

Donor Product-Subsidies to Increase Consumption: Implications of Consumer Awareness and Profit-Maximizing Intermediaries

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Abstract

Increasingly, donors that subsidize socially-desirable products in the developing world are shifting from distributing through non-commercial to commercial channels, ceding control of the product price to for-profit intermediaries. This paper advises a donor as to how the donor's loss of price control and the level of consumer awareness—defined as the fraction of the consumer population that is informed of the product's benefits—influence the donor's optimal subsidy and utility: First, in shifting to the commercial channel, the donor should increase (decrease) the subsidy when consumer awareness is low (high). Second, with the commercial channel, the donor should be prepared to increase the subsidy as awareness increases, which is contrary to her actions with a non-commercial channel. Third, contrary to the lesson obtained with non-commercial distribution, with commercial distribution the donor can be hurt by increased awareness. This occurs when awareness is moderate. The implication is that a donor that operates in such a setting should be wary in encouraging entities (e.g., governments, non-governmental organizations) to institute campaigns that increase the awareness of the product's benefits. The intermediary's decision of whether to target either only informed consumers or the broad market drives our results.

1 Introduction

Donors fund subsidies to lower the price, and hence increase the purchase and use, of socially-beneficial products in the developing world. For example, malaria is estimated to cause more than 200 million illnesses and 400,000 deaths annually (World Health Organization 2015). Because the recommended drugs to treat malaria, artemisinin combination therapies (ACTs), are expensive to produce, they are unaffordable to many in sub-Saharan Africa, the region which bears the heaviest burden of malaria (Morris et al. 2015). Historically, donor efforts to lower the cost of malaria drugs have focused on non-commercial channels, such as public health systems. Because

the geographic reach of these non-commercial channels is limited, for-profit firms such as drug shops are an important source for those seeking treatment for malaria (Adeyi and Atun 2010, Morris et al. 2014) (For example, in the Democratic Republic of Congo and Nigeria, which together account for a third of Africa’s malaria cases, the commercial channel accounts for more than 85% of malaria drug volume (Adeyi and Atun 2010).) Consequently, in recent years, donors have shifted their efforts in subsidizing recommended malaria drugs to commercial channels (Adeyi and Atun 2010, Morris et al. 2014). A key distinction between these two types of channels, and a cause for concern for donors in making this transition, is that for-profit firms control the price (Arrow et al. 2004, Adeyi and Atun 2010).

Similarly, donors fund subsidies to increase the purchase and use of improved cook stoves (ICS) because they are more energy-efficient and less-polluting than traditional cook stoves. Historically, donor efforts to lower the price of ICS have focused on non-commercial channels, with distribution through non-governmental organizations or government agencies (World Bank 2010). These organizations sell the product to consumers at the fixed, reduced price dictated by the subsidy program. In recent years, donors have shifted their efforts to commercial channels based on the belief that commercial channels have greater potential for achieving the long-run goal of efficient distribution to a large population (Gaul 2009, Broder 2010, World Bank 2010, Shrimali et al. 2011, Simon et al. 2014).

Although donors can recommend a price to the for-profit firms that distribute the ICS, those firms control the price. For example, the World Bank (2010) documents that in a United States Agency for International Development (2009) program in Bangladesh, for-profit firms sold the ICS at a price much higher (as much as \$14) than what the Agency had recommended (\$7). Gaul (2009) documents examples in which donors provide price-setting ICS producers with per-unit subsidies, ranging from €1 to €17, which corresponds to roughly 15% to 50% of the market price.

A key common element in the malaria drug- and ICS-subsidy examples is the shift to distribution through commercial channels, wherein the donor gives up control over the price. A second common element is that demand for the product is influenced by both the price and consumer awareness of the product’s benefits, which is often limited (see Cohen et al. 2010 and Morris et al. 2014 for ACTs, and Gaul 2009, World Bank 2010 and Mobarak et al. 2012 for ICS). Specifically, only a fraction of the population is aware of the effectiveness of the recommended malaria drugs, and only a fraction of the population is aware of the fuel-cost savings and reduced-pollution benefits of ICS. In Africa, with the exception of a few localities, the fraction of the population aware of the benefits of ICS is low (World Bank 2014). For example, in Maputo, Mozambique, 64% of surveyed consumers

were not aware of ICS' pollution-reducing health benefits (Risseeuw 2012). In the Gondar region of Ethiopia, only 20% of surveyed women understood that pollution from traditional stoves is harmful to children. In Uganda, 58-60% of surveyed consumers were "not sure" of ICS' benefits to users (TNS 2013).

The purpose of this paper is to advise a donor as to how the nature of the distribution channel and the level of consumer awareness influence her subsidy-design decision and utility. Specifically, we explore how the donor's loss of price control and how the awareness level—defined as the fraction of the consumer population acquainted with the product that is informed of the product's benefits— influence the donor's optimal subsidy and utility. We show how and why the donor's loss of price control *reverses* the impact of awareness on the donor's optimal subsidy and utility.

Intuitively, the donor benefits from consumers' increased awareness of the product's benefits because such awareness makes consumers more prone to purchase, increasing the sales quantity. Indeed, when the donor controls the price, she always benefits from increased awareness—due to this sales quantity effect. Our first contribution is to demonstrate when and how the presence of a price-setting intermediary reverses this result. The driver behind this reversal—and indeed all of our key results—is the intermediary's strategic market-targeting decision. As awareness increases, it becomes increasingly attractive for the price-setting intermediary to abandon the segment that is not informed of the product's benefits. Convincing the intermediary to continue to serve the broad market requires that the donor increase the subsidy. So long as awareness is not too high, it is optimal for the donor to incur this additional cost. Consequently, when the awareness is moderate, the donor's utility *decreases* in the awareness.

Our second contribution is to demonstrate how the presence of a price-setting intermediary changes the optimal subsidy, and how the subsidy is affected by the awareness level. First, accounting for the intermediary's market-targeting decision leads the donor to optimally *increase* the subsidy as awareness increases through a moderate range. This reverses the result that holds under donor price control, wherein the optimal subsidy never increases in the awareness. Second, the presence of a price-setting intermediary weakly increases the donor's subsidy if and only if awareness is sufficiently low. More precisely, when awareness is moderately low, the donor *strictly increases* the subsidy so as to persuade the intermediary to serve the broad market. As awareness increases, it becomes increasingly expensive for the donor to persuade the intermediary to serve the broad market. Consequently, the donor gives up on serving the broad market more quickly when she distributes through a price-setting intermediary. Therefore, the presence of a price-setting intermediary causes the donor to *strictly decrease* the subsidy when awareness is moderately high.

The managerial contribution of these reversal results is to provide insight to donors that are shifting from distributing products through non-commercial channels to commercial channels. The results provide guidance by illuminating when lessons obtained in a setting with a non-commercial channel continue to hold and when they are reversed.

There is a growing literature in operations management on the use of subsidies and other mechanisms to stimulate the production, purchase and use of socially-beneficial products. Motivated by the influenza vaccine product, a body of research identifies social-welfare enhancing interventions that influence manufacturer production decisions in settings where the production yield is uncertain and consumers' purchasing decisions are influenced by the fraction of the population that is vaccinated. Chick et al. (2008) shows that a properly designed supply-side intervention, namely a cost-sharing contract, induces the manufacturer to produce the welfare-maximizing quantity. Arifoğlu et al. (2012) and Natarajan and Swaminathan (2015) observe that combining a supply-side intervention with a demand-side intervention, such as a subsidy, may be beneficial. Mamani et al. (2013) extend Chick et al. (2008) and propose a subsidy scheme that effectively encourages the purchase and use of the vaccine in the geographic location where it is most needed. Adida et al. (2013) show that a menu of subsidies is useful in addressing the incentive problem that arises with production yield uncertainty. Dai et al. (2016) show that properly designed contractual incentives are useful in stimulating early-stage production.

Motivated by socially-beneficial products other than vaccines, Taylor and Xiao (2014), Raz and Ovchinnikov (2015), Cohen et al. (2016), Berenguer et al. (2017) and Chemama et al. (2018) examine subsidizing a profit-maximizing, price-setting intermediary that faces uncertain demand and makes stocking and pricing decisions. Cohen et al. (2016) examine the effect of demand uncertainty on the optimal subsidy. Chemama et al. (2018) extend Cohen et al. (2016) and show that the subsidy-designer should commit to the subsidy level in advance. Taylor and Xiao (2014), Raz and Ovchinnikov (2015) and Berenguer et al. (2017) examine how a donor should optimally subsidize the intermediary based on its purchases and/or sales. Berenguer et al. (2017) show subsidizing sales may be optimal when the intermediary is profit-maximizing, but subsidizing purchases is optimal when the intermediary is sales-maximizing. Levi et al. (2017, 2018) examine the effectiveness of uniform subsidies with heterogenous profit-maximizing intermediaries. Our study differs from these in that we focus on the impact of consumers' awareness rather than demand uncertainty or intermediary heterogeneity.

A substantial literature in marketing and economics examines incentives of profit-maximizing firms to provide information about their products, e.g., through informative advertising. See Dra-

nove and Jin (2010) for a review of literature on disclosure of product-quality information. For example, in Kuksov and Lin (2010), consumers are uncertain as to whether a product is of low or high quality, and a firm with a high-quality product communicates this if the cost of doing so is not too high. Because for-profit firms in the developing world have relatively little incentive to incur costs to promote socially-beneficial products (IMC Worldwide 2014, Ruiz and Savadogo 2014), we treat the level of consumer awareness as exogenous.

