. *Suppose that* $q_0 = q_1 = q \geq t + \sigma$. *Then* $W^*(c_0, c_1) < W^M(c_0, c_1)$ *for all* $|c_0 - c_1| < \frac{1}{2}\frac{t}{\sigma}$, $W^*(c_0, c_1) \geq W^M(c_0, c_1)$ *for all* $\frac{1}{2}\frac{t}{\sigma} \leq |c_0 - c_1| \leq 2\frac{t}{\sigma}$, *and* $W^*(c_0, c_1) = W^M(c_0, c_1)$ *for all* $|c_0 - c_1| \geq 2\frac{t}{\sigma}$.

The effect of mandatory labeling on social welfare is positive for small cost differentials, it is negative for cost differentials in some intermediate range, and it is null for large cost differentials.

Figure 6 illustrates the effect of mandatory disclosure on *ex ante* expected social welfare (before cost shocks are known) when costs are drawn independently from the uniform distribution, i.e. it depicts $\int_0^1\int_0^1 (W^M(c_0, c_1) - W^*(c_0, c_1))dc_0 dc_1$ as a function of σ for $t = 1$ and $q \geq t + \sigma$. For small σ it is likely that $|c_0 - c_1| < \frac{1}{2}\frac{t}{\sigma}$, which, as shown in Proposition 3, implies that the effect of the policy on welfare is likely positive. However, for large σ, it is likely that $|c_0 - c_1| \geq \frac{1}{2}\frac{t}{\sigma}$, and the losses in social welfare due to mandatory labeling, on average, offset the welfare gains that are achieved when costs are similar across varieties.

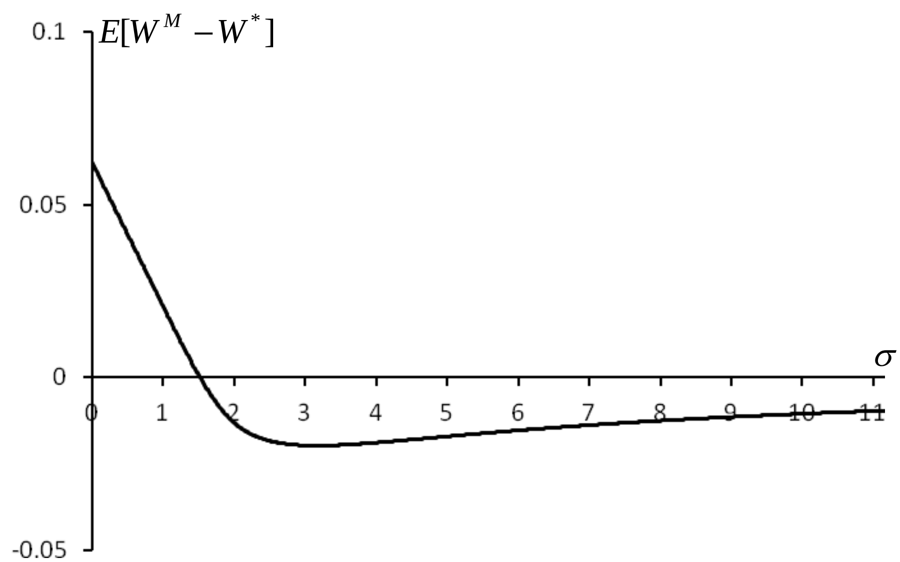

Figure 6. The effect of mandatory labeling on expected welfare and cost variability

Also, it is of interest to investigate how the degree of correlation between cost shocks (keeping the marginal distribution fixed) affects conditions under which mandatory labeling increases expected social welfare. When shocks are more positively (negatively) dependent, small (large) cost differentials are more likely, which implies that welfare is more likely to increase (decrease) under mandatory labeling. For example, if the shocks exhibit perfect positive dependence, i.e. $\Pr(C_0 = C_1) = 1$, the ex post welfare necessarily increases under mandatory labeling. On the other hand, if the shocks exhibit perfect negative dependence, i.e. $\Pr(C_0 = 1 - C_1) = 1$, and are drawn from a uniform distribution, then $E[W^*(C_0, C_1)] < (\geq) E[W^M(C_0, C_1)]$ depending on whether $t > (\leq) \sigma$. To summarize, mandatory labeling tends to decrease expected social welfare when cost variability is large and shocks are negatively correlated.

If $\frac{t}{2} + \sigma \leq q < t + \sigma$, mandatory labeling affects not only the allocation of varieties across consumers but also the total number of consumers who participate in the market. As in the case of the covered market, prices for labeled varieties maximize (8) and fall under mandatory labeling $p_i^L(c_0, c_1) = \frac{1}{2}(q + \sigma c_i) \leq p_i^*(c_0, c_1)$, $i = 0,1$, and consumers are made better off by the policy as they enjoy lower prices without suffering any loss from not being offered an unlabeled variety. However, social welfare is now more likely to decrease because fewer consumers participate in the market under mandatory labeling even though some trade between the seller and each consumer is better than no trade.[14]

Finally, if $\frac{t}{2} < q < \frac{t}{2} + \sigma$, the price for the more expensive labeled variety increases after the policy goes into effect. Nonetheless, the overall impact on consumer welfare (as a group) remains positive, and the impact on social welfare is ambiguous as in the previous two cases. For $q \leq \frac{t}{2}$, the policy has no effect, because the seller never offers an unlabeled variety.

[14] Because the market is necessarily covered when the seller offers an unlabeled product, mandatory labeling can only decrease the number of consumers who participate in the market. Wolinsky (1987) showed that mandatory labeling may decrease social welfare because of its effect on the market size.

Mandatory disclosure with asymmetric quality

Now we consider the effect of mandatory disclosure on welfare when quality is asymmetric across varieties with $\Delta = q_0 - q_1 > 0$. For moderate quality asymmetry, compared with the symmetric quality case, mandatory disclosure is more (less) likely to decrease overall welfare when the high-quality variety is cheaper (more expensive) than the low-quality variety. Suppose that quality asymmetry and cost variability are small relative to the variability in idiosyncratic valuations, $0 < \Delta + \sigma \le t$, and the average quality is high, $q \ge t + \sigma$.[15]

In this case under mandatory labeling the equilibrium prices are given by

$$p_i^L(c_0, c_1) = q + \tfrac{1}{2}(\tfrac{1}{2} - i)\Delta - \tfrac{1}{2}t - \tfrac{1}{4}\sigma(c_{-i} - c_i) \le p_i^*(c_0, c_1),\ i = 0,1,$$

where the inequality follows by (15), which confirms that consumers are made better off. Now the supply of the high-quality variety under mandatory labeling is given by $x_1^M(c_0, c_1) = \frac{1}{2} + \frac{\sigma}{4t}(c_1 - c_0) + \frac{\Delta}{4t}$, whereas under the socially efficient allocation it is given by $x_1^s(c_0, c_1) = \frac{1}{2} + \frac{\sigma}{2t}(c_1 - c_0) + \frac{\Delta}{2t}$. For $c_0 \le c_1$ ($c_0 > c_1$) the supply of the high-quality variety under voluntary labeling is given by $x_1^*(c_0, c_1) = \frac{3}{4} + \frac{\sigma}{4t}(c_1 - c_0) + \frac{\Delta}{4t}$ ($x_1^*(c_0, c_1) = \frac{1}{4} + \frac{\sigma}{4t}(c_1 - c_0) + \frac{\Delta}{4t}$).

Substituting $x_1^*(c_0, c_1)$ and $x_1^M(c_0, c_1)$ in $W(\hat{x}, c_0, c_1) = \int_0^{\hat{x}}(q_0 - tx - \sigma c_0)dx + \int_{\hat{x}}^1 (q_1 - t(1-x) - \sigma c_1)dx$, we find that the change in *ex post* social welfare due to full disclosure is given by

$$W^M(c_0, c_1) - W^*(c_0, c_1) = \begin{cases} \frac{1}{8}(\frac{1}{2}t - \sigma(c_1 - c_0) - \Delta), \text{if } \ c_0 \le c_1 \\ \frac{1}{8}(\frac{1}{2}t - \sigma(c_0 - c_1) + \Delta), \text{if } \ c_0 > c_1 \end{cases}. \tag{18}$$

As shown in (18), a greater quality asymmetry decreases (increases) $W^M(c_0, c_1) - W^*(c_0, c_1)$ for $c_0 \le c_1$ ($c_0 > c_1$). As the quality differential, Δ, increases, for $c_0 \le c_1$ the distortion due to the undersupply of the high-quality variety *worsens* under mandatory

[15] The first condition assures that the seller finds it optimal to target the segments of consumers with strong preference for a particular variety and the segment of indifferent consumers with offers tailored to their preferences (i.e. labeled "0", "1", and an unlabeled product). The second condition assures that the market is covered before and after the policy, so that the policy only affects the relative varietal supply rather than the overall volume of sales.

labeling relative to the distortion due to the oversupply of the high-quality variety under voluntary labeling. But, for $c_0 > c_1$ the distortion due to the undersupply of the high-quality variety is *less severe* under mandatory labeling relative to the distortion due to the undersupply of the high-quality variety under voluntary labeling.

