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Price-based and Cost-based Regulations for a Monopoly with Quality Choice

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Abstract: This paper compares price-based (price-cap) regulation with cost-based (rate-of-return) regulation in a model in which service quality is considered. Price-based regulation strengthens cost-reducing efforts and lowers price compared to cost-based regulation. When the increasing rate of disutility of cost-reducing efforts is small, price-based regulation makes quality and consumer surplus higher than cost-based regulation. In this case, cost-passthrough adjustments added to price-based regulation never improves quality and consumer surplus. Next, we consider a possible alternative to cost-passthrough adjustments, which always attains a higher level of quality and larger consumer surplus than price-based regulation.

keywords: price-based regulation, cost-based regulation, price-cap regulation, rate-of-return regulation, quality, congestion

JEL classification number: L51, L97, L15

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1 Introduction

Many authorities currently use price-based (price-cap) regulation as a regulatory method instead of cost-based (rate-of-return) regulation. The use of price-based regulation, however, presents a difficult problem. While a regulator can force a monopoly to lower its price by imposing an upper limit on the price, a regulator cannot provide firms with incentives to improve quality. In the economics literature, Spence (1975) and others[1] suggest that quality deteriorates under price-based regulation. However, none of them afford us a theoretical analysis inclusive of quality that definitely addresses the problem. Thus, we still cannot settle important policy questions such as whether or not the shift from cost-based to price-based regulation inevitably causes a monopoly to reduce its level of quality and whether or not price-based regulation should be abandoned in favor of another type of regulation when the level of quality supplied by a monopoly is low. The purpose of this paper is to tackle these problems. We compare price-based regulation with cost-based regulation in a model in which a monopoly can select its level of service quality and show the influences of both regulations on price, cost-reducing efforts, and quality. As a result, our analysis clarifies the effect of both regulations on consumer surplus.

To set up a model as simply as possible, the paper focuses on service congestion as a representative aspect of service quality. Although quality is essentially multidimensional, congestion-type quality represents an important aspect of services supplied by public utilities. For example, important quality measures in electricity supply are the frequency and the length of breakdowns, which mostly result from

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[1] See, for example, Noam (1991), Rovizzi and Thompson (1992), and Vickers and Yarrow (1988).

congestion. In telecommunications, ease of connection to lines and the transfer speed of data are important quality measures that are also closely related to network congestion.

The major results of this paper are as follows. First, we consider the polar case where no congestion exists and compare price-based regulation with cost-based regulation on the condition that the monopoly's profits remain unchanged, regardless of the regulatory method. In this case, price-based regulation increases cost-reducing efforts and lowers price compared to cost-based regulation. As a result, price-based regulation yields greater consumer surplus than cost-based regulation. In the absence of congestion, price-based regulation is always superior to cost-based regulation.

Second, we focus on the case where congestion exists. In this case too, provided the monopoly's profits are kept fixed, cost-reducing efforts and price are respectively stronger and lower under price-based regulation than under cost-based regulation. As the regulation is more price-based, the level of quality becomes higher as long as the increasing rate of disutility of cost-reducing efforts is small. Therefore, if this rate is small, consumer surplus increases as the regulation is made more price-based, because price falls and quality ameliorates. On the contrary, if the increasing rate of disutility of cost-reducing efforts is large, the level of quality falls as the regulation is made more price-based. In this case, consumer surplus decreases, if the surplus-deteriorating effect of a decrease in quality outweighs the surplus-improving effect of a decrease in price.

In reality, the regulator cannot obtain information about a monopoly's disutility of cost-reducing efforts. Therefore, the regulator cannot know whether or not price-based regulation should be altered to (or mixed with) cost-based regulation to improve quality, when price-based regulation is leading to low quality. Thus, we next consider a regulation with an upper limit on price that is contingent on an index of quality, which we call quality-plus regulation. Our analysis shows that quality-plus regulation achieves higher levels of quality and consumer surplus than price-based regulation.

Although the worldwide trend of deregulation is reducing the number of monopolies, it is important to analyze which regulation, price-based or cost-based, is a more appropriate regulatory tool for monopolies. First, as pointed out by Braeutigam and Panzar (1993), "The value of PC's [price-cap regulations] as a policy innovation for the control of natural monopoly remains an open question (P.197)." Our analysis provides a theoretical framework that can deal with this problem. Second, even if deregulation proceeds, monopolies will remain in many industries where economies of scale are very significant, such as nationwide transmission services in the supply of electricity and local telephone networks in telecommunications. Our analysis is useful in redesigning regulatory schemes for the remaining monopolies, because it explicitly takes into account the level of quality, which is disregarded in most analyses but is actually very significant for consumers.

The structure of this paper is as follows. In section 2 we set up a model. In section 3 we compare price-based regulation with cost-based regulation. In section 4 we introduce quality-plus regulation which is compared with price-based regulation. In section 5 we conduct numerical simulations which illustrate our results. Section 6 concludes our analysis.

2 Model

A monopoly firm supplies a service. The monopoly's costs to provide the service consist of a unit production cost times quantity and capacity costs. The monopoly can reduce its unit production cost by its own efforts, e, which are unobservable to the regulator. For simplicity, the form of the cost function is assumed to be $C = (a-e)x + bQ$, where a and b are fixed parameters, and x and Q denote quantity and production capacity respectively. C and x are hypothesized to be observable and verifiable. Taking into account the fact that huge costs will be needed to make Q verifiable, we assume that Q is observable but unverifiable. The monopoly firm incurs monetary disutility $\varphi(e)$ from cost-reducing efforts, e. This disutility function, which is unobservable to the regulator, increases with the effort level (i.e., $\varphi'(e) \geq 0$) at an increasing rate (i.e., $\varphi''(e) > 0$).

The level of congestion is measured by the quantity produced per unit of capacity, $\frac{x}{Q}$. For analytical simplicity, we use the inverse of the congestion measure as a measure of quality, q, i.e., $q \equiv \frac{Q}{x}$. This definition means that enhanced capacity leads to improved quality (i.e., reduced congestion) *ceteris paribus* and vice versa. In our analysis, Q is nominal in the sense that it is possible that the quantity produced exceeds production capacity (i.e., $x > Q$), in which case the service supply continues but its quality deteriorates. Since Q has been assumed to be unverifiable, congestion, $\frac{Q}{x}$, is also unverifiable. Using $q \equiv \frac{Q}{x}$, we rewrite the cost function as $C = (a-e+bq)x$, where $a-e+bq > 0$ is assumed to hold.

The market demand function for the service is given by $x(p,q)$, where p denotes price, which is assumed to be observable and verifiable. We assume that the market demand function itself is observable but unverifiable because it will be very costly to verify the market demand function, which sometimes fluctuates[2]. For the sake of analytical simplicity, we assume that this demand function is separable in p and q, i.e., $x(p,q) = f(p) + g(q)$, where $x_p = f_p < 0$, $x_q = g_q > 0$, and $x_{qq} = g_{qq} < 0$. We hereafter use subscripts to denote partial derivatives. $x_{qq} < 0$ is necessary to guarantee that consumer surplus is concave in q. Consumer surplus from this service is $S(p,q) \equiv \int_p^{\infty} x(p',q)dp'$.

The profits of the monopoly firm are:

$$\pi(p,q,e) \equiv px(p,q) - (a - e + bq)x(p,q) - \varphi(e).$$

In all our analyses stated below, we assume that there exists a unique interior solution.

3 Price-based Regulation vs. Cost-based Regulation

In this section, we compare price-based regulation with cost-based regulation. Price-based regulation can be written as

$$\bar{p} \geq p \tag{1}$$

where $\bar{p}$ denotes the upper limit on the price of the monopoly's service that is determined by the regulator. Cost-based regulation can be expressed as

$$C \geq px. \tag{2}$$

Dividing both sides of Eq. (2) by x, we obtain another form of cost-based regulation:

$$\frac{C}{x} = a - e + bq \geq p \tag{3}$$

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[2] This assumption implies that the regulator cannot calculate the value of q based on x and p. That is, without this assumption, q would become verifiable.

Combining Eq. (1) with Eq. (3), we obtain the regulatory constraint that includes both price-based and cost-based regulations:

$$\alpha(a - e + bq) + (1 - \alpha)\bar{p} \geq p \qquad (4)$$

where $0 \leq \alpha < 1$[3]. Eq. (4) reduces to price-based regulation when $\alpha = 0$ and becomes more cost-based as α approaches 1. We assume that this regulatory constraint is always binding.

