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Abstract

This paper investigates the effects of alternative forms of regulation on the market penetration and capacity, which are determined by a profit-maximizing monopolist providing priority service to consumers. For continuous priority service, a minimum reliability standard, price cap and rate of return regulation lead to larger capacity than in the absence of regulation. A minimum reliability standard reduces the market penetration while price cap and rate of return regulation increase it. The regulatory effects on the market penetration and capacity are also examined for discrete priority service, and policy implications of these effects are discussed for electricity supply industry.

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1. INTRODUCTION

Priority service is a nonlinear pricing mechanism that efficiently rations the usage of scarce resources through consumer self-selection of a reliability level of service (Harris and Raviv, 1981; Chao and Wilson, 1987; Viswanathan and Tse, 1989; Wilson, 1989; Spulber, 1993; Crew and Fernando, 1994). Based on a knowledge of the distribution of consumers' willingness to pay for the service, suppliers of priority service design a menu of options characterized by service reliability and prices. Prior to the provision of service, consumers choose the level of reliability that maximizes their expected surplus. When the capacity of the supply facility is insufficient, suppliers ration consumers' usage according to the reliability level that each consumer has chosen.

The electricity supply industry has significant potential for applying priority service to consumers. In fact, 'standard' supply and 'interruptible' supply contracts are often applied on an optional basis to electricity transmission and distribution. Although generation of electricity has been liberalized in many countries, local monopoly is still a dominant structure for transmission and distribution sectors. In these sectors, how to regulate the monopolist that offers priority service is an important policy issue, because there is a serious concern about the lack of incentives for the monopolist to properly expand the capacity of transmission and distribution facilities. Because the investment costs of these facilities are substantial, the monopolist may choose to constrain investment so that the rationing of the usage of the facilities frequently occurs. Although the application of priority service attains efficient rationing in the short run, it may result in inefficient investment in the facilities in the long run.

A straightforward way of securing a sufficient level of capacity is to impose a minimum reliability constraint on the monopolist. In electricity supply, a reliability level can be defined in terms of an engineering index, for example, as the product of annual duration and frequency of supply interruption per consumer who experienced power interruption. This reliability regulation prevents excessive rationing and requires transmission and distribution monopolists to properly expand their network facilities to observe minimum reliability requirements. Although minimum reliability regulation is expected to achieve secure supply of the service, it may result in the exit of additional consumers who prefer an inexpensive service, thereby reducing welfare if the regulator sets a substantially high minimum reliability standard.

Rate of return regulation, which has been a traditional form of regulating the investment of utilities, is an alternative way of securing service reliability. Rate of return regulation is expected to achieve a secure supply of service by providing a monopolist with economic incentives for investment, however, it leads to an allocatively inefficient choice of input in production (Crew and Kleindorfer, 1980). In contrast with a minimum reliability standard, reliability levels of lower priority are not directly regulated. Thus, the monopolist can lower service reliability to consumers preferring inexpensive service through an increase in market penetration, while it can achieve a high reliability for consumers preferring high priority through additional investment.

Rate of return regulation has raised a serious concern about substantial regulatory costs and the lack of incentives for the regulated monopolist to reduce production costs. This concern has led to the application of price cap regulation, which imposes a ceiling on the price level of service, to such industries as telecommunications, water, gas, and electricity supply. Price cap regulation is expected to raise the number of consumers receiving the service by constraining the price level of service. However, the application of price cap regulation to the monopolist offering priority service leads to excessive rationing if the monopolist does not have any incentive to expand the capacity of the facilities.

This paper investigates how these alternative forms of regulation affect the market penetration and capacity of the facilities of a profit-maximizing monopolist that offers priority service to consumers. A benchmark for the analysis is the case of an unregulated profit-maximizing monopolist that restricts market penetration and investment, thereby reducing social welfare. For continuous priority service, both a minimum reliability standard and rate of return regulation lead to larger capacity than in the absence of regulation. Both regulatory schemes raise reliability levels for all priority classes except the highest, whose reliability is always equal to unity for continuous priority service when reliability is defined as the probability that service is supplied. While a minimum reliability standard leads to the exit of consumers preferring inexpensive service from the market, rate of return regulation raises market penetration through the provision of an inexpensive service with a low reliability. Price cap regulation also raises market penetration through the provision of an inexpensive service with a low reliability. Surprisingly, price cap regulation leads to larger capacity than in the absence of regulation because the prices of higher priority classes reflect the surplus loss of consumers choosing lower priority. To lower the prices of higher priority classes, the regulated monopolist must reduce the surplus loss of lower priority consumers. Capacity addition contributes to this reduction.

The analysis of regulatory effects on market penetration and capacity is extended to the case where the number of priority classes is finite and each reliability level is discrete. Price cap regulation also results in an increase in market penetration in the case of discrete priority service, while the effect of rate of return regulation on market penetration is not obvious. As with continuous priority service, rate of return regulation also increases capacity, while the effect of price cap regulation on capacity is not obvious in the discrete case. In contrast with continuous priority service where the reliability of the highest priority class is independent of capacity, any change in capacity affects the reliability of the highest priority class in discrete priority service. Thus, for the price of the highest priority to be lowered, it is necessary either to reduce the surplus loss of consumers choosing lower reliability or to reduce the reliability of the highest priority class. For discrete priority service, price cap regulation lowers capacity in comparison with an unregulated monopoly if the reduction in the surplus of the highest class consumers, because of the lowered reliability, exceeds the reduction of the surplus loss of lower priority consumers. The effects of a minimum reliability standard on discrete priority service are the same as those on continuous priority service.

The literature on priority service has mainly focused on how to design the menu of service and seldom on regulatory issues.[1] The issue of how to regulate the monopolist offering priority service is closely related to the literature on product differentiation of the regulated monopolist. Besanko et al. (1987) make a comparison of price cap regulation with a minimum quality standard in the context of vertical product differentiation. Besanko and Donnenfeld (1988) examine the effects of rate of return regulation on product variety. In these studies, the quality level for one class of service is independent from that of another class of service. The paper applies these regulatory schemes to markets where service quality is defined as priority assigned to each class of service, and the service quality chosen by consumers with a lower willingness to pay depends on the service quality chosen by those with a higher willingness to pay. Despite this difference in the characteristic of service quality, regulatory impacts on market penetration in this paper are consistent with those of Besanko et al. (1987) and Besanko and Donnenfeld (1988). That is, a minimum quality standard decreases market penetration while both price cap regulation and rate of return regulation increase it. The paper extends the analysis to discrete differentiation of service reliability, which has more practical relevance than continuous differentiation, while Besanko et al. (1987) and Besanko and Donnenfeld (1988) only examine continuous differentiation of product quality.

Section 2 describes a basic model of monopolistic provision of priority service with a continuous set of classes of the service. Section 3 investigates how alternative forms of regulating reliability, price, and investment affect market penetration and capacity. Section 4 extends the model to priority service with discrete classes, and compares welfare effects of alternative regulatory schemes based on an illustrative numerical example with two classes of priority service. Section 5 applies a model of priority service to the electricity supply industry and discusses policy implications of regulatory impacts on market penetration and capacity. Section 6 summarizes the results of the paper. The appendix section presents derivation of the objective function, proofs of propositions, and the effects of average reliability regulation on market penetration and capacity.

2. THE MODEL

A monopolist is assumed to provide each consumer with one unit of product that is supplied through the use of the monopolist's facilities. Prior to supplying the product, the monopolist chooses a level of capacity of these facilities. The amount of available capacity is uncertain, and the supply of the product is rationed whenever the level of available capacity is less than the total demand for the product. The probability that the available capacity of the monopolist's facilities is equal to or larger than X units of total demand is described by $F(X, K)$, where K is the level of capacity the monopolist has chosen prior to the provision of the product. It is assumed that $F_X(X, K) < 0$ and $F_K(X, K) > 0$, where a subscript stands for a partial derivative of the function. These assumptions imply that a decrease in total demand and an increase in capacity raises service reliability. Information about $F(X, K)$ is known to the monopolist and the regulator prior to the provision of the service.