Complementing this theoretical research are empirical studies on the impact of subsidies for health products in the developing world. See Morris et al. (2014) for a review of studies on the impact of subsidies for recommended malaria drugs on retail prices and consumer purchases. Evidence on the simultaneous impact of information and subsidies on demand is mixed. For example, Dupas (2009) finds that providing information about the negative health consequences of malaria alongside a subsidy for an insecticide-treated bed net does not impact the demand curve. In contrast, Ashraf et al. (2013) find that informing consumers that an unfamiliar product is similar to a familiar product does impact the demand curve. Our study differs in that we focus on consumers' existing awareness of the benefits of a particular product, rather than the provision of other information at the point of sale.

§2 presents the model. §3 presents results. §4 discusses extensions.

2 Model

A donor desires to stimulate the purchase and use of a product (e.g., a superior malaria drug or cook stove) which is sold to end consumers by an intermediary. Although the product is superior to alternatives, not all consumers acquainted with the product understand the product's benefits. For example, of the consumers that know that the drug is used to treat malaria, only a fraction of consumers are informed of the efficacy of the drug. Uninformed consumers believe that the drug's efficacy is typical, whereas informed consumers understand its superior efficacy. Similarly, uninformed consumers believe that the cook stove's performance in terms of fuel cost requirements and household pollution is typical, whereas informed consumers understand its superior performance.

The consumer population acquainted with the product is normalized to one. Awareness $a \in [0, 1]$ denotes the fraction of consumers that are informed of the product's benefits. A consumer with valuation intensity θ values the product at θq_I if she is informed of the product's benefits and at θq_U if she is not, where $q_I > q_U > 0$. A particular consumer's valuation intensity θ will depend on her need for the product (e.g., severity of malaria symptoms, intensity of cook stove use) and economic condition (e.g., income level); q_j , where $j \in \{I, U\}$, represents the consumer-

perceived quality level, where uninformed consumers do not perceive the product's full benefits. We assume that for both informed and uninformed consumers, θ is distributed uniformly on $[0, 1]$. The assumptions that the consumer valuation has a multiplicative form and that the valuation intensity has a uniform distribution are common in the literature on product quality and pricing (e.g., Moorthy 1988 and Choudhary et al. 2005). At price p , the fraction of the informed segment that purchases is $\max(1 - p/q_I, 0)$, and the fraction of the uninformed segment that purchases is $\max(1 - p/q_U, 0)$. Hence, the quantity sold by the intermediary under awareness a and price p is $Q(a, p) = a \max(1 - p/q_I, 0) + (1 - a) \max(1 - p/q_U, 0)$.

The donor (she) provides a per-unit subsidy $s \geq 0$ to the intermediary (he). The intermediary sells to end consumers at per-unit price $p \geq 0$ and incurs per-unit distribution cost $c \geq 0$. First, consider the scenario in which the intermediary controls the price p . In that case, the intermediary chooses p to maximize his profit

$$(p - c + s)Q(a, p). \quad (1)$$

Let $p^*(a, s)$ denote the intermediary's profit-maximizing price. The donor receives utility $v \geq 0$ per unit purchased by consumers. The donor chooses the subsidy s to maximize her utility

$$(v - s)Q(a, p^*(a, s)). \quad (2)$$

Next, consider the scenario in which the donor controls the price p . In that case, the donor jointly determines the price p and subsidy s to maximize her utility

$$(v - s)Q(a, p),$$

subject to ensuring that the intermediary does not incur a loss. Because the donor's utility decreases in p and the intermediary does not incur a loss if and only if the price exceeds the intermediary's subsidized cost $p \geq c - s$, the donor's optimal price is $p = c - s$. The subsidy s is the amount by which the donor reduces the price below the cost c , and the intermediary's margin is zero. Hence, the donor chooses the subsidy s to maximize her utility

$$(v - s)Q(a, c - s). \quad (3)$$

This setting corresponds to the case where the intermediary is a non-commercial entity (e.g., a non-governmental organization) that is willing to distribute the product at the price set by the donor. It also corresponds to the case where the intermediary is a commercial entity (e.g., a for-profit retailer) and the donor can enforce strict price control. Nonetheless, for simplicity in exposition, we refer to the case where the donor (intermediary) controls the price as corresponding to the non-

commercial (commercial) channel. To exclude the uninteresting extreme cases where the donor's optimal subsidy is either zero or equal to the intermediary's distribution cost c , we focus on the case where the donor's utility per unit purchased by consumers is moderate $v \in (q_I - c, q_U + c)$.

3 Results

§3.1 and §3.2 characterize the donor's optimal subsidy when the donor controls the price and when the intermediary controls the price, respectively. §3.3 and §3.4 show how the presence of a price-setting intermediary changes the impact of awareness on the subsidy and the donor's utility, respectively.

3.1 Subsidy under Donor Price Control

In this section, we consider the setting where the donor controls the price. The donor's price $p = c - s$, and she chooses the subsidy s to maximize her utility (3). Because the maximum willingness to pay of an uninformed consumer is q_U , the intermediary serves only informed consumers if the donor sets a price higher than q_U , i.e., $c - s > q_U$, or equivalently, offers a subsidy s lower than $c - q_U$. If instead the donor offers a subsidy higher than $c - q_U$, then the intermediary serves consumers in both the uninformed and informed segments. In the former case where $s < c - q_U$, the donor's utility is $\Pi_I(a, s) = (v - s)Q_I(a, c - s)$, where $Q_I(a, p) = a(1 - p/q_I)$. In the latter case where $s \geq c - q_U$, the donor's utility is $\Pi_B(a, s) = (v - s)Q_B(a, c - s)$, where $Q_B(a, p) = a(1 - p/q_I) + (1 - a)(1 - p/q_U)$. We say that the donor (or intermediary) *targets the informed segment* if the intermediary serves only informed consumers, and *targets the broad market* if he serves consumers in both the uninformed and informed segments. The subscript I is mnemonic for targeting the informed segment, and B is mnemonic for targeting the broad market. From the preceding analysis, we can rewrite the donor's problem as

$$\max \left\{ \sup_{s < c - q_U} \Pi_I(a, s), \sup_{s \geq c - q_U} \Pi_B(a, s) \right\}.$$

Note that both $\Pi_I(a, s)$ and $\Pi_B(a, s)$ are concave in the subsidy s with maximizers

$$s_I = (v + c - q_I)/2$$

and

$$s_B(a) = [v + c - q_I q_U / (a q_U + (1 - a) q_I)] / 2.$$

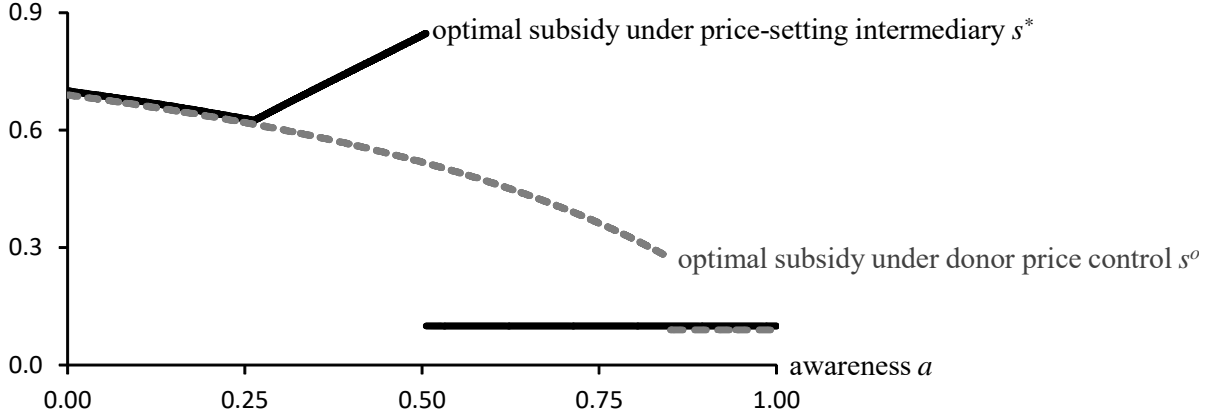


Figure 1: Donor's Optimal Subsidy as Function of Awareness. Parameters are $c = 1.0$, $v = 1.2$, $q_I = 2.0$ and $q_U = 0.8$. Proposition 1's threshold is $\hat{a} = 0.85$, and Proposition 2's thresholds are $\underline{a} = 0.26$ and $\bar{a} = 0.51$.

Proposition 1 characterizes the donor's optimal subsidy as function of the awareness a .

Proposition 1. *Under donor price control and awareness a , the donor's optimal subsidy is*

$$s^o(a) = \begin{cases} s_B(a) & \text{if } a \leq \hat{a} \\ s_I & \text{if } a > \hat{a}, \end{cases} \quad (4)$$

where $\hat{a} = \{a \mid \Pi_I(a, s_I) = \Pi_B(a, s_B(a))\}$.

Intuitively, when awareness a is low, the uninformed segment is too large to ignore, and the donor targets the broad market, serving consumers of both segments. Because consumers that are not aware of the product's benefits have a lower valuation for the product, reaching these consumers requires that the donor offer a generous subsidy $s^o(a) = s_B(a) > s_I$. In contrast, when awareness a is high so that the informed segment is large, the donor targets the informed segment by offering a stingy subsidy $s^o(a) = s_I < s_B(a)$. The dashed line in Figure 1 depicts the donor's optimal subsidy under donor price control as a function of the awareness a . When awareness is low, so that the donor targets both segments, the effectiveness of the subsidy in increasing sales diminishes as the size of the informed segment grows because informed consumers are less price sensitive than the uninformed consumers. Consequently, the optimal subsidy decreases in a . When awareness is high, so that the donor targets the informed segment, the donor's problem is one of selling to homogenous consumers with private valuations. The donor's optimal subsidized price is the result of trading off extracting additional revenue versus increasing the purchase probability, implying that the optimal subsidized price is independent of the population size of informed consumers.