A basis of comparison is needed to compare the different kinds of regulation. We assume that the regulator keeps a monopoly indifferent among regulatory methods, i.e., the regulator keeps the rent given to a monopoly unchanged. This basis of comparison is plausible, because, in reality, the regulator tries to adjust a monopoly's profits if the change in regulatory methods increases or decrease its profits too much[4]. Thus, the regulator sets $\bar{p}$ so as to yield the same level of profits regardless of the value of α. We focus on the effect of a change in the value of α on price, quality, and cost-reducing efforts, holding the monopoly's profits constant. As a result, we derive the effect of a change in α on consumer surplus.

3-1 When no Congestion Exists

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[3] When $\alpha = 1$, the model degenerates. This is a familiar property of rate-of-return regulation models that arises when the revenue allowed equals the firm's costs. See Baumol and Klevorick (1971) and Klevorick (1970) on this point.

[4] In UK, the Labour government introduced a "windfall" tax on regulated industries that earn huge profits by the change in regulatory methods. If the regulator did not care about the level of profits a monopoly earns, however, we could consider other bases of comparison. For instance, the regulator might choose to keep the monopoly's service price constant.

First, as a benchmark, we focus on the polar case where $b = 0$ and $x(p,q) \equiv f(p)$. In this case, the monopoly's production costs do not depend on capacity, and the monopoly possesses infinite capacity (i.e., $Q = \infty$). Thus, no congestion exists and service quality has no influence on the market demand. The profit-maximization problem for the monopoly in this situation, (M1), can be written as

$$\text{(M1)} \quad \begin{array}{l} \max_{\{p,e\}} \ \pi(p,e) \equiv px(p) - (a-e)x(p) - \varphi(e) \\ s.t. \ \ \alpha(a-e) + (1-\alpha)\bar{p} \geq p \end{array}$$

Solving (M1), we obtain the following proposition.

Proposition 1

When we compare price-based regulation with cost-based regulation in a situation where no congestion exists, the following properties hold.

(1) Cost-reducing efforts increases and price decreases as the regulation is more price-based:

$$\frac{de(\alpha)}{d\alpha} < 0,$$

$$\frac{dp(\alpha)}{d\alpha} \geq 0.$$

(2) Consumer surplus increases as the regulation is more price-based:

$$\frac{dS(p(\alpha))}{d\alpha} \leq 0.$$

The proof is stated in the Appendix. As Cabral and Riordan (1989) points out, price-based regulation makes cost-reducing efforts higher than cost-based regulation. Under price-based regulation, the monopoly retains all of the increased profits from cost-reduction. Under cost-based regulation, however, the allowed profits remain zero whether or not the monopoly reduces its costs. That is, the monopoly does not acquire the profits resulting from its cost-reducing efforts. Thus, under cost-based regulation, cost-reducing efforts vanish. It follows, therefore, that cost-reducing efforts become stronger as the regulation is more price-based.

Stronger cost-reducing efforts make the monopoly's marginal costs lower. Since we consider the situation where the change in the value of α has no influence on the monopoly's profits, the price must decline as the marginal cost decreases. A decrease in price increases consumer surplus. Proposition 1 shows that price-based regulation yields greater consumer surplus than cost-based regulation, without affecting the monopoly's profits, in the absence of congestion. That is, without congestion, price-based regulation always Pareto-dominates cost-based regulation[5].

3-2 When Congestion Exists

Next, we consider the case where service congestion exists. The maximization problem in this case, (M2), can be formulated as

$$\text{(M2)} \quad \begin{aligned} &\max_{\{p,q,e\}} \ \pi(p,q,e) \\ &s.t. \ \ \alpha(a-e+bq)+(1-\alpha)\overline{p} \geq p. \end{aligned}$$

Solving (M2) yields the following proposition.

Proposition 2

When we compare price-based regulation with cost-based regulation in a situation

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[5] Schmalensee (1989) obtains this result using numerical simulation methods. Cremenz (1991) shows that price-cap regulation attains higher social welfare than rate-or-return regulation in a dynamic model.

where congestion exists, the following properties hold.

(1) Cost-reducing efforts increases and price decreases as the regulation is more price-based:

$$\frac{de(\alpha)}{d\alpha} < 0,$$

$$\frac{dp(\alpha)}{d\alpha} \geq 0.$$

(2) If $\varphi''(e) < \frac{(1-\alpha)x_q}{b}$, service quality increases as the regulation is more price-based：

$$\frac{dq(\alpha)}{d\alpha} < 0.$$

If $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$, service quality decreases as the regulation is more price-based：

$$\frac{dq(\alpha)}{d\alpha} > 0.$$

(3) If $\varphi''(e) < \frac{(1-\alpha)x_q}{b}$, consumer surplus increases as the regulation is more price-based：

$$\frac{dS(p(\alpha), q(\alpha))}{d\alpha} < 0.$$

If $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$, consumer surplus is increased by a shift from price-based to cost-based regulation at $\alpha = 0$:

$$\left.\frac{dS(p(\alpha), q(\alpha))}{d\alpha}\right|_{\alpha=0} > 0.$$

The proof is stated in the Appendix. Proposition 2-(1) shows that, under price-based regulation, cost-reducing efforts become higher and price lower than under cost-based regulation. With respect to this result, the same explanation as Proposition 1 holds. That is, as the regulation is more price-based, the profits from cost-reducing efforts become higher. The efforts therefore increase as the regulation is more price-based (i.e., α is closer to 0). Holding the monopoly's profits constant, an increase in cost-reducing efforts lowers price.

Proposition 2-(2) shows that there are two effects that influence service quality. First, an increase in cost-reducing efforts caused by a shift from cost-based to price-based regulation upgrades quality. The reason for this is that if a monopoly can change not only its price but also its quality, it may improve quality instead of lowering price when cost-reducing efforts are strengthened. We call this effect on quality, which results from a change in cost-reducing efforts, the incentive effect. The incentive effect makes quality higher (lower) as the regulation is more price-based (cost-based).

Second, as first noted by Spence (1975), cost-based regulation itself has an effect on service quality levels. Under cost-based regulation, a monopoly is allowed to raise its price if upgrading quality increases its costs. Therefore, the monopoly has no incentive to lower service quality. We call this quality-preserving characteristic of cost-based regulation the cost-based effect. The cost-based effect makes quality higher (lower) as the regulation is more cost-based (price-based) and thereby counteract the incentive effect.

The key is whether or not the incentive effect exceeds the cost-based effect. This is determined by the magnitude of the increasing rate of disutility of cost-reducing efforts, $\varphi''(e)$. If the increasing rate of disutility of cost-reducing efforts is small enough to satisfy $\varphi''(e) < \frac{(1-\alpha)x_q}{b}$, the disutility is not so sensitive to a change in cost-reducing efforts that the efforts are easy to vary (see Figure 1). This implies that the incentive effect is large and as a result the accompanied increase in quality is large. That is, if $\varphi''(e) < \frac{(1-\alpha)x_q}{b}$, quality ameliorates as the regulation is more price-based, because an increase in quality from the incentive effect is large enough to negate a decrease in quality from the cost-based effect.

On the contrary, suppose that the increasing rate of disutility of cost-reducing efforts is large enough to satisfy $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$. In this case, the disutility of the efforts is so sensitive to the change in the effort level that the efforts are difficult to vary (see Figure 1). This implies that the incentive effect is small and consequently the accompanied increase in quality is small. That is, if $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$, quality falls as the regulation is more price-based, because the decrease in quality resulting from the cost-based effect outweighs the increase in quality from the incentive effect.

Note that $\frac{dq(\alpha)}{d\alpha} > 0$ holds when $\alpha \approx 1$, because $\alpha \approx 1$ yields $\frac{(1-\alpha)x_q}{b} \approx 0$. In this case, $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$ is always true. That is, the cost-based effect outweighs the incentive effect when $\alpha \approx 1$. The reason is that when $\alpha \approx 1$, i.e., the regulation is almost fully cost-based, the incentive effect disappears. This result implies that $\varphi''(e) < \frac{(1-\alpha)x_q}{b}$ does not always hold for $0 \le \alpha < 1$, i.e., the regulatory shift from cost-based to price-based regulation never monotonically upgrades service quality. If the increasing rate of disutility of cost-reducing efforts is large, however, it is possible that $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$ always holds in which case the shift from cost-based to price-based regulation monotonically lowers quality.