Yet, a small increase in quality asymmetry has no impact on the change in expected social welfare due to full disclosure, $dE[W^M(C_0,C_1) - W^*(C_0,C_1)]/d\Delta = 0$, because the distribution of C_0, C_1 is symmetric. This is because a small increase in quality asymmetry increases the supply of the high-quality variety at the same rate before and after mandatory disclosure.

Nonetheless, for *large* quality asymmetry mandatory disclosure may increase expected social welfare even when relative input cost variability is large. Consider the special case with negatively dependent binary cost shocks in Section 3.2 and suppose that $\sigma > 1+\Delta$ and $\Delta < 2(\sqrt{2}-1)$ (area IV in Figure 3). With these parameters the seller supplies only the least-cost variety before and after the policy, but the market size under mandatory disclosure depends on which variety is cheaper. Under voluntary labeling we have $x_1^*(0,1) = 1$ and $x_1^*(1,0) = 0$, so that $W^*(0,1) = \int_0^1 (q_0 - x)dx = \frac{1}{2} + \Delta$, $W^*(1,0) = \int_0^1 (q_1 - (1-x))dx = \frac{1}{2} - \Delta$, and $E[W^*(C_0,C_1)] = \frac{1}{2}$. Under mandatory labeling, as shown in the proof of Proposition 2, the supply of variety 0 is $\frac{1}{2}q_0$ for $(c_0,c_1) = (0,1)$, and the supply of variety 1 is $\frac{1}{2}q_1$ for $(c_0,c_1) = (1,0)$, so that $W^M(0,1) = \int_0^{0.5q_0} (q_0 - x)dx$ $= \frac{3}{8}(1+\Delta)^2$, $W^M(1,0) = \int_{0.5q_1}^1 (q_1 - (1-x))dx = \frac{3}{8}(1-\Delta)^2$, and $E[W^M(C_0,C_1)] = \frac{3}{8}(1+\Delta^2)$. And so, for $\Delta > \frac{1}{\sqrt{3}}$ mandatory labeling *increases* expected social welfare and the gain in welfare is increasing with Δ. If quality asymmetry is sufficiently large, welfare gains from avoiding overconsumption of the low-quality variety when $(c_0,c_1) = (1,0)$ offset welfare losses from underconsumption of the high-quality variety when $(c_0,c_1) = (0,1)$.

5. Competition

Here we show that product variety may not be disclosed in equilibrium with competition among multi-product sellers. Consider a market with two spatially differentiated firms, *A* and *B*, that are located at the opposite ends of the "street" of unit length (see Figure 7). Both firms source varieties, 0 and 1, in the same upstream market (i.e. the realizations of C_0, C_1 are common to both firms). Firms are price-takers in the upstream market but independently choose prices and disclosure strategy in the downstream market.

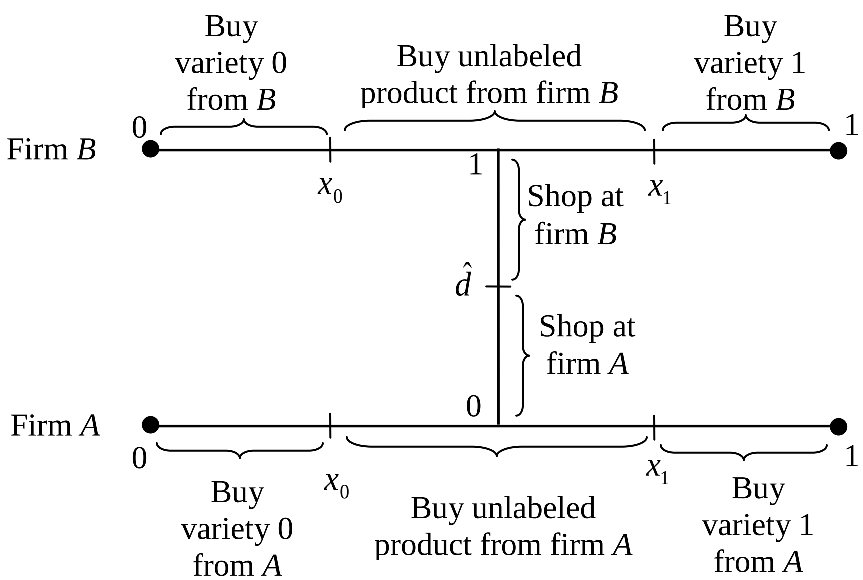

Figure 7. Spatially differentiated firms and purchasing decisions

Now each buyer is characterized by two "location" parameters $x \in [0,1]$ and $d \in [0,1]$, where, as before, x is the location of the buyer's ideal variety in the product space, and d is the buyer's address on the street. For each buyer his taste x and address d are drawn independently from a uniform distribution on the unit interval. A consumer with (x,d) who buys a unit of variety $i = 0,1,n$ from firm *A* (respectively, *B*) at price $p_{i,A}$ ($p_{i,B}$) obtains expected utility $s_i(x, p_{i,A}) - \beta d$ (respectively, $s_i(x, p_{i,B}) - \beta(1-d)$), where β is the traveling cost (both ways) per unit of distance. We assume that the traveling cost is not too high, $0 < \beta < q - \frac{t}{2}$, so that firms are in direct competition with each other. We also suppose that cost shocks are binary and negatively dependent, $\Pr((C_0, C_1) = (1,0)) = \Pr((C_0, C_1) = (0,1)) = \frac{1}{2}$, and cost variability is high, $q_0 = q_1 = q \leq \sigma$, so that in equilibrium only variety i with $c_i = 0$ is offered for sale.

Consider an equilibrium in which both firms offer only an unlabeled variety, and consumers' beliefs are unchanged from their priors. That is, $h_{n,A} = h_{n,B} = h_n = \frac{1}{2}$, so that $s_n(x, p_{n,j}) = q - \frac{1}{2}t - p_{n,j}$, $j = A, B$, where $h_{n,j}$ is the consumers' belief that an unlabeled product supplied by firm j consists of variety 1. We assume that in equilibrium all consumers are served in the market. Then all consumers with

$$s_n(x, p_{n,A}) - \beta d \geq (<) s_n(x, p_{n,B}) - \beta(1-d) \tag{19}$$

buy one unit of an unlabeled variety from firm *A* (conversely, firm *B*). And so, by (19), all consumers with $d \leq (>) \hat{d} = 1 + \frac{p_{n,B} - p_{n,A}}{2\beta}$ shop at firm *A* (*B*), and each firm earns

$$\max_{p_{n,j} \leq q - \frac{1}{2}t} \pi_j(p_{n,A}, p_{n,B}) = (\tfrac{1}{2} + \tfrac{p_{n,-j} - p_{n,j}}{2\beta}) p_{n,j}, \; j = A, B. \tag{20}$$

It is easy to verify that the Nash-Bertrand equilibrium (conditional on both firms offering only an unlabeled variety) is given by $p_{n,A} = p_{n,B} = \beta$, and each firm earns $\frac{1}{2}\beta$.

Now we show that neither firm wants to deviate and offer a labeled product. Suppose to the contrary that a firm deviates and offers a labeled variety (possibly along with an unlabeled variety). Then consumers immediately find out which variety is cheaper because $q \leq \sigma$ and firms will never supply the more expensive variety. This leads to full disclosure of the identity of the variety that is offered by *both* firms. Suppose that $(c_0, c_1) = (0,1)$. If firm *A* deviates and offers labeled variety 0 at $p_{0,A}$, then all consumers with

$$s_0(x, p_{0,A}) - \beta d = q - tx - p_{0,A} - \beta d \geq \max[q - tx - p_{n,B} - \beta(1-d), 0], \tag{21}$$

will shop at firm A, where $p_{n,B} = \beta$. And so, firm *A* that labels its products earns at most

$$\max_{p_{0,A}} \pi_A(p_{0,A}, p_{n,B}) = \max_{p_{0,A}} \int_0^1 \min[\tfrac{1}{2} + \tfrac{p_{n,B} - p_{0,A}}{2\beta}, \tfrac{q - tx - p_{0,A}}{\beta}] dx p_{0,A} \tag{22}$$

$$\leq \max_{p_{0,A}} (\tfrac{1}{2} + \tfrac{p_{n,B} - p_{0,A}}{2\beta}) p_{0,A} = \max_{p_{n,A}} (\tfrac{1}{2} + \tfrac{p_{n,B} - p_{n,A}}{2\beta}) p_{n,A} = \max_{p_{n,A} \leq q - \frac{1}{2}t} \pi_A(p_{n,A}, p_{n,B}),$$

where the first equality follows by (21), and the last equality follows by (20). This shows that neither firm can gain from labeling its products. Furthermore, the inequality in (22) is strict, and therefore each firm strictly loses from deviating for $\beta > \frac{q-t}{2}$.

