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**THE WELFARE ECONOMICS OF OPTIONAL WATER  
METERING WITH ASYMMETRIC INFORMATION**

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# The welfare economics of optional water metering with asymmetric information

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## Abstract

The paper develops a model of decentralized metering decisions when selective metering is socially optimal. Households choose between two-part tariffs. Decentralization achieves social efficiency when the regulator, who knows household characteristics, gives household-specific compensation (via a reduction in the lump-sum charge on choosing to have a meter), while allowing for the cost of metering. Relative to the status quo of no metering the full-information scheme provides a Pareto improvement. With asymmetric information the first-best allocation of meters can be achieved when only small consumers should have meters. When large consumers alone should be metered it is not possible to separate customers. An exogenous signal that is highly correlated with the unknown type can, however, help to alleviate this problem. The policy of requiring meters to be provided free is problematic because the first-best allocation does not enable all the water supplier's costs to be recovered.

Keywords: water metering, optional two-part tariffs, asymmetric information.

JEL numbers: D82, L51, Q25.

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## **1. Introduction**

Water supplies around the world are under pressure from rising demand and climate change. New York City embarked on a programme of universal metering after a severe drought in 1986. In many countries, however, metering of households is not universal. In Buenos Aires domestic customers are allowed to choose whether to be metered or not. In England and Wales a policy of selective metering was adopted in the 1980s and was given additional impetus when the water industry was privatised in 1989. While some households (those who use garden sprinklers or swimming pools, and those in houses built since 1990) have been metered, the majority have been given the option of choosing a meter or remaining unmetered and paying a lump-sum charge that relates to the value of the property. Just over a quarter of households in England and Wales now have meters, and in regions that suffer more severely from water shortages, such as East Anglia, more than half of households have chosen to be metered. In 2006 a small water company in the south-east of England applied under national legislation to be allowed to meter compulsorily all customers in part of its supply area.

This paper assesses the efficiency of metering policies. When is it socially beneficial to install meters? Can incentive schemes be designed to ensure that efficient decisions about whether to be metered or not are made by consumers? What effect does asymmetric information have on the design of incentive schemes? Metering, when accompanied by marginal cost pricing, eliminates the deadweight cost of over-consumption. Installing and operating meters, however, is costly, so metering is only worthwhile if the benefit from reducing over-consumption exceeds the cost of metering. This may mean that metering should be selective rather than universal, which raises the issue of which households should be metered. If a regulator has full information about each customer then it is straightforward to decentralize the decision-making about metering to households. The households choose between alternative two-part tariffs: the tariff for a metered supply has a positive price per unit of water consumed and a lump-sum charge, while the tariff for an unmetered supply is just a lump-sum fee, with the price per unit being zero automatically. The first result is that efficient decisions about metering are made if a switching consumer pays the cost of metering but also receives compensation equal to the price multiplied by the amount of water consumed when not metered. This can be implemented by giving a

reduction in the lump-sum charge for taking a meter that, in general, is household-specific.

The full-information scheme has the attractive feature that it induces a weak Pareto improvement, as long as the lump-sum fee that the household pays for an unmetered supply does not change. The water company is compensated for any lost profits caused by switching and the consumer is at least as well off as before. This is analogous to the Efficient Component Pricing Rule for pricing access to the network of a vertically integrated utility (Armstrong *et al.*, 1996). The problem is that the scheme requires the regulator to know each household's consumption, in particular it needs to know the demand of each household when unmetered. It is very unlikely that the regulator will know how much water a particular household consumes when there is no meter – indeed it is almost axiomatic that it will not know this.

The main aim of the paper is to characterize the mechanism design problem of a welfare-maximizing regulator who wants to ensure that the appropriate households choose meters when households know their own types but the regulator does not. The type of a household is a factor that determines its demand, such as the number of household members, aggregate household income, the number of bathrooms, or the size of the garden. A higher-type consumer demands more water at every positive price than a lower-type consumer. The central result is that when low-type (or small) consumers only should be metered the first-best allocation can be achieved in spite of the information asymmetry, but when metering should apply only to high-type (or large) consumers the first-best allocation is not incentive compatible. The discount on the lump-sum fee necessary to persuade large consumers to switch to a meter will also persuade small consumers to take one, which is socially inefficient. A natural model of demand where the first-best is not incentive compatible has the type being the number of household members. With no other information available the best the regulator can do is to use a pooling allocation, so there is either universal metering or no metering. The regulator may, however, be able to avoid such extremes if there is an observable signal about the consumer's demand that is correlated with the consumer's unknown type and that can be used as the basis of the two lump-sum charges. This allows individual households to decide whether to have a meter or not and is better than a pooling allocation if the signal is sufficiently informative.

The model of metering choices can be used to assess the policy in England and Wales that requires water companies to provide free meters to those who choose them. This policy cannot achieve a first-best outcome if the water utility has to cover its costs, because the cost of providing free meters must be met by raising the marginal price of water above marginal cost. The alternative of raising the lump-sum charge paid by those who should remain without meters does not work because this induces these consumers to choose meters as well.

Two recent papers consider the economics of water metering and customer choice. Both assume that the regulator has full information. Chambouleyron (2003) has a model where the demand function is multiplicative in the consumer's type and shows that decentralization of metering decisions can be efficient. The full-information scheme presented in Section 2 builds on and generalizes this insight. When asymmetric information is introduced in Section 3 it is found that with the demand function used by Chambouleyron the first-best metering allocation is not incentive compatible. Barrett and Sinclair (1999) model metering choices when there is a fixed supply of water. Consumers have linear demand functions that differ in their intercepts. A regulator chooses the marginal price and the lump-sum fees to maximize social welfare subject to the constraint that demand from metered and unmetered customers equals the fixed supply. Section 5 presents a more general version of this model and applies it to capacity expansion and leakage reduction. In an early paper Rajah and Smith (1993) discuss the efficiency and distributional effects of alternative charging policies, including optional metering. They argue that whether the right households choose to be metered will depend on how closely the charges for unmetered supplies proxy the charges that would apply if they were metered. They also point out (p. 100) on the basis of an empirical model of water consumption of households in the Severn Trent area of England that "there is a clear correlation between household size and water consumption" and as a consequence in their simulations large households would tend to be worse off with compulsory and universal water metering.