The role of Proposition 1 is to provide a benchmark for understanding how the presence of a

price-setting intermediary changes the impact of awareness on the donor's optimal subsidy.

3.2 Subsidy under Price-setting Intermediary

In this section, we consider the setting where the intermediary controls the price. The intermediary chooses the price p to maximize his profit (1). The intermediary's key decision is whether to set a high price $p > q_U$ and target the informed segment or set a low price $p \leq q_U$ and target the broad market, serving consumers of both segments. The intermediary's problem is

$$\max \left\{ \sup_{p > q_U} \Lambda_I(p, s), \sup_{p \leq q_U} \Lambda_B(p, s) \right\},$$

where $\Lambda_I(p, s) = (p - c + s)Q_I(a, p)$ and $\Lambda_B(p, s) = (p - c + s)Q_B(a, p)$. Let $p_j(s)$ denote the maximizer of $\Lambda_j(p, s)$ for $j \in \{B, I\}$. Then $p_I(s) = (c - s + q_I)/2$ and $p_B(s) = \{c - s + q_I q_U / [a q_U + (1 - a) q_I]\}/2$.

Lemma 1. *Under awareness a and subsidy s , the intermediary's optimal price is*

$$p^*(a, s) = \begin{cases} p_I(s) & \text{if } s < \bar{s}(a) \\ p_B(s) & \text{if } s \geq \bar{s}(a), \end{cases}$$

where $\bar{s}(a) = c - q_U + (q_I - q_U) \sqrt{a q_U / [a q_U + (1 - a) q_I]}$.

Intuitively, a more generous subsidy makes it more attractive for the intermediary to sell a larger quantity, which she does by setting a lower price. When the subsidy is stingy, $s < \bar{s}(a)$, the intermediary sets a high price $p^*(a, s) > q_U$, targeting the informed segment. When the subsidy is generous, $s \geq \bar{s}(a)$, the intermediary sets a low price $p^*(a, s) < q_U$, targeting the broad market.¹ Because the threshold $\bar{s}(a)$ is increasing in the awareness a , the intermediary's target-market price decision parallels that of the donor: the intermediary targets the informed segment if and only if the awareness is high.

We now turn to the donor's problem. The donor chooses the subsidy s to maximize her utility (2), where (from Lemma 1) the intermediary's sales quantity is

$$Q(a, p^*(a, s)) = \begin{cases} Q_I(a, p_I(s)) & \text{if } s < \bar{s}(a) \\ Q_B(a, p_B(s)) & \text{if } s \geq \bar{s}(a). \end{cases}$$

We can rewrite the donor's problem as

$$\max \left\{ \sup_{s < \bar{s}(a)} \Pi_I(a, s)/2, \sup_{s \geq \bar{s}(a)} \Pi_B(a, s)/2 \right\},$$

¹From the perspective of consumers, as the donor increases her subsidy through the range $s \in (0, \bar{s}(a))$, only informed customers benefit; as the donor increases the subsidy in the range $s \geq \bar{s}(a)$, both segments benefit. This parallels the result under donor price control, where the threshold $\bar{s}(a)$ is replaced by $c - q_U$.

where $\Pi_I(a, s)/2$ represents the donor's utility when the subsidy induces the intermediary to target the informed segment, and $\Pi_B(a, s)/2$ represents the donor's utility when the subsidy induces the intermediary to target the broad market. The donor's subsidy design problem under a price-setting intermediary partially parallels the problem under donor price control examined in §3.1. The main distinction is that under a price-setting intermediary, the donor must offer a larger subsidy to induce the intermediary to target the broad market $\bar{s}(a) > c - q_U$.

Proposition 2. *Under a price-setting intermediary and awareness a , the donor's optimal subsidy is*

$$s^*(a) = \begin{cases} s_B(a) & \text{if } a \leq \underline{a} \\ \bar{s}(a) & \text{if } \underline{a} < a \leq \bar{a} \\ s_I & \text{if } a > \bar{a}, \end{cases} \quad (5)$$

where $\underline{a} = \{a \mid s_B(a) = \bar{s}(a)\}$ and $\bar{a} = \{a \mid \Pi_I(a, s_I) = \Pi_B(a, \bar{s}(a))\}$.

We discuss Proposition 2 at the start of the next section, wherein we discuss how the introduction of a price-setting intermediary changes the structure of the donor's optimal subsidy.

3.3 Impact of Awareness on Subsidy

This section examines how the presence of a price-setting intermediary changes the impact of awareness on the donor's optimal subsidy. Proposition 3, which is illustrated in Figure 1, characterizes the impact of awareness a , the fraction of consumers that are informed of the product's benefits, on the optimal subsidy s .

To build intuition, we describe the donor's optimal subsidy under a price-setting intermediary (Proposition 2), which is depicted graphically as the solid line in Figure 1. In designing a subsidy, the donor's key decision is whether and how to induce the intermediary to target the broad market or the informed segment. The general structure (and intuition for) which segment to target follows that for the case under donor price control discussed at the end of §3.1: the donor induces the intermediary to target the broad market if and only if awareness is sufficiently small $a \leq \bar{a}$. However, the way in which the donor induces the intermediary to target the broad market differs structurally under a price-setting intermediary. For the same reasons discussed at the end of §3.1, the donor's optimal subsidy under a price-setting intermediary is high and decreasing in awareness a when awareness is low $a \leq \underline{a}$, and is low and invariant to awareness when awareness is high $a > \bar{a}$. However, contrast emerges under a price-setting intermediary when awareness is moderate $a \in (\underline{a}, \bar{a})$. Under donor price control, the donor's optimal subsidy weakly decreases in the awareness. In contrast, under a price-setting intermediary, the donor's optimal subsidy *strictly increases* in awareness for $a \in (\underline{a}, \bar{a})$.

Because the donor values consumption and because consumption is higher when the intermediary targets the broad market, the donor induces the intermediary to target the broad market, provided that the uninformed segment is not too small, i.e., awareness $a \leq \bar{a}$. When awareness is low $a \leq \underline{a}$, so that the uninformed segment is large, serving the broad market is naturally attractive to the intermediary. However, as awareness a increases, it becomes increasingly attractive for the intermediary to abandon the shrinking uninformed segment. Therefore, persuading the intermediary to continue to serve the broad market requires that the donor increase the subsidy as awareness a increases through the moderate range $a \in (\underline{a}, \bar{a})$. This is increasingly costly to the donor, and so when the awareness a exceeds the threshold \bar{a} , the donor gives up on persuading the intermediary to serve the broad market. The donor does so by dropping the subsidy from a high level to a low one.

Proposition 3. *With donor price control, the donor's optimal subsidy $s^o(a)$ weakly decreases in awareness a . With a price-setting intermediary, the donor's optimal subsidy $s^*(a)$ strictly increases in awareness for $a \in (\underline{a}, \bar{a})$ and weakly decreases for $a \in [0, \underline{a}) \cup (\bar{a}, 1]$.*

The implication of Proposition 3 is that donors should be careful in changing their subsidies in response to changes in awareness. Awareness can be influenced by a variety of factors. For example, public health media campaigns communicate the benefits of products such as a class of malaria drugs or improved cook stoves (Amin et al. 2007, Rehfuess et al. 2014). For a donor distributing such a product, the effect of such campaigns is to increase the fraction of the population that is aware of the product's benefits. How should the donor respond to greater awareness? A donor that historically distributed products through a non-commercial channel should be wary of applying lessons from that environment when she shifts to distributing the product through a commercial channel. Specifically, Proposition 3 indicates that a donor distributing products through a non-commercial channel should respond to greater awareness by reducing the subsidy, because informed consumers are less price sensitive. Applying this prescription when distributing through a commercial channel can have the counterproductive consequence of persuading the profit-maximizing intermediary to abandon the uninformed segment. Consequently, donors distributing products through commercial channels should be wary of concluding that public health media campaigns reduce the need for generous subsidies. When awareness is moderate, the opposite is true.

Consider a donor that historically distributed products through a non-commercial channel. When the donor shifts to distributing through a commercial channel, ceteris paribus, should the donor increase or decrease the subsidy level? Proposition 4 reveals that the answer to this question depends on the consumers' awareness of the product's benefits. When awareness is low, the donor

should (weakly) increase the subsidy; when awareness is high, the donor should (weakly) decrease the subsidy. This result is depicted graphically in Figure 1.

Proposition 4. *The presence of a price-setting intermediary increases the donor's optimal subsidy $s^*(a) \geq s^o(a)$ if awareness is low $a \in [0, \bar{a})$, strictly so if and only if the awareness is moderately low $a \in (\underline{a}, \bar{a})$. The presence of a price-setting intermediary decreases the donor's optimal subsidy $s^*(a) \leq s^o(a)$ if awareness is high $a \in [\bar{a}, 1]$, strictly so if and only if the awareness is moderately high $a \in (\bar{a}, \hat{a})$.*

For low levels of awareness $a \leq \bar{a}$, the donor sets a subsidy so as to induce the intermediary to target the broad market, regardless of whether the donor or the intermediary controls the price. When the donor controls the price, she dictates through the subsidy level which segments the intermediary will target. In contrast, when the intermediary controls the price, the donor must set the subsidy anticipating the intermediary's self-interested market-targeting decision. As awareness increases, it becomes increasingly attractive for a price-setting intermediary to abandon the shrinking uninformed segment. Consequently, in the upper end of this awareness range $a \in (\underline{a}, \bar{a})$, persuading the price-setting intermediary to serve the broad market requires the donor to offer a generous subsidy. This explains why at moderately low awareness $a \in (\underline{a}, \bar{a})$, the presence of a price-setting intermediary strictly *increases* the donor's optimal subsidy.