Competition does not necessarily lead to disclosure of the identity of the currently available variety because labeling cannot increase sales for the disclosing firm. On the one hand, consumers, who prefer the currently available variety, are attracted by the cheap unlabeled product offered by the competitor (that consumers now know consists of their preferred variety). On the other hand, consumers, who prefer the currently unavailable variety and were previously purchasing an unlabeled variety, may now prefer to stay out of the market.[16]

6. Conclusions

We have developed a theory of product information disclosure through labeling by a multi-product firm that faces random input costs. Compared to the literature on quality disclosure (Milgrom 2008), the approach adopted in this paper is more general since it allows for "incomplete disclosure," i.e. the case in which the firm can optimally choose to simultaneously supply the products with disclosed and undisclosed attributes. In our model nondisclosure of variety is due to two-sided uncertainty whereas consumers do not know which variety is cheaper to supply and the firm does not observe buyers' preferences.

The main findings of the paper are that (i) full nondisclosure can occur in equilibrium even when disclosure *per se* is costless, (ii) mandatory disclosure can reduce welfare even when all consumers participate in the market before and after the policy is implemented and when the implementation of the policy does not add additional costs, (iii) competition might not lead to disclosure. We show that the extent of nondisclosure depends on the difference in overall quality, heterogeneity in consumer preferences, and cost variability. Furthermore, we show that in imperfectly competitive markets regulation by transparency may not automatically increase welfare because distortions in allocation of varieties across consumers continue to exist under full disclosure. We find that mandatory disclosure of variety *decreases* welfare when relative input costs are volatile and varieties are similar in overall quality. Welfare falls because mandatory disclosure may not only reduce the size of the market, but also worsen the distortion in

[16] Wolinsky (1987) considers a duopoly model where each firm i supplies a single variety (brand) i and consumers cannot distinguish between brands (i.e. between characteristics of products supplied by different firms) unless they are labeled as such.

the allocation of the market shares across varieties: the market share allocated to the cheaper variety tends to be too large under voluntary disclosure, but it tends to be too small under mandatory disclosure.

When varieties are differentiated by experience attributes, a more realistic assumption is that consumers are initially uninformed about their valuations for different varieties and slowly learn about them by purchasing different products over time (Bergemann and Valimaki 2006). With consumer learning the provision of information about product variety has two additional "dynamic" effects that are absent in the static setting: (i) Inexperienced consumers (i.e. those who have not tried one or both varieties) are willing to pay *more* because they will be able to make better purchasing decisions *in the future* if they know which variety they buy today; (ii) Incompletely experienced consumers (i.e. those who have tried only one variety) with negative experiences may buy *less frequently* because they stop buying the variety for which they have low valuations as soon as they learn about it. An interesting distinction is whether, without labels, consumers can tell which varieties they have already tried. If they cannot, withholding the identity of a product's variety benefits the seller because consumers with low valuations buy more frequently and stay in the market longer as they are not sure whether or not they have encountered both varieties in their previous trials and keep on hoping that the variety that they like is still out there. Our goal in future work is to sort out these effects and to explore optimal disclosure of product characteristics in a dynamic model with consumer learning.

Appendix

To prove Lemma 1 it will be useful to establish the following property of the profit function. Let

$$\hat{\pi}(h_n, c_0, c_1) = \max_{p_0, p_1, p_n} \pi(p_0, p_1, p_n, h_n, c_0, c_1) \tag{A1}$$

denote the maximum profits for given costs c_0, c_1 and fixed consumers' beliefs h_n (here h_n is a constant number rather than a function of the posted prices).

Lemma 0. *Suppose that* $q_0 = q_1 = q \geq \frac{1}{2}t + \sigma$. *Then* $\hat{\pi}(h_n, c_0, c_1)$ *is unimodal in* h_n *with the peak at* $h_n = \frac{1}{2}$ *for all* $c_0, c_1 \in [0,1]$.

Proof: Suppose that $c_0 \leq c_1$ and consider the seller's problem of choosing prices to maximize $\pi(p_0, p_1, p_n, h_n, c_0, c_1)$ for given fixed h_n, c_0, and c_1.

If $h_n \in (0, \frac{1}{2})$, then $\partial s_0(x, p_0)/\partial x < \partial s_n(x, p_n)/\partial x < 0 < \partial s_1(x, p_1)/\partial x$. Hence, provided that all three products are offered, (1) becomes:

$$s_0(x_0, p_0) = q_0 - tx_0 - p_0 = (1-h_n)(q_0 - tx_0) + h_n(q_1 - t(1-x_0)) - p_n = s_n(x_0, p_n) \tag{A2}$$

$$s_n(y_1, p_n) = (1-h_n)(q_0 - ty_1) + h_n(q_1 - t(1-y_1)) - p_n = 0$$

$$s_1(x_1, p_1) = q_1 - t(1-x_1) - p_1 = 0,$$

where $0 \leq x_0 = y_0 < y_1 \leq x_1 \leq 1$. To proceed, it will be convenient to work with the system of inverse demand functions whereas prices p_i, $i = 0,1,n$, are functions of the marginal types x_i and y_i, $i = 0,1$, and consumers' beliefs h_n. From (A2) it follows that $p_0(x_0, y_1, h_n) = p_n(y_1, h_n) + th_n(1-2x_0)$, $p_n(y_1, h_n) = q - t((1-h_n)y_1 + h_n(1-y_1))$, and $p_1(x_1) = q - t(1-x_1)$. And so, the profit function can be rewritten as

$\pi(x_0, y_1, x_1, h_n, c_0, c_1) = x_0(p_0(x_0, y_1, h_n) - \sigma c_0) + (y_1 - x_0)(p_n(y_1, h_n) - \sigma c_0)$
$+ (1-x_1)(p_1(x_1) - \sigma c_1)$.

Similarly, if $h_n \in (\frac{1}{2}, 1)$, then the profit function becomes $\pi(x_0, y_0, x_1, h_n, c_0, c_1)$
$= x_0(p_0(x_0) - \sigma c_0) + (x_1 - y_0)(p_n(y_0, h_n) - \sigma c_0) + (1-x_1)\ (p_1(y_0, x_1, h_n) - \sigma c_1)$, where $p_0(x_0) = q - tx_0$, $p_n(y_0, h_n) = q - t((1-h_n)y_0 + h_n(1-y_0))$, and $p_1(y_0, x_1, h_n)$
$= p_n(y_0, h_n) - t(1-h_n)(1-2x_1)$.

Because $\pi(x_0, y_1, x_1, h_n, c_0, c_1)$ is linear in h_n on $(0, \frac{1}{2})$ and $\pi(x_0, y_0, x_1, h_n, c_0, c_1)$ is linear in h_n on $(\frac{1}{2}, 1)$, by the envelope theorem, it follows that $\hat{\pi}(h_n, c_0, c_1)$ achieves its maximum at $h_n = \frac{1}{2}$ if $\hat{\pi}(\frac{1}{2}, c_0, c_1) \geq \max[\hat{\pi}(0, c_0, c_1), \hat{\pi}(1, c_0, c_1)]$. It is easy to verify that

$$\hat{\pi}(0, c_0, c_1) = \begin{cases} \frac{(q-\sigma c_0)^2}{4t} + \frac{(q-\sigma c_1)^2}{4t}, \text{ if } q \leq t + \sigma \frac{c_0 + c_1}{2} \\ q - \frac{1}{2}t - \sigma \frac{c_0 + c_1}{2} + \frac{(\sigma(c_0 - c_1))^2}{4t}, \text{ if } q > t + \sigma \frac{c_0 + c_1}{2} \text{ and } \sigma \frac{c_1 - c_0}{2} \leq t, \\ q - t - \sigma c_0, \text{ if } q > t + \sigma \frac{c_0 + c_1}{2} \text{ and } \sigma \frac{c_1 - c_0}{4} > t \end{cases} \tag{A3}$$

$$\hat{\pi}(1, c_0, c_1) = \begin{cases} \frac{(q-\sigma c_0)^2}{4t} + \frac{(q-\sigma c_0)^2}{4t}, \text{ if } q \leq t + \sigma c_0 \\ q - \frac{1}{2}t - \sigma c_0, \text{ if } q > t + \sigma c_0 \end{cases}, \text{ and} \tag{A4}$$

$$\hat{\pi}(\tfrac{1}{2}, c_0, c_1) = q - \tfrac{1}{2}t - \sigma c_0 + \tfrac{t}{16} + \tfrac{t}{16}\max[1 + 2\sigma \tfrac{c_0 - c_1}{t}, 0]^2. \tag{A5}$$

By comparing (A3) and (A4), it follows that $\hat{\pi}(1, c_0, c_1) \geq \hat{\pi}(0, c_0, c_1)$ for all $c_0, c_1 \in [0,1]$, and so we only need to show that

$$\hat{\pi}(\tfrac{1}{2}, c_0, c_1) \geq \hat{\pi}(1, c_0, c_1). \tag{A6}$$

By comparing (A4) and (A5), it immediately follows that (A6) holds when $q > t + \sigma c_0$. And so, it only remains to show that (A6) also holds when $q \leq t + \sigma c_0$. Note that $\sigma + \frac{1}{2}t \leq q \leq t + \sigma c_0$ implies $1 \leq \frac{t}{2\sigma} + c_0$, so that (A6) is implied by

$$q - \tfrac{1}{2}t - \sigma c_0 + \tfrac{t}{16} + \tfrac{1}{16t}(t + 2\sigma(c_0 - c_1))^2 \geq \tfrac{(q-\sigma c_0)^2}{2t}. \tag{A7}$$