Mansur and Olmstead (2006) estimate water demand equations for a random sample of metered households in the USA and Canada. Family size is a significant

determinant of water demand in all of the models they estimate, with an extra household member on average adding around 20 per cent to the typical household's total water demand (see Mansur and Olmstead, 2006, Tables 2 and 3). Some evidence about the characteristics of households taking the metering option in England and Wales is presented by Sims *et al.* (2005, p. 17). Metered households in Yorkshire tend to have smaller household sizes, older average age and more water-using appliances per-household and per-person than households without meters. Sims *et al.* (2005, p. 18) state that the latter effect may be because "metering is an option taken up by households whose children have left home". This again indicates that the number of household members is an important determinant of consumption and of the metering decision.

The plan of the paper is as follows. Section 2 contains the full-information model of optimal and optional metering. Section 3 shows how incentive schemes can be designed when there is asymmetric information. Section 4 assesses the policy of requiring the firm to offer free meters. Section 5 adapts the full-information model to allow for capacity constraints. Conclusions are in Section 6.

## **2. The model with full information**

Separate two-part tariffs are set for households/consumers who choose to be metered and those who do not. The lump-sum part of each tariff is  $A_i$ ,  $i = \{m, n\}$  where  $m$  stands for "metered" and  $n$  stands for "no meter". For households without meters the unit price is automatically zero. Households with meters face a positive unit price,  $p$ . The tariffs are thus  $\{A_m, p\}$  and  $\{A_n, 0\}$ . Initially no consumer has a meter. Preferences are quasi-linear. The relevant part of the utility function is  $U(Q, t)$ , which depends on the quantity consumed,  $Q$ , and on the consumer's type,  $t$ , and is increasing and strictly concave in  $Q$  up to the satiation level of demand. The demand function,  $Q(p, t)$ , thus decreases in the price. There is a finite level of demand,  $Q(0, t)$ , at which the consumer is satiated and which is the demand when there is no meter. The type is a household characteristic that influences demand, such as the number of people in the household, the size or value of the property or the presence or otherwise of a garden or a swimming pool. Assumptions about the way the type affects utility and demand will be required when information is asymmetric.

Household welfare when metered is consumer surplus minus the lump-sum charge,  $S(p, t) - A_m$ , where  $S(\cdot) \equiv U(Q(p, t), t) - pQ(p, t)$ . When the household does not have a meter its welfare is  $S(0, t) - A_n$  where  $S(0, t) \equiv U(Q(0, t), t)$ . Roy's Identity implies that  $S_p(p, t) = -Q(p, t)$ , with the subscript denoting a partial derivative. This says that the marginal cost to the consumer of a price increase is the extra cost of buying the original quantity. Strict concavity of the utility function for demand below the satiation level implies that  $S(p, t)$  is strictly convex in the price, and thus lies above its tangents, so

$$(1) \quad S(p, t) - S(0, t) + pQ(0, t) > 0$$

given  $p > 0$ . Inequality (1) is a consequence of the fact that the demand curve slopes down. It has a useful interpretation. Suppose that the consumer begins without a meter, and is then put on a meter and thus pays the positive unit price,  $p$ , instead of a price of zero. Let the lump-sum charge be reduced at the same time by  $pQ(0, t)$ . This makes the original bundle of water and other goods just affordable with the new positive price, so the consumer is now better off. The change in consumer welfare is given by the left-hand side of (1) and is the loss of consumer surplus plus the compensation. The reduction in the lump-sum charge acts as Slutsky compensation that makes the consumer better off than when there is no meter. Inequality (1) is used throughout the welfare analysis.

The firm is controlled by a welfare-maximizing regulator. Information is symmetric between the firm and the regulator so they are treated as one entity. The marginal cost of production,  $c$ , is positive and constant. The model is extended to allow for capacity constraints in Section 5. Social welfare is the sum of consumer surplus and profits, and all lump-sum charges cancel out in the welfare function. The welfare-maximizing price for metered customers equals marginal cost because the regulator can choose the lump-sum charges for metered and unmetered supplies and thus recover any fixed costs. Since consumer surplus and profits are weighted equally rent minimization is not an objective. In the analysis below the firm's profit can be set to zero if the two lump-sum charges are set appropriately, so zero profits can be achieved if desired.

A fixed cost of  $m > 0$  is incurred by the firm when supplying a meter and its associated services to a household. The metering cost is assumed to be the same for

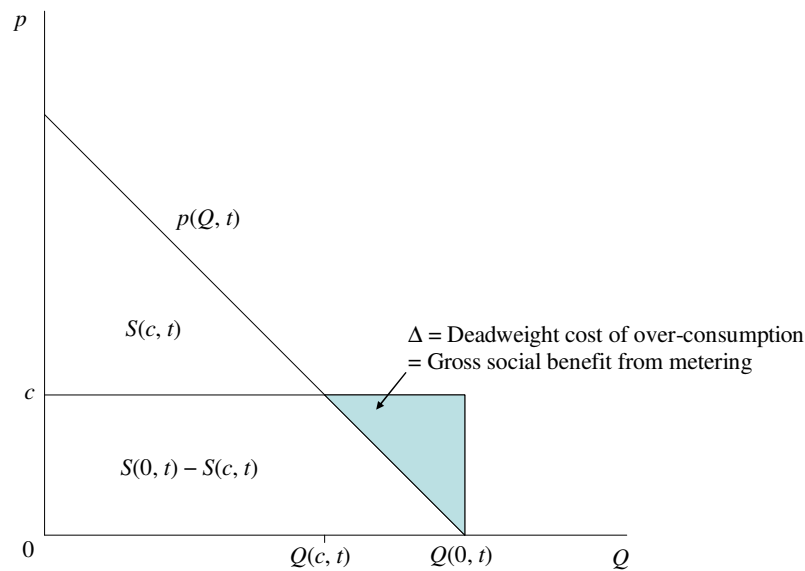
each household, but similar results hold when there is heterogeneity in the cost of metering households. In this section it is assumed that the firm knows each customer's type and thus both lump-sum fees can depend on the customer's type. What is the effect on a type- $t$  consumer of switching to a meter? Consumer surplus falls because of the increase in price, but the lump-sum charge also changes. The consumer switches if and only if

$$(2) \quad S(c, t) - S(0, t) - A_m(t) + A_n(t) \geq 0,$$

i.e. the reduction in the lump-sum charge outweighs the loss of consumer surplus.<sup>1</sup> Society has a different calculation. Social welfare with the customer on a meter is  $W_m(t) = S(c, t) - m$  since marginal cost pricing implies that operating profits are zero. Social welfare derived from the same customer not having a meter is  $W_n(t) = S(0, t) - cQ(0, t)$  because the lump-sum charge cancels when adding consumer welfare and profits. A meter is socially valuable if and only if  $W_m(t) - W_n(t) \geq 0$ , i.e.

$$(3) \quad S(c, t) - S(0, t) + cQ(0, t) - m \geq 0.$$

This is illustrated in Figure 1.