As awareness increases through the range $a \in (\underline{a}, 1)$, ensuring that the price-setting intermediary targets the broad market requires an increasingly generous subsidy. Consequently, when the awareness a exceeds the threshold \bar{a} , the donor gives up on persuading the intermediary to serve the broad market, and instead shifts to a stingy subsidy appropriate for the informed market. In contrast, the price-setting donor does not face the intermediary price-mark-up problem, so it is attractive for the price-setting donor to continue to serve the broad market with a generous subsidy through the awareness range $a \in (\bar{a}, \hat{a})$. The subsidy targeting the broad market is more generous because uninformed consumers are more price sensitive. This explains why at moderately high awareness $a \in (\bar{a}, \hat{a})$, the presence of a price-setting intermediary strictly *decreases* the donor's optimal subsidy.

How might a donor reason about how she should change the subsidy when she shifts from distributing through a non-commercial to a commercial channel? First, because a price-setting intermediary passes through only a portion of the donor's subsidy to consumers, the presence of the intermediary reduces the effectiveness of the subsidy in increasing the purchase quantity. This *subsidy-effectiveness effect* favors reducing the subsidy. Second, because the quantity that the intermediary sells is smaller, due to his price markup, the marginal cost of increasing the subsidy

is reduced because the subsidy is applied to fewer units. This *subsidy-cost effect* favors increasing the subsidy. In our model, these two effects cancel out, which can be seen by observing that the donor's subsidy is unchanged at low and high levels of awareness. While these effects are relatively obvious, the contribution of Proposition 4 is to identify a third force at work, the *market-targeting effect*, which reflects the implications of the intermediary's self-interested market-targeting decision for the donor's subsidy. As Proposition 4 reveals, this effect is more subtle than the previous effects in that it compels the donor to either increase or decrease the subsidy, depending on the awareness level. When awareness is moderately low $a \in (\underline{a}, \bar{a})$, such that the donor would like to persuade the price-setting intermediary to target the broad market, the donor should increase the subsidy. When awareness is moderately high $a \in (\bar{a}, \hat{a})$, such that the donor would like the price-setting intermediary to abandon the uninformed segment, the donor should decrease the subsidy.

3.4 Impact of Awareness on Donor Utility

This section examines how the presence of a price-setting intermediary changes the impact of awareness on the donor's utility. As awareness increases, a set of previously uninformed consumers become informed of the product's benefits and thus are more prone to purchasing, resulting in a higher sales quantity. We refer to this as the *quantity effect*. The quantity effect benefits the donor because the increased sales quantity occurs without increasing the per-unit subsidy. Based on the quantity effect, one might conjecture that the donor should always benefit from an increase in awareness. Proposition 5 shows that this conjecture holds when the donor controls the price. However, under a price-setting intermediary, the donor benefits from increased awareness when awareness is either low or high, but is *hurt* by increased awareness when awareness is moderate; the result is depicted in Figure 2.

Proposition 5. *With donor price control, the donor's utility strictly increases in awareness a . With a price-setting intermediary, the donor's utility strictly decreases in awareness for $a \in (\check{a}, \bar{a})$ and strictly increases for $a \in [0, \check{a}) \cup (\bar{a}, 1]$, where $\check{a} \in (\underline{a}, \bar{a})$.*

As discussed in §3.3, when awareness a increases through the range $a \in (\underline{a}, \bar{a})$, persuading the price-setting intermediary to continue to target the broad market requires that the donor increase the subsidy. We refer to this as the *subsidy effect*. The subsidy effect hurts the donor because of the higher subsidy payment. Consequently, whether the donor benefits from increased awareness depends on the trade-off between the beneficial quantity effect and the harmful subsidy effect. To understand which effect dominates it is critical to understand how the magnitude of each effect depends on the awareness level a .

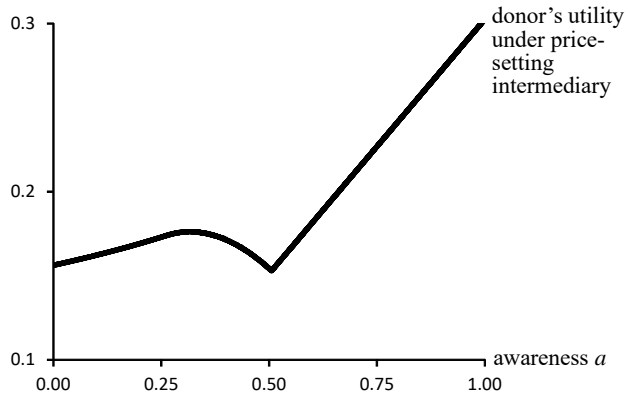


Figure 2: Donor's Utility as Function of Awareness. Parameters are $c = 1.0$, $v = 1.2$, $q_I = 1.5$ and $q_U = 0.8$.

To understand how the magnitude of the quantity effect depends on the awareness level, it is first useful to understand how the magnitude of the quantity effect depends on the price p . To do so, it is useful to classify the consumers into three categories, for any given price p . *Purchasers* are consumers with valuation intensities that are sufficiently high $\theta \in (p/q_U, 1]$ that they will purchase the product even if they are uninformed of the product's benefits. *Non-purchasers* are consumers with valuation intensities that are sufficiently low $\theta \in [0, p/q_I)$ that they will not purchase the product even if they are informed. *Information-dependents* are consumers with moderate valuation intensities $\theta \in (p/q_I, p/q_U)$ such that they will purchase if and only if they are informed.

Because the quantity effect is the increase in sales quantity resulting from uninformed consumers becoming informed, the magnitude of the effect is driven by the size of the information-dependents consumer category. How does the price impact the size of the information-dependents? When the price increases, the information-dependents category grows at the high end of the valuation intensity range because a subset of purchasers (those with the lowest valuations) become information-dependents. When the price increases, the information-dependents category shrinks at the low end of the valuation intensity range because a subset of information-dependents (those with the lowest valuations) become non-purchasers. Because uninformed purchasers are more price sensitive than informed non-purchasers, the growth from purchasers becoming information-dependents exceeds the shrinkage from information-dependents becoming non-purchasers. This implies that as the price increases, the size of the information-dependents category—and hence the magnitude of the quantity effect—increases.

Having established that the quantity effect grows as the price increases, we now turn to the impact of awareness on the magnitude of the quantity effect. As the awareness a increases through

the range $a \in (\underline{a}, \bar{a})$, the donor's optimal subsidy increases, resulting in a lower price and thus a smaller quantity effect.

Next we turn to the subsidy effect. As the awareness a increases through the range $a \in (\underline{a}, \bar{a})$, the magnitude of the subsidy effect grows because it becomes increasingly costly for the donor to persuade the intermediary not to abandon the shrinking uninformed segment.

In sum, under a price-setting intermediary, as the awareness a increases over the range $a \in (\underline{a}, \bar{a})$, the beneficial-to-the-donor quantity effect shrinks while the harmful-to-the-donor subsidy effect grows. Consequently there exists a threshold awareness level $\check{a} \in (\underline{a}, \bar{a}]$ such that the quantity effect outweighs the subsidy effect so that the donor benefits from an increase in awareness when $a \in (\underline{a}, \check{a})$, and is hurt by an increase in awareness when $a \in (\check{a}, \bar{a})$.

The implication of Proposition 5 is that a donor should be wary in encouraging entities (e.g., government ministries of health, non-governmental organizations) to institute public health media campaigns aimed at communicating the benefits of the donor's product. Although such campaigns benefit the donor when she distributes the product through a non-commercial channel, they can hurt the donor when she distributes through the commercial channel. A donor need only be concerned about this negative impact when she perceives that the awareness campaign will tempt the commercial channel to raise the price of the product and abandon the shrinking uninformed segment. Proposition 5 reveals that this will not be a concern when the awareness level prior to the campaign is high $a > \bar{a}$, or when the awareness level after the media campaign will be low $a < \check{a}$.

To what extent should a donor encourage others to increase consumers' awareness of the benefits of the product the donor is subsidizing? To provide a more complete answer to this question, Proposition 6 complements Proposition 5 by focusing on how the magnitude of the donor's *marginal* value of awareness changes in the awareness level, and how this depends on whether the donor controls the price.

Proposition 6. *With donor price control, the donor's marginal value of awareness increases in awareness for $a \in [0, \hat{a})$, and jumps up to a constant and stays at the constant for $a \in [\hat{a}, 1]$. With a price-setting intermediary, the donor's marginal value of awareness increases in awareness for $a \in [0, \underline{a})$, decreases in awareness for $a \in [\underline{a}, \bar{a})$, and jumps up to a constant and stays at the constant for $a \in [\bar{a}, 1]$.*

Recall that under donor price control, the donor serves the broad market for $a \in [0, \hat{a})$, and reduces the subsidy as the awareness a increases. The reduced subsidy leads to a higher price, implying that the beneficial-to-the-donor quantity effect strengthens as a increases over $a \in [0, \hat{a})$. Consequently, the donor's marginal value of awareness increases as the awareness increases over the range $a \in [0, \hat{a})$.

When the awareness a reaches to the threshold \hat{a} , the donor serves only the informed segment and the subsidy is independent of the awareness, implying that the price stays at the constant level. At this awareness threshold, the quantity effect reaches its largest level and remains unchanged as awareness further increases. Therefore, the donor's marginal value of awareness reaches the highest level at $a = \hat{a}$ and stays constant as a increases.