Prior to the supply of the service, the monopolist offers consumers with a menu of tariff options characterized by two non-negative continuous variables: the reliability level of the service, denoted by r, and the price of the service, denoted by p.[2] Consumers subscribe to one of these tariff options, and those choosing a lower reliability level are rationed more frequently than those choosing a higher reliability level. A price function that is optimal for consumers, denoted by $p(r)$, describes the charge a consumer would pay for service reliability r for one unit of product over the time interval subject to supply interruption. The consumer's willingness to pay for the supply of service is denoted by v, whose distribution is described by $D(v)$ over the interval $[0, V]$. It is assumed that $D(v)$ is twice differentiable, $D_v(v) < 0$ and $D_{vv}(v) \leq 0$. Without loss of generality, the highest value of the consumers' willingness to pay is normalized so that $V = 1$. The willingness to pay is private information, and the monopolist only knows the distribution about the willingness to pay prior to offering priority service.

The expected surplus that a consumer obtains from the service, denoted by S, is defined as the difference between the expected utility, which is a function of service reliability and the consumer's willingness to pay for the service, and the price of the service, which is a function of service reliability:

$$S = u(r, v) - p(r), \tag{1}$$

where the expected utility is represented by a thrice-continuously differentiable function $u(r, v)$ with $u(0, v) = 0$ and $u(r, 0) = 0$. That $r = 0$ is taken as equivalent to the decision of not receiving the service at any time. The utility function is assumed to satisfy the following properties:[3]

(i) $u_r(r, v) > 0$ for $v \in (0, 1]$, and $u_r(r, 0) = 0$,

(ii) $u_v(r, v) > 0$ ($\forall$ $r > 0$),

(iii) $u_{rv}(r, v) = u_{vr}(r, v) > 0$,

(iv) $u_{rr}(r, v) \leq 0$,

(v) $u_{vv}(r, v) \leq 0$,

(vi) $u_{vrr}(r, v) = 0$,

and

(vii) $u_{rvv}(r, v) \leq 0$.

The third assumption is necessary for the self-selection condition that a cross-partial derivative of the utility function is positive. The fourth and fifth assumptions imply non-increasing marginal utility with respect to either reliability or willingness to pay. The sixth assumption indicates that a change in service reliability does not affect a cross-partial derivative of the utility function. The last assumption implies that the cross-partial derivative of the utility function is a non-increasing function of willingness to pay.

Given the price function $p(r)$, consumers are assumed to choose their level of reliability from a service menu so as to maximize their expected surplus. A reliability level for consumers whose willingness to pay is v is given by:

$$r(v) = \underset{r}{\arg.\max.}\{u(r, v) - p(r)\}. \tag{2}$$

For a menu of service to be consistent with utility maximization, the reliability level should be a non-decreasing function of the consumers' willingness to pay, i.e., $r_v(v) \leq 0$.[4] In addition, applying the envelope theorem in the theory of self-selection yields (Wilson, 1989, p.16):

$$\frac{dS}{dv} = u_v[r(v), v]. \tag{3}$$

Finally, the participation constraint for consumers with the lowest willingness to pay indicates:

$$S(v_0) \equiv u[r(v_0), v_0] - p(v_0) = 0, \tag{4}$$

where v_0 is the lowest level of willingness to pay among consumers receiving the service, and $p(v_0) = p[r(v_0)]$. The service is never supplied to consumers whose willingness to pay is less than v_0. If $v_0 = 0$, all consumers receive the service.[5]

For the rationing of supply to be efficient for the monopolist, the reliability level must be equal to the probability that the service is supplied (Wilson, 1989).[6] That is:

$$r(v) = F[D(v), K] = F(v, K). \tag{5}$$

The rationing of usage can then be efficiently implemented by assigning priority to consumers in order of decreasing reliability. With the knowledge about the distribution functions of willingness to pay and available capacity, the monopolist can design the optimal menu of priority service that induces consumer self-selection of $r(v)$.

The monopolist determines the capacity of its facilities and the lowest willingness to pay to maximize its expected profit. The objective function for the unregulated monopolist is to maximize the following expected profit subject to (3), (4), and (5):

$$\left|\int_{v_0}^{1} p(v)D_v(v)dv\right| - cK - c_0, \tag{6}$$

where c_0 is a fixed cost and c is the constant marginal cost of capacity. Substituting (3), (4), and (5) into (6) yields the following objective function for the unregulated monopolist (see Appendix A for derivation):

$$\max._{K,v_0} \quad \int_{v_0}^{1} \{u[F(v,K),v] - u_v[F(v,K),v]G(v)\}(-D_v(v))dv - cK - c_0 \tag{7}$$

where $G(v) \equiv D(v)/[-D_v(v)]$. The value of $1 - v_0$ indicates the market penetration of the service. The function $G(v)$ implies the reciprocal of the hazard rate for the distribution of consumers' willingness to pay. As in the literature on nonlinear pricing, $G(v)$ is non-increasing, which holds because of the assumption that $D_{vv}(v) \leq 0$.

The first-order conditions for v_0 and K are:

$$u[F(v_0, K), v_0]D_v(v_0) \quad - \quad u_v[F(v_0, K), v_0]G(v_0)D_v(v_0) \quad = \quad 0\,, \tag{8}$$

$$\int_{v_0}^{1} \{u_r[F(v, K), v] - u_{vr}[F(v, K), v]G(v)\}F_K(v, K)(-D_v(v))dv \quad = \quad c\,, \tag{9}$$

The marginal cost of capacity is equal to the expected marginal revenue with respect to K, which exceeds the marginal willingness to pay for capacity addition. Thus, the unregulated monopolist would install smaller capacity than the welfare-maximizing case. With smaller capacity, the monopolist restricts demand for the service by setting a higher v_0 than for the welfare-maximizing case where $v_0 = 0$, thereby excluding some consumers from the market. Exclusion of consumers leads to loss of surplus. The smaller capacity and market penetration leads to a reduction of welfare. For the second-order conditions to hold, the expected marginal revenue with respect to v_0 (the left-hand side of (8)) is assumed to be a decreasing function of v_0, and that with respect to K (the left-hand side of (9)) is assumed to be a decreasing function of K.

3. EFFECTS OF ALTERNATIVE FORMS OF REGULATION

3.1 Minimum Reliability Standard

Reliability is a crucial attribute of quality of supply and has been subject to regulation. Examples include the electricity supply industry where the regulator sets minimum reliability standards based on engineering practice and electric utilities are required to satisfy the standards. As for a reliability standard, an index measuring the loss of load probability is often applied to the electricity supply industry.[7] To satisfy the minimum reliability constraint, the monopolist must expand the capacity of its facilities for the service. Thus, the application of a minimum reliability standard appears to contribute to capacity addition.[8]

Suppose that the monopolist is obliged to supply service with reliability equal to or higher than R ($R > 0$). Under this reliability regulation, the monopolist maximizes the expected profit subject to:

$$r(v_0) = F[D(v_0), K] = F(v_0, K) \geq R \, , \tag{10}$$

Because $r_v(v) = F_D D_v > 0$, a minimum reliability standard implies that the constraint is binding only for the lowest level of reliability, i.e., $r(v_0)$. Because the reliability level for $v > v_0$ always exceeds $r(v_0)$, the constraint is not binding over the interval $(v_0, 1]$. This is in contrast to the model of Besanko et al. (1987) where, for $v > v_0$, the minimum quality constraint is binding over an interval $[v_0, v]$, and product quality is constant over $[v_0, v]$. The Lagrangian function for the profit-maximizing monopolist subject to a minimum reliability standard, denoted by L, can be written as:

$$L = \int_{v_0}^{1} \{u[F(v,K),v] - u_v[F(v,K),v]G(v)\}(-D_v(v))dv - cK - c_0 + \lambda_q[F(v_0,K) - R], \tag{11}$$

where λ_q is a non-negative Lagrange multiplier for the constraint (10).