**Figure 1**  
**The Welfare Effects of Metering**

<sup>1</sup> It is assumed that when the consumer is indifferent a meter is chosen.

The loss of consumer surplus is the trapezoid  $S(0, t) - S(c, t)$ . The saving on operating costs is the rectangle  $cQ(0, t)$ . The deadweight loss from over-consumption,  $\Delta(t) \equiv S(c, t) - S(0, t) + cQ(0, t)$ , is the gross social benefit of metering and, by inequality (1), is strictly positive. If the cost of metering,  $m$ , is zero then all should be metered. If the cost of production,  $c$ , is zero then no-one should be metered because the optimal price is zero and this can be achieved without expensive metering. More generally when  $m > 0$  and  $c > 0$  it is likely that the social optimum has some households being metered and others not, with more metering being desirable when  $c$  rises and less when  $m$  rises.

Suppose the consumer can choose whether or not to install a meter. The following proposition shows that the social and private decisions can be brought into line by equating (2) and (3).

**Proposition 1.** *With full information the first-best allocation is achieved with decentralized metering decisions if the lump-sum fee for a metered supply payable by a type- $t$  household is  $A_m(t) = A_n(t) + m - cQ(0, t)$ .*

The consumer who switches faces an additional charge for the cost of metering,  $m$ , but also receives individual Slutsky compensation of  $cQ(0, t)$ , which is the marginal price multiplied by the quantity consumed without a meter. When asymmetric information is introduced the lump-sum charge resembles that in Proposition 1, except that the compensation is no longer type-dependent. The lump-sum charge for a metered supply in Proposition 1 has the same structure as the access price given by the efficient component pricing rule (ECPR) for a vertically integrated access provider (see Baumol, 1983, and Armstrong *et al.*, 1996).<sup>2</sup> The charge equals the cost of metering,  $m$ , plus the opportunity cost to the firm of the profits lost when the customer changes to a meter,  $A_n(t) - cQ(0, t)$ . The firm is indifferent to a consumer switching to a meter because there is exact compensation for any lost profits. Thus, when Proposition 1 applies, weak Pareto improvements are achieved by a policy of

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<sup>2</sup> The ECPR has been applied to access pricing in the telecommunications industries of the UK and New Zealand, and in several regulated railway systems.

allowing optional metering, compared to the alternative policies of no metering or compulsory metering.<sup>3</sup>

If  $A_n(t) = cQ(0, t)$ , so the unmetered charge equals the cost of supplying the unmetered customer, the firm earns no rents and  $A_m(t) = m$  for all types. Rajah and Smith (1993, page 92) state that “Non-metered charges that lead to the same pattern of household payments that would have occurred if charged on the basis of their current level of consumption will encourage the efficient take-up of metering.” In terms of the current model this statement assumes that  $A_m = m$ , which is only efficient if  $A_n(t) = cQ(0, t)$ . Proposition 1 shows that efficiency can be achieved more generally because what matters is that the reduction in the lump-sum charge on taking a meter is appropriate.

### 3. Meter choices and asymmetric information

#### 3.1 Types, utility and full-information welfare maximization

Now suppose the firm knows the distribution from which types are drawn but not the individual customer’s type. Types are distributed continuously on the positive support  $[\underline{t}, \bar{t}]$ . A continuous distribution is assumed for analytical convenience and is not essential. The distribution function can take any form. The effect of a rise in  $t$  on the marginal utility of water consumption,  $U_{Q_t}$ , is assumed to be strictly positive for  $Q < Q(0, t)$  and non-negative at the satiation quantity. At all positive prices higher-type consumers have larger marginal utilities and thus demand more. Demand functions of consumers of different types do not cross, though they may coincide when the price is zero. This is the standard Spence-Mirrlees sorting condition used in models of nonlinear pricing (see Tirole, 1988, p. 157).

An implication of the sorting condition is that a price increase reduces the consumer surplus of a higher-type consumer more than that of a lower-type one. When the price increases from  $p$  to  $p'$  the loss of consumer surplus is the integral of demand over this range,  $S(p, t) - S(p', t) = \int_p^{p'} Q(z, t) dz$ , which rises with  $t$  because at every positive price a higher  $t$  implies higher demand. This result can be written generally as

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<sup>3</sup> A similar principle is behind the optional two-part tariff scheme designed by Willig (1978).

$$(4) \quad S(p', t) - S(p, t) > S(p', t') - S(p, t')$$

for all  $p' > p$  and  $t' > t$ . In the language of modern comparative statics the surplus function  $S(p, t)$  has strictly decreasing differences.

The full-information welfare maximum is now characterized when the sorting condition holds. Recall that the gross social benefit of metering is  $\Delta(t)$ . If  $\Delta(t) > m$  for all  $t \in [\underline{t}, \bar{t}]$  then all consumers should be metered. If the inequality goes the other way then metering is so expensive that no-one should be metered. The focus will be on the intermediate case in which some should be metered and others should not. For this case assume there is a unique interior solution with a cut-off type,  $t^*$ , satisfying  $\underline{t} < t^* < \bar{t}$  and defined by  $\Delta(t^*) - m = 0$ . Whether it is small consumers, with types below  $t^*$ , or large ones who should be metered depends on the way the type affects the deadweight loss, i.e. on the sign of  $\Delta'(t) = S_t(c, t) - S_t(0, t) + cQ_t(0, t)$ . The sorting condition implies both that  $S_t(c, t) - S_t(0, t) < 0$  and that  $Q_t(0, t) \geq 0$ , so the derivative in general can be of either sign. Note, though, that when the satiation quantity is the same for all types,  $Q_t(0, t) = 0$ , it follows that  $\Delta'(t) < 0$ . To explore the sign of the derivative in the general case write the deadweight loss as  $\Delta(t) = \int_0^c [Q(0, t) - Q(p, t)] dp$ , so that

$$(5) \quad \Delta'(t) = \int_0^c [Q_t(0, t) - Q_t(p, t)] dp.$$

From (5) a sufficient condition for  $\Delta'(t) < 0$  is that  $Q_t$  is strictly increasing in  $p$  for all  $p > 0$ . By the symmetry of cross-partial derivatives this is the same as saying that if a higher type has lower sensitivity of demand to price ( $Q_p$ , which is negative, moves closer to zero) then the deadweight loss falls as the type rises. Similarly a sufficient condition for  $\Delta'(t) > 0$  is that  $Q_t$  is strictly decreasing in  $p$ .