Because the left-hand side of (A7) is non-increasing in c_1, we are done if we show that (A7) holds for $c_1 = 1$. Substituting $c_1 = 1$, upon some manipulation, we can rewrite (A7) as

$$\tfrac{1}{2}(\tfrac{1}{4}t^2 + (\tfrac{1}{2}t - \sigma(1 - c_0))^2) \geq (t + \sigma c_0 - q)^2.$$

But, by $\frac{1}{2}t + \sigma \leq q$, we have

$$(t + \sigma c_0 - q)^2 \leq (\tfrac{1}{2}t - \sigma(1 - c_0))^2 \leq \tfrac{1}{2}(\tfrac{1}{4}t^2 + (\tfrac{1}{2}t - \sigma(1 - c_0))^2),$$

which verifies that (A7) holds. ■

Proof of Lemma 1: The proof proceeds in three steps. In Step 1, we restate (3) as a problem of optimizing over public signals and pricing strategy conditional on those signals. In Step 2, we show that public signals should be uninformative about the identity of the cheaper variety. In Step 3, we derive the exact formula.

Step 1. Suppose that in a best equilibrium the pure pricing strategy is a garbled signal of relative costs, i.e.

$$\Pr(C_0 \leq C_1 \mid p_i^*(C_0, C_1) = p_i, i = 0,1,n) \in (0,1) \text{ for each } (p_0, p_1, p_n) \in P^*. \tag{A8}$$

Then the pricing strategy $p_i^*(c_0, c_1)$, $i = 0,1,n$, generates a collection of subsets $\Omega = \{\mathrm{C}_z\}_{z=0}^{K}$, $0 \leq K \leq \infty$, where each $\mathrm{C}_z = \{(c_0, c_1) : p_i^*(c_0, c_1) = p_i, i = 0,1,n\}$ for some $(p_0, p_1, p_n) \in P^*$, $\mathrm{C}_z \subseteq [0,1]\times[0,1]$, $\mathrm{C}_z \cap \mathrm{C}_k = \varnothing$ for all $z \neq k$, $\bigcup_{z=0}^{T} \mathrm{C}_z = [0,1]\times[0,1]$, and $\iint_{\substack{(c_0,c_1)\in \mathrm{C}_z \\ c_0 \leq c_1}} g(c_0, c_1) dc_0 dc_1 < \iint_{(c_0,c_1)\in \mathrm{C}_z} g(c_0, c_1) dc_0 dc_1$. The last inequality follows from (A8).

Then, in accordance with the Bayesian updating, consumers' beliefs are given by:

$$h_n(p_0, p_1, p_n) = h_n(\mathrm{C}_z) = \Pr(C_0 \geq C_1 \mid (C_0, C_1) \in \mathrm{C}_z) = \frac{\iint_{\substack{(c_0,c_1)\in \mathrm{C}_z \\ c_0 \geq c_1}} g(c_0, c_1) dc_0 dc_1}{\iint_{(c_0,c_1)\in \mathrm{C}_z} g(c_0, c_1) dc_0 dc_1},$$

where $\mathrm{C}_z = \{(c_0, c_1) : p_i^*(c_0, c_1) = p_i, i = 0,1,n\}$. Therefore, there is no loss of generality in assuming that consumers observe signals $Z \in \{0,..., K\}$ with $\Pr(Z = z \mid (C_0, C_1) \in \mathrm{C}_z)$ $= 1$ and $\Pr(Z = z \mid (C_0, C_1) \notin \mathrm{C}_z) = 0$.

And so, we consider the following approximation to (3):

$$\max_{\{p_0(.), p_1(.), p_n(.), \mathrm{C}_z\}_{z=0}^{K}} \sum_{z=0}^{K} \iint_{(c_0,c_1)\in \mathrm{C}_z} \pi(p_0(\mathrm{C}_z), p_1(\mathrm{C}_z), p_n(\mathrm{C}_z), h_n(\mathrm{C}_z), c_0, c_1) g(c_0, c_1) dc_0 dc_1 \tag{A9}$$

$$= \max_{\{p_0(.), p_1(.), p_n(.), \mathrm{C}_z\}_{z=0}^{K}} \sum_{z=0}^{K} \iint_{(c_0,c_1)\in \mathrm{C}_z} \sum_{i=0,1,n} D_i(p_0(\mathrm{C}_z), p_1(\mathrm{C}_z), p_n(\mathrm{C}_z), h_n(\mathrm{C}_z))(p_i - \sigma c_i) g(c_0, c_1) dc_0 dc_1$$

$$= \max_{\{\mathrm{C}_z\}_{z=0}^{K}} \sum_{z=0}^{K} \max_{p_0(\mathrm{C}_z), p_1(\mathrm{C}_z), p_n(\mathrm{C}_z)} \iint_{(c_0,c_1)\in \mathrm{C}_z} dG(c_0, c_1) \sum_{i=0,1,n} D_i(p_0(\mathrm{C}_z), p_1(\mathrm{C}_z), p_n(\mathrm{C}_z), h_n(\mathrm{C}_z))(p_i(\mathrm{C}_z) - \sigma \frac{\iint_{(c_0,c_1)\in \mathrm{C}_z} c_i dG(c_0, c_1)}{\iint_{(c_0,c_1)\in \mathrm{C}_z} dG(c_0, c_1)})$$

$$= \max_{\{\mathrm{C}_z\}_{z=0}^{K}} \sum_{z=0}^{K} \hat{\pi}(h_n(\mathrm{C}_z), c_0(\mathrm{C}_z), c_1(\mathrm{C}_z)) \iint_{(c_0,c_1)\in \mathrm{C}_z} dG(c_0, c_1),$$

where $c_i(\mathrm{C}_z) = E[C_i \mid (C_0, C_1) \in \mathrm{C}_z] = \iint\limits_{(c_0,c_1)\in \mathrm{C}_z} c_i g(c_0, c_1) dc_0 dc_1 \Big/ \iint\limits_{(c_0,c_1)\in \mathrm{C}_z} g(c_0, c_1) dc_0 dc_1$, is the expected cost of variety i conditional on $(C_0, C_1) \in \mathrm{C}_z$, and $p_i(\mathrm{C}_z) = p_i(c_0, c_1)$ for all $(c_0, c_1) \in \mathrm{C}_z$, $i = 0,1,n$ and each z.

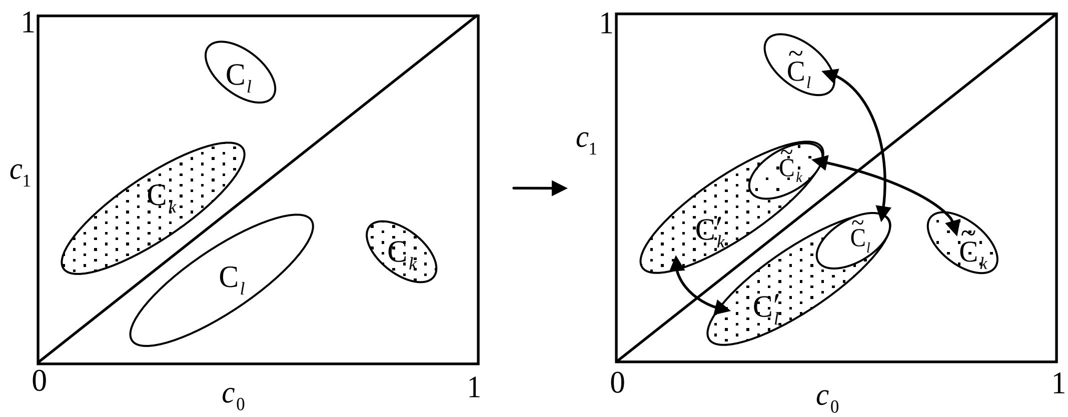

Figure 8. Elements of Ω and $\tilde{\Omega}$

Step 2. It is convenient to view (A9) as a two-stage optimization problem: (1) find maximum profits for given $\mathrm{C}_z \in \Omega$, and (2) find an optimal Ω. We first show that at optimum $h_n(\mathrm{C}_z) = \frac{1}{2}$ for each z. We argue by contradiction. So suppose that there exists $\mathrm{C}_k \in \Omega$ with $h_n(\mathrm{C}_k) < \frac{1}{2}$ (the case with $h_n(\mathrm{C}_k) > \frac{1}{2}$ is analogous). Without loss of generality, we focus on a symmetric solution whereas for each $\mathrm{C}_z \in \Omega$ there exists a "mirror" set $\mathrm{C}_s \in \Omega$, $z \neq s$, such that $(c_0, c_1) \in \mathrm{C}_z$ if and only if $(c_1, c_0) \in \mathrm{C}_s$. Then, by symmetry, there also exists $\mathrm{C}_l \in \Omega$ with

$$\iint\limits_{(c_0,c_1)\in \mathrm{C}_k} dG(c_0, c_1) = \iint\limits_{(c_0,c_1)\in \mathrm{C}_l} dG(c_0, c_1) \text{ and } \iint\limits_{\substack{(c_0,c_1)\in \mathrm{C}_k \\ c_0 \le c_1}} dG(c_0, c_1) = \iint\limits_{\substack{(c_0,c_1)\in \mathrm{C}_l \\ c_0 \ge c_1}} dG(c_0, c_1), \qquad \text{(A10)}$$

so that $h_n(\mathrm{C}_l) = 1 - h_n(\mathrm{C}_k) > \frac{1}{2}$. This is illustrated in the first panel in Figure 8.