Now we focus on consumer surplus. The implications of Proposition 1 for consumer surplus are altered if quality is incorporated in the model. As we show in Proposition 2-(2), if $\varphi''(e) < \frac{(1-\alpha)x_q}{b}$, quality improves as the regulation is more price-based. At the same time, price decreases. As a result, consumer surplus is always larger as the regulation is more price-based. If $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$, however, we cannot obtain a straightforward result because more price-based regulation lowers both quality and price. The net effect on consumer surplus as the regulation is more price-based depends on whether or not the surplus-enhancing effect of a decrease in price exceeds the surplus-deteriorating effect of a decrease in quality. When $\alpha = 0$, the latter dominates the former. In this case, a shift from price-based to cost-based regulation enlarges consumer surplus.

In implementing price-cap regulation, the regulator sometimes takes cost-passthrough into consideration to avoid quality-deterioration resulting from a lack of investment[6]. According to the result of Proposition 2, this cost-passthrough may have adverse effects on quality and consumer surplus. If the increasing rate of disutility of cost-reducing efforts is small, more price-based regulation makes quality higher and consumer surplus larger. It therefore follows that the cost-passthrough added to price-cap regulation increases neither quality nor consumer surplus. That is, even if the regulator adds cost-passthrough to price-based regulation so as to upgrade quality, the result may be that both quality and consumer surplus decrease.

4 A Remedy

The problem is that the regulator cannot know whether $\varphi''(e) < \frac{(1-\alpha)x_q}{b}$ or $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$ because the increasing rate of disutility of cost-reducing efforts, $\varphi''(e)$, is unobservable. Thus, the regulator cannot know the effect of cost-passthrough added to price-based regulation on quality and consumer surplus. It is possible that cost-passthrough, which is designed to upgrade quality and consumer surplus, actually decreases them. As a remedy for this problem, we will now consider an alternative to cost-passthrough, which always ameliorates quality and consumer surplus compared to price-based regulation.

Now suppose that the regulator can use a quality index, $I(q)$, where $I_q > 0$ and $I(q)$ is assumed to be verifiable[7]. Here, we focus on a regulation with an upper limit on the price that is contingent on such a quality index. We call this quality-plus regulation[8]. Quality-plus regulation can be written as

$$f(I(q)) \geq p, \tag{5}$$

where $f_I > 0$. Eq. (5) shows that an increase in quality raises the allowed price, $f(I(q))$, by increasing the quality index. Substituting quality-plus regulation for cost-based regulation in Eq. (4), we obtain the following new regulatory constraint:

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[6] See, for instance, Armstrong et al. (1994).

[7] See Lynch et al. (1994) for the practical method to index service quality.

[8] Noam (1991) proposes a similar regulatory policy for telecommunication industries.

$$\alpha(f(I(q)))+(1-\alpha)\bar{p}\geq p \qquad (6)$$

We rewrite Eq. (6) as

$$\hat{p}+\alpha f(I(q))\geq p \qquad (7)$$

where $\hat{p}\equiv(1-\alpha)\bar{p}$. The regulation shown in Eq. (7) is identical to price-based regulation when $\alpha=0$ and becomes more quality-plus (i.e., dependent on the quality index) as α moves closer to 1. As is the analyses in section 3, Eq. (7) is assumed to be binding and we focus on a situation in which a monopoly's profits remain unchanged. In this case, the regulator adjusts $\hat{p}$ so as to yield the same level of profits regardless of the value of α. The maximization problem can be formulated as follows.

$$(\text{M3})\begin{array}{l}\max_{\{p,q,e\}}\ \pi(p,q,e)\\ s.t.\ \ \hat{p}+\alpha f(I(q))\geq p\end{array}$$

We derive Proposition 3 by solving (M3).

Proposition 3

When we compare price-based regulation with quality-plus regulation in the presence of congestion, the following properties hold.

(1) Price increases as the regulation is more quality-plus：

$$\frac{dp(\alpha)}{d\alpha}\geq 0.$$

(2) Service quality increases as the regulation is more quality-plus:

$$\frac{dq(\alpha)}{d\alpha}>0.$$

(3) If $f_I<-\dfrac{x_q}{\alpha x_p I_q}$, cost-reducing efforts increase as the regulation is more quality-plus：

$$\frac{de(\alpha)}{d\alpha} > 0 .$$

(4) If $f_I < \frac{S_q}{\alpha x I_q}$, consumer surplus increases as the regulation is more quality-plus：

$$\frac{dS(p(\alpha), q(\alpha))}{d\alpha} > 0 .$$

The proof is stated in the Appendix. Under quality-plus regulation, the monopoly retains the incentive to improve quality, because the upper limit on price depends on an index that reflects the level of service quality. Thus, quality-plus regulation attains higher quality and price than price-based regulation. The increase in quality enlarges market demand, and a larger market demand makes cost-reducing incentives stronger. For example, suppose that the market demand is 10. In this case, a unit increase in cost-reducing efforts decreases the monopoly's costs by 10, because $C_e = -x$. Next, suppose that the market demand increases to 20. Now, a unit increase in cost-reducing efforts decreases the monopoly's costs by 20. Since a larger demand makes the profits from cost-reducing efforts larger, increased demand results in stronger cost-reducing efforts. In the same way, a lower quantity demanded, resulting from an increase in price, decreases such efforts. If the increase in demand from upgrading quality is larger than the decrease in demand from an increase in price, i.e., $x_q + \alpha x_p f_I I_q > 0$ ($f_I < -\frac{x_q}{\alpha x_p I_q}$), cost-reducing efforts increase as we move from price-based regulation to quality-plus regulation.

If the regulation is more quality-plus, both price and quality become higher. If $f_I < \frac{S_q}{\alpha x I_q}$, the effect of an increase in price is dominated by the effect of an increase in quality and, consequently, consumer surplus increases. Note that $f_I < \frac{S_q}{\alpha I_q}$ always holds when α is zero or when f_I is sufficiently small. This means that the regulatory shift from fully price-based regulation to quality-plus regulation certainly increases consumer surplus and that the increase in consumer surplus continues as the regulation is more quality-plus, unless the regulator makes the upper limit of price too dependent on the index of quality. Therefore, quality-plus regulation is a desirable alternative to cost-based adjustments such as cost-passthrough for investment costs, if the quality of service supplied by public utilities is low under price-based regulation.

5 Simulation

We will now conduct a numerical simulation and illustrate our results. In the ensuing simulation, we will use the following simple functions and parameters.

$$x = -p + 5q^{0.5},\quad C = (1 - e + 2q)x,\quad \pi = 0.5,\quad \varphi = e^n,$$

$$f(I) = \gamma I,\quad I(q) = q,\quad 0 \le \alpha \le 0.95$$ [9]

First, we compare price-based regulation with cost-based regulation in three cases: (Case 1) $n = 1.55$, (Case 2) $n = 1.75$, and (Case 3) $n = 2.00$. The results are shown in Table 1 and Figure 2.

In all cases, regulation that is more price-based (i.e., a smaller α) induces greater cost-reducing efforts and lower prices. Regarding service quality, for $\alpha \le 0.3$ in Case 1 and $\alpha \le 0.2$ in Case 2, more price-based regulation results in higher quality, because

[9] Since the degeneration problem arises when $\alpha = 1$, as we note in footnote 3, we set the maximum value of α at 0.95.

$\varphi''(e) < \frac{(1-\alpha)x_q}{b}$ holds. Otherwise, more price-based regulation leads to lower quality, because $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$ holds. Especially in Case 3, quality is decreased as the regulation is more price-based, since $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$ holds for any value of α.

Consumer surplus is higher as the regulation is more price-based for $\alpha \le 0.6$ in Case 1 and $\alpha \le 0.4$ in Case 2. Since $\varphi''(e) < \frac{(1-\alpha)x_q}{b}$ holds for $\alpha \le 0.3$ in Case 1 and $\alpha \le 0.2$ in Case 2, smaller α makes consumer surplus larger for those α. For $0.4 \le \alpha \le 0.6$ in Case 1 and $0.3 \le \alpha \le 0.4$ in Case 2, $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$ holds and consumer surplus is larger as α is smaller. This implies that a decrease in price makes consumer surplus so large that it overcomes the surplus-deteriorating effect of a decrease in quality. For any other value of α, $\varphi''(e) > \frac{(1-\alpha)x_q}{b}$ holds and consumer surplus is lower as α is smaller: the surplus-deteriorating effect of a decrease in quality exceeds the surplus-enhancing effect of a decrease in price. In the end, the value of α that yields the largest consumer surplus is 0 in Case 1 and 0.95 in Cases 2 and 3. In Case 1, for $\alpha \le 0.6$, a smaller α makes consumer surplus much higher, but a smaller α does not have as great an effect on consumer surplus when $\alpha \ge 0.7$. Thus, consumer surplus is largest when $\alpha = 0$, i.e., the regulation is fully price-based. On the contrary, in Case 2, a smaller α does not substantially increase consumer surplus when $\alpha \le 0.4$, but a smaller α does when $\alpha \ge 0.5$. Therefore, consumer surplus attains its largest value when $\alpha = 0.95$, i.e., the regulation is fully cost-based. In Case 3, consumer surplus is always smaller when the regulation is more price-based and, consequently, it is largest when $\alpha = 0.95$.