Two useful sets of conditions are sufficient (but not necessary, in either case) for a unique interior solution to exist. First, if  $\Delta(\underline{t}) - m > 0$  (so the smallest consumer should be metered),  $\Delta(\bar{t}) - m < 0$  (the largest consumer should not be metered) and  $\Delta'(t) < 0$  for all  $t$  (the gross social benefit of metering declines monotonically with the

type) then a unique interior cut-off type,  $t^*$ , exists with all those below  $t^*$  being the ones to be metered. Second, if  $\Delta(\underline{t}) - m < 0$ ,  $\Delta(\bar{t}) - m > 0$  and  $\Delta'(t) > 0$  for all  $t$ , again there is a unique cut-off value of  $t$ , and this time the opposite should happen – all larger consumers should be metered while all smaller ones should not be. These conditions will be used in Section 3.3.

### 3.2 Implementing the first-best allocation when universal metering is optimal

Suppose first that social welfare is maximized when all households have meters. Can this solution be decentralized by giving consumers the right to choose a meter? Not surprisingly the full-information outcome can be achieved straightforwardly. Households choose between the tariffs  $\{A_m, c\}$  and  $\{A_n, 0\}$  where both  $A_m$  and  $A_n$  are independent of the type because the regulator does not know the type.

**Proposition 2.** *When it is optimal for all consumers to be metered, and information is asymmetric, the socially efficient outcome is achieved with  $A_m = A_n + m - cQ(0, \bar{t})$ .*

**Proof.** Using (2) the net benefit to a consumer of type  $t$  from choosing a meter with this lump-sum charge is  $S(c, t) - S(0, t) + cQ(0, \bar{t}) - m$ . Since  $Q$  is non-decreasing in  $t$ :

$$S(c, t) - S(0, t) + cQ(0, \bar{t}) - m \geq S(c, t) - S(0, t) + cQ(0, t) - m \geq 0$$

where the second inequality holds because all consumers should be metered. Thus all households will choose a meter.

The intuition is that the lump-sum charge for a metered supply gives compensation of  $cQ(0, \bar{t})$  to all consumers. This is sufficient for the largest consumer to want to switch. For all smaller consumers the amount  $cQ(0, \bar{t})$  is at least as large as the Slutsky compensation  $cQ(0, t)$  that would persuade them to switch, because  $Q(0, t) \leq Q(0, \bar{t})$  for  $t \leq \bar{t}$ .

*Example 1. Additive demand.*

If the direct demand function is  $Q = t + q(p)$  then the gross social benefit of metering,  $\Delta$ , is independent of type since  $Q_{pt} = 0$ . If the gross social benefit exceeds the metering cost,  $m$ , then all should be metered (and all will choose to be).

It is possible for the lump-sum charge to vary across consumers if the existing unmetered charge varies according to an observable factor. What matters for the incentive to switch is the difference between the two lump-sum charges. The observable factor might be the property value. Denote this by  $\sigma$ , so the existing unmetered lump-sum charge is  $A_n(\sigma)$ . If consumers have the option of remaining on their existing unmetered tariffs then they will all be better off with universal metering. This follows from revealed preference. This comes, however, at the expense of lower profits for the firm. A consumer of type  $t$  and property value  $\sigma$  who is unmetered would give the firm profits of  $A_n(\sigma) - cQ(0, t)$ , whereas the profit when this consumer switches to a meter is  $A_n(\sigma) - cQ(0, \bar{t})$ . Since  $Q(0, t) \leq Q(0, \bar{t})$  by the sorting condition, profits fall or at most stay constant. Alternatively if the regulator wants profits to be zero rather than to guarantee that consumers are better off,  $A_n$  should equal  $cQ(0, \bar{t})$  for all households.

### 3.3 Implementation when selective metering is optimal.

Now suppose it is socially optimal for some consumers to have meters, but not all. Initially assume that a unique interior optimum holds with small consumers with types below a cut-off level,  $t^*$ , being the ones who should be metered. Can the customers be given appropriate incentives to choose, or not choose, a meter? Households who should be metered are those with types in  $[\underline{t}, t^*]$ , while households with types in  $(t^*, \bar{t}]$  should not be metered.<sup>4</sup> The firm asks consumers whether they want a meter or not. Those who accept a meter face the tariff  $\{A_m, c\}$ . Those who choose not to be metered face the tariff  $\{A_n, 0\}$ . The lump-sum charges are set to ensure that tariffs are chosen appropriately by consumers. Consumers who should be metered will choose to have one if

$$(6) \quad S(c, t) - A_m \geq S(0, t) - A_n \text{ for } t \in [\underline{t}, t^*],$$

which says that the utility from being metered is at least that from not having a meter. The corresponding incentive constraint for consumers who should not have meters is

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<sup>4</sup> It is assumed that the consumer of type  $t^*$  is included in the class to be metered.

$$(7) \quad S(0,t) - A_n \geq S(c,t) - A_m \text{ for } t \in (t^*, \bar{t}].$$

There is an equivalent direct revelation mechanism in which consumers report their types and are given incentives to be truthful. In this game consumers have local incentive constraints in addition to the ones in (6) and (7). For example someone choosing a meter must be at least as well off announcing their true type as announcing another type in the set of those to be metered. Since the marginal price for metered consumers is fixed at  $c$  and is not type-dependent these local incentive constraints are satisfied if and only if the lump-sum charge,  $A_m$ , is also independent of the type – otherwise all consumers who want a meter will simply announce the type that minimizes the lump-sum charge for a metered supply. Similarly the lump-sum charge for an unmetered supply cannot be type-dependent. Throughout it is assumed that all households always consume water and thus the participation constraints that normally appear in mechanism design models do not bind.