The first-order condition for v_0 is:

$$u[F(v_0,K),v_0]D_v(v_0) \quad - \quad u_v[F(v_0,K),v_0]G(v_0)D_v(v_0) \quad = \quad -\lambda_q F_v(v_0,K). \tag{12}$$

Because $F_v(v, K) = F_D D_v > 0$, the right-hand side of (12) becomes negative when the minimum reliability constraint is binding. Given capacity, the expected marginal revenue with respect to v_0 becomes negative at the optimum for the monopolist subject to a binding constraint on the minimum level of service reliability. This implies that minimum reliability regulation aggravates surplus loss because of the exit of additional consumers from the market. The next proposition confirms this.

PROPOSITION 1. *Under minimum reliability regulation, the profit-maximizing monopolist offering continuous priority service provides the service to fewer consumers than in the absence of regulation*.

PROOF. See Appendix B.

The first-order condition for K is:

$$\int_{v_0}^{1} \{u_r[F(v,K),v] - u_{vr}[F(v,K),v]G(v)\} F_K(v,K)(-D_v(v))dv \quad = \quad c - \lambda_q F_K(v_0,K). \tag{13}$$

Because $F_K(v_0, K) > 0$, the second term on the right-hand side of (13) becomes negative when the minimum reliability constraint is binding. Given the market penetration, the expected marginal revenue with respect to K at the optimum is lower than that for the unregulated monopoly. Thus, minimum reliability regulation leads to an increase in the capacity of the facilities, which is confirmed by the following proposition:

PROPOSITION 2. *Under minimum reliability regulation, the profit-maximizing monopolist offering continuous priority service installs larger capacity for the service than in the absence of regulation*.

PROOF. See Appendix B.

The effect of minimum reliability regulation on price depends on consumer preferences. Following (Chao and Wilson, 1987), the price of continuous priority service can be written as:

$$p[F(v,K)] = p[F(v_0,K)] + \int_{v_0}^{v} u_r[F(t,K),t]F_D D_v dt\ . \tag{14}$$

The first term on the right-hand side of (14) is the price for consumers with the lowest willingness to pay, while the second term is the surplus loss of consumers whose willingness to pay is lower than v. The second term implies that consumers with higher priority compensate for the surplus loss of consumers with lower priority. For consumers with a high willingness to pay, increases in v_0 and K under minimum reliability regulation lead to a lower price in comparison with the unregulated monopoly. This is because the reduction in the surplus loss of consumers with lower values of v because of increases in v_0 and K exceeds the increase in the price for consumers with v_0. In contrast, minimum reliability regulation raises prices for consumers with low willingness to pay, because a reduction in the surplus loss of consumers with lower values of v in response to an increase in K is lower than the increase in the price for consumers with v_0.

An increase in capacity under minimum reliability regulation contributes to improvement in reliability for all but the highest class of priority in comparison with the unregulated monopoly. The improvement of service reliability raises consumer surplus. However, this increase in consumer surplus may be offset by a loss of surplus because of the exclusion of consumers with low values of v from the market. Thus, the welfare effects of minimum reliability regulation are ambiguous.

3.2 Rate of Return Regulation

Rate of return regulation imposes a constraint on the return on capital. The rate of return constraint is given as follows:

$$sK \geq \int_{v_0}^{1} \{u[F(v,K),v] - u_v[F(v,K),v]G(v)\}(-D_v(v))dv\,, \tag{15}$$

where s denotes an allowed rate of return and $s > c$ for regulation to be effective. The Lagrangian function for the profit-maximizing monopolist subject to rate of return regulation can be written as:

$$L = (1-\lambda_r)\int_{v_0}^{1} \{u[F(v,K),v] - u_v[F(v,K),v]G(v)\}(-D_v(v))dv - cK - c_0 + \lambda_r sK\,, \tag{16}$$

where λ_r is a non-negative Lagrange multiplier for the constraint (15), and $\lambda_r < 1$.

The first-order conditions for v_0 and K are:

$$(1-\lambda_r)\{\, u[F(v_0,K),v_0]D_v(v_0) - u_v[F(v_0,K),v_0]G(v_0)D_v(v_0)\ \} = 0\,, \tag{17}$$

$$\int_{v_0}^{1} \{u_r[F(v,K),v] - u_{vr}[F(v,K),v]G(v)\}F_K(v,K)(-D_v(v))dv \quad = \quad c - \frac{\lambda_r(s-c)}{1-\lambda_r}. \tag{18}$$

A familiar effect of rate of return regulation on capacity holds in case of continuous priority service: rate of return regulation results in larger capacity than in the absence of regulation (see

Appendix C for the proof). This is indicated by a decrease in the effective cost of capital because of regulation on the right-hand side of (18). The effect of rate of return regulation on market penetration is in contrast with that of a minimum reliability standard, as indicated by the next proposition.

PROPOSITION 3. *Under rate of return regulation, the profit-maximizing monopolist offering continuous priority service provides the service to more consumers than in the absence of regulation.*

PROOF. See Appendix D.

While the effects of rate of return regulation on prices depend on consumer preference in terms of a minimum reliability standard, its effects on consumer surplus are obvious: rate of return regulation raises consumer surplus in comparison with the unregulated monopoly. Intuitively, an increase in market penetration together with capacity addition contributes to an increase in surplus for all consumers receiving the service. In fact, the improvement in consumer surplus, because of rate of return regulation, is confirmed by totally differentiating consumer surplus with respect to s:

$$\begin{aligned}
&\frac{d}{ds}\int_{v_0}^{1}\{u[F(v,K),v]-p[F(v,K)]\}(-D_v)dv \\
&=\frac{d}{ds}\int_{v_0}^{1}u_v[F(v,K),v]G(v)(-D_v)dv \\
&=\frac{dv_0}{ds}u_v[F(v_0,K),v_0]G(v_0)D_v(v_0)+\frac{dK}{ds}\int_{v_0}^{1}u_{vr}[F(v,K),v]F_K G(v)(-D_v)dv.
\end{aligned} \tag{19}$$

Both terms on the right-hand side of the last equation in (19) are negative because of Proposition 3 and dK/ds < 0 (see Appendix C for proof). Thus, application of rate of return regulation leads to an increase in consumer surplus in comparison with the unregulated monopoly.

3.3 Price Cap Regulation

Suppose that a ceiling, denoted by P, is placed on the price schedule of the service provided by the monopolist. Because $\partial p/\partial v = p_r[F(D(v), K)]F_D D_v > 0$, the constraint is binding only on the price of the highest priority and the constraint is not binding on prices for $v < V$. This is in contrast with the model of Besanko et al. (1987) in which for $v < V$, a price constraint is binding over an interval [v, V] and the price is constant over [v, V]. From (3) and (4), the price under efficient rationing can be written as:

$$p[F(v,K)] = u[F(v,K), v] - \int_{v_0}^{v} u_v[F(t,K),t]dt\,. \tag{20}$$

Using (20), the price cap constraint is written as:

$$u[F(1,K),1] - \int_{v_0}^{1} u_v[F(v,K),v]dv \le P\,. \tag{21}$$

The Lagrangian function for the profit-maximizing monopolist under price cap regulation is:

$$L = \int_{v_0}^{1} \{u[F(v,K),v] - u_v[F(v,K),v]G(v)\}(-D_v(v))dv - cK - c_0 + \lambda_p\{P - p[F(1,K)]\}\,, \tag{22}$$

where λ_p is a Lagrange multiplier for the constraint (21).