Second, we consider upgrading quality by using quality-plus regulation. Case 3, which yielded the lowest quality in the above three cases, is taken up as an example. We show three results with different γ s, i.e., $\gamma = 1.5,\ 2.0,\ 2.5$, in Table 2 and Figure 3.

For all γ, as Proposition 3-(1) and (2) shows, price and quality are larger as the regulation is more quality-plus (i.e., α is larger). When $\gamma = 2.5$ and $\alpha \geq 0.8$, cost-reducing efforts and consumer surplus decrease as α increases, because $f_I > \frac{S_q}{\alpha x I_q}$ and $f_I > -\frac{x_q}{\alpha x_p I_q}$. Otherwise, both are larger if the regulation is more quality-plus. This result is consistent with our theoretical results. When α or f_I is sufficiently small, i.e., an increase in quality does not make prices so high (in this example, $\gamma = 1.5$, $\gamma = 2.0$, and $\gamma = 2.5$ and $\alpha \leq 0.8$), quality-plus regulation improves consumer surplus compared to price-based regulation.

6 Concluding Remarks

This paper compares price-based regulation with cost-based regulation in a model in which service quality is considered. Price-based regulation induces greater cost-reducing efforts and results in a lower price than cost-based regulation. The increasing rate of disutility of cost-reducing efforts determines whether or not quality increases as the regulation is more price-based. If this rate is small, both quality and consumer surplus are higher as the regulation is more price-based. If the rate is large, however, quality deteriorates when the regulation is price-based, in which case consumer surplus decreases if a decrease in quality makes consumer surplus so small as to upset the surplus-enhancing effect of a decrease in price. Since the regulator has no information about the increasing rate of the disutility of cost-reducing efforts, it cannot know whether price-based regulation makes quality and consumer surplus higher or lower than cost-based regulation. Thus, the regulator does not know whether or not the adoption of cost-based adjustments such as cost-passthrough improves quality and consumer surplus, when the quality of service supplied by public utilities is low under price-based regulation. We then proceed to quality-plus regulation, in which an upper limit of price depends on a quality index. Our analysis shows that the regulator can surely raise both quality and consumer surplus by shifting from price-based to quality-plus regulation.

Lastly, we comment on how the implications of our research can be applied to actual situations where quality is multidimensional. This paper is especially concerned with service congestion, but quality in our model can be regarded as quality other than congestion. In this case, we have only to consider that the form of the cost function is $C = (a - e + bq)x$, which shows that an increase in quality linearly raises the monopoly's marginal (and average) cost. This new interpretation of the cost function has no effect on our analysis.

Appendix

Proof of Proposition 1

We set up the Lagrangian for the maximization problem (M1) as follows.

$$\Lambda = px(p) - (a-e)x(p) - \varphi(e)$$
$$+\lambda[\alpha(a-e) + (1-\alpha)\bar{p} - p]$$

where $\lambda \geq 0$. Since we consider the case where the constraint is binding, $\lambda > 0$. The first order conditions for the maximization are

$$\frac{\partial \Lambda}{\partial p} = x + px_p - (a-e)x_p - \lambda = 0, \qquad \text{(A1)}$$

$$\frac{\partial \Lambda}{\partial e} = x - \varphi'(e) - \lambda\alpha = 0, \qquad \text{(A2)}$$

$$\frac{\partial \Lambda}{\partial \lambda} = \alpha(a-e) + (1-\alpha)\bar{p} - p = 0. \qquad \text{(A3)}$$

Totally differentiating Eqs. (A1)-(A3), we obtain

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} dp \\ de \\ d\lambda \end{bmatrix} = \begin{bmatrix} B_{11} \\ B_{21} \\ B_{31} \end{bmatrix} d\alpha + \begin{bmatrix} B_{12} \\ B_{22} \\ B_{32} \end{bmatrix} d\bar{p} \qquad \text{(A4)}$$

where

$$A_{11} = \Lambda_{pp} = 2x_p + (p-a+e)x_{pp},$$

$$A_{12} = A_{21} = \Lambda_{pe} = x_p,$$

$$A_{13} = A_{31} = \Lambda_{p\lambda} = -1,$$

$$A_{22} = \Lambda_{ee} = -\varphi'',$$

$$A_{23} = A_{32} = \Lambda_{e\lambda} = -\alpha,$$

$$A_{33} = \Lambda_{\lambda\lambda} = 0,$$

$$B_{11} = -\Lambda_{p\alpha} = 0,$$

$$B_{21} = -\Lambda_{e\alpha} = \lambda,$$

$$B_{31} = -\Lambda_{\lambda\alpha} = -(a - e - \bar{p})$$

$$B_{12} = -\Lambda_{p\bar{p}} = 0,$$

$$B_{22} = -\Lambda_{e\bar{p}} = 0,$$

$$B_{32} = -\Lambda_{\lambda\bar{p}} = -(1-\alpha).$$

Define $\pi^1(\alpha, \bar{p})$ by

$$\pi^1(\alpha, \bar{p}) \equiv \max_{\{p,e\}} \left\{ px(p) - (a-e)x(p) - \varphi(e) : \alpha(a-e) + (1-\alpha)\bar{p} = p \right\}.$$

If $\pi^1(\alpha, \bar{p}) = \bar{\pi}^1$, where $\bar{\pi}^1$ is a non-negative constant,

$$\pi^1{}_\alpha d\alpha + \pi^1{}_{\bar{p}} d\bar{p} = 0. \tag{A5}$$

From the envelope theorem, Eq. (A5) can be rewritten as

$$(a - e - \bar{p})d\alpha + (1-\alpha)d\bar{p} = 0. \tag{A6}$$

Substituting Eq. (A6) for Eq. (A4), we obtain

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} dp \\ de \\ d\lambda \end{bmatrix} = \begin{bmatrix} B_{11} \\ B_{21} \\ 0 \end{bmatrix} d\alpha.$$

By Cramer's rule, we have,

$$\frac{dp(\alpha)}{d\alpha} = \frac{\begin{vmatrix} B_{11} & A_{12} & A_{13} \\ B_{21} & A_{22} & A_{23} \\ 0 & A_{32} & A_{33} \end{vmatrix}}{\Delta} = \frac{\lambda\alpha}{\Delta} \geq 0 \tag{A7}$$

where $\Delta \equiv \begin{vmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{vmatrix} > 0$ from the second order condition for the maximization.

In the same way, we derive

$$\frac{de(\alpha)}{d\alpha} = \frac{-\lambda}{\Delta} < 0. \tag{A8}$$

Regarding consumer surplus, from (A7) we obtain

$$\frac{dS(p(\alpha))}{d\alpha} = S_p \frac{dp(\alpha)}{d\alpha}$$
$$= -x\frac{dp(\alpha)}{d\alpha} \le 0.$$

Q.E.D.

Proof of Proposition 2

We set up the Lagrangian for the maximization problem (M2) as follows:

$$\Lambda = px(p,q) - (a - e + bq)x(p,q) - \varphi(e)$$
$$+\lambda[\alpha(a - e + bq) + (1-\alpha)\overline{p} - p]$$

where $\lambda \ge 0$. Since we assume that the constraint is binding, $\lambda > 0$. The first order conditions for the maximization are

$$\frac{\partial\Lambda}{\partial p} = x + px_p - (a - e + bq)x_p - \lambda = 0, \quad \text{(A9)}$$

$$\frac{\partial\Lambda}{\partial q} = px_q - (a - e + bq)x_q - bx + \lambda\alpha b = 0, \quad \text{(A10)}$$

$$\frac{\partial\Lambda}{\partial e} = x - \varphi'(e) - \lambda\alpha = 0, \quad \text{(A11)}$$

$$\frac{\partial\Lambda}{\partial \lambda} = \alpha(a - e + bq) + (1-\alpha)\overline{p} - p = 0. \quad \text{(A12)}$$