The next proposition confirms that the first-best allocation can be implemented when it is small consumers who should be metered.

**Proposition 3.** *When it is efficient to meter all consumers below a cut-off level,  $t^*$ , and for all larger consumers to remain without meters, the lump-sum charge  $A_m = A_n + m - cQ(0, t^*)$  implements the first-best outcome when there is asymmetric information.*

Proof. The net benefit to a consumer of a meter is  $S(c,t) - S(0,t) + cQ(0,t^*) - m$ . From the decreasing differences result, (4), and the definition of  $t^*$  it follows that

$$S(c,t) - S(0,t) + cQ(0,t^*) - m > S(c,t^*) - S(0,t^*) + cQ(0,t^*) - m \equiv 0$$

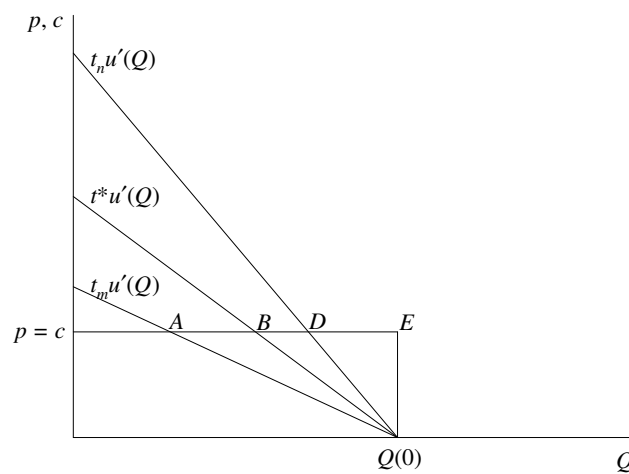
for all  $t < t^*$ . All types below  $t^*$  will choose meters, as required. Similarly all consumers with types  $t \in (t^*, \bar{t}]$  will, appropriately, choose not to have meters because  $S(c,t) - S(0,t) + cQ(0,t^*) - m < 0$ . The type- $t^*$  consumer is indifferent between having a meter or not.

The intuition for the fact that the first-best can be implemented is similar to that for the case where universal metering is optimal. Each consumer who asks to be metered

receives compensation of  $cQ(0, t^*)$  and pays the metering cost,  $m$ . The cut-off consumer is indifferent between being metered or not. For all smaller consumers this compensation is more than sufficient to make them want to switch. For all larger consumers this amount is below their individual Slutsky compensation levels that would persuade them to switch. If zero profits are required the lump-sum charge for an unmetered supply can be set to achieve this.<sup>5</sup>

*Example 2. Inverse demand that is multiplicative in the type.*

Let the utility function be the one that is commonly used in models of non-linear pricing:  $U = tu(Q)$ . Inverse demand is  $p = tu'(Q)$  and direct demand is  $Q = q(p/t)$ . All consumers have the same satiation quantity defined by  $u'(Q(0)) = 0$ . It follows that  $\Delta'(t) < 0$  and if there is an interior solution it is unique and smaller consumers are the ones who should be metered.



**Figure 2**  
**Implementing the first-best allocation**

<sup>5</sup> To obtain zero profits the lump-sum charge for an unmetered supply should equal the cost of supplying the marginal customer,  $cQ(0, t^*)$ , times the fraction of customers who are metered, plus the average cost of supplying unmetered households times the fraction of customers who do not have a meter.

The case of multiplicative inverse demand is illustrated in Figure 2. Inverse demand functions are drawn for a small consumer with type  $t_m$  who should be metered, a large consumer of type  $t_n$  who should not be metered and for the cut-off type  $t^*$ . The deadweight cost of over-consumption falls as  $t$  rises – it is  $AEQ(0)$  for the small consumer,  $BEQ(0)$  for the cut-off consumer and  $DEQ(0)$  for the large consumer. The cost of metering,  $m$ , is represented by the triangle  $BEQ(0)$ . The net benefit to the small consumer from choosing a meter is  $ABQ(0)$ .

Up to now the asymmetry of information has not caused a problem for implementation of the first-best allocation. When, however, it is large consumers who should be metered and small ones who should not, the first-best allocation cannot be implemented.

**Proposition 4.** *When it is efficient for all consumers below a cut-off type not to have a meter and for all larger consumers to be metered the full-information outcome cannot be implemented when information is asymmetric.*

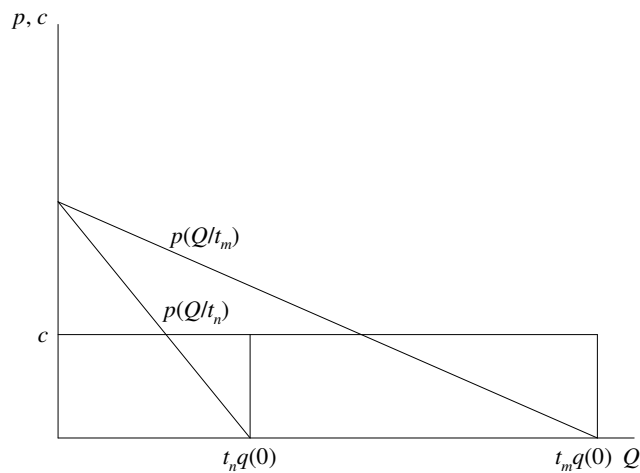
Proof. Incentive compatibility requires that  $S(0,t) - A_n \geq S(c,t) - A_m$  for  $t \in [\underline{t}, t^*)$  and  $S(c,t) - A_m \geq S(0,t) - A_n$  for  $t \in [t^*, \bar{t}]$ . Consider any pair of types,  $\{t_n, t_m\}$ , where  $t_n < t^* < t_m$ , so  $t_n$  should not be metered and  $t_m$  should be. The incentive compatibility constraints together imply that  $S(c, t_n) - S(0, t_n) \leq A_m - A_n \leq S(c, t_m) - S(0, t_m)$ . This, however, is not consistent with the decreasing differences inequality, (4), which in turn is a consequence of the sorting condition.