The first-order conditions for v_0 and K are:

$$u[F(v_0,K),v_0]D_v(v_0) \quad - \quad u_v[F(v_0,K),v_0]G(v_0)D_v(v_0) \quad = \quad \lambda_p u_v[F(v_0,K),v_0], \tag{23}$$

$$\begin{aligned}&\int_{v_0}^{1} \{u_r[F(v,K),v] - u_{vr}[F(v,K),v]G(v)\}F_K(v,K)(-D_v(v))dv \\ &\quad = c - \lambda_p \int_{v_0}^{1} u_{vr}[F(v,K),v]F_K(v,K)dv + \lambda_p u_r[F(1,K),1]F_K(1,K).\end{aligned}$$

(24)

Because $u_{vr} > 0$ and $F_K(v, K) > 0$, the second term on the right-hand side of (24) is negative. The third term on the right-hand side of (24) equals zero because the highest reliability, which is equal to $F(1, K)$, is always equal to unity and is not affected by any change in capacity. Thus, given the market penetration, the expected marginal revenue with respect to K is lower under price cap regulation than that under the unregulated monopoly. In fact, price cap regulation leads to an increase in capacity.

PROPOSITION 4. *If a ceiling is imposed on the price of the service, the profit-maximizing monopolist offering continuous priority service installs larger capacity than in the absence of regulation.*

PROOF. See Appendix E.

The next proposition indicates that the monopolist lowers the optimal value of v_0 if the service price is capped.

PROPOSITION 5. *If a price ceiling is imposed on the price of the service, the profit-maximizing monopolist offering continuous priority service provides the service to more consumers than in the absence of regulation.*

PROOF. See Appendix F.

As in a minimum reliability standard and rate of return regulation, whether the application of price cap regulation leads to a price decrease for each class depends on consumer preferences. Price cap regulation raises consumer surplus in comparison with the unregulated monopoly because Propositions 4 and 5 imply that both terms on the right-hand side of the following equation, which indicates the regulatory effects on consumer surplus, become negative:

$$\frac{d}{dP}\int_{v_0}^{1}\{u[F(v,K),v]-p[F(v,K)]\}(-D_v)dv$$
$$=\frac{dv_0}{dP}u_v[F(v_0,K),v_0]G(v_0)D_v(v_0)+\frac{dK}{dP}\int_{v_0}^{1}u_{vr}[F(v,K),v]F_K G(v)(-D_v)dv.$$

An increase in market penetration together with capacity addition raises the surplus of consumers under price cap regulation as well as under rate of return regulation. These consumers would be excluded from the market in the absence of regulation.

4. PRIORITY SERVICE WITH FINITE CLASSES

The previous sections assume a continuous set of classes of priority service. In practice, however, priority classes are discrete because of a technical or institutional difficulty in continuously differentiating service reliability. In the electricity supply industry, two distinct classes of priority, say, 'standard' and 'interruptible' classes are often applied to consumers. This section applies the model in the previous sections to discrete priority service to examine whether the results for continuous priority service also hold for the discrete case.

4.1 Unregulated Monopolist

Each priority class of the service is defined as the interval of willingness to pay for the service; $[v_0, v_1]$, $[v_1, v_2]$, $[v_2, v_3]$,..., $[v_{n-1}, v_n]$, where $0 < v_0 < v_1 < v_2 < ... < v_{n-1} < v_n = 1$. The service reliability for class i, denoted by r_i, is defined as:

$$r_i = \frac{1}{D(v_{i-1}) - D(v_i)} \int_{D(v_i)}^{D(v_{i-1})} F(X, K)dX , \qquad i = 1,..., n. \qquad (25)$$

Equation (25) implies that consumers in each priority class are assumed to be rationed at random within that class when the available capacity is insufficient to supply the entire class (Chao et al., 1988). Note that in contrast with the continuous class case, the reliability for the first priority class is no longer equal to unity and thus reliability is affected by a change in capacity.

The incentive compatibility constraint implies that consumers whose willingness to pay is equal to v_i must be indifferent between the class i, $[v_{i-1}, v_i]$, and class $i + 1$, $[v_i, v_{i+1}]$. Then, the price for class $i + 1$ is defined as $p_{i+1} = p_i + u(r_{i+1}, v_i) - u(r_i, v_i)$. This can be rewritten as:

$$p_i = p_1 + \sum_{j=1}^{i-1}[u(r_{j+1}, v_j) - u(r_j, v_j)] \quad , \quad i = 2,..., n; \tag{26}$$

$$p_1 = u(r_1, v_0). \tag{27}$$

Equation (27) holds because of an individual rationality constraint for consumers with v_0.

The monopolist determines K and v_i (i = 0,..., n-1) to maximize its expected profit subject to constraints (25), (26), and (27). The expected revenue of the monopolist is defined as:

$$\sum_{i=1}^{n} p_i [D(v_{i-1}) - D(v_i)], \tag{28}$$

where $D(v_n) = D(1) = 0$. Substituting (26) and (27) into (28) yields:

$$u(r_1, v_0)D(v_0) \quad + \quad \sum_{i=1}^{n-1}[u(r_{i+1}, v_i) - u(r_i, v_i)]D(v_i)\,. \tag{29}$$

For the monopolist offering discrete priority service, marginal revenue with respect to v_0 is given by:

$$[u_r(r_1, v_0)D(v_0) - u_r(r_1, v_1)D(v_1)]\frac{\partial r_1}{\partial v_0} + u_v(r_1, v_0)D(v_0) + u(r_1, v_0)D_v(v_0)\,. \tag{30}$$

Marginal revenue with respect to v_i for $i > 0$ is given by:

$$\begin{aligned} &u_r(r_i, v_{i-1})D(v_{i-1})\frac{\partial r_i}{\partial v_i} - u_r(r_{i+1}, v_{i+1})D(v_{i+1})\frac{\partial r_{i+1}}{\partial v_i} + [u_v(r_{i+1}, v_i) - u_v(r_i, v_i)]D(v_i) \\ &\quad + \left(u_r(r_{i+1}, v_i)\frac{\partial r_{i+1}}{\partial v_i} - u_r(r_i, v_i)\frac{\partial r_i}{\partial v_i}\right)D(v_i) + [u(r_{i+1}, v_i) - u(r_i, v_i)]D_v(v_i), \end{aligned}$$

$$i = 1, \ldots, n\text{-}1. \tag{31}$$

The first-order conditions for v_i indicate that marginal revenue with respect to v_i is equal to zero for all $i = 0, \ldots, n$-1. Marginal revenue with respect to K, which is equal to the marginal cost of capacity at the optimum, is given by:

$$u_r(r_1, v_0)\frac{\partial r_1}{\partial K}D(v_0) + \sum_{i=1}^{n-1}\left(u_r(r_{i+1}, v_i)\frac{\partial r_{i+1}}{\partial K} - u_r(r_i, v_i)\frac{\partial r_i}{\partial K}\right)D(v_i)\,. \tag{32}$$

The second-order conditions for profit maximization are assumed to hold for the case of discrete priority service.

4.2 Effects of Alternative Forms of Regulation

Minimum reliability standard

Suppose that the monopolist offering priority service with a finite number of classes must satisfy the constraint $r_1 \geq R$. Then, the first-order condition of profit maximization for v_0 is:

$$[u_r(r_1, v_0)D(v_0) - u_r(r_1, v_1)D(v_1)]\frac{\partial r_1}{\partial v_0} + u_v(r_1, v_0)D(v_0) + u(r_1, v_0)D_v(v_0) = -\lambda_q \frac{\partial r_1}{\partial v_0}\,, \tag{33}$$

when the minimum reliability constraint is binding. The right-hand side of (33) becomes positive because $\partial r_1/\partial v_0 > 0$ (see Appendix G for the proof). Given capacity, the application of the minimum reliability regulation appears to raise v_0, relative to the unregulated case. In fact, totally differentiating $R - r_1 = 0$ and applying the implicit function theorem yields:

$$\frac{dv_0}{dR} = -\frac{1}{-\dfrac{\partial r_1}{\partial v_0}} > 0\,. \tag{34}$$

Thus, Proposition 1, which indicates a decrease in market penetration because of a minimum reliability standard, also holds in the discrete case.