The same insights can be applied to explain the result that with a price-setting intermediary, the donor's marginal value of awareness increases in awareness for $a \in [0, \underline{a})$ and jumps up to a constant and stays at the constant for $a \in [\bar{a}, 1]$. The result that the donor's marginal value of awareness decreases in awareness for $a \in [\underline{a}, \bar{a})$ can be explained by recalling that as a increases over the range $[\underline{a}, \bar{a})$, the beneficial quantity effect shrinks and the harmful subsidy effect grows.

An implication of Proposition 6 is that donors should be most encouraging of efforts to marginally increase the fraction of the consumer population aware of the product's benefits when that fraction is already high. In contrast, donors have relatively little to gain by such efforts when this fraction is small.

4 Extensions

In this section, we discuss several extensions of our base model: endogenous awareness effort, distinct distribution costs and population sizes, and alternative ways to model the donor's utility.

4.1 Endogenous Awareness Effort

Although we have focused on the donor's subsidy decision, taking awareness as being exogenous, in some settings a donor's efforts to increase the purchase and use of particular products include both a subsidy and an effort to increase consumers' awareness of the product's benefits. Consider an extended model in which the donor chooses, in addition to the subsidy s , the awareness $a \in [\tilde{a}, 1]$ at cost $\beta k(a)$, where \tilde{a} is the initial awareness and $k(\cdot)$ is increasing. We refer to β the cost of awareness effort. The results in our base model have direct implications for this extended model.

First, our core result in Proposition 3 regarding how the awareness level affects the donor's optimal subsidy under each channel mirrors the result regarding how the cost of awareness effort β affects the donor's optimal subsidy, because the optimal awareness level is monotone in the cost of awareness effort. The intuitive result that a reduction in the cost of awareness effort always increases the awareness level and thus reduces the need for and hence the magnitude of the subsidy holds under donor price control. In contrast, when the intermediary controls the price, the donor

may need to respond to a reduction in the cost of awareness effort by *increasing* the subsidy when the cost of awareness effort is moderate.

Second, it follows from the proofs of Propositions 5 and 6 that, for any given awareness level, the marginal value of awareness is higher when the donor rather than the intermediary controls the price. Consequently, the optimal awareness effort is higher under donor price control. Nonetheless, the message of Proposition 4 that the presence of a price-setting intermediary can either increase or decrease the donor's optimal subsidy continues to hold.

Third, Proposition 5's sufficient conditions for the donor's utility to decrease in the awareness under the commercial channel imply that even if increasing awareness is costless, $\beta = 0$, the donor distributing through a price-setting intermediary should avoid embarking on small efforts to increase awareness, if the initial awareness level is moderate $\tilde{a} \in (\tilde{a}, \bar{a})$. This contrasts for the prescription for the price-setting donor, who should always embark on efforts to increase awareness, if they are sufficiently inexpensive.

Finally, Propositions 5 and 6 have an additional implication for the donor's awareness effort decision. When the donor distributes through a non-commercial channel, the marginal value of awareness is increasing. This favors large awareness campaigns. In contrast, when the donor distributes through a commercial channel, the marginal value of awareness is decreasing if and only if the awareness is moderate. This favors the donor pursuing either small or large awareness efforts, but avoiding intermediate efforts, when the initial awareness level is small, as is the case for ICS in rural areas (IMC Worldwide 2014). The awareness of the benefits of ICS is higher in urban areas (IMC Worldwide 2014). To the extent that initial awareness level is sufficiently high $\tilde{a} > \bar{a}$, the donor need not be concerned that her efforts to increase awareness will be counterproductive.

These insights are driven by the finding that moderate levels of awareness are unattractive to the donor distributing through a price-setting intermediary because of the high subsidy required to persuade the intermediary to target the broad market.

4.2 Distinct Distribution Costs and Population Sizes

For simplicity, we have assumed that the commercial and non-commercial channel have the same distribution cost c and the same consumer population size. In reality, due to private-sector efficiencies, the commercial channel may have a lower distribution cost and/or access to a larger consumer population. Consider an extended model in which the distribution cost and/or the consumer population size differ by channel. Because our analysis for each channel is valid for any distribution cost and population size, the analytical results for each channel (namely, how the optimal subsidy and

donor's utility change in the awareness) continue to hold. For each channel, the optimal subsidy increases in the distribution cost but is unaffected by the consumer population size. The result comparing the optimal subsidy across channels is modified accordingly.

4.3 Donor's Utility

Although we have assumed the donor is not constrained by a budget, this assumption is not essential in the following sense: The donor's objective function in our donor-utility formulation can be viewed as the Lagrange function of an alternative formulation wherein the donor's objective is to maximize the sales quantity subject to a finite budget. A small (large) budget in the budget formulation corresponds to a low (high) per-unit utility v in the donor-utility formulation. The two formulations parallel one another in that the formal results in §3.1 and §3.2 continue to hold in the budget formulation.

Although we have assumed that donor's utility is linear in the quantity purchased, the formal results in §3.3 and §3.4 continue to hold when the donor's utility is a concave, increasing function of the quantity purchased.

Our base model assumes that the donor's utility from the adoption of the socially-beneficially product is captured solely through the quantity sold. Some donors may derive utility not only directly from the quantity sold, but also from the consumer surplus generated by the purchase of the product. A consumer's surplus from purchase is her valuation less the price. Consider an extended model in which the donor's utility from the base model is augmented by the consumer surplus:

$$(v - s)Q(a, p) + CS_I(a, p) + CS_U(a, p),$$

where $CS_I(a, p) = a \int_{p/q_I}^1 (\theta q_I - p) d\theta$ is the surplus of informed consumers and $CS_U(a, p) = (1 - a) \int_{p/q_U}^1 (\theta q_U - p) d\theta$ is the surplus of uninformed consumers. (Note in the special case $v = 0$, the donor's utility from consumption is solely from the consumer surplus.)

Following the proof approach in Propositions 1 and 2, one can show that under awareness a , the donor's optimal subsidy under donor price control $s^o(a) = \min(c, v)$ (with some abuse of notation), and the donor's optimal subsidy under intermediary price control $s^*(a)$ is given by (5), where $s_B(a) = \{2v + c - q_I q_U / [a q_U + (1 - a) q_I]\} / 3$, $s_I = (2v + c - q_I) / 3$ and the donor's utility $\Pi_j(a, s)$ is augmented by the consumer surplus for $j \in \{I, B\}$. Thus, our main result that the donor with a commercial channel should be prepared to increase the subsidy as awareness increases, which is contrary to her actions with a non-commercial channel (Proposition 3), continues to hold. The

other main result from our base model is that under the commercial channel, the donor can be hurt by increased awareness when awareness is moderate (Proposition 5). We observed this phenomenon numerically in the extended model. We conclude that our core results described in Propositions 3 and 5 are robust to this extension.

5 Conclusion

As noted in §1, increasingly, donors interested in encouraging the purchase and use of socially-beneficial products are shifting their attention from distributing through non-commercial channels in which they control the price to commercial channels wherein the price is delegated to a for-profit intermediary. This paper provides guidance to donors in how they should approach this transition. The main change in distributing through a price-setting intermediary is the need to account for the intermediary's market-targeting decision.

Accounting for this decision leads to three main implications. First, in shifting to the commercial channel, the donor should increase the subsidy when consumer awareness of the product's benefits is low, and decrease the subsidy when awareness is high. Second, with the commercial channel, the donor should be prepared to increase the subsidy as awareness increases, which is contrary to her actions when she distributes through a non-commercial channel. Third, contrary to the lesson obtained with non-commercial distribution, with commercial distribution the donor can be hurt by increased awareness. The implication is that the donor should be wary in encouraging entities (e.g., government ministries of health, non-governmental organizations) to institute awareness campaigns aimed at communicating the benefits of the donor's product. The donor should be especially concerned when the initial level awareness is moderate, and the campaign has a relatively small impact. Then the effect of the campaign is to encourage the intermediary to raise the price, excluding consumers that are not informed of the product's benefits, to the donor's detriment.

Although donors are interested in increasing the purchase and use of specific products, our model has only captured the purchase decision. The extent to which the product achieves its positive intended social benefit depends on the degree to which the product is used properly. The empirical evidence for the impact of ICS is mixed. For example, Smith-Sivertsen et al. (2009) find that usage by recipients of ICS is sufficient to obtain benefits in reduced carbon dioxide exposure and respiratory irritation. In contrast, Hanna et al. (2016) find usage and health benefits are limited. A concern in shifting from the non-commercial to the commercial channel in the distribution of recommended malaria drugs is that the for-profit intermediaries may lack the capabilities and incentives to encourage proper use of the drugs (Arrow et al. 2004, Morris et al. 2014). In

general, the extent to which a product is properly used depends on the information provided by the intermediary at the point of sale, and any efforts by the intermediary to follow up with the user (e.g., to make sure that ICS are properly maintained and used). To the extent that the non-commercial channel is more capable and motivated to provide this guidance, the value to the donor of a sale through the non-commercial channel would be higher than a sale through the commercial channel. This would alter our results by pushing down the optimal subsidy for the commercial channel.

As donors shift their efforts from non-commercial to commercial channels, they have more options than transferring the subsidized-product approach to this new channel. For example, in the context of ICS, there is active debate around whether donors should subsidize products directly or indirectly, through, for example, research and development work to design effective ICS and then training to building capabilities of local stove producers (Simon et al. 2014). Additional research is required to inform how donors ought to pursue such indirect subsidy efforts, and to compare their performance with direct subsidies.