The reason that incentive compatibility is inconsistent with the sorting condition when it is larger consumers who should be metered is the following. Suppose that the compensation for choosing a meter is  $cQ(0, \bar{t})$ . This certainly induces the top consumer to choose a meter, but also more than compensates all smaller consumers, who will thus also choose to be metered. Cutting the compensation to a level that will stop small consumers choosing a meter will also cause the large consumers not to choose a meter. Setting the compensation at the level that worked in Proposition 3, i.e.  $cQ(0, t^*)$ , would induce the large consumers not to have a meter and the small ones to choose a meter, which is exactly the opposite of what should happen.

*Example 3. Direct demand is multiplicative in the type.*

Let the direct utility function be  $U = tu(Q/t)$ . An interpretation is that  $t$  is the number of members of the household, each of whom consumes  $Q/t$  units of water and obtains utility of  $u(Q/t)$  and  $U$  thus represents a utilitarian household welfare function. Household demand is  $Q = tq(p)$ . The cross-partial derivative is  $Q_{pt} = q'(p) < 0$ , so the deadweight loss rises with the type. If there is an interior optimum it is unique and larger consumers are the ones who should be metered.

Example 3 is illustrated in Figure 3, which shows the inverse demand functions of a small customer with type  $t_n$ , who should not be metered, and a large customer (type  $t_m$ ) who should have a meter. A large customer who receives compensation for taking a meter of  $t_m c q(0)$  would switch. Unfortunately this would induce the small consumer to switch as well.



**Figure 3**

**The first-best allocation cannot be implemented**

With the following utility function implementation of partial metering is feasible when demand is strictly concave but not when demand is strictly convex.

*Example 4. Additive shifts to inverse demand.*

Let the inverse demand function be  $p = t + f(Q)$  where  $f(Q)$  is decreasing. Consumers with higher types have uniformly higher willingness to pay. Direct demand is  $Q = q(p - t)$ . The cross-partial derivative is  $Q_{pt} = -q''$ . If demand is strictly concave then  $\Delta'(t) < 0$ , Proposition 3 applies and the first-best can be implemented. If demand is strictly convex then  $\Delta'(t) > 0$  and Proposition 4 applies, so incentive compatibility is not feasible.

It is not surprising that the sorting condition and incentive compatibility can come into conflict. The marginal price for the unmetered customers is zero by definition and thus cannot be manipulated to eliminate inappropriate incentives. In standard monopoly nonlinear pricing models small consumers face a higher marginal price in order to induce large customers not to switch to the bundle or tariff designed for the smaller type. When it is large consumers who should be metered they should face a positive marginal price and small consumers should face a zero marginal price, which is the other way round from the standard nonlinear pricing outcome. In addition the principal, as a social welfare maximizer, has an objective function that depends on the consumer's type and such problems can exhibit nonresponsiveness (see Laffont and Martimort, 2002, page 53, and Guesnerie and Laffont, 1984).

What can be done when the types cannot be separated by a direct revelation mechanism or an equivalent? One option is to accept a pooling allocation.<sup>6</sup> All consumers could be induced to opt for a meter, or the compensation could be set so low that no-one chooses a meter. It may be, though, that the regulator can use a signal about the household's type to offset the information asymmetry. In England and Wales the signal would be the observable household characteristic that is used to determine the unmetered water charge, known as the "rateable value" of the property (a measure of the property's rental value previously used as the tax base for local government). Suppose that there are two types,  $\{\underline{t}, \bar{t}\}$ , and large types should be metered and small types should not have meters. Denote the signal of a small type by

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<sup>6</sup> It might be thought that a second-best policy that allows the marginal price for a metered supply,  $p$ , to differ from marginal cost could work. Incentive compatibility still, however, does not hold for all positive values of  $p$  since consumer surplus has decreasing differences (and there is no point in setting  $p = 0$  and incurring metering costs).

$\underline{\sigma}$  and that of a large type by  $\bar{\sigma}$ . Let  $\mu$  be the probability of obtaining the large signal conditional on the actual type being large. The conditional probability of a small signal given a small type is also  $\mu$ . The signal is informative if  $\mu > 0.5$  and is perfectly informative when  $\mu = 1$ . When the large signal is observed the lump-sum charge in the metered tariff is  $A_m(\bar{\sigma}) = A_n(\bar{\sigma}) + m - cQ(0, \bar{t})$  and when the small signal is observed the charge is  $A_m(\underline{\sigma}) = A_n(\underline{\sigma}) + m - cQ(0, \underline{t})$ .<sup>7</sup> The tariff is designed so that a large signal induces both types of household to choose a meter, while households with small signals choose to remain without meters.<sup>8</sup> Thus when the signal is correct the appropriate decision is made, but when the signal is incorrect the decision is socially inefficient. Whether this policy beats the alternative of either all being metered or none being metered depends on how informative the signal is. The analysis is in the Appendix. With an uninformative signal it is better to have either all metered or none metered, but if the signal is fully informative the first-best is achieved. There is a cut-off value of  $\mu$  that lies between 0.5 and 1, above which it is preferable to have the policy based on the signal. Not surprisingly the more informative the signal the more valuable it is. It is important to note that the signal must not only be a good indicator of the true type it also must serve as a feasible charging base for unmetered customers.

In summary, when only small consumers should be metered, the first-best allocation is achieved by a lump-sum charge for a meter that is not type-dependent. When only large consumers should be metered, the first-best is not implementable, but using a sufficiently informative signal to determine compensation is better than an all-or-nothing policy.

#### **4. The policy of providing free meters**

Water companies in England and Wales are obliged by the Water Industry Act 1999 to provide meters free of charge. Since it is not costless to produce and install meters it is not clear that there is an efficiency rationale for this policy. The firm would need to recover the costs of metering through increasing either the lump-sum charges paid by the remaining unmetered customers or the unit price of water. If full metering is

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<sup>7</sup> For the small signal any higher charge for a metered supply will also work.

<sup>8</sup> The decreasing differences result, and the assumption that it is socially valuable to meter the large consumer but not the small consumer, may be used to confirm this.

optimal then the first-best is not achievable without government subsidy. The first-best allocation requires price to equal marginal cost. With the firm being required to set  $A_m = 0$  the metering costs will not be covered. If a government subsidy for metering is not available then the only way to achieve budget balance is to raise the marginal price of water above marginal cost until it equals average cost.