The first-order condition of profit maximization for K is:

$$u_r(r_1, v_0)\frac{\partial r_1}{\partial K} D(v_0) + \sum_{i=1}^{n-1}\left(u_r(r_{i+1}, v_i)\frac{\partial r_{i+1}}{\partial K} - u_r(r_i, v_i)\frac{\partial r_i}{\partial K}\right) D(v_i) = c - \lambda_q \frac{\partial r_1}{\partial K}\,. \tag{35}$$

Because $\partial r_1/\partial K > 0$, (35) indicates that a minimum reliability standard reduces the effective marginal cost of capacity in comparison to the unregulated case. Given market penetration, a decrease in the effective marginal cost of capacity leads to an expansion of capacity. The effect on capacity of minimum reliability regulation is confirmed by totally differentiating $R - r_1 = 0$ and by applying the implicit function theorem:

$$\frac{dK}{dR} = -\frac{1}{-\frac{\partial r_1}{\partial K}} > 0 . \qquad (36)$$

Thus, Proposition 2, which indicates an increase in capacity because of a minimum reliability standard, also holds in the discrete case. The effects of minimum reliability regulation on market penetration and capacity are consistent with those found in continuous priority service.

Rate of return regulation

When rate of return regulation is applied to the monopolist offering discrete priority service, the right-hand side of (15) is replaced by total revenue defined in (29). Then the first-order conditions for v_0 and K are:

$$(1-\lambda_r)\left\{[u_r(r_1, v_0)D(v_0) - u_r(r_1, v_1)D(v_1)]\frac{\partial r_1}{\partial v_0} + u_v(r_1, v_0)D(v_0) + u(r_1, v_0)D_v(v_0)\right\} = 0, \qquad (37)$$

$$u_r(r_1, v_0)\frac{\partial r_1}{\partial K}D(v_0) + \sum_{i=1}^{n-1}\left(u_r(r_{i+1}, v_i)\frac{\partial r_{i+1}}{\partial K} - u_r(r_i, v_i)\frac{\partial r_i}{\partial K}\right)D(v_i) = c - \frac{\lambda_r(s-c)}{1-\lambda_r}. \qquad (38)$$

The capacity-enhancing effect of rate of return regulation also holds for discrete priority classes because totally differentiating the rate of return constraint with equality, applying the implicit function theorem and substituting (38) yields:

$$\frac{dK}{ds} = -\frac{K}{\dfrac{s-c}{1-\lambda_r}} < 0 \quad .$$

The effect of rate of return regulation on market penetration is not obvious in the case of discrete priority service because the monopolist determines not only v_0 but also v_1, ..., v_{n-1}, whose values depend on s. The effect of rate of return regulation on v_0 depends on dv_i/ds (i = 1,..., n–1), which has a complicated form.[9]

Price cap regulation

Suppose that the monopolist offering discrete priority service must satisfy the constraint that $P \geq p_n$. Then, the first-order condition of profit maximization for v_0 is:

$$[u_r(r_1,v_0)D(v_0) - u_r(r_1,v_1)D(v_1)]\frac{\partial r_1}{\partial v_0} + u_v(r_1,v_0)D(v_0) + u(r_1,v_0)D_v(v_0) = \lambda_p \frac{\partial p_n}{\partial v_0}. \tag{39}$$

The effect of price cap regulation for discrete priority service depends on the term $\partial p_n/\partial v_0$, which corresponds to $\partial p[F(1, K)]/\partial v_0$ for continuous priority service. As in the continuous case, $\partial p_n/\partial v_0$ is positive (see Appendix H for the proof). Thus, price cap regulation for discrete priority service leads to larger market penetration than in the absence of regulation. This is confirmed by totally differentiating $P - p_n = 0$ and applying the implicit function theorem:

$$\frac{dv_0}{dP} = -\frac{1}{-\dfrac{\partial p_n}{\partial v_0}} > 0.$$

The increase in market penetration because of price cap regulation for discrete priority service is consistent with Proposition 5 for the continuous case.

The first-order condition for K is:

$$u_r(r_1, v_0)\frac{\partial r_1}{\partial K}D(v_0) + \sum_{i=1}^{n-1}\left(u_r(r_{i+1}, v_i)\frac{\partial r_{i+1}}{\partial K} - u_r(r_i, v_i)\frac{\partial r_i}{\partial K}\right)D(v_i) = c + \lambda_p \frac{\partial p_n}{\partial K}, \qquad (40)$$

where:

$$\frac{\partial p_n}{\partial K} = \frac{\partial r_n}{\partial K}u_r(r_n, v_{n-1}) + \sum_{i=1}^{n-1}\frac{\partial r_i}{\partial K}\left[u_r(r_i, v_{i-1}) - u_r(r_i, v_i)\right]. \qquad (41)$$

The sign of $\partial p_n/\partial K$ in (41) depends on how capacity affects the surplus of the highest class consumers (the first term on the right-hand side of (41)) and surplus loss of lower class consumers because of the existence of the highest class (the second term on the right-hand side of (41)). On the one hand, capacity expansion raises the surplus of the highest class consumers through an increase in the reliability level for the highest class. On the other hand, capacity expansion lowers the surplus loss of lower class consumers because of the existence of the highest class consumers, by raising reliability levels for all consumers receiving the service. In contrast with the continuous case where capacity does not affect the surplus of the highest class consumers, the reliability for the highest priority class is raised by addition to capacity because consumers with $v = 1$ and those with $v = v_{n-1} < 1$ face the same reliability under discrete priority service.

If the reduction in the surplus loss exceeds the gain in the surplus, $\partial p_n/\partial K < 0$, and the application of a price ceiling leads to larger capacity than the unregulated case. This is because totally differentiating $P - p_1 = 0$ and applying the implicit function theorem yields:

$$\frac{dK}{dP} = -\frac{1}{-\dfrac{\partial p_n}{\partial K}} < 0 .$$

The capital-enhancing effect of price cap regulation for discrete priority service is consistent with the continuous case. However, the application of price cap regulation leads to lower capacity than the unregulated case if the gain in the surplus for the highest priority class exceeds the reduction in the surplus loss for lower priority classes, i.e., $\partial p_n/\partial K > 0$.

Note that when $n = 1$, $\partial p_1/\partial K > 0$ from (41). For the nondifferentiated product case of $n = 1$, the application of a price ceiling leads to lower capacity than the unregulated case. This adverse effect of price cap regulation on investment under distributed preferences for service is consistent with the literature on price cap regulation for nondifferentiated products that indicates an incentive for the regulated monopolist to underinvest in quality (Armstrong et al., 1994, p.173).

4.3 A Comparison of Alternative Forms of Regulation: A Numerical Example with Two Priority Classes

The effects of alternative regulatory forms on prices, consumer surplus and welfare are difficult to establish. Using a numerical example with two priority classes, these effects are compared among three forms of regulation.[10] The available capacity distributes according to a function $F(X, K) = 1 - (X/K)$, and the willingness to pay for the service distributes according to a function $D(v) = 1 - v$. The expected utility is the product of the willingness to pay and reliability, i.e., $u = vr$. Three first-order conditions for K, v_0, and v_1 and a regulatory constraint with equality under each regulatory scheme are simultaneously solved by a numerical method.