References

- Adida, E., D. Dey, H. Mamani. 2013. Operational issues and network effects in vaccine markets. *European Journal of Operational Research* **231** 414-427.
- Adeyi, O., R. Atun. 2010. Universal access to malaria medicines: Innovation in financing and delivery. *Lancet* **376** 1869-1871.
- Amin, A. A., D. Zurovac, B. B. Kangwana, J. Greenfield, D. N. Otieno, W. S. Akhwale, R. W. Snow. 2007. The challenges of changing national malaria drug policy to artemisinin-based combinations in Kenya. *Malaria Journal* **6**(72).
- Arifoğlu, K., S. Deo, S. M. R. Iravani. 2012. Consumption externality and yield uncertainty in the influenza vaccine supply chain: Interventions in demand and supply sides. *Management Science* **58**(6) 1072-1091.
- Arrow, K. J., C. Panosian, H. Gelband. 2004. *Saving Lives, Buying Time: Economics of Malaria Drugs in an Age of Resistance*. National Academies Press, Washington, DC.
- Ashraf, N., B. K. Jack, E. Kamenica. 2013. Information and subsidies: Complements or substitutes? *Journal of Economic Behavior and Organization* **88** 133-139.
- Berenguer, G., Q. Feng, J. G. Shanthikumar, L. Xu. 2017. The effects of subsidies on increasing consumption through for-profit and not-for-profit newsvendors. *Production and Operations Management* **26**(6) 1191-1206.
- Broder, J. M. 2010. Developing nations to get clean-burning stoves. *New York Times* (Sept. 20)

A8.

- Chemama, J., M. C. Cohen, R. Lobel, G. Perakis. 2018. Consumer subsidies with a strategic supplier: Commitment vs. flexibility. *Management Science*, Forthcoming.
- Chick, S. E., H. Mamani, D. Simchi-Levi. 2008. Supply chain coordination and influenza vaccination. *Operations Research* **56**(6), 1493-1506.
- Choudhary, V., A. Ghose, T. Mukhopadhyay, U. Rajan. 2005. Personalized pricing and quality differentiation. *Management Science* **51**(7), 1120-1130.
- Cohen, J. M., O. Sabot, K. Sabot, M. Gordon, I. Gross, D. Bishop, M. Odhiambo, Y. Ipuge, L. Ward, A. Mwita, C. Goodman. 2010. A pharmacy too far? Equity and spatial distribution of outcomes in the delivery of subsidized artemisinin-based combination therapies through private drug shops. *BMC Health Services Research* **10**(1) 1-12.
- Cohen, M., R. Lobel, G. Perakis. 2016. The impact of demand uncertainty on consumer subsidies for green technology adoption. *Management Science*. **62**(5) 1235-1258.
- Dai, T., S.-H. Cho, F. Zhang. 2016. Contracting for on-time delivery in the U.S. influenza vaccine supply chain. *Manufacturing & Service Operations Management* **18**(3) 332-346.
- Dranove, D., G. Z. Jin. 2010. Quality disclosure and certification: Theory and practice. *Journal of Economic Literature* **48**(4) 935-963.
- Dupas, P., 2009. What matters (and what does not) in households' decision to invest in malaria prevention. *American Economic Review: Papers & Proceedings* **99**(2) 224-230.
- Gaul, M. 2009. Subsidy schemes for the dissemination of improved stoves. Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany.
- Hanna, R., E. Duflo, M. Greenstone. 2016. Up in smoke: The influence of household behavior on the long-run impact of improved cooking stoves. *American Economic Journal: Economic Policy* **8**(1) 80-114.
- IMC Worldwide. 2014. Results-based financing for clean cookstoves in Uganda. Africa Clean Cooking Energy Solutions Program of the World Bank, Washington D.C.
- Kuksov, D., Y. Lin. 2010. Information provision in a vertically differentiated competitive marketplace. *Marketing Science*. **29**(1) 122-138.
- Levi, R., G. Perakis, G. Romero. 2017. On the effectiveness of uniform subsidies in increasing market consumption. *Management Science* **63**(1) 40-57.
- Levi, R., G. Perakis, G. Romero. 2018. Near-optimality of uniform co-payments for subsidies and taxes allocation problems. *Operations Research*, Forthcoming.
- Mamani, H., S. E. Chick, D. Simchi-Levi. 2013. A game-theoretic model of international influenza

- vaccination coordination. *Management Science* **59**(7) 1650-1670.
- Mobarak, A. M., P. Dwivedi, R. Bailis, L. Hildemann, G. Miller. 2012. Low demand for nontraditional cookstove technologies. *Proceedings of the National Academy of Sciences of the United States of America* **109**(27) 10815-10820.
- Moorthy, K. 1988. Product and price competition in a duopoly. *Marketing Science* **7**(2) 141-168.
- Morris, A., A. Ward, B. Moonen, O. Sabot, J. M. Cohen. 2015. Price subsidies increase the use of private sector ACTs: Evidence from a systematic review. *Health Policy and Planning* **30**(3) 397-405.
- Natarajan, K. V., J. M. Swaminathan. 2015. Coordinating demand and supply in funding-constrained developing country health supply chains. Working Paper, University of Minnesota.
- Raz, G., A. Ovchinnikov. 2015. Coordinating pricing and supply of public interest goods using government rebates and subsidies. *IEEE Transactions on Engineering Management* **62**(1) 65-79.
- Rehfuess E. A., E. Puzzolo, D. Stanistreet, D. Pope, N. G. Bruce. 2014. Enablers and barriers to large-scale uptake of improved solid fuel stoves: A systematic review. *Environmental Health Perspectives*. **122**(2) 120–130.
- Risseuw, N. 2012. Household energy in Mozambique: A study on the socioeconomic and cultural determinants of stove and fuel transitions. Energy Research Center for the Netherlands, Amsterdam, Netherlands.
- Ruiz, S. R., W. Savadogo. 2014. Building businesses cases to reach scale: A study of biomass cookstove business models in Asia and Africa. StovePlus and Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, Germany.
- Shrimali, G., X. Slaski, M. C. Thurber, H. Zerriffi. 2011. Improved stoves in India: A study of sustainable business models. *Energy Policy* **39**(12) 7543-7556.
- Simon, G. L., R. Bailis, J. Baumgartner, J. Hyman, A. Laurent. 2014. Current debates and future research needs in the clean cookstove sector. *Energy for Sustainable Development* **20** 49-57.
- Smith-Sivertsen, T., E. Díaz, D. Pope, R. T. Lie, A. Díaz, J. McCracken, P. Bakke, B. Arana, K. R. Smith, N. Bruce. 2009. Effect of reducing indoor air pollution on women's respiratory symptoms and lung function: The RESPIRE randomized trial, Guatemala. *American Journal of Epidemiology*. **170**(2) 211-220.
- Taylor, T. A., W. Xiao. 2014. Subsidizing the distribution channel: Donor funding to improve the availability of malaria drugs. *Management Science*. **60**(10) 2461-2477.
- TNS. 2013. Uganda clean cooking consumer research. London, England.
- United States Agency for International Development. 2009. Commercialization of improved cook-

stoves for reduced indoor air pollution in urban slums of northwest Bangladesh. Washington, DC. World Bank. 2010. Improved cookstoves and better health in Bangladesh: Lessons from household energy and sanitation programs. Washington, DC.

World Bank. 2014. Clean and improved cooking in sub-saharan africa: A landscape report. Washington, DC.

World Health Organization. 2015. World Malaria Report 2015. Geneva, Switzerland.

Appendix

Lemma A1 is useful in the proofs of Propositions 1 and 2. Lemma A2 is useful in the proof of Proposition 1.

Lemma A1. $(v + q_I - c)^2 \geq 4(v - c + q_U)(q_I - q_U)$.

Proof of Lemma A1: Because

$$\begin{aligned}
& (v + q_I - c)^2 - 4(v - c + q_U)(q_I - q_U) \\
&= (v + q_I - c)^2 - 4(v - c + q_I - q_I + q_U)(q_I - q_U) \\
&= (v + q_I - c)^2 - 4(v - c + q_I)(q_I - q_U) + 4(q_I - q_U)^2 \\
&= (v - c - q_I + 2q_U)^2 \\
&\geq 0,
\end{aligned}$$

the result holds. ■

For use in Lemma A2 and the proofs of Lemma 1 and Propositions 1 and 2, let

$$\begin{aligned}
\pi_I(a) &= \Pi_I(a, s_I) \\
\pi_B(a) &= \Pi_B(a, s_B(a)) \\
\hat{c}(a) &= q_U - (q_I - q_U)\sqrt{aq_U/[aq_U + (1 - a)q_I]}.
\end{aligned}$$

Lemma A2. $\pi_I(\hat{a}) = \pi_B(\hat{a})$, where $\hat{a} = \{a | c - v = \hat{c}(a)\}$.

Proof of Lemma A2: By definition of $\pi_I(a)$ and $\pi_B(a)$,

$$\begin{aligned}
\pi_I(a) - \pi_B(a) &= (v - s_I)a[1 - (c - s_I)/q_I] \\
&\quad - [v - s_B(a)][1 - [c - s_B(a)][aq_U + (1 - a)q_I]/(q_Uq_I)] \\
&= a(v - c + q_I)^2/(4q_I) \\
&\quad - \{(v - c)[aq_U + (1 - a)q_I] + q_Uq_I\}^2/[4q_Uq_I(aq_U + (1 - a)q_I)] \\
&= \frac{(1 - a)}{4q_U} \left[-(v - c)^2 - 2(v - c)q_U - \frac{q_Uq_I((1 + a)q_U - aq_I)}{aq_U + (1 - a)q_I} \right] \\
&= \frac{(1 - a)}{4q_U} \left[-(v - c + q_U)^2 + \frac{aq_U^3 + (1 - a)q_U^2q_I - q_Uq_I((1 + a)q_U - aq_I)}{aq_U + (1 - a)q_I} \right] \\
&= \frac{(1 - a)}{4q_U} \left[-(v - c + q_U)^2 + (q_I - q_U)^2 \frac{aq_U}{aq_U + (1 - a)q_I} \right],
\end{aligned}$$

which implies the result. ■

Note, by Lemma A2, that the definition of \hat{a} in Lemma A2 is equivalent to the definition in Proposition 1. Lemma A3 is useful in the proof of Proposition 2.