Consider a transformed (more fine) cover $\tilde{\Omega} = \{\tilde{\mathrm{C}}_z\}_{z=0}^{K+1}$, where $\tilde{\mathrm{C}}_z = \mathrm{C}_z$ for all $z \neq k, l$, $\tilde{\mathrm{C}}_k = \mathrm{C}_k \setminus \mathrm{C}'_k$, $\tilde{\mathrm{C}}_l = \mathrm{C}_l \setminus \mathrm{C}'_l$, $\tilde{\mathrm{C}}_{K+1} = \mathrm{C}'_k \cup \mathrm{C}'_l$, and $\mathrm{C}'_k \subset \{(c_0, c_1) \in \mathrm{C}_k : c_0 \le c_1\}$ and $\mathrm{C}'_l \subset \{(c_0, c_1) \in \mathrm{C}'_l : c_0 \ge c_1\}$ are such that

$$\iint_{(c_0,c_1)\in C'_k} g(c_0,c_1)dc_0dc_1 = \iint_{\substack{(c_0,c_1)\in C_k \\ c_0\le c_1}} g(c_0,c_1)dc_0dc_1 - \iint_{\substack{(c_0,c_1)\in C_k \\ c_0\ge c_1}} g(c_0,c_1)dc_0dc_1 \text{ and} \tag{A11}$$

$$\iint_{(c_0,c_1)\in C'_l} g(c_0,c_1)dc_0dc_1 = \iint_{\substack{(c_0,c_1)\in C_l \\ c_0\ge c_1}} g(c_0,c_1)dc_0dc_1 - \iint_{\substack{(c_0,c_1)\in C_l \\ c_0\le c_1}} g(c_0,c_1)dc_0dc_1 .$$

By (A10) and (A11), we have $\iint_{(c_0,c_1)\in C'_k} g(c_0,c_1)dc_0dc_1 = \iint_{(c_0,c_1)\in C'_l} g(c_0,c_1)dc_0dc_1$, and

$$h_n(\tilde{C}_k) = h_n(\tilde{C}_l) = h_n(\tilde{C}_{K+1}) = \tfrac{1}{2} . \tag{A12}$$

Now, by (A9), we have

$$\sum_{z=0}^{K} \iint_{(c_0,c_1)\in C_z} \hat{\pi}(h_n(C_z), c_0(C_z), c_1(C_z)) g(c_0,c_1)dc_0dc_1$$

$$< \sum_{z=0}^{K} \iint_{(c_0,c_1)\in C_z} \hat{\pi}(h_n(\tilde{C}_z), c_0(C_z), c_1(C_z)) g(c_0,c_1)dc_0dc_1$$

$$\le \sum_{z=0}^{K+1} \iint_{(c_0,c_1)\in \tilde{C}_z} \hat{\pi}(h_n(\tilde{C}_z), c_0(\tilde{C}_z), c_1(\tilde{C}_z)) g(c_0,c_1)dc_0dc_1 .$$

The first (strict) inequality follows because, by assumption, $h_n(\tilde{C}_z) = h_n(C_z)$ and $\hat{\pi}(h_n(C_z), c_0(C_z), c_1(C_z)) = \hat{\pi}(h_n(\tilde{C}_z), c_0(C_z), c_1(C_z))$ for all $z \ne k,l$, and $\hat{\pi}(h_n(C_z), c_0(C_z), c_1(C_z)) < \hat{\pi}(h_n(\tilde{C}_z), c_0(C_z), c_1(C_z))$ for $z = k,l$, where the inequality follows from Lemma 0 because, by construction, $h_n(C_k) < h_n(\tilde{C}_z) = \tfrac{1}{2} < h_n(C_l)$. The second inequality follows because expected profits cannot decrease when Ω becomes more fine, i.e. if each C_z becomes smaller and their number *K* increases. Specifically, we have

$$\hat{\pi}(h_n(\tilde{C}_z), c_0(C_z), c_1(C_z)) = \hat{\pi}(h_n(\tilde{C}_z), c_0(\tilde{C}_z), c_1(\tilde{C}_z)) \text{ for all } z \ne k,l ,$$

and

$$\sum_{z=k,l} \iint_{(c_0,c_1)\in C_z} \hat{\pi}(h_n(\tilde{C}_z), c_0(C_z), c_1(C_z)) dG(c_0,c_1)$$

$$= \sum_{z=k,l} \Big(\iint_{(c_0,c_1)\in \tilde{C}_z} dG(c_0,c_1) + \iint_{(c_0,c_1)\in C'_z} dG(c_0,c_1) \Big) \max_{\vec{p}(C_z)} \pi(\vec{p}(C_z), \tfrac{1}{2}, c_0(C_z), c_1(C_z))$$

$$\leq \sum_{z=k,l} \iint_{(c_0,c_1)\in\tilde{C}_z} dG(c_0,c_1) \max_{\vec{p}(\tilde{C}(z))} \pi(\vec{p}(\tilde{C}_z), \tfrac{1}{2}, c_0(\tilde{C}_z), c_1(\tilde{C}_z))$$

$$+ \iint_{(c_0,c_1)\in\tilde{C}_{K+1}} dG(c_0,c_1) \max_{\vec{p}(\tilde{C}_{K+1})} \pi(\vec{p}(\tilde{C}_{K+1}), \tfrac{1}{2}, c_0(\tilde{C}_{K+1}), c_1(\tilde{C}_{K+1}))$$

$$= \sum_{z=k,l,K+1} \iint_{(c_0,c_1)\in\tilde{C}_z} \hat{\pi}(h_n(\tilde{C}_z), c_0(\tilde{C}_z), c_1(\tilde{C}_z)) dG(c_0,c_1).$$

The first equality follows by (A1) and (A12). The inequality follows because re-optimization over prices cannot decrease the seller's profits. This yields the desired contradiction.

<u>Step 3</u>. In Step 2 we showed that an optimal Ω is such that $h_n(C_z) = \frac{1}{2}$ for each $C_h \in \Omega$. Consider a collection of pairs of points $\{(c_0,c_1),(m_0(c_0,c_1),m_1(c_0,c_1))\}_{0\leq c_0\leq c_1\leq 1}$, where the maps $m_i(c_0,c_1):[0,1]\times[0,1]\to[0,1]$, $i=0,1$, satisfy the following conditions:

(a) $g(c_0,c_1) = g(m_0(c_0,c_1),m_1(c_0,c_1))$,

(b) $0 \leq m_1(c_0,c_1) \leq m_0(c_0,c_1) \leq 1$, and

(c) $(m_0(c_0,c_1),m_1(c_0,c_1)) \neq (m_0(c_0',c_1'),m_1(c_0',c_1'))$ if $(c_0,c_1)\neq(c_0',c_1')$ for all $0\leq c_0\leq c_1\leq 1$, $0\leq c_0'\leq c_1'\leq 1$.

We have $E[C_i \mid (C_0,C_1)\in\{(c_0,c_1),(m_0(c_0,c_1),m_1(c_0,c_1))\}] = \frac{1}{2}(c_i + m_i(c_0,c_1))$, $i=0,1$, and $E[\min[C_0,C_1] \mid (C_0,C_1)\in\{(c_0,c_1),(m_0(c_0,c_1),m_1(c_0,c_1))\}] = \frac{1}{2}(c_0 + m_1(c_0,c_1))$ for any $c_0 \leq c_1$. For example, $m_0(c_0,c_1) = c_1$ and $m_1(c_0,c_1) = c_0$ satisfy conditions (a) – (c).