Table 1 summarizes the optimal values of key variables for the cases $c = 0.2$ and $c_0 = 0$. For comparison, the allowed rate of return is set equal to the rate of return on capital at the optimum under a minimum reliability standard with $R = 0.6$, and a price ceiling equal to p_2 at the optimum under rate of return regulation. Rate of return regulation results in larger capacity and more consumers subscribing to the service than a minimum reliability standard with an identical rate of return. A minimum reliability standard leads to higher reliability levels and prices for both priority classes than rate of return regulation that sets s equal to the rate of return under a minimum reliability standard with $R = 0.6$. A minimum reliability standard with $R = 0.6$ worsens both consumer surplus and welfare, while rate of return regulation contributes to an improvement in consumer surplus and welfare. The improvement in consumer surplus and welfare is also found in the case of price cap regulation that sets P equal to p_2 under rate of return regulation. In comparison to rate of return regulation, the effects on capacity and market penetration of price cap regulation are modest because a price ceiling, which is set equal to the optimal value of p_2 under rate of return regulation, is slightly lower than the optimal value of p_2 under the unregulated monopoly. Thus, rate of return regulation leads to larger consumer surplus and welfare than price cap regulation.

[Table 1 here]

5. APPLICATION: ELECTRICITY SUPPLY INDUSTRY

Priority service has relevance to the practice of regulating electricity supply industries where interruptible rates are available on an optional basis. The insights of the analysis of regulatory effects on capacity and market penetration that are determined by the monopolist offering priority service have important implications for regulatory policy of electricity supply industries. The insufficient capacity of electrical networks and the exit of low-cost generators restrict opportunities for power trade, thereby reducing welfare gains from competitive markets. For liberalized power markets to be efficient, appropriate schemes should be applied to the regulation of transmission and distribution sectors.

5.1 Electricity Distribution

Interruptible rates have been investigated (Tschirhart and Jen, 1979; Woo and Toyama, 1986; Smith, 1989; Tan and Varaiya, 1993) and are provided on an optional basis mainly to commercial and industrial customers receiving service from electricity distribution utilities. Prices of interruptible services are discounted according to the number and duration of outages over certain time intervals. In electricity distribution in some European countries, price cap regulation has recently replaced rate of return regulation because price cap regulation involves less regulatory costs and provides more incentive for cost reduction. Price cap regulation, however, raises a concern about unreliable supply of service because of a lack of incentive for investment (Armstrong et al., 1994, p.173).

In the case of discrete priority service, the effect of price cap regulation on investment is not obvious. If price cap regulation leads to insufficient investment, residential customers who subscribe to standard rates (i.e., high-priority classes) and rely on power supply from local distribution utilities may receive lower surplus than rate of return regulation, which provides the distribution utility with much incentive for investment. For the regulator whose primary concern is constraining price levels, however, the application of price cap regulation is justified on the ground that it leads to a larger number of customers subscribing to the service. The increase in market penetration is particularly beneficial for some business customers who can easily switch to inexpensive backup generators upon interruption of the utility's service.

Minimum reliability regulation is not desirable for priority service because it restricts demand for low reliability, thereby leading to loss of surplus of some business customers preferring inexpensive power supply from the distribution utility. Alternatively, the regulator can impose a constraint on the average reliability level of distribution utilities. In essence, the effects of average reliability regulation on market penetration and capacity are similar to those of a minimum reliability standard; reliability regulation leads to larger capacity but lower market penetration than in the absence of regulation. See Appendix I for details of the effects of average revenue regulation.

In countries that apply price cap regulation of the RPI-X form to electricity distribution, such as the Netherlands, Norway, Spain and the United Kingdom, service reliability is also regulated along with other attributes of supply quality. In Norway, for example, the regulator sets a target for reliability that is defined as the expected outage costs, and applies either penalty or reward to the utility depending on the difference between the expected and actual outage costs (Gronli, 2003). The Netherlands and the United Kingdom also apply similar forms of performance-based regulation that set targets for service reliability in terms of the number of supply interruptions and duration of outages (Tahvanainen et al., 2004). In Spain, distribution utilities must satisfy minimum standards on outage occurrence and duration, and these utilities are penalized when they fail to satisfy the standards (Rothwell and Gomez, 2003).

These additional schemes of quality regulation are effective in preventing underinvestment.[11] However, they incur additional regulatory costs for enforcing standards and targets that may offset a cost reduction induced by RPI-X regulation. In addition, reliability regulation may have an adverse effect on the market penetration of the distribution service and may exclude customers preferring inexpensive service from the market if interruptible rates are applied to the distribution service.

5.2 Electricity Transmission

Reliability management of electric power systems, which used to be implemented through coordination among regulated utilities, is one of the main issues in deregulated electricity markets. The efficient management of system reliability is a crucial factor for the generation sector to be competitive because generators rely on transmission networks to send power to consumers. Reliability-differentiated pricing such as priority service can be applied to electricity transmission as an efficient method of reliability management (Chao and Peck, 1998; Woo et al., 1998; Deng and Oren, 2001). Examples include tariff options of 'firm' and 'non-firm' transmission services in the PJM Regional Transmission Organization in the United States. Even if the number of classes is two, efficiency gain from priority service in the short run is sufficient in comparison to random rationing such as rotating outages (Chao and Wilson, 1987; Wilson, 1989).

In the long run, the way to promote transmission investment in competitive power markets is one of the most challenging tasks for reliability management because there has been a growing concern about reliability of transmission networks (Joskow, 2005). To promote transmission investment, the Energy Policy Act of 2005 requires U.S. transmission utilities, which have been subject to rate of return regulation, to comply with reliability standards set and enforced by an Electric Reliability Organization (Young, 2006). The combination of rate of return regulation with reliability standards is expected to secure reliability of transmission networks as both regulatory schemes contribute to an increase in capacity. However, this combination of regulatory schemes may discourage competition in generation if the adverse effect on market penetration of reliability standards is dominant.

The effect of regulation on market penetration is important in the long run when generators in competitive markets receive reliability-differentiated transmission service from the monopolist owning and operating transmission networks. A minimum reliability standard reduces market penetration, thereby discouraging competition among generators. Thus, a minimum reliability standard applied to the transmission sector has an adverse impact on competition in generation markets. In contrast, price cap regulation, which has been applied to the transmission sector of such countries as Argentina, Norway and the United Kingdom (Armstrong et al., 1994; Braton, 1997; Rudnick and Raineri, 1997), increases the number of generators receiving reliability-differentiated transmission service, thereby encouraging competition in generation. This procompetitive effect of price cap regulation is expected to increase efficiency in power markets.

Joskow (2005) argues that regulatory schemes for transmission investment should be designed to strike a proper balance between reliability and price. As is often the case in engineering practice, if the regulator highly values reliability levels for all discrete classes of priority service, constraining the minimum or average reliability level can be justified as an effective regulatory scheme. Rate of return regulation is also effective in achieving a reliable supply of transmission service. If a price reduction in the transmission service is a major concern for the regulator, price cap regulation has an appealing feature of securing low price levels. The imposition of a price ceiling on reliability-differentiated tariffs of electricity transmission deserves consideration if the regulatory agency puts more priority on promoting competition in generation than on a secure supply of transmission service.

6. CONCLUSION

This paper addresses the issue of how to regulate a monopolist that offers priority service to consumers. Although priority service has been extensively analyzed in the literature, an explicit analysis of how regulatory schemes affect priority service in the long run has seldom been conducted. Using a model for both continuous and discrete priority classes, this paper investigates the effects of alternative regulatory schemes on market penetration and capacity of the facilities of the monopolist. In comparison to an unregulated monopoly, a minimum reliability standard, rate of return regulation and price cap regulation raise the capacity of the facilities in case of continuous priority service. For discrete priority service, capital-enhancing effects of a minimum reliability standard and rate of return regulation are also found, but the effect of price cap regulation on capacity is ambiguous. In contrast with a minimum reliability standard that reduces market penetration, price cap regulation increases market penetration for both continuous and discrete classes of priority service. Rate of return regulation also increases market penetration in case of continuous priority service, but the effect of rate of return regulation on market penetration is not obvious in case of discrete priority service.