Totally differentiating Eqs. (A9) – (A12), we obtain

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} dp \\ dq \\ de \\ d\lambda \end{bmatrix} = \begin{bmatrix} B_{11} \\ B_{21} \\ B_{31} \\ B_{41} \end{bmatrix} d\alpha + \begin{bmatrix} B_{12} \\ B_{22} \\ B_{32} \\ B_{42} \end{bmatrix} d\overline{p} \quad \text{(A13)}$$

where

$$A_{11} = \Lambda_{pp} = 2x_p + mx_{pp} \;\; (m \equiv p - (a - e + bq)),$$

$$A_{12} = A_{21} = \Lambda_{pq} = x_q - bx_p,$$

$$A_{13} = A_{31} = \Lambda_{pe} = x_p,$$

$$A_{14} = A_{41} = \Lambda_{p\lambda} = -1,$$

$$A_{22} = \Lambda_{qq} = -2bx_q + mx_{qq},$$

$$A_{23} = A_{32} = \Lambda_{qe} = x_q,$$

$$A_{24} = A_{42} = \Lambda_{q\lambda} = \alpha b,$$

$$A_{33} = \Lambda_{ee} = -\varphi'',$$

$$A_{34} = A_{43} = \Lambda_{e\lambda} = -\alpha,$$

$$A_{44} = \Lambda_{\lambda\lambda} = 0,$$

$$B_{11} = -\Lambda_{p\alpha} = 0,$$

$$B_{21} = -\Lambda_{q\alpha} = -\lambda b,$$

$$B_{31} = -\Lambda_{e\alpha} = \lambda,$$

$$B_{41} = -\Lambda_{\lambda\alpha} = -(a - e + bq - \overline{p})$$

$$B_{12} = -\Lambda_{p\overline{p}} = 0,$$

$$B_{22} = -\Lambda_{q\overline{p}} = 0,$$

$$B_{32} = -\Lambda_{e\overline{p}} = 0,$$

$$B_{42} = -\Lambda_{\lambda\overline{p}} = -(1-\alpha).$$

Define $\pi^2(\alpha, \overline{p})$ by

$$\pi^2(\alpha, \overline{p}) \equiv \max_{\{p,q,e\}} \{px(p,q) - (a - e + bq)x(p,q) - \varphi(e)$$
$$:\alpha(a - e + bq) + (1-\alpha)\overline{p} = p\}.$$

If $\pi^2(\alpha, \overline{p}) = \overline{\pi}^2$ where $\overline{\pi}^2$ is a non-negative constant, then $m > 0$ and

$$\pi^2{}_{\alpha} d\alpha + \pi^2{}_{\overline{p}} d\overline{p} = 0. \qquad \text{(A14)}$$

From the envelope theorem, Eq. (A14) can be rewritten as

$$(a-e+bq-\bar{p})d\alpha+(1-\alpha)d\bar{p}=0\,. \tag{A15}$$

Substituting Eq. (A15) for Eq. (A13), we obtain

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix}\begin{bmatrix} dp \\ dq \\ de \\ d\lambda \end{bmatrix}=\begin{bmatrix} B_{11} \\ B_{21} \\ B_{31} \\ 0 \end{bmatrix}d\alpha\,.$$

By Cramer's rule, we have

$$\frac{dp(\alpha)}{d\alpha}=\frac{\begin{vmatrix} B_{11} & A_{12} & A_{13} & A_{14} \\ B_{21} & A_{22} & A_{23} & A_{24} \\ B_{31} & A_{32} & A_{33} & A_{34} \\ 0 & A_{42} & A_{43} & A_{44} \end{vmatrix}}{\Delta}=\frac{\lambda\alpha(-b^2\varphi''+A_{22})}{\Delta}\geq 0 \tag{A16}$$

where $\Delta\equiv\begin{vmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{vmatrix}<0$ from the second order condition for the maximization and $m>0$, $x_q>0$, and $x_{qq}<0$ yields $A_{22}<0$. In the same way,

$$\frac{de(\alpha)}{d\alpha}=\frac{\lambda\{(1-\alpha)bx_q-mx_{qq}\}}{\Delta}<0$$

and

$$\frac{dq(\alpha)}{d\alpha}=\frac{\lambda\{(1-\alpha)x_q-b\varphi''\}}{\Delta}$$

which show that

$$\frac{dq(\alpha)}{d\alpha}<0 \text{ if } \varphi''<\frac{(1-\alpha)x_q}{b} \tag{A17}$$

and

$$\frac{dq(\alpha)}{d\alpha}>0 \text{ if } \varphi''>\frac{(1-\alpha)x_q}{b}\,. \tag{A18}$$

With respect to consumer surplus, we derive

$$\frac{dS(p(\alpha),q(\alpha))}{d\alpha} = S_p \frac{dp(\alpha)}{d\alpha} + S_q \frac{dq(\alpha)}{d\alpha}$$
$$= -x\frac{dp(\alpha)}{d\alpha} + S_q \frac{dq(\alpha)}{d\alpha} \ .$$

From Eq. (A16) and Eq. (A17), $\frac{dS(p(\alpha),q(\alpha))}{d\alpha} < 0$ if $\varphi'' < \frac{(1-\alpha)x_q}{b}$. From Eq. (A16) and Eq. (A18), $\frac{dS(p(\alpha),q(\alpha))}{d\alpha} > 0$ if $\varphi'' > \frac{(1-\alpha)x_q}{b}$ and $\alpha = 0$.

Q.E.D.

Proof of Proposition 3

The Lagrangian for the maximization problem (M3) is

$$\Lambda = px(p,q) - (a - e + bq)x(p,q) - \varphi(e)$$
$$+\lambda(\hat{p} + \alpha f(I(q)) - p)$$

where $\lambda \geq 0$. Since we focus on the case where the constraint is binding, $\lambda > 0$. The first order conditions for the maximization are

$$\frac{\partial \Lambda}{\partial p} = x + px_p - (a - e + bq)x_p - \lambda = 0, \tag{A19}$$

$$\frac{\partial \Lambda}{\partial q} = px_q - (a - e + bq)x_q - bx + \lambda \alpha f_I I_q = 0, \tag{A20}$$

$$\frac{\partial \Lambda}{\partial e} = x - \varphi'(e) = 0, \tag{A21}$$

$$\frac{\partial \Lambda}{\partial \lambda} = \hat{p} + \alpha f(I(q)) - p = 0. \tag{A22}$$

Totally differentiation Eqs. (A19) – (A22), we obtain

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} dp \\ dq \\ de \\ d\lambda \end{bmatrix} = \begin{bmatrix} B_{11} \\ B_{21} \\ B_{31} \\ B_{41} \end{bmatrix} d\alpha + \begin{bmatrix} B_{12} \\ B_{22} \\ B_{32} \\ B_{42} \end{bmatrix} d\hat{p} \tag{A23}$$

where

$$A_{11} = \Lambda_{pp} = 2x_p + (p - a + e - bq)x_{pp} \, ,$$

$$A_{12} = A_{21} = \Lambda_{pq} = x_q - bx_p \, ,$$

$$A_{13} = A_{31} = \Lambda_{pe} = x_p \, ,$$

$$A_{14} = A_{41} = \Lambda_{p\lambda} = -1 \, ,$$

$$A_{22} = \Lambda_{qq} = -2bx_q + (p - a + e - bq)x_{qq} + \lambda\alpha \frac{d^2(f(I(q)))}{dq^2} \, ,$$

$$A_{23} = A_{32} = \Lambda_{qe} = x_q \, ,$$

$$A_{24} = A_{42} = \Lambda_{q\lambda} = \alpha f_I I_q \, ,$$

$$A_{33} = \Lambda_{ee} = -\varphi'' \, ,$$

$$A_{34} = A_{43} = \Lambda_{e\lambda} = 0 \, ,$$

$$A_{44} = \Lambda_{\lambda\lambda} = 0 \, ,$$

$$B_{11} = -\Lambda_{p\alpha} = 0 \, ,$$

$$B_{21} = -\Lambda_{q\alpha} = -\lambda f_I I_q \, ,$$

$$B_{31} = -\Lambda_{e\alpha} = 0 \, ,$$

$$B_{41} = -\Lambda_{\lambda\alpha} = -f(I(q))$$

$$B_{12} = -\Lambda_{p\hat{p}} = 0 \, ,$$

$$B_{22} = -\Lambda_{q\hat{p}} = 0 \, ,$$

$$B_{32} = -\Lambda_{e\hat{p}} = 0 \, ,$$

$$B_{42} = -\Lambda_{\lambda\hat{p}} = -1 \, .$$

Define $\pi^3(\alpha, \hat{p})$ by

$$\pi^3(\alpha, \hat{p}) \equiv \max_{\{p,q,e\}} \left\{ px(p,q) - (a - e + bq)x(p,q) - \varphi(e) : \hat{p} + \alpha f(I(q)) = p \right\} .$$