Lemma A3.

$$\pi_I(a) \leq \pi_B(a) \text{ for } a \leq \hat{a},$$

where the first inequality is strict if and only if the second is strict.

Proof of Lemma A3 and Proposition 1: The proof is structured as follows. We define a threshold \tilde{a} , where $\tilde{a} \geq \hat{a}$. We then examine a Case 1, which corresponds to $a \geq \tilde{a}$ and show $s^o(a) = s_I$. Next we examine Case 2, which corresponds to $a < \tilde{a}$, and show $s^o(a) = s_B(a)$ if $a \leq \hat{a}$, and $s^o(a) = s_I$ if $\hat{a} < a < \tilde{a}$.

Case 1. $s_B(a) \leq c - q_U$, which by the definition of $s_B(a)$, can be rewritten as $a \geq \tilde{a}$, where

$$\tilde{a} = \{a | c - v = \tilde{c}(a)\}$$

and

$$\tilde{c}(a) = q_U - (q_I - q_U)aq_U/[aq_U + (1 - a)q_I].$$

It follows from the condition $s_B(a) \leq c - q_U$ that $\sup_{s > c - q_U} \Pi_B(a, s) = \Pi_B(a, c - q_U)$, which together with $\Pi_B(a, c - q_U) = \Pi_I(a, c - q_U)$, implies $\sup_{s > c - q_U} \Pi_B(a, s) \leq \sup_{s \leq c - q_U} \Pi_I(a, s)$. This, together with the result $s_I \leq s_B(a) \leq c - q_U$, implies that $s^o(a) = s_I$.

Case 2. $s_B(a) > c - q_U$, i.e., $a < \tilde{a}$. Note that the condition $s_B(a) > c - q_U$ can be rewritten as

$$q_Iq_U/(aq_U + (1 - a)q_I) < v - c + 2q_U. \quad (6)$$

Note

$$\begin{aligned}
\pi'_I(a) - \pi'_B(a) &= (v - s_I)[1 - (c - s_I)/q_I] - [v - s_B(a)][c - s_B(a)](1/q_U - 1/q_I) \\
&= (v - c + q_I)^2/(4q_I) - [q_U^2 q_I^2 / (aq_U + (1 - a)q_I)^2 - (v - c)^2](q_I - q_U)/(4q_U q_I) \\
&> (v - c + q_I)^2/(4q_I) - [(v - c + 2q_U)^2 - (v - c)^2](q_I - q_U)/(4q_U q_I) \\
&= (v - c + q_I)^2/(4q_I) - 4(v - c + q_U)(q_I - q_U)/(4q_I) \\
&\geq 0,
\end{aligned} \tag{7}$$

where the first inequality follows from (6) and the second inequality is due to Lemma A1. From Lemma A2, $\pi_I(\hat{a}) = \pi_B(\hat{a})$. It follows from the definitions of \tilde{a} and \hat{a} that $\hat{a} \leq \tilde{a}$. This implies that Lemma A3 holds and that

$$\pi_I(a) > \pi_B(a) \text{ for } \hat{a} < a < \tilde{a}.$$

If $a \leq \hat{a}$, then $a < \tilde{a}$, i.e., $s_B(a) > c - q_U$, implying that $\sup_{s > c - q_U} \Pi_B(a, s) = \pi_B(a) \geq \pi_I(a) \geq \sup_{s \leq c - q_U} \Pi_I(a, s)$. Thus, $s^o(a) = s_B(a)$. Suppose $\hat{a} < a < \tilde{a}$. Then

$$\begin{aligned}
0 &= c - v - \hat{c}(\hat{a}) \\
&= c - v - q_U + (q_I - q_U)\sqrt{\hat{a}q_U/[\hat{a}q_U + (1 - \hat{a})q_I]} \\
&< c - v - q_U + (q_I - q_U)\sqrt{aq_U/[aq_U + (1 - a)q_I]} \\
&\leq c - v - q_U + q_I - q_U \\
&= 2(c - q_U - s_I),
\end{aligned} \tag{8}$$

where the first equality follows from the definition of \hat{a} in Lemma A2, and the strict inequality holds because $\hat{a} < a$. By inequality (8), $s_I \leq c - q_U$. Hence, $\sup_{s \leq c - q_U} \Pi_I(a, s) = \pi_I(a) > \pi_B(a) \geq \sup_{s > c - q_U} \Pi_B(a, s)$, implying that $s^o(a) = s_I$. ■

Lemma A4 is useful in the proof of Lemma 1. For use in Lemma A4 and the proof of Lemma 1, let

$$\begin{aligned}
\lambda_I(s) &= \Lambda_I(p_I(s), s) \\
\lambda_B(s) &= \Lambda_B(p_B(s), s) \\
\bar{s}(a) &= c - q_U + (q_I - q_U)\sqrt{aq_U/[aq_U + (1 - a)q_I]}.
\end{aligned}$$

Lemma A4. $\lambda_I(\bar{s}(a)) = \lambda_B(\bar{s}(a))$.

Proof of Lemma A4: By definition of $\lambda_I(s)$ and $\lambda_B(s)$,

$$\begin{aligned}
\lambda_I(s) - \lambda_B(s) &= [p_I(s) - c + s]a[1 - p_I(s)/q_I] \\
&\quad - [p_B(s) - c + s][1 - p_B(s)[aq_U + (1 - a)q_I]/(q_Uq_I)] \\
&= a(q_I - c + s)^2/(4q_I) \\
&\quad - \{q_Uq_I/[aq_U + (1 - a)q_I] - c + s\}\{1 - (c - s)[aq_U + (1 - a)q_I]/(q_Uq_I)\}/4 \\
&= (1 - a)\{2(c - s)q_U - (c - s)^2 - q_Uq_I[(1 + a)q_U - aq_I]/[aq_U + (1 - a)q_I]\}/(4q_U) \\
&= (1 - a)\{(q_I - q_U)^2aq_U/[aq_U + (1 - a)q_I] - (q_U - c + s)^2\}/(4q_U),
\end{aligned}$$

implying that $\lambda_I(\bar{s}(a)) - \lambda_B(\bar{s}(a)) = 0$. ■

Proof of Lemma 1. The proof is structured as follows. We define a threshold $\tilde{s}(a)$, where $\tilde{s}(a) \leq \bar{s}(a)$. We then examine a Case 1, which corresponds to $s \leq \tilde{s}(a)$ and show the optimal price $p^*(a, s) = p_I(s)$. Next we examine Case 2, which corresponds to $s > \tilde{s}(a)$, and show $p^*(a, s) = p_B(s)$ if $s \geq \bar{s}(a)$, and $p^*(a, s) = p_I(s)$ if $\tilde{s}(a) < s < \bar{s}(a)$.

Case 1. $p_B(s) \geq q_U$, which by the definition of $p_B(s)$, can be rewritten as $s \leq \tilde{s}(a)$, where

$$\tilde{s}(a) = c - q_U + (q_I - q_U)aq_U/[aq_U + (1 - a)q_I].$$

It follows from the condition $p_B(s) \geq q_U$ that $\sup_{p \leq q_U} \Lambda_B(p, s) = \Lambda_B(q_U, s)$, which together with $\Lambda_B(q_U, s) = \Lambda_I(q_U, s)$, implies $\sup_{p \leq q_U} \Lambda_B(p, s) \leq \sup_{p > q_U} \Lambda_I(p, s)$. This, together with the result $p_I(s) \geq p_B(s) \geq q_U$, implies that $p^*(a, s) = p_I(s)$.

Case 2. $p_B(s) < q_U$, i.e., $s > \tilde{s}(a)$. Note that the condition $p_B(s) < q_U$ implies that

$$c - s < q_U. \tag{9}$$

Note

$$\begin{aligned}
\lambda'_I(s) - \lambda'_B(s) &= a[1 - p_I(s)/q_I] - a[1 - p_B(s)/q_I] - (1 - a)[1 - p_B(s)/q_U] \\
&= (1 - a)(c - s - q_U)/(2q_U) \\
&< 0,
\end{aligned}$$

where the inequality follows from (9). From Lemma A4, $\lambda_I(\bar{s}(a)) = \lambda_B(\bar{s}(a))$. It follows from the definitions of $\tilde{s}(a)$ and $\bar{s}(a)$ that $\bar{s}(a) \geq \tilde{s}(a)$. Therefore,

$$\lambda_I(s) \leq \lambda_B(s) \text{ for } s \geq \bar{s}(a)$$

and

$$\lambda_I(s) > \lambda_B(s) \text{ for } \tilde{s}(a) < s < \bar{s}(a).$$

If $s \geq \bar{s}(a)$, then $p_B(s) \leq q_U$, implying that $\sup_{p \leq q_U} \Lambda_B(p, s) = \lambda_B(s) \geq \lambda_I(s) \geq \sup_{p > q_U} \Lambda_I(p, s)$. Thus, $p^*(a, s) = p_B(s)$. Suppose $\tilde{s}(a) < s < \bar{s}(a)$. The second inequality implies $p_I(s) > q_U$. Hence, $\sup_{p > q_U} \Lambda_I(p, s) = \lambda_I(s) > \lambda_B(s) \geq \sup_{p \leq q_U} \Lambda_B(p, s)$, implying that $p^*(a, s) = p_I(s)$. ■

Lemma A5 is useful in the proof of Proposition 2, where, recall, $\underline{a} = \{a | s_B(a) = \bar{s}(a)\}$.