What about when partial metering is optimal? For simplicity suppose that there is full information. It might be thought that any losses from free metering could be recovered by raising the lump-sum fees for those who remain without meters. Unfortunately this is not feasible, because it induces those who should not have meters to choose them. Let there be two types, with households of type  $t_m$  being the ones who should have a meter and those of type  $t_n$  being the ones who should not have a meter. With full information the firm can set two different lump-sum fees for unmetered supplies, depending on the type. The lump-sum fee for a metered supply is constrained to be zero for both types.

**Proposition 5.** *When the firm is required to provide meters at no charge the first-best allocation does not provide sufficient revenue to cover all costs if all consumers are allowed to choose a meter.*

Proof. It has already been shown that when the first-best allocation has full metering the costs of metering cannot be recovered. Consider the case where the first-best involves metering consumers of type  $t_m$  and not metering those of type  $t_n$ . The type to be metered chooses correctly if the firm sets  $A_n(t_m) = cQ(0, t_m) - m$ . A meter is then chosen, but the cost of metering,  $m$ , must be recovered from the unmetered type because the lump-sum fee actually paid is zero. To ensure that the type who should not be metered chooses correctly it must be that  $S(0, t_n) - A_n(t_n) \geq S(c, t_n)$ . Subtract  $S(0, t_n)$  and add  $cQ(0, t_n)$  to both sides of this inequality to obtain  $cQ(0, t_n) - A_n(t_n) \geq S(c, t_n) - S(0, t_n) + cQ(0, t_n)$ . By inequality (1) the right-hand side is positive, so  $cQ(0, t_n) > A_n(t_n)$ . This means that the lump-sum charge for the unmetered customer does not even cover the cost of serving this customer, let alone the additional cost of the meter for the other customer.

The problem comes from the combination of allowing both types to choose and the requirement to set the lump-sum charge for a meter to zero. There would be no problem if consumers were not allowed to choose. The firm could give the type- $t_m$  consumer a free meter, not allow the other consumer to have one and set a charge for this customer equal to the cost of supply plus the cost of metering the household that has chosen a meter. If, though, this policy is combined with the ability to choose then both consumers choose a meter and costs are not covered. If choice is to be combined with free meters then the second-best nature of the problem has to be recognized. The firm should set the lowest feasible price above marginal cost that just covers all costs. The revenue requirement includes the cost of metering the metered type and the loss on the unmetered customer (whose lump-sum charge is below the cost of supply). There is no guarantee that it remains socially optimal for type  $t_m$ , who should be metered in a first-best world, to be metered when the price exceeds marginal cost.

### **5. Metering and limited capacity**

Debates about water policy are often predicated on the assumption that supplies of water are limited. In this section the model is adapted to allow for a capacity constraint. The full-information problem is to choose who should be metered and the marginal price to maximize social welfare subject to the resource constraint. While the first fundamental theorem of welfare economics implies that efficient allocation is achieved when all consumers are metered and face the same marginal price that just clears the market, this does not necessarily apply when meters are costly. Again selective metering may be optimal. The solution to the full-information problem is an optimal price and a cut-off type, combined with a statement about whether it is types below the cut-off type or above it who should be metered. The focus in this section is on characterizing the first-best allocation. When there is asymmetric information the analysis of Section 3 applies with the optimal price,  $p^*$ , replacing the exogenous first-best price,  $c$ , in the Propositions.

The first-best allocation is now characterized when selective metering is optimal. Assume that consumer types are distributed uniformly on  $[\underline{t}, \bar{t}]$  and that the marginal operating cost,  $c$ , is zero (both assumptions are without loss of generality). The gross benefit of metering a type- $t$  household is  $\Delta(p, t) \equiv S(p, t) - S(0, t) + pQ(0, t)$  where  $p$  is

the chosen marginal price. Putting a customer of type  $t$  on a meter changes their consumer surplus by  $S(p, t) - S(0, t)$ , generates extra operating profits of  $pQ(p, t)$  and benefits other consumers by  $p[Q(0, t) - Q(p, t)]$ , which is the value of the water released because of the reduction in demand with metering. Adding these three terms gives the gross benefit expression. Suppose first that  $\Delta_t(p, t) \leq 0$ , so the gross benefit is non-increasing in the type. The utility functions in Examples 1 and 2 both satisfy this assumption. The resource constraint, following Barrett and Sinclair (1999), is that the demands of the metered and unmetered customers should equal the capacity level,  $K$ , so

$$(8) \quad \int_{\underline{t}}^{\tilde{t}} Q(p, t) dt + \int_{\tilde{t}}^{\bar{t}} Q(0, t) dt = K$$

where  $\tilde{t}$  is the cut-off type (all those below this are metered).<sup>9</sup> There is no non-price rationing. Equation (8) defines the price,  $p$ , as a function of  $\tilde{t}$ , i.e.  $p(\tilde{t}; K)$  for a given capacity. The effect of more metering on the price is

$$(9) \quad \frac{\partial p}{\partial \tilde{t}} = \frac{Q(0, \tilde{t}) - Q(p, \tilde{t})}{\int_{\underline{t}}^{\tilde{t}} Q_p(p, t) dt} < 0.$$

With another customer on a meter the amount of water taken by unmetered customers falls by the numerator of (9), so there is more available for metered customers and the marginal price falls. The regulator's problem is to choose  $\tilde{t}$  to maximize welfare, which is the consumer surplus of the metered customers and the profits earned from them (allowing for metering costs) plus the surplus of the unmetered customers:

$$W(\tilde{t}; K) = \int_{\underline{t}}^{\tilde{t}} [S(p(\tilde{t}; K), t) + p(\tilde{t}; K)Q(p(\tilde{t}; K), t) - m] dt + \int_{\tilde{t}}^{\bar{t}} S(0, t) dt.$$

The assumption that  $\Delta_t(p, t) \leq 0$  implies that welfare is concave in  $\tilde{t}$ . Writing the optimal value of  $\tilde{t}$  as  $t^*$  and the implied price as  $p^*$  the first-order condition for an interior solution, using (9), is

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<sup>9</sup> Barrett and Sinclair (1999) assume that demand is linear and the type shifts the demand function additively. The current model, which uses a general demand function, turns out to be much simpler to analyze than their model using a specific functional form.

$$(10) \quad S(p^*, t^*) - S(0, t^*) + p^* Q(0, t^*) - m = 0.$$

The change in surplus for the marginal consumer, plus the extra operating profit for the firm,  $p^*Q(p^*, t^*)$ , and the benefit to other consumers,  $p^*(Q(0, t^*) - Q(p^*, t^*))$ , should equal the cost of metering. Equation (10) and the resource constraint, (8), fully characterize the price and the amount of metering. The comparative statics results follow simply. A higher cost of metering,  $m$ , leads to less metering ( $t^*$  falls) and thus a higher marginal price to clear the market. Greater capacity, i.e. a larger  $K$ , leads to less metering and a lower price. Part of the benefit is taken as lower aggregate metering costs and part as higher consumer surplus.