If $\pi^3(\alpha, \hat{p}) = \overline{\pi}^3$ where $\overline{\pi}^3$ is a non-negative constant,

$$\pi^3{}_\alpha d\alpha + \pi^3{}_{\hat{p}} d\hat{p} = 0 . \qquad \text{(A24)}$$

Applying the envelope theorem, from Eq. (A24) we have,

$$f(I(q))d\alpha + d\hat{p} = 0 . \qquad \text{(A25)}$$

Substituting Eq. (A25) for Eq. (A23), we obtain

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} dp \\ dq \\ de \\ d\lambda \end{bmatrix} = \begin{bmatrix} B_{11} \\ B_{21} \\ B_{31} \\ 0 \end{bmatrix} d\alpha .$$

By Cramer's rule, we have

$$\frac{dp(\alpha)}{d\alpha} = \frac{\begin{vmatrix} B_1 & A_{12} & A_{13} & A_{14} \\ B_2 & A_{22} & A_{23} & A_{24} \\ B_3 & A_{32} & A_{33} & A_{34} \\ 0 & A_{42} & A_{43} & A_{44} \end{vmatrix}}{\Delta} = \frac{-\lambda\alpha(f_I I_q)^2 \varphi''}{\Delta} \geq 0 \qquad \text{(A26)}$$

where $\Delta \equiv \begin{vmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{vmatrix} < 0$ from the second order condition for the maximization. In the same way, we derive

$$\frac{dq(\alpha)}{d\alpha} = \frac{-\lambda f_I I_q \varphi''}{\Delta} > 0 . \qquad \text{(A27)}$$

Regarding cost-reducing efforts,

$$\frac{de(\alpha)}{d\alpha} = \frac{-\lambda f_I I_q (\alpha x_p f_I I_q + x_q)}{\Delta} .$$

Thus, $\dfrac{de(\alpha)}{d\alpha} > 0$ if $f_I < -\dfrac{x_q}{\alpha x_p I_q}$.

With respect to consumer surplus, from Eq. (A26) and Eq. (A27) we obtain

$$\frac{dS(p(\alpha),q(\alpha))}{d\alpha} = S_p \frac{dp(\alpha)}{d\alpha} + S_q \frac{dq(\alpha)}{d\alpha}$$

$$= \frac{\lambda f_I I_q \varphi'' \left\{ \alpha x f_I I_q - S_q \right\}}{\Delta}.$$

Therefore, $\frac{dS(p(\alpha),q(\alpha))}{d\alpha} > 0$ if $f_I < \frac{S_q}{\alpha x I_q}$.

Q.E.D.

(Case 1) $n = 1.55$

α	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
$\overline{p}$	1.904	1.834	1.731	1.610	1.474	1.325	1.164	0.988	0.793	0.569	0.436
p	1.904	1.923	1.957	1.997	2.044	2.101	2.175	2.277	2.442	2.788	3.202
q	0.681	0.554	0.508	0.490	0.485	0.493	0.512	0.550	0.621	0.786	0.991
x	2.222	1.799	1.608	1.502	1.439	1.408	1.403	1.429	1.497	1.646	1.777
e	1.925	1.210	0.889	0.690	0.546	0.433	0.339	0.256	0.180	0.108	0.072
S	2.469	1.617	1.293	1.128	1.036	0.991	0.985	1.021	1.121	1.355	1.579
$k1$	-0.880	-0.729	-0.503	-0.243	0.043	0.351	0.688	1.067	1.526	2.182	2.719

(Case 2) $n = 1.75$

α	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
$\overline{p}$	1.920	1.804	1.683	1.555	1.420	1.276	1.122	0.956	0.772	0.558	0.430
p	1.920	1.922	1.932	1.949	1.977	2.018	2.080	2.175	2.338	2.690	3.115
q	0.458	0.453	0.451	0.453	0.459	0.471	0.493	0.531	0.602	0.768	0.975
x	1.463	1.444	1.427	1.415	1.409	1.412	1.429	1.467	1.542	1.692	1.822
e	0.788	0.724	0.659	0.592	0.525	0.457	0.389	0.319	0.247	0.168	0.124
S	1.070	1.043	1.019	1.001	0.993	0.997	1.021	1.076	1.189	1.431	1.661
$k1$	-0.455	-0.248	-0.032	0.196	0.434	0.685	0.950	1.231	1.540	1.909	2.150

(Case 3) $n = 2.00$

α	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
$\overline{p}$	1.854	1.738	1.617	1.492	1.362	1.224	1.079	0.921	0.747	0.544	0.421
p	1.854	1.856	1.862	1.875	1.897	1.931	1.985	2.073	2.229	2.580	3.012
q	0.416	0.417	0.420	0.425	0.434	0.448	0.471	0.510	0.581	0.746	0.955
x	1.371	1.373	1.378	1.385	1.397	1.417	1.447	1.497	1.581	1.739	1.874
e	0.686	0.652	0.615	0.575	0.531	0.484	0.432	0.374	0.309	0.230	0.182
S	0.940	0.943	0.949	0.959	0.976	1.003	1.048	1.121	1.250	1.512	1.755
$k1$	0.062	0.258	0.457	0.658	0.861	1.066	1.272	1.475	1.672	1.855	1.936

$$k1 \equiv \varphi'' - \frac{(1-\alpha)x_q}{b}$$

Table 1: Price-based regulation ($\alpha = 0$) vs. cost-based regulation ($\alpha = 0.95$)

$\gamma = 1.5$

α	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$\hat{p}$	1.854	1.791	1.726	1.660	1.591	1.519	1.444	1.364	1.278	1.184	1.078
p	1.854	1.855	1.857	1.863	1.871	1.886	1.908	1.942	1.994	2.075	2.203
q	0.416	0.426	0.437	0.451	0.468	0.489	0.516	0.551	0.597	0.660	0.750
x	1.371	1.407	1.448	1.495	1.549	1.611	1.684	1.769	1.869	1.988	2.127
e	0.686	0.704	0.724	0.748	0.775	0.806	0.842	0.885	0.935	0.994	1.063
S	0.940	0.990	1.049	1.118	1.200	1.298	1.418	1.565	1.747	1.976	2.261
$k2$	-∞	-36.817	-17.407	-10.909	-7.636	-5.649	-4.300	-3.312	-2.544	-1.918	-1.387
$k3$	-∞	-36.817	-17.407	-10.909	-7.636	-5.649	-4.300	-3.312	-2.544	-1.918	-1.387

$\gamma = 2.0$

α	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$\hat{p}$	1.854	1.770	1.682	1.591	1.495	1.391	1.278	1.150	1.000	0.810	0.551
p	1.854	1.856	1.861	1.872	1.892	1.929	1.995	2.112	2.331	2.764	3.676
q	0.416	0.429	0.446	0.468	0.498	0.538	0.597	0.687	0.832	1.086	1.563
x	1.371	1.421	1.479	1.549	1.634	1.739	1.869	2.032	2.230	2.445	2.574
e	0.686	0.710	0.740	0.775	0.817	0.870	0.935	1.016	1.115	1.223	1.287
S	0.940	1.009	1.094	1.200	1.335	1.512	1.747	2.064	2.486	2.990	3.314
$k2$	-∞	-36.156	-16.715	-10.180	-6.861	-4.815	-3.392	-2.310	-1.426	-0.666	0.000
$k3$	-∞	-36.156	-16.715	-10.180	-6.861	-4.815	-3.392	-2.310	-1.426	-0.666	0.000

$\gamma = 2.5$

α	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$\hat{p}$	1.854	1.748	1.637	1.519	1.391	1.248	1.079	0.863	0.551	0.036	-0.714
p	1.854	1.856	1.865	1.886	1.929	2.018	2.203	2.625	3.676	5.904	7.442
q	0.416	0.433	0.456	0.489	0.538	0.616	0.750	1.007	1.563	2.608	3.262
x	1.371	1.434	1.512	1.611	1.739	1.907	2.127	2.393	2.574	2.171	1.589
e	0.686	0.717	0.756	0.806	0.870	0.953	1.063	1.196	1.287	1.085	0.794
S	0.940	1.029	1.144	1.298	1.512	1.818	2.261	2.863	3.314	2.356	1.262
$k2$	-∞	-35.487	-16.004	-9.414	-6.019	-3.870	-2.311	-1.059	0.000	0.780	1.116
$k3$	-∞	-35.487	-16.004	-9.414	-6.019	-3.870	-2.311	-1.059	0.000	0.780	1.116

$$k2 \equiv f_I - \left(-\frac{x_q}{\alpha x_p I_q} \right), \quad k3 \equiv f_I - \frac{S_q}{\alpha x I_q}.$$

