Revisiting Rate of Return Regulation under Uncertainty

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Abstract: This paper revisits the literature on rate of return (ror) regulation under uncertainty and makes three contributions. (1) It shows that earlier ror regulation results were all incorrectly obtained, because the expected profit function is generally not differentiable. (2) It reveals the difference between two types of ror regulation: regulating the expected ror (type I), and regulating the ror in every state (type II). There are always Averch-Johnson (A-J) effects under type I regulation, but not necessarily under type II regulation. (3) It re-derives the A-J effect under certainty by a new and nontechnical approach, without using the Lagrangian multiplier.

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1. Introduction

The recent energy crisis in California has heightened interest in learning more about a regulated monopoly’s behavior. By revisiting the literature on rate of return (ror) regulation under uncertainty, which began with Peles and Stein (1976), this paper makes three contributions towards understanding a regulated monopoly’s behavior.

First, it reveals the difference between two types of ror regulation: 1) regulating the expected ror (type I), and 2) regulating the ror in every state (type II). There are always A-J effects under type I regulation, but not necessarily under type II regulation. Second, it shows that earlier A-J (or anti-AJ) effects under uncertainty, whether correct or incorrect, were all incorrectly obtained. All earlier works assumed type II regulation and differentiability, although the monopolist’s expected constrained profit (under type II regulation) is generally not differentiable. Third, it provides a new and nontechnical derivation of the A-J effects under certainty, which is much simpler than the Lagrangian multiplier method.

Peles and Stein’s (1976, 1979) two-stage model captures three important features of a regulated utility industry: (1) the monopoly operates under ror regulation; (2) it faces uncertain demands; and (3) it makes long-term decisions about capital investment and short-term decisions about labor and fuel usage. It therefore provides a sound framework upon which elaborations can be built in future studies. The results below suggest that in future studies it will be important to check whether type I regulation is socially more efficient than type II regulation and to check which type is used.

2. Description of the Problem

Averch and Johnson (1962) treated a regulated monopoly as a profit maximization
problem with two-inputs and a rate of return constraint. Let \( p(q) \) be the inverse demand function, \( q(K, L) \) be the monopoly’s production function, \((K, L)\) be the units of capital and labor, with unit costs \( r \) for capital and \( w \) for labor. Without rate of return regulation, the monopoly will choose \((K, L)\) to maximize its profit

\[
\pi(K, L) = p(q(K, L))q(K, L) - rK - wL.
\]

The first order conditions for a \( \pi \)-max solution are:

\[
\pi_K = \frac{\partial \pi}{\partial K} = MRq_K - r = 0, \quad \text{and} \quad \pi_L = \frac{\partial \pi}{\partial L} = MRq_L - w = 0,
\]

where \( MR = p+qp' \) is the marginal revenue, and \( q_K \) and \( q_L \