When  $\Delta_t(p, t) > 0$ , so the gross benefit of metering increases with the type, all those types above the cut-off level should have meters. The optimal price and cut-off type are determined by equation (10) again and the new resource constraint, which is  $\int_{\underline{t}}^{\bar{t}} Q(0, t) dt + \int_{\bar{t}}^{\bar{t}} Q(p, t) dt = K$ . As before there is an incentive compatibility problem when the gross benefit of metering rises with the type and information is asymmetric.

Now suppose that capacity is a choice variable. The marginal social benefit of extra capacity is  $p^*$ , which is the marginal utility of output obtained by metered customers. Customers without meters do not benefit from extra capacity because there is no rationing and they are already satiated.<sup>10</sup> Capacity expansion is socially valuable if the unit price in the metered tariff exceeds the marginal rental cost of capacity. If capacity should be expanded then, by the comparative statics result, there is less need for metering and the unit price should fall, and the capacity expansion should continue until the unit price equals the marginal cost of capacity.

In any water supply system there is leakage, and water companies in England and Wales are routinely criticized for their high leakage rates. Leakage can be modelled by defining gross capacity as  $K^*$  and net capacity as  $K = (1 - l)K^*$  where  $l$  is the

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<sup>10</sup> In a more general model where effective capacity is random, perhaps because of uncertain rainfall, extra reservoirs may benefit unmetered customers because they reduce the likelihood of emergency rationing measures being imposed. See Mansur and Olmstead (2006) for an empirical study that estimates the welfare costs of non-price rationing of water.

percentage leakage rate. There is then a choice between providing extra resources by investing in extra gross capacity,  $K^*$ , and reducing the leakage rate (which itself is expensive and is a form of capital maintenance). The marginal social benefit of gross capacity expansion is reduced to  $p^*(1 - l)$  because of the leakage. There is a cost-minimization problem for the firm. Reducing leakage is effectively an alternative method of increasing capacity. A final point about capacity and leakage is that when all households have meters the firm is likely to be much better informed about where leakage is occurring than when there is partial metering and thus the costs of cutting leakage will be reduced. In Australia universal metering was adopted for this reason rather than because it provided a charging base.<sup>11</sup>

## **6. Conclusions**

Incentive schemes for optional metering can be designed to promote first-best outcomes, but care needs to be taken when there is an information asymmetry. Empirical evidence indicates that household size is an important determinant of water demand, and it is in exactly this case that incentive compatibility does not hold. Fortunately when incentive compatibility does not hold an alternative policy that uses a signal of the household's unknown type can be used as long as the signal is highly correlated with the underlying type and can also serve as a charging base for unmetered supplies. The current policy in England and Wales of requiring privatized water companies to offer free meters was analyzed and found to have potential distortions, and the point was made that requiring the water company to provide free meters entails a distortion in its tariff structure to recover the costs. Progress in the design of policy for selective metering will require detailed econometric analysis of the demand for water of both metered and unmetered households.

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<sup>11</sup> I am grateful to Claude Piccinin for this point.

## Appendix

*Using a signal when the first-best allocation is not implementable.*

Suppose that fraction  $\pi$  of consumers are of the large type and  $(1 - \pi)$  are of the small type, and only the former should be metered in the first-best allocation. The expected welfare from metering all consumers is

$$(A1) \quad \pi[S(c, \bar{t}) - m] + (1 - \pi)[S(c, \underline{t}) - m].$$

Expected welfare when no-one is metered is

$$(A2) \quad \pi[S(0, \bar{t}) - cQ(0, \bar{t})] + (1 - \pi)[S(0, \underline{t}) - cQ(0, \underline{t})].$$

Assume that (A1) exceeds (A2), so metering all is better than metering no-one. The alternative policy to having all metered uses the signal and gives expected welfare of:

$$(A3) \quad \begin{aligned} & \mu\pi[S(c, \bar{t}) - m] + (1 - \mu)\pi[S(0, \bar{t}) - cQ(0, \bar{t})] \\ & + (1 - \mu)(1 - \pi)[S(c, \underline{t}) - m] + \mu(1 - \pi)[S(0, \underline{t}) - cQ(0, \underline{t})] \end{aligned}$$

The expression in (A3) is interpreted as follows. There are four possibilities: large consumers correctly choose a meter, each type chooses the wrong option and small consumers correctly choose not to be metered. Expression (A3) weights the welfare obtained in each of these outcomes by the relevant probability. The probability of the signal being correct is  $\mu$ . The difference between (A3) and (A1), i.e. the advantage of using the signal, is:

$$(A4) \quad D = (\mu - 1)\pi[\Delta(\bar{t}) - m] - \mu(1 - \pi)[\Delta(\underline{t}) - m]$$

where  $\Delta(t) \equiv S(c, t) - S(0, t) + cQ(0, t)$  for  $t = \{\underline{t}, \bar{t}\}$ . When  $\mu = 0.5$  the signal is uninformative and  $D$  has the same sign as the difference between (A2) and (A1), which is negative. When  $\mu = 1$  there are no inappropriate decisions and the first-best level of welfare is achieved. The cut-off value of  $\mu$  at which the regulator is indifferent between the policies is found by setting (A4) to zero:

$$\mu^* = \frac{\pi [\Delta(\bar{t}) - m]}{\pi [\Delta(\bar{t}) - m] - (1 - \pi) [\Delta(\underline{t}) - m]}.$$

The cut-off value satisfies  $0.5 < \mu^* < 1$ , because expected welfare when all are metered is higher than that with none metered and  $\Delta(\underline{t}) - m < 0$ . A similar analysis works if it is better to meter none rather than for all to be metered.

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