Because price cap regulation mitigates the adverse effect of the monopoly on market penetration, it contributes to promoting competition in generation markets where generators often rely on transmission service from the monopolist owning and operating the electrical networks. Rate of return regulation provides the transmission and distribution monopolists offering priority service with much greater incentive to increase capacity, thereby contributing to the mitigation of concerns about secure supply of electricity. Minimum reliability regulation contributes to the improvement in reliability for all classes of priority but it aggravates the exit of additional consumers from the market.

In practice, a dominant form of implementing priority service is the provision of two classes of service reliability. Examples include the electricity supply industry where customers can choose either standard or interruptible rates. There has been a growing concern about service reliability in the electricity supply industry as a global trend toward liberalization has emerged. A series of large-scale collapses of electric power systems occurring in North America, Scandinavia and Italy in 2003 confirmed the importance of securing a reliable supply of electricity in competitive power markets.

To secure reliable power supply, reliability standards have been applied to the transmission and distribution sectors in many countries. These standards depend on the type of interruption (planned or unplanned), outage duration, voltage levels, and regional features affecting power supply. Although this paper does not explicitly take account of these attributes in the regulatory analysis of priority service, it does indicate that when market penetration is important, reliability standards may be harmful under either price cap regulation, which has recently been applied to the transmission and distribution sectors of some European countries, or under rate of return regulation, which is still a dominant form of regulating the transmission and distribution sectors in the United States.

NOTES

1. Notable exceptions are studies on second-best priority pricing, which investigate a two-dimensional priority service that maximizes welfare subject to a revenue constraint (Wilson,

1989; Spulber, 1992).

2. Prices for consumers with low willingness to pay could be negative if priority service is Pareto superior to the single-price service with random rationing. The case of a negative price for service is beyond the scope in this paper.

3. All properties except $u_{vrr}(r, v) = 0$ are also assumed in Besanko et al. (1987). Chao and Wilson (1987) also assume that $u_{vrr}(r, v) = 0$.

4. Combining the assumption that $u_{rv} > 0$ with the second-order condition of utility maximization, $u_{rr} - p_{rr} < 0$, implies that $r_v(v) \geq 0$. Totally differentiating $S(v) = u[r(v), v] - p(v)$ and using the first-order condition of utility maximization, $u_r - p_r = 0$, yields (3).

5. To focus on the regulatory effect on market penetration, this paper does not consider the case where the regulator forces the monopolist to provide service to all consumers, i.e., $v_0 = 0$.

6. The profit-maximizing monopoly solution for priority service requires efficient rationing (Chao et al., 1988, p.82)

7. Reliability standards are investigated from an economic perspective by Telson (1975), Crew and Kleindorfer (1978), and Munasinghe and Gellerson (1979).

8. An alternative way of regulating reliability is to impose a constraint on the average level of supply reliability. As in a minimum reliability standard, the average reliability regulation reduces market penetration and expands capacity compared to the unregulated monopoly case. Details of these effects are discussed in Appendix I.

9. For instance, the effect of s on v_0 for $n = 2$ is given by:

$$\frac{dv_0}{ds} = \left(\frac{dK}{ds}\right)\frac{MR_{v_1K}MR_{v_0v_1} - MR_{v_0K}MR_{v_1v_1}}{MR_{v_0v_0}MR_{v_1v_1} - MR_{v_1v_0}MR_{v_0v_1}},$$

where MR_{ij} denotes a cross-partial derivative of the expected marginal revenue with respect to ith and jth variables.

10. The functional forms of supply probability, demand and utility in this section are the same as those assumed for the numerical example in Chao et al. (1988).

11. An alternative mechanism of securing supply reliability is to impose capacity obligations on distribution companies. See Joskow and Tirole (2006) for the effects of such mechanisms.

APPENDIX A: Derivation of the objective function of the unregulated monopolist

From (1) and (5), the expected profit of the monopolist in (6) can be written as:

$$-\int_{v_0}^{1} u[F(v,K),v]D_v(v)dv \quad - \quad cK \quad - c_0 \quad + \int_{v_0}^{1} S(v)D_v(v)dv\,, \tag{A1}$$

where the expected surplus, $S(v)$, is a function of consumer's willingness to pay for the service. Integrating the last term in (A1) by parts yields:

$$\int_{v_0}^{1} S(v)D_v(v)dv = S(1)D(1) - S(v_0)D(v_0) - \int_{v_0}^{1} D(v)S_v(v)dv. \tag{A2}$$

Substituting (3) and (4) into the right-hand side of (A2) yields:

$$\int_{v_0}^{1} S(v)D_v(v)dv = -\int_{v_0}^{1} u_v[F(v,K),v]D(v)dv. \tag{A3}$$

From (A1) and (A3), we have the expected profit of the monopolist in (7).

APPENDIX B: Proof of Propositions 1 and 2

Under the binding constraint on a minimum reliability level, the optimal values of K and v_0 must satisfy the following equation:

$$R - F[D(v_0), K] = 0. \tag{A4}$$

Totally differentiating (A4) and applying the implicit function theorem yields:

$$\frac{dv_0}{dR} = -\frac{1}{-F_D D_v} > 0, \tag{A5}$$

$$\frac{dK}{dR} = -\frac{1}{-F_K} > 0. \tag{A6}$$

Inequalities (A5) and (A6) imply that an increase in the minimum reliability standard leads to larger capacity and lower market penetration.

Q.E.D.

APPENDIX C: Proof of the capital-enhancing effect of rate of return regulation

Under the binding rate of return constraint on capital, the optimal value of K must satisfy the following equation:

$$sK - \int_{v_0}^{1} \{u[F(v,K),v] - u_v[F(v,K),v]G(v)\}(-D_v(v))dv = 0. \tag{A7}$$

Totally differentiating (A7), applying the implicit function theorem and substituting (18) yields:

$$\frac{dK}{ds} = -\frac{K}{\frac{s-c}{1-\lambda_r}} < 0\,. \tag{A8}$$

Inequality (A8) indicates that a decrease in the allowed rate of return leads to capacity expansion.

Q.E.D.

APPENDIX D: Proof of Proposition 3

The expected surplus for consumers with v can be written as:

$$S = u[F(v, K), v] - p[F(v, K)]. \tag{A9}$$

For consumers with v_0, totally differentiating (A9) with $S = 0$ yields:

$$0 = dv_0\left\{u_r[F(v_0,K),v_0]F_D D_v + u_v[F(v_0,K),v_0] - \frac{dp}{dr}F_D D_v\right\}$$
$$+ dK\left\{u_r[F(v_0,K),v_0]F_K - \frac{dp}{dr}F_K\right\}. \tag{A10}$$

Substituting the first-order condition for utility maximization, dp/dr = u_r, into (A10) yields:

$$u_v[F(v_0, K), v_0] = 0. \tag{A11}$$

Note that (A11) holds for such cases as rate of return regulation and price cap regulation where no constraint is imposed on reliability. Totally differentiating marginal revenue with respect to v_0 at the optimum, which is equal to zero from (17) for $\lambda_r > 0$, and substituting (A11) leads to:

$$\frac{dv_0}{ds}MR_{v_0v_0} + \frac{dK}{ds}u_r[F(v_0,K),v_0]F_K D_v = 0, \tag{A12}$$

where MR_{v0v0} denotes a second-partial derivative of expected marginal revenue of the monopolist. For the second-order conditions to hold, MR_{v0v0} must be negative. Thus, from (A8), $dv_0/ds > 0$ in (A12). This implies that a reduction in the allowed rate of return leads to an increase in market penetration.

Q.E.D.

APPENDIX E: Proof of Proposition 4

Under the binding constraint on prices, the following equation must hold at the optimum:

$$P - u(1,1) + \int_{v_0}^{1} u_v[F(v,K),v]dv = 0\,. \tag{A13}$$

Totally differentiating (A13) and applying the implicit function theorem yields:

$$\frac{dK}{dP} = -\frac{1}{\int_{v_0}^{1} u_{vr}[F(v,K),v]F_K dv} < 0\,. \tag{A14}$$

Inequality (A14) indicates that a decrease in the price cap leads to capacity expansion.