And so, as the cardinality of Ω that consists of subsets of $[0,1]\times[0,1]$ with equal probability mass above and below the 45-degree line, increases, in the limit (A9) approaches:

$$\max_{\{m_0(.,.)),m_1(.,.)\}} \int_0^1\int_{c_0}^1 2\hat{\pi}(\tfrac{1}{2}, \tfrac{c_0+m_0(c_0,c_1)}{2}, \tfrac{c_1+m_1(c_0,c_1)}{2}) g(c_0,c_1)dc_0dc_1 \text{ subject to (a), (b), and (c).} \quad \text{(A13)}$$

Next we derive the formula for $\hat{\pi}(\frac{1}{2}, \frac{c_0+m_0(c_0,c_1)}{2}, \frac{c_1+m_1(c_0,c_1)}{2})$. Substituting

$$D_i(p_0,p_1,p_n,\tfrac{1}{2}) = \tfrac{1}{2} + 2\tfrac{p_n-p_i}{t},\ i=0,1, \text{ and } D_n(p_0,p_1,p_n,\tfrac{1}{2}) = 2\tfrac{p_0+p_1-2p_n}{t}, \quad \text{(A14)}$$

where $p_0 \leq q, p_1 \leq q, p_n \leq q - \frac{t}{2}$, into (A1) with $h_n = \frac{1}{2}$, it is easy to verify that

$$\hat{\pi}(\tfrac{1}{2},\tfrac{c_0+m_0(c_0,c_1)}{2},\tfrac{c_1+m_1(c_0,c_1)}{2})=\tfrac{\max[t+\sigma(m_1(c_0,c_1)-m_0(c_0,c_1)),0]^2}{16t}+\tfrac{\max[t+\sigma(c_0-c_1),0]^2}{16t}+q-\tfrac{t}{2}-\sigma\tfrac{c_0+m_1(c_0,c_1)}{2},$$

where the prices conditional on the public signals that $(C_0,C_1)\in\{(c_0,c_1),(m_0(c_0,c_1),$ $m_1(c_0,c_1))\}$ are given by:

$$p_0(\tfrac{c_0+m_0(c_0,c_1)}{2},\tfrac{c_1+m_1(c_0,c_1)}{2})=q-\tfrac{\max[t+\sigma(m_1(c_0,c_1)-m_0(c_0,c_1)),0]}{4},$$

$$p_1(\tfrac{c_0+m_0(c_0,c_1)}{2},\tfrac{c_1+m_1(c_0,c_1)}{2})=q-\tfrac{\max[t+\sigma(c_0-c_1),0]}{4},$$

$$p_n(\tfrac{c_0+m_0(c_0,c_1)}{2},\tfrac{c_1+m_1(c_0,c_1)}{2})=q-\tfrac{1}{2}t.$$

And so, (A13) becomes

$$\int_0^1\int_{c_0}^1 2(\tfrac{\max[2t+\sigma(m_1(c_0,c_1)-m_0(c_0,c_1)),0]^2}{16t}+\tfrac{\max[2t+\sigma(c_0-c_1),0]^2}{16t}+q-\tfrac{1}{2}t-\sigma\tfrac{c_0+m_1(c_0,c_1)}{2})g(c_0,c_1)dc_0dc_1$$

$$=\int_0^1\int_{c_0}^1(\tfrac{\max[t+\sigma(c_0-c_1),0]^2}{4t}+2(q-\tfrac{1}{2}t-\sigma c_0))g(c_0,c_1)dc_0dc_1\ .$$

The equality follows because

$$\int_0^1\int_{c_0}^1(\tfrac{\max[2t+\sigma(m_1(c_0,c_1)-m_0(c_0,c_1)),0]^2}{16t}+q-\tfrac{1}{2}t-\sigma m_1(c_0,c_1))g(c_0,c_1)dc_0dc_1$$

$$=\int_0^1\int_{c_0}^1(\tfrac{\max[2t+\sigma(m_1(c_0,c_1)-m_0(c_0,c_1)),0]^2}{16t}+q-\tfrac{1}{2}t-\sigma m_1(c_0,c_1))g(m_0(c_0,c_1),m_1(c_0,c_1))dc_0dc_1$$

$$=\int_0^1\int_{c_0}^1(\tfrac{\max[2t+\sigma(c_0-c_1),0]^2}{16t}+q-\tfrac{1}{2}t-\sigma c_0)g(c_0,c_1)dc_0dc_1\ ,$$

where the first equality follows by (a), and the second equality follows from (b) and (c) by the change of variables. ■

Proof of Proposition 1: We first show that the pricing strategy in (9) and consumers' beliefs in (6), constitute a perfect Bayesian equilibrium, i.e. satisfy conditions (i) and (ii). Let

$$\pi^*(c_0,c_1)=\pi(p_0^*(c_0,c_1),p_1^*(c_0,c_1),p_n^*(c_0,c_1),h_n^*(p_0^*(c_0,c_1),p_1^*(c_0,c_1),p_n^*(c_0,c_1)),c_0,c_1)$$

$$=\tfrac{\max[t-\sigma|c_0-c_1|,0]^2}{8t}+q-\tfrac{1}{2}t-\sigma\min[c_0,c_1]$$

denote the ex post equilibrium profits, where the second equality is obtained by substitution of (A14) evaluated at (9) into (2). Now we can rewrite condition (i) as follows:

$$\pi^*(c_0,c_1) \geq \pi(p_0,p_1,p_n,h_n^*(p_0,p_1,p_n),c_0,c_1) \;\; \forall p_0,p_1,p_n,\; c_0,c_1. \qquad \text{(A15)}$$

First, we show that (A15) holds for any $p_i = p_i^*(\underline{c},\bar{c})$, $i=0,1,n$, $\underline{c},\bar{c}\in[0,1]$, i.e. for all c_0,c_1

$$\pi^*(c_0,c_1) = \max_{\substack{\underline{c},\bar{c}\in[0,1],\\ \underline{c}\leq\bar{c}}} \pi(p_0^*(\underline{c},\bar{c}),p_1^*(\underline{c},\bar{c}),p_n^*(\underline{c},\bar{c}),h_n^*(p_0^*(\underline{c},\bar{c}),p_1^*(\underline{c},\bar{c}),p_n^*(\underline{c},\bar{c})),c_0,c_1)$$

$$= \max_{\substack{\underline{c},\bar{c}\in[0,1],\\ \underline{c}\leq\bar{c}}} \sum_{i=0,1} \tfrac{1}{2}\left(1+\tfrac{p_n^*(\underline{c},\bar{c})-p_i^*(\underline{c},\bar{c})}{t}\right)(p_i^*(\underline{c},\bar{c})-\sigma c_i)$$

$$+\tfrac{p_0^*(\underline{c},\bar{c})+p_1^*(\underline{c},\bar{c})-2p_n^*(\underline{c},\bar{c})}{2t}(p_n^*(\underline{c},\bar{c})-\sigma\min[c_0,c_1])$$

$$= \max_{\substack{\underline{c},\bar{c}\in[0,1],\\ \underline{c}\leq\bar{c}}} \tfrac{\max[t+\sigma(\underline{c}-\bar{c}),0]}{4t}\left(\tfrac{1}{2}t-\tfrac{\max[t+\sigma(\underline{c}-\bar{c}),0]}{4}+\sigma\min[c_1-c_0,0]\right)$$

$$+\tfrac{\max[t+\sigma(\underline{c}-\bar{c}),0]}{4t}\left(\tfrac{1}{2}t-\tfrac{\max[t+\sigma(\underline{c}-\bar{c}),0]}{4}+\sigma\min[c_0-c_1,0]\right)+q-\tfrac{1}{2}t-\sigma\min[c_0,c_1]$$

$$= \max_{\substack{\underline{c},\bar{c}\in[0,1],\\ \underline{c}\leq\bar{c}}} \tfrac{\max[t+\sigma(\underline{c}-\bar{c}),0]}{2t}\left(\tfrac{1}{2}t-\tfrac{\max[t+\sigma(\underline{c}-\bar{c}),0]}{4}-\tfrac{1}{2}\sigma\,|c_1-c_0|\right)+q-\tfrac{1}{2}t-\sigma\min[c_0,c_1]$$

$$= \tfrac{\max[t-\sigma|c_0-c_1|,0]^2}{8t}+q-\tfrac{1}{2}t-\sigma\min[c_0,c_1].$$

The first equality follows from (A14) , and the second equality follows by (9). To obtain the last equality, note that for $|c_1-c_0|<\tfrac{t}{\sigma}$ an optimal solution is such that $\bar{c}-\underline{c}=|c_1-c_0|$, and for $|c_1-c_0|\geq\tfrac{t}{\sigma}$ an optimal solution is such that $|\bar{c}-\underline{c}|\geq\tfrac{t}{\sigma}$.

Next we verify that the seller never wants to deviate from (9) when $q\geq\tfrac{1}{2}t+\sigma$. From (6) it follows that if the seller deviates from the non-revealing prices, i.e. $p_0,p_1,p_n\notin P^*$, he cannot earn more than $q-\tfrac{1}{2}t-\sigma\min[c_0,c_1]$ or (8). Because $\pi^*(c_0,c_1)\geq q-\tfrac{1}{2}t-\sigma\min[c_0,c_1]$, there are two cases to consider depending on whether the seller covers the market under full disclosure: (1) $q\geq t+\sigma\tfrac{c_0+c_1}{2}$ and (2) $q<t+\sigma\tfrac{c_0+c_1}{2}$. Suppose that $c_0\leq c_1$ ($c_0>c_1$ is treated analogously).