Lemma A5. $\underline{a} \leq \hat{a}$.

Proof of Lemma A5: By definition of $s_B(a)$, we have $[v + c - q_I q_U / (\underline{a} q_U + (1 - \underline{a}) q_I)] / 2 = \bar{s}(\underline{a})$, which implies that

$$\begin{aligned} 2\bar{s}(\underline{a}) &= v + c - q_I q_U / [\underline{a} q_U + (1 - \underline{a}) q_I] \\ &= \bar{s}(\hat{a}) + c - q_I q_U / [\underline{a} q_U + (1 - \underline{a}) q_I] \\ &\leq \bar{s}(\hat{a}) + c - q_U \\ &\leq 2\bar{s}(\hat{a}), \end{aligned}$$

where the second equality follows from the definition of \hat{a} in Lemma A2. This, together with the fact that $\bar{s}(a)$ increases in a , implies $\underline{a} \leq \hat{a}$. ■

Proof of Proposition 2. The proof is structured as follows. We examine a Case 1, which corresponds to $a \leq \underline{a}$ and show $s^*(a) = s_B(a)$. Next we examine Case 2, which corresponds to $a > \underline{a}$, and show there exists $\bar{a} \in [\underline{a}, \hat{a}]$ such that $s^*(a) = \bar{s}(a)$ if $a \in (\underline{a}, \bar{a}]$, and $s^*(a) = s_I$ if $a > \bar{a}$.

Case 1. $s_B(a) \geq \bar{s}(a)$, which, because $s_B(a) - \bar{s}(a)$ is strictly decreasing in a , can be rewritten as $a \leq \underline{a}$, where $\underline{a} = \{a | s_B(a) = \bar{s}(a)\}$. It follows from the condition $s_B(a) \geq \bar{s}(a)$ that

$$\begin{aligned} \sup_{s \geq \bar{s}(a)} \Pi_B(a, s) &= \pi_B(a) \\ &\geq \pi_I(a) \\ &\geq \sup_{s < \bar{s}(a)} \Pi_I(a, s), \end{aligned}$$

where the first inequality follows from Lemma A3 and the fact that $a \leq \underline{a}$ implies $a \leq \hat{a}$ (by Lemma A5). Therefore, $s^*(a) = s_B(a)$ for $a \leq \underline{a}$.

Case 2. $s_B(a) < \bar{s}(a)$, i.e., $a > \underline{a}$. Because $s_B(a)$ is the maximizer of the concave function $\Pi_B(a, s)$, $\sup_{s \geq \bar{s}(a)} \Pi_B(a, s) = \Pi_B(a, \bar{s}(a))$. Let $\bar{\pi}_B(a) = \Pi_B(a, \bar{s}(a))$. Then

$$\begin{aligned} \bar{\pi}'_B(a) &= \partial \Pi_B(a, s) / \partial a |_{s=\bar{s}(a)} + \partial \Pi_B(a, s) / \partial s |_{s=\bar{s}(a)} d\bar{s}(a) / da \\ &\leq \partial \Pi_B(a, s) / \partial a |_{s=\bar{s}(a)} \\ &= [v - \bar{s}(a)][c - \bar{s}(a)](q_I - q_U) / (q_I q_U) \\ &\leq [v - \bar{s}(\underline{a})][c - \bar{s}(\underline{a})](q_I - q_U) / (q_I q_U), \end{aligned} \tag{10}$$

where the first inequality follows from the result that $\partial\Pi_B(a, s)/\partial s|_{s=\bar{s}(a)} \leq 0$ (because of the condition $s_B(a) < \bar{s}(a)$) and $d\bar{s}(a)/da \geq 0$, and the last inequality is due to $a > \underline{a}$ and $\bar{s}(a)$ being increasing in a . Further $\pi'_I(a) = (v - c + q_I)^2/(4q_I)$. This together with (10) implies

$$\begin{aligned}\pi'_I(a) - \bar{\pi}'_B(a) &\geq (v - c + q_I)^2/(4q_I) - [v - \bar{s}(\underline{a})][c - \bar{s}(\underline{a})](q_I - q_U)/(q_I q_U) \\ &\geq (v - c + q_I)^2/(4q_I) - (v - c + q_U)q_U(q_I - q_U)/(q_I q_U) \\ &\geq 0,\end{aligned}$$

where the second inequality is due to $\bar{s}(\underline{a}) \geq c - q_U$ and the third inequality follows from Lemma A1. This, together with the results that $\bar{\pi}_B(\underline{a}) \geq \pi_I(\underline{a})$ and $\pi_I(\hat{a}) = \pi_B(\hat{a}) \geq \bar{\pi}_B(\hat{a})$, implies that there exists $\bar{a} \in [\underline{a}, \hat{a}]$ such that $\bar{\pi}_B(a) \geq \pi_I(a)$ for $a \in (\underline{a}, \bar{a}]$, i.e., $s^*(a) = \bar{s}(a)$, and $\bar{\pi}_B(a) \leq \pi_I(a)$ for $a > \bar{a}$, i.e., $s^*(a) = s_I$ because $s_I \leq s_B(a) < \bar{s}(a)$. ■

Proof of Proposition 3: The result that the donor's optimal subsidy under donor price control $s^o(a)$ decreases in a follows from (4) and the observations that $s_B(a)$ decreases in a , s_I is independent of a , and $s_B(a) \geq s_I$ for $a \in [0, 1]$. The donor's optimal subsidy under a price-setting intermediary $s^*(a)$ is given by (5). This, together with the result that $\bar{s}(a)$ strictly increases in a , implies that $s^*(a)$ strictly increases in a for $a \in (\underline{a}, \bar{a})$, and weakly decreases in a for $a \in [0, \underline{a}] \cup (\bar{a}, 1]$. ■

Proof of Proposition 4: We have shown in the proof of Proposition 2 that $\bar{a} \in [\underline{a}, \hat{a}]$. If $a \leq \underline{a}$, then $s^*(a) = s^o(a) = s_B(a)$. If $\underline{a} < a \leq \bar{a}$, then $s^*(a) = \bar{s}(a)$ and $s^o(a) = s_B(a)$. Because $s_B(a) - \bar{s}(a)$ is strictly decreasing in a , $\bar{s}(a) > s_B(a)$ for $\underline{a} < a$, implying that $s^*(a) > s_B(a)$. If $\bar{a} < a < \hat{a}$, then $s^*(a) = s_I$ and $s^o(a) = s_B(a)$. Because $s_I < s_B(a)$, $s^*(a) < s^o(a)$. If $a \geq \hat{a}$, then $s^*(a) = s^o(a) = s_I$. ■

Proof of Propositions 5 and 6: Under donor price control, the donor's optimal utility is

$$\Pi^o(a) = \begin{cases} \Pi_B(a, s_B(a)) & \text{if } a \leq \hat{a} \\ \Pi_I(a, s_I) & \text{if } a > \hat{a}, \end{cases}$$

which implies that $d\Pi^o(a)/da = [v - s_B(a)][c - s_B(a)](1/q_U - 1/q_I) > 0$ for $a \leq \hat{a}$ and $d\Pi^o(a)/da = (v - s_I)[1 - (c - s_I)/q_I] > 0$ for $a > \hat{a}$. Hence, under donor price control, the donor's optimal utility strictly increases in awareness a . Because $s_B(a) < (v + c)/2$ and $s_B(a)$ strictly decreases in a , $d\Pi^o(a)/da$ strictly increases in a for $a \leq \hat{a}$; $d\Pi^o(a)/da$ is constant for $a > \hat{a}$. Further, it follows from the proof of Lemma A3 and Proposition 1 that $d\Pi^o(a)/da < (v - s_I)[1 - (c - s_I)/q_I]$ for all $a \leq \hat{a}$ (see inequality (7)). Hence, the donor's marginal value of awareness strictly increases in awareness for $a \in [0, \hat{a})$, and jumps up to a constant and stays at the constant for $a \in [\hat{a}, 1]$.

Under a price-setting intermediary, the donor's optimal utility is

$$\Pi^*(a) = \begin{cases} \Pi_B(a, s_B(a))/2 & \text{if } a \leq \underline{a} \\ \Pi_B(a, \bar{s}(a))/2 & \text{if } \underline{a} < a \leq \bar{a} \\ \Pi_I(a, s_I)/2 & \text{if } a > \bar{a}, \end{cases}$$

which strictly increases in a for $a \leq \underline{a}$ and for $a > \bar{a}$. Consider the regime $\underline{a} < a \leq \bar{a}$. With some effort one can show that

$$\frac{d^2\Pi^*(a, \bar{s}(a))}{da^2} = -\frac{q_I q_U (q_I - q_U) \{(v - c + q_U)[aq_U + (1 - a)q_I] + 3aq_U(q_I - q_U)\}}{8(aq_U)^{3/2}[aq_U + (1 - a)q_I]^{5/2}} < 0,$$

implying that there exists $\check{a} \in (\underline{a}, \bar{a}]$ such that $\Pi^*(a)$ strictly increases in a for $a \in (\underline{a}, \check{a}]$ and strictly decreases in a for $a \in (\check{a}, \bar{a}]$. Further, the above inequality, together with the result that $\Pi_B(a, s_B(a))$ is convex in a and $\Pi_I(a, s_I)$ is linear in a , implies that with a price-setting intermediary, the donor's marginal value of awareness, $d\Pi^*(a)/da$, increases in awareness for $a \in [0, \underline{a}]$, decreases in awareness for $a \in [\underline{a}, \bar{a})$, and jumps up to a constant and stays at the constant for $a \in [\bar{a}, 1]$. ■