Q.E.D.

APPENDIX F: Proof of Proposition 5

From Appendix D, (A11) also holds in the case of price cap regulation. Substituting (A11) into (23) leads to $u[F(v_0, K), v_0] = 0$. Totally differentiating $u[F(v_0, K), v_0] = 0$ yields:

$$\frac{dv_0}{dP}\{u_v[F(v_0,K),v_0]+u_r[F(v_0,K),v_0]F_D D_V\}+\frac{dK}{dP}u_r[F(v_0,K),v_0]F_K=0. \tag{A15}$$

Because $u_v[F(v_0, K), v_0] = 0$ and $\mathrm{d}K/\mathrm{d}P < 0$ from Proposition 4, (A15) indicates that $\mathrm{d}v_0/\mathrm{d}P > 0$. Thus, a decrease in the price cap leads to an increase in market penetration.

Q.E.D.

APPENDIX G: Proof of $\partial r_1/\partial v_0 > 0$

From (25), differentiating r_1 with respect to v_0 yields:

$$\frac{\partial r_1}{\partial v_0}=D_v(v_0)\left\{\frac{F[D(v_0),K]-r_1}{D(v_0)-D(v_1)}\right\}. \tag{A16}$$

Because $F[D(v_0), K] = r(v_0) < r_1$, the right-hand side of (A16) is positive.

Q.E.D.

APPENDIX H: Proof of $\partial p_n/\partial v_0 > 0$

From (26) and (27), the price for the highest priority can be written as:

$$p_n \quad = \quad u(r_1, v_0) \quad + \quad \sum_{i=1}^{n-1} [u_r(r_{i+1}, v_i) - u_r(r_i, v_i)]\,. \tag{A17}$$

Given v_1, v_2, ..., v_{n-1}, a change in v_0 does not affect reliability of the ith class for $i > 1$. Thus, differentiating (A17) with respect to v_0 yields:

$$\frac{\partial p_n}{\partial v_0} = u_r(r_1, v_0)\frac{\partial r_1}{\partial v_0} + u_v(r_1, v_0) - u_r(r_1, v_1)\frac{\partial r_1}{\partial v_0}. \tag{A18}$$

Substituting (A16) into (A18) yields:

$$\frac{\partial p_n}{\partial v_0} = u_v(r_1, v_0) - \frac{r_1 D_v(v_0)[u_r(r_1, v_0) - u_r(r_1, v_1)]}{D(v_0) - D(v_1)} + \frac{r(v_0) D_v(v_0)[u_r(r_1, v_0) - u_r(r_1, v_1)]}{D(v_0) - D(v_1)}. \tag{A19}$$

The third term on the right-hand side of (A19) is positive because $D_v(v) < 0$ and $u_{rv}(r, v) > 0$.

Approximating $D(v)$ by a Taylor deployment around $v = v_0$, the first and second terms on the right-hand side of (A19) can be written as:

$$\frac{D_v(v_0)}{D(v_0)-D(v_1)}\{(v_0-v_1)u_v(r_1,v_0)-r_1[u_r(r_1\ ,v_0)-u_r(r_1,v_1)]\}-\frac{u_v(r_1,v_0)D_{vv}(v_0)(v_1-v_0)^2}{2[D(v_0)-D(v_1)]}. \tag{A20}$$

The second term on the right-hand side of (A20) becomes nonnegative, because $D_{vv}(v_0) \leq 0$.

According to the mean value theorem:

$$u_{rv}(r_1,v) = \frac{u_r(r_1,v_0)-u_r(r_1,v_1)}{v_0-v_1}, \qquad v_0 < v < v_1, \tag{A21}$$

$$u_{vr}(r,v_0) = \frac{u_v(r_1,v_0)-u_v(0,v_0)}{r_1-0}, \qquad 0 < r < r_1, \tag{A22}$$

where $u_v(0, v) = 0$. Substituting (A21) and (A22) into (A20) yields:

$$\frac{r_1(v_0-v_1)D_v(v_0)[u_{rv}(r,v_0)-u_{rv}(r_1,v)]}{D(v_0)-D(v_1)}-\frac{u_v(r_1,v_0)D_{vv}(v_0)(v_1-v_0)^2}{2[D(v_0)-D(v_1)]}. \tag{A23}$$

Because $u_{rvv}(r, v) \leq 0$ and $u_{vrr}(r, v) = 0$, $u_{rv}(r, v_0) - u_{rv}(r_1, v) \geq 0$, for $0 < r < r_1$ and $v_0 < v < v_1$.

Thus, both the first and second terms in (A20) become nonnegative, and the right-hand side of

(A19) becomes positive.

Q.E.D.

APPENDIX I: Effects of average reliability regulation on market penetration and capacity

Suppose that the profit-maximizing monopolist offering continuous priority service is subject to a binding constraint on the average reliability level, denoted by r_a. The constraint on average reliability level can be written as:

$$R_a \le r_a \equiv \int_{v_0}^{1} F[D(v),K]\frac{-D_v(v)}{D(v_0)}dv = \frac{1}{D(v_0)}\int_0^{D(v_0)} F(X,K)dX\ , \tag{A24}$$

where R_a indicates the regulated level of reliability. Totally differentiating $R_a - r_a = 0$ and applying the implicit function theorem leads to:

$$\frac{dv_0}{dR_a} = -\frac{\{D(v_0)\}^2}{-D_v(v_0)\left\{F[D(v_0),K]D(v_0) - \int_0^{D(v_0)} F(X,K)dX\right\}}\ . \tag{A25}$$

Because $F_D < 0$, the term in parentheses on the right-hand side of (A25) must be negative. Thus, $\mathrm{d}v_0/\mathrm{d}R_a > 0$, and the application of average revenue regulation reduces market penetration in comparison to the unregulated case for continuous priority service. For discrete priority service, the constraint on average reliability can be written as:

$$R_a \le r_a \equiv \sum_{i=1}^{n} r_i \frac{[D(v_{i-1}) - D(v_i)]}{D(v_0)} = \frac{1}{D(v_0)} \int_0^{D(v_0)} F(X, K) dX \ ,$$

which is the same as the reliability constraint in the continuous case. Thus, $dv_0/dR_a > 0$, and the application of average revenue regulation reduces market penetration for discrete priority service. As for the regulatory effect on capacity, totally differentiating $R_a - r_a = 0$ and applying the implicit function theorem also leads to $dK/dR_a > 0$ for both continuous and discrete classes of priority service. Thus, for both cases, applying average reliability regulation raises capacity in comparison to the unregulated monopoly case.

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Table 1 Optimal values of key variables with two priority classes: $c = 0.2$ and $c_0 = 0$

	No regulation	Min. reliability	Rate of return	Price cap	Welfare optimal
		($R = 0.6000$)	($s = 0.3236$)	($P = 0.5623$)	
v_0	0.6360	0.7006	0.6046	0.6297	0.2720
K	0.4249	0.4437	0.4889	0.4280	0.8498
v_1	0.8180	0.9444	0.8023	0.8052	0.6360
r_1	0.3575	0.6000	0.3934	0.3398	0.3575
r_2	0.7858	0.9374	0.7978	0.7724	0.7858
p_1	0.2274	0.4204	0.2378	0.2140	0.0972
p_2	0.5778	0.7390	0.5623	0.5623	0.3697
Rate of return	0.3449	0.3236	0.3236	0.3437	0.2000
Profit	0.0616	0.0548	0.0604	0.0615	0
Consumer Surplus	0.0308	0.0274	0.0387	0.0315	0.1231
Welfare	0.0923	0.0822	0.0991	0.0930	0.1231