In case (1), we have

$$\pi_L(c_0,c_1)=\begin{cases}\frac{1}{2t}(t+\sigma\frac{c_1-c_0}{2})^2+q-t-\sigma c_1, \text{ if } \sigma(c_1-c_0)\le 2t \\ q-t-\sigma c_0, \text{ if } \sigma(c_1-c_0)>2t\end{cases}.$$

If $\sigma(c_1-c_0)>2t$ then it is easy to verify that

$$\pi_L(c_0,c_1)=q-t-\sigma c_0<\frac{\max[t+\sigma(c_0-c_1),0]^2}{8t}+q-\tfrac{1}{2}t-\sigma c_0=q-\tfrac{1}{2}t-\sigma c_0=\pi^*(c_0,c_1).$$

If $\sigma(c_1-c_0)\le 2t$, then we also have

$$\pi_L(c_0,c_1)=\tfrac{1}{2t}(t+\sigma\tfrac{c_1-c_0}{2})^2+q-t-\sigma c_1\le q-\tfrac{1}{2}t-\sigma c_0\le\pi^*(c_0,c_1),$$

where the first inequality follows by assumption.

In case (2), we need to show that $q\ge\frac{1}{2}t+\sigma$ implies that

$$\pi_L(c_0,c_1)=\sum_{i=0,1}\frac{(q-\sigma c_i)^2}{4t}\le\frac{(t+\sigma(c_0-c_1))^2}{8t}+q-\tfrac{1}{2}t-\sigma c_0=\pi^*(c_0,c_1) \qquad \text{(A16)}$$

for all c_0,c_1, where the last equality follows because $\sigma(c_1-c_0)\le\sigma(2-c_1-c_0)<t$ as, by assumption, $\frac{1}{2}t+\sigma\le q$ and $q<t+\sigma\frac{c_0+c_1}{2}$. Upon some manipulation, the inequality in (A16) can be rewritten as

$$y(c_0,c_1)\equiv\tfrac{1}{2}(c_0+c_1)^2\sigma^2+\sigma((3t-2q)c_0+(t-2q)c_1)+2((t-q)^2-\tfrac{1}{4}t^2)<0. \qquad \text{(A17)}$$

Note that the function $y(c_0,c_1)$ is decreasing in c_1 for all c_0 because

$$\frac{\partial y(c_0,c_1)}{\partial c_1}=(c_0+c_1)\sigma^2+\sigma(t-2q)<2\sigma(\sigma+\tfrac{1}{2}t-q)\le 0.$$

Hence, we only need to check that (A17) holds for all $(c_0,c_1)=(c,c)$ such that $q<t+\sigma c$, where $c\in[0,1]$. But it is easy to verify that

$$y(c,c)=2((c\sigma+t-q)^2-\tfrac{1}{4}t^2)=2(c\sigma+\tfrac{1}{2}t-q)(c\sigma+\tfrac{3}{2}t-q)\le 0,$$

where the inequality follows because $c\sigma+\frac{1}{2}t-q\le\sigma+\frac{1}{2}t-q\le 0$, and by assumption, $c\sigma+\frac{3}{2}t-q>c\sigma+t-q>0$.

Because $\int_0^1\int_0^1\pi^*(c_0,c_1)dc_0dc_1$ equals the upper bound established in Lemma 1, this equilibrium is a best equilibrium. ■

Proof of Proposition 2: Substituting $D_i(p_0,p_1,p_n,\frac{1}{2})=\frac{1}{2}+(\frac{1}{2}-i)\Delta+p_n-p_i$, $i=0,1$, and $D_n(p_0,p_1,p_n,\frac{1}{2})=p_0+p_1-2p_n$, (17) becomes

$$\max_{p_i \le 1+(\frac{1}{2}-i)\Delta,\, p_n \le \frac{1}{2}} \sum_{i=0,1} (\tfrac{1}{2} + (\tfrac{1}{2} - i)\Delta + p_n - p_i)(p_i - \tfrac{1}{2}\sigma) + (p_0 + p_1 - 2p_n)p_n \qquad \text{(A18)}$$

subject to

$$\sum_{i=0,1} (\tfrac{1}{2} + (\tfrac{1}{2} - i)\Delta + p_n - p_i)(p_i - (1-i)\sigma) + (p_0 + p_1 - 2p_n)p_n \ge \pi_L(1{,}0) \text{ and} \qquad \text{(A19)}$$

$$\sum_{i=0,1} (\tfrac{1}{2} + (\tfrac{1}{2} - i)\Delta + p_n - p_i)(p_i - i\sigma) + (p_0 + p_1 - 2p_n)p_n \ge \pi_L(0{,}1), \qquad \text{(A20)}$$

where $\pi_L(1{,}0) = \frac{1}{4}\max[1 + \frac{1}{2}\Delta - \sigma, 0]^2 + \frac{1}{4}(1 - \frac{1}{2}\Delta)^2$ and $\pi_L(0{,}1) = \frac{1}{4}(1 + \frac{1}{2}\Delta)^2$ $+ \frac{1}{4}\max[1 - \frac{1}{2}\Delta - \sigma, 0]^2$. The first-order conditions for (A18) are

$$(\tfrac{1}{2} + \tfrac{1}{2}\Delta + 2p_n - 2p_0)(1 + \mu + \lambda) + \tfrac{1}{2}\sigma + \mu\sigma \ge 0, \qquad \text{(A21)}$$

$$(\tfrac{1}{2} - \tfrac{1}{2}\Delta + 2p_n - 2p_1)(1 + \mu + \lambda) + \tfrac{1}{2}\sigma + \lambda\sigma \ge 0, \qquad \text{(A22)}$$

$$(2(p_0 + p_1) - \sigma - 4p_n)(1 + \mu + \lambda) \ge 0, \qquad \text{(A23)}$$

where μ and λ are the Lagrange multipliers on the constraints in (A19) and (A20). Summing together (A20) and (A21) implies that (A22) must hold as a strict inequality, i.e. at optimum $p_n = \frac{1}{2}$. Substituting $p_n = \frac{1}{2}$, $\pi_L(1{,}0)$, and $\pi_L(0{,}1)$, (A18) becomes

$$\max_{p_i \le 1+(\frac{1}{2}-i)\Delta,\, i=0,1} \sum_{i=0,1} (1 + (\tfrac{1}{2} - i)\Delta - p_i)(p_i - \tfrac{1}{2} - \tfrac{1}{2}\sigma) + \tfrac{1}{2}$$

subject to

$$\sum_{i=0,1} (1 + (\tfrac{1}{2} - i)\Delta - p_i)(p_i - \tfrac{1}{2} - (1-i)\sigma) + \tfrac{1}{2} \ge \tfrac{1}{4}\max[1 + \tfrac{1}{2}\Delta - \sigma, 0]^2 + \tfrac{1}{4}(1 - \tfrac{1}{2}\Delta)^2 \text{ and} \qquad \text{(A24)}$$

$$\sum_{i=0,1} (1 + (\tfrac{1}{2} - i)\Delta - p_i)(p_i - \tfrac{1}{2} - i\sigma) + \tfrac{1}{2} \ge \tfrac{1}{4}(1 + \tfrac{1}{2}\Delta)^2 + \tfrac{1}{4}\max[1 - \tfrac{1}{2}\Delta - \sigma, 0]^2. \qquad \text{(A25)}$$

There are five cases that need to be considered.

Case (a). Suppose that $\sigma \le 1 - \Delta$. In this case, as we will verify next, constraints (A24) and (A25) do not bind, and the seller offers all three products at prices $p_0 = \frac{3+\Delta+\sigma}{4}$, $p_1 = \frac{3-\Delta+\sigma}{4}$, and $p_n = \frac{1}{2}$. Substituting $p_0 = \frac{3+\Delta+\sigma}{4}$ and $p_1 = \frac{3-\Delta+\sigma}{4}$, (A24) and (A25) reduce to, respectively,

$$\tfrac{1+\Delta-\sigma}{4}\tfrac{1+\Delta-3\sigma}{4} + \tfrac{(1-\Delta)^2-\sigma^2}{16} + \tfrac{1}{2} \ge \tfrac{1}{4}(1 + \tfrac{1}{2}\Delta - \sigma)^2 + \tfrac{1}{4}(1 - \tfrac{1}{2}\Delta)^2 \text{ and}$$

$$\tfrac{(1+\Delta)^2-\sigma^2}{16} + \tfrac{1-\Delta-\sigma}{4}\tfrac{1-\Delta-3\sigma}{4} + \tfrac{1}{2} \ge \tfrac{1}{4}(1 + \tfrac{1}{2}\Delta)^2 + \tfrac{1}{4}(1 - \tfrac{1}{2}\Delta - \sigma)^2.$$

Upon simplification these inequalities become $\sigma^2 - 2\sigma - 1 \le 0$, which holds for all $\sigma \le 1 - \Delta$.