Table 2: Price-based regulation ($\alpha = 0$) vs. quality-plus regulation ($\alpha = 1$) when $n = 2.00$

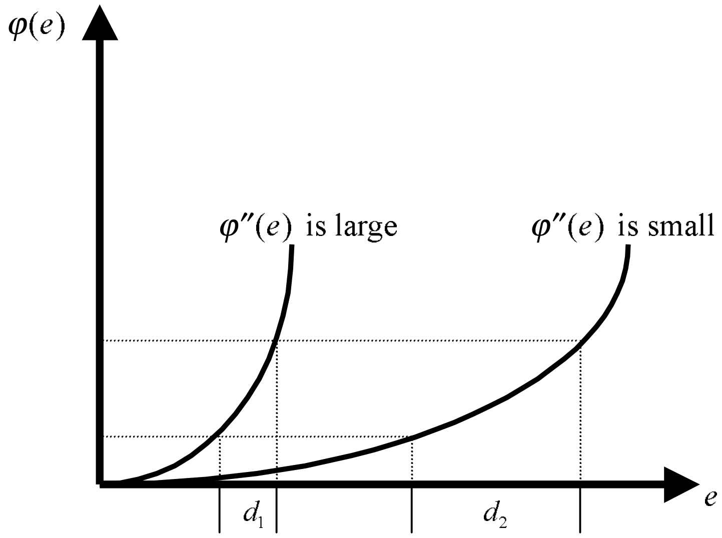
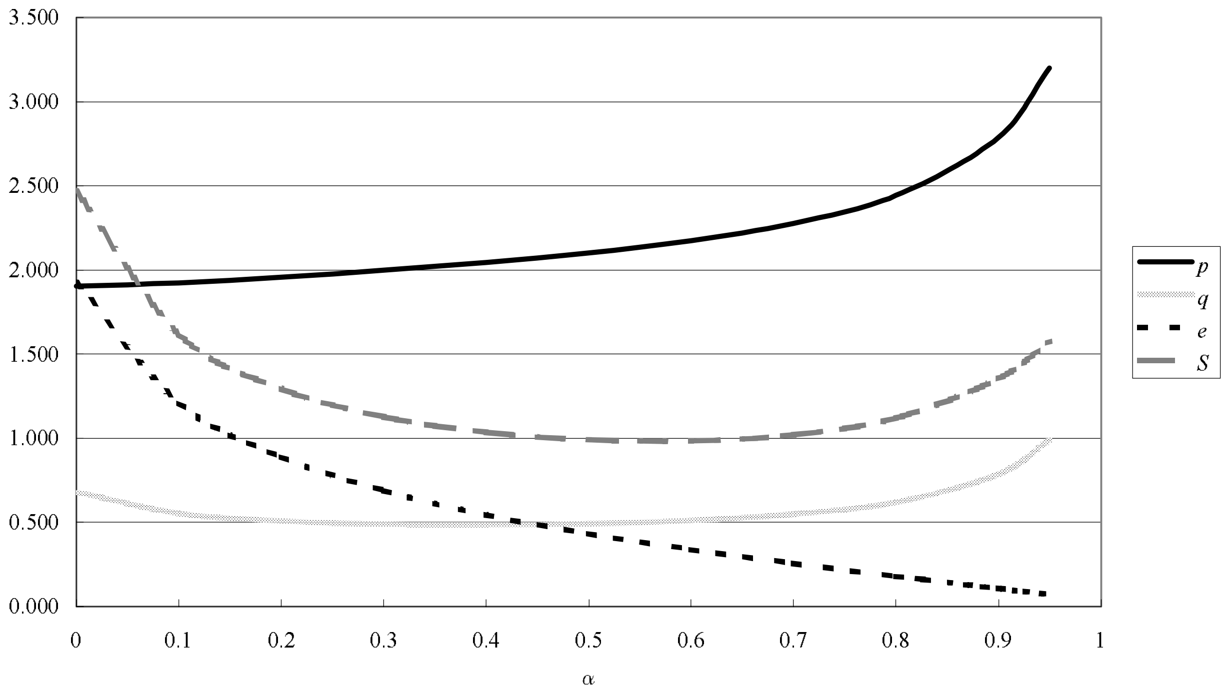


Figure 1: For the same change in $\varphi(e)$, the change in e is larger when $\varphi''(e)$ is small (i.e., $d_1 < d_2$).

(Case 1) $n = 1.55$



(Case 2) $n = 1.75$

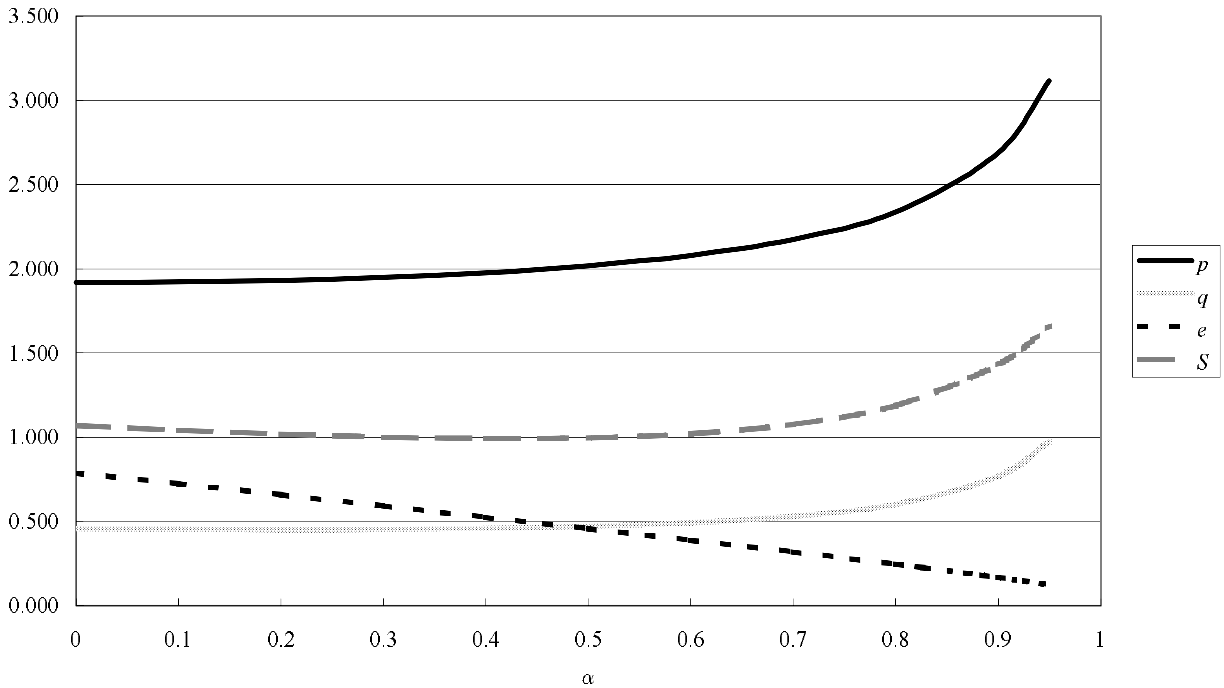


Figure 2: Price-based regulation vs. cost-based regulation when $n = 1.55$ and $n = 1.75$