Case (b). Suppose that $1 - \Delta < \sigma \le 1 - \frac{1}{2}\Delta$. In this case, again, at optimum constraints (A24) and (A25) do not bind, and the seller offers labeled variety 0 and an unlabeled variety at prices $p_0 = \frac{3+\Delta+\sigma}{4}$ and $p_n = \frac{1}{2}$. Substituting $p_0 = \frac{3+\Delta+\sigma}{4}$ and $p_1 = 1 - \frac{\Delta}{2}$ (the choke-off price for the low-quality variety) in (A24), it becomes

$$\tfrac{1+\Delta-\sigma}{4}\,\tfrac{1+\Delta-3\sigma}{4} + \tfrac{1}{2} \ge \tfrac{1}{4}(1 + \tfrac{1}{2}\Delta - \sigma)^2 + \tfrac{1}{4}(1 - \tfrac{1}{2}\Delta)^2,$$

which, upon simplification reduces to $\sigma^2 - 4\sigma + \Delta^2 - 2\Delta - 1 \le 0$. This inequality holds if

$$2 - \sqrt{5 - (\Delta^2 - 2\Delta)} \le \sigma \le 2 + \sqrt{5 - (\Delta^2 - 2\Delta)}. \tag{A26}$$

Similarly, substituting $p_0 = \frac{3+\Delta+\sigma}{4}$ and $p_1 = 1 - \frac{\Delta}{2}$ in (A25), it becomes

$$\tfrac{(1+\Delta)^2-\sigma^2}{16} + \tfrac{1}{2} \ge \tfrac{1}{4}(1 + \tfrac{1}{2}\Delta)^2 + \tfrac{1}{4}(1 - \tfrac{1}{2}\Delta - \sigma)^2,$$

which, upon simplification reduces to $5\sigma^2 - 4(2-\Delta)\sigma + \Delta^2 - (1 + 2\Delta) \le 0$. This inequality holds if

$$\tfrac{2(2-\Delta)-\sqrt{17-14\Delta+3\Delta^2}}{5} \le \sigma \le \tfrac{2(2-\Delta)+\sqrt{17-14\Delta+3\Delta^2}}{5}. \tag{A27}$$

But it is easy to verify that (A26) and (A27) are implied by $1 - \Delta < \sigma \le 1 - \frac{1}{2}\Delta$.

Case (c). Suppose that $1 - \frac{1}{2}\Delta < \sigma \le 1 + \frac{1}{2}\Delta$. In this case the equilibrium pricing strategy is the same as in case (b). Constraint (A24) is unchanged, and condition (A26) is implied by $1 - \frac{1}{2}\Delta < \sigma \le 1 + \frac{1}{2}\Delta$. Constraint (A25) becomes

$$\tfrac{(1+\Delta)^2-\sigma^2}{16} + \tfrac{1}{2} \ge \tfrac{1}{4}(1 + \tfrac{1}{2}\Delta)^2,$$

which, upon simplification, becomes $\sigma \le \sqrt{5 - 2\Delta}$, and is also implied by $\sigma \le 1 + \frac{1}{2}\Delta$.

Case (d). Suppose that $1 + \frac{1}{2}\Delta < \sigma \le 1 + \Delta$. For $\Delta < 2(\sqrt{2} - 1)$ the equilibrium pricing strategy is the same as in cases (b) and (c), and constraints (A24) and (A25) do not bind. Substituting $p_0 = \frac{3+\Delta+\sigma}{4}$ and $p_1 = 1 - \frac{\Delta}{2}$ in (A24), it now becomes

$$\tfrac{1+\Delta-\sigma}{4}\,\tfrac{1+\Delta-3\sigma}{4} + \tfrac{1}{2} \ge \tfrac{1}{4}(1 - \tfrac{1}{2}\Delta)^2,$$

which, upon simplification, reduces to $5 + 6\Delta - 4\sigma(1+\Delta) + 3\sigma^2 \ge 0$. This inequality holds because the left-hand side is increasing in σ for $1 + \frac{1}{2}\Delta < \sigma < 1 + \Delta$ (the derivative of the left-hand side with respect to σ is $-4(1+\Delta)+6\sigma > -4-4\Delta+6+3\Delta = 2-\Delta > 0$, where we used $1+\frac{1}{2}\Delta < \sigma$), and it is positive at $\sigma = 1+\frac{1}{2}\Delta$. Constraint (A25) is the same as in case (c), and therefore holds because $\sigma \le \sqrt{5-2\Delta}$ is implied by $\sigma \le 1+\Delta$ for $\Delta < 2(\sqrt{2}-1)$.

If $\Delta \ge 2(\sqrt{2}-1)$, then constraint (A25) binds and p_0 satisfies

$$(1+\tfrac{1}{2}\Delta - p_0)(p_0-\tfrac{1}{2})+\tfrac{1}{2} = \tfrac{1}{4}(1+\tfrac{1}{2}\Delta)^2. \tag{A28}$$

The larger root is $p_0 = \frac{3+\Delta+\sqrt{(5-2\Delta)}}{4}$. We also need to check that constraint (A24) is satisfied at $p_0 = \frac{3+\Delta+\sqrt{(5-2\Delta)}}{4}$, $p_1 = 1-\frac{\Delta}{2}$ for $\Delta \ge 2(\sqrt{2}-1)$ and $1+\frac{1}{2}\Delta < \sigma \le 1+\Delta$:

$$(\tfrac{1+\Delta}{4}-\tfrac{1}{4}\sqrt{5-2\Delta})(\tfrac{1+\Delta}{4}+\tfrac{1}{4}\sqrt{5-2\Delta}-\sigma)+\tfrac{1}{2} \ge \tfrac{1}{4}(1-\tfrac{1}{2}\Delta)^2.$$

This, upon simplification, becomes

$$\sigma \le \frac{2\Delta}{(1+\Delta-\sqrt{5-2\Delta})}, \tag{A29}$$

which is implied by $\sigma \le 1+\Delta$ and $\Delta \ge 2(\sqrt{2}-1)$.

Case (e). Suppose that $\sigma > 1+\Delta$. For $\Delta < 2(\sqrt{2}-1)$ constraints (A24) and (A25) do not bind, and all consumers buy an unlabeled variety at $p_n = \frac{1}{2}$ ($p_0 = 1+\frac{\Delta}{2}$, $p_1 = 1-\frac{\Delta}{2}$). Substituting $p_0 = 1+\frac{\Delta}{2}$, $p_1 = 1-\frac{\Delta}{2}$, $p_n = \frac{1}{2}$ in constraints (A24) and (A25), they become, respectively, $\frac{1}{2} \ge \frac{1}{4}(1-\frac{1}{2}\Delta)^2$ and $\frac{1}{2} \ge \frac{1}{4}(1+\frac{1}{2}\Delta)^2$. Both inequalities hold for $\Delta < 2(\sqrt{2}-1)$.

As in case (d), for $\Delta \ge 2(\sqrt{2}-1)$ constraint (A25) binds and p_0 satisfies equation (A28), i.e. $p_0 = \frac{3+\Delta+\sqrt{(5-2\Delta)}}{4}$ (with $p_1 = 1-\frac{\Delta}{2}$ and $p_n = \frac{1}{2}$), and constraint (A24) is satisfied provided that condition (A29) holds.

If condition (A29) does not hold, then in the best equilibrium the seller offers only labeled variety 0 at $p_0 = \frac{1}{2}(1+\frac{\Delta}{2})$ for $(c_0, c_1) = (0,1)$ or only labeled variety 1 at $p_1 = \frac{1}{2}(1-\frac{\Delta}{2})$ for $(c_0, c_1) = (1,0)$. This is because there are no "non-revealing" prices $p_0 \le 1+\frac{\Delta}{2}$, $p_1 \le 1-\frac{\Delta}{2}$, $p_n \le \frac{1}{2}$ such that constraints (A24) and (A25) are *simultaneously* satisfied. ■

Proof of Proposition 3: Substituting $x_1^*(c_0,c_1)$ and $x_1^M(c_0,c_1)$, and subtracting $W^*(c_0,c_1)$ from $W^M(c_0,c_1)$ yields

$$W^M(c_0,c_1)-W^*(c_0,c_1)=\begin{cases}\frac{1}{8}(\frac{1}{2}t-\sigma|c_0-c_1|), \text{if } |c_0-c_1|\le\frac{t}{\sigma}\\ \frac{1}{2}(\frac{1}{2}t-\sigma|c_0-c_1|+\frac{3}{8t}(\sigma(c_0-c_1))^2), \text{if } \frac{t}{\sigma}<|c_0-c_1|\le 2\frac{t}{\sigma}\\ 0, \text{if } |c_0-c_1|>2\frac{t}{\sigma}\end{cases}.$$

It is easy to verify that $W^M(c_0,c_1)>W^*(c_0,c_1)$ for all $|c_0-c_1|<\frac{1}{2}\frac{t}{\sigma}$, $W^M(c_0,c_1)$ $\le W^*(c_0,c_1)$ for all $\frac{1}{2}\frac{t}{\sigma}\le|c_0-c_1|\le 2\frac{t}{\sigma}$, and $W^M(c_0,c_1)=W^*(c_0,c_1)$ for all $|c_0-c_1|\ge 2\frac{t}{\sigma}$. ■

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