(Case 3) $n = 2.00$

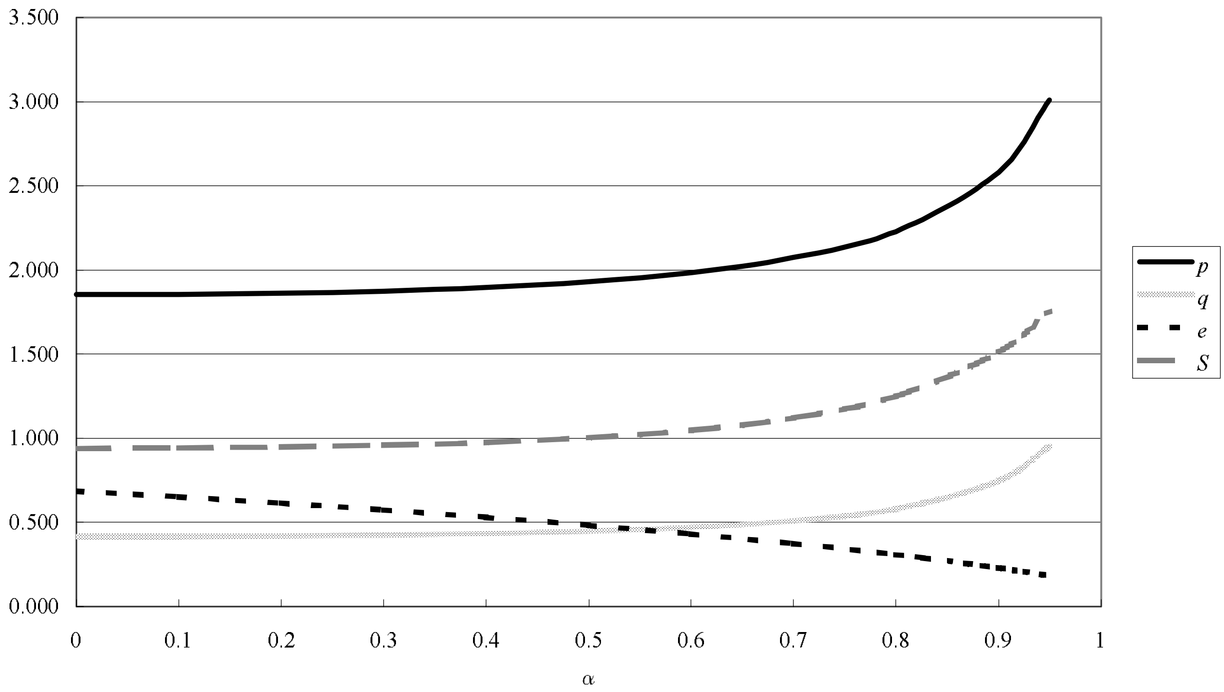


Figure 2: Price-based regulation vs. cost-based regulation when $n = 2.00$

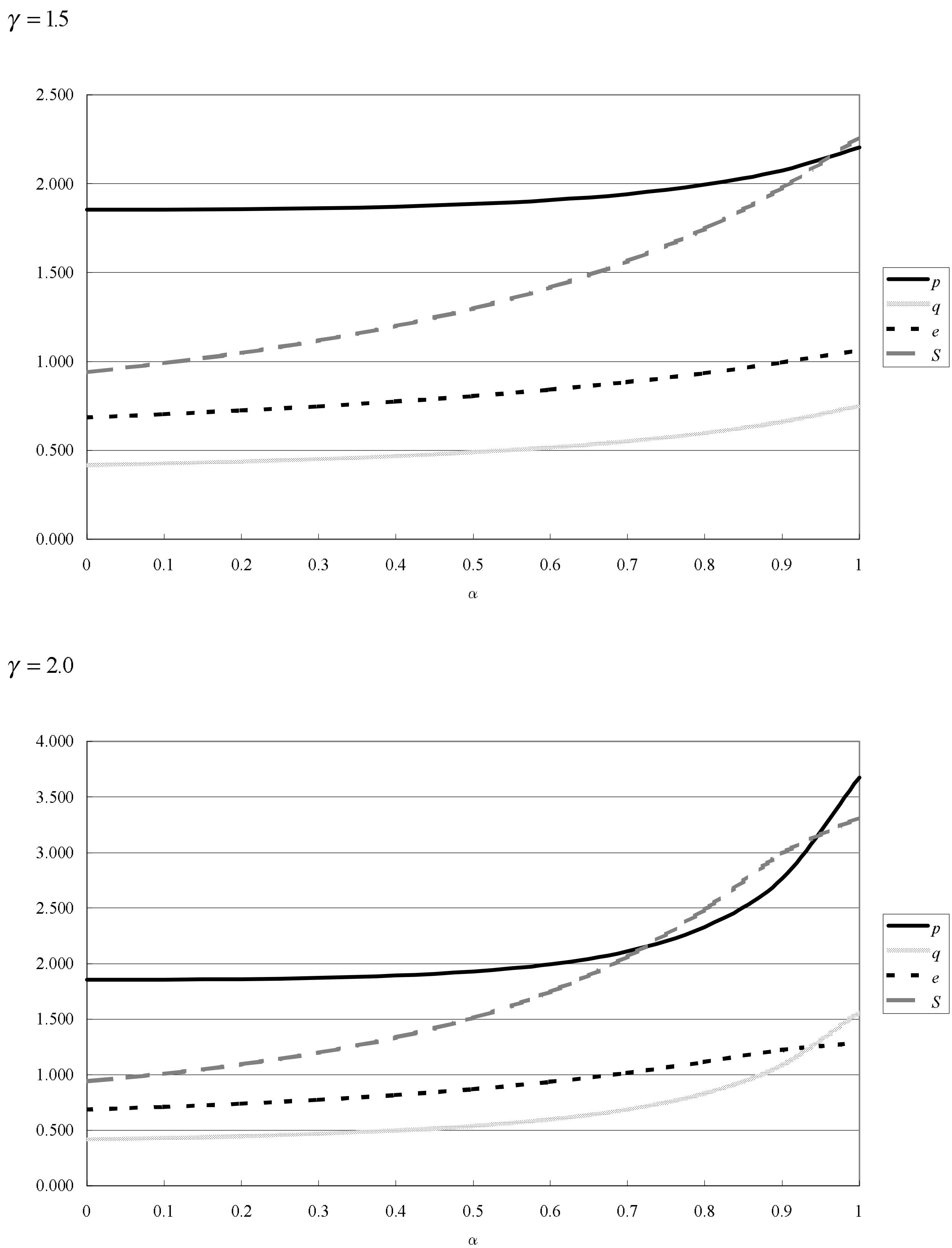


Figure 3: Price-based regulation vs. quality-plus regulation when $\gamma = 1.5$ and $\gamma = 2.0$

$\gamma = 2.5$

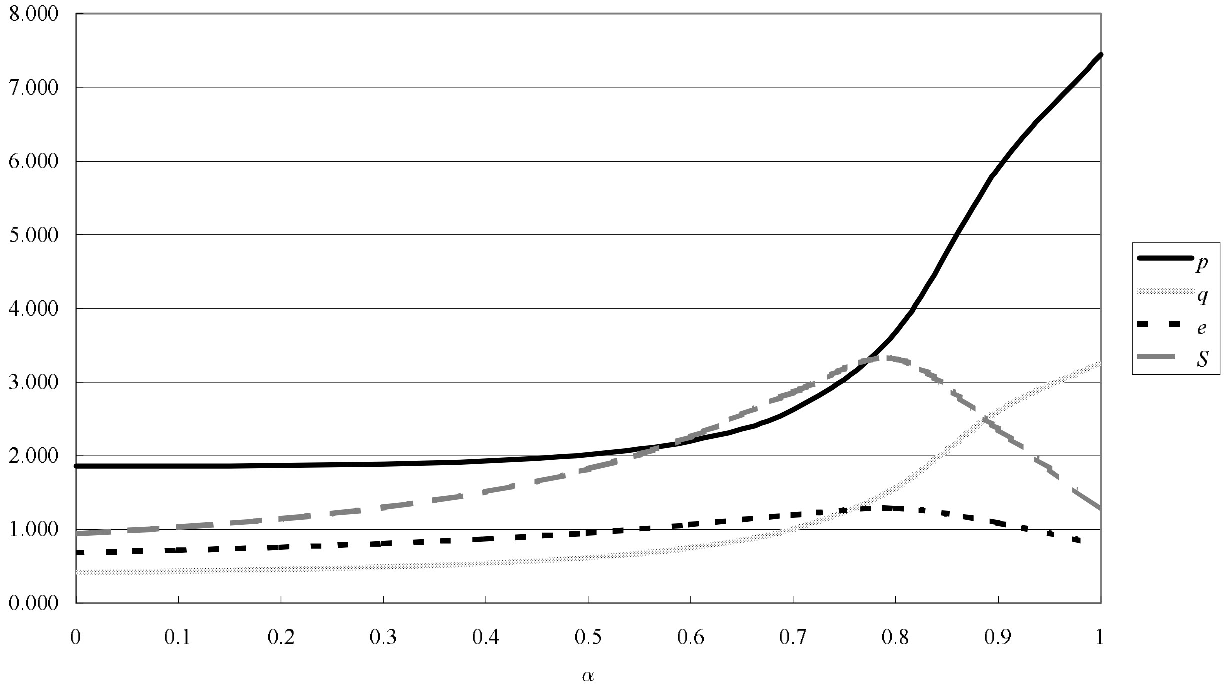


Figure 3: Price-based regulation vs. quality-plus regulation when $\gamma = 2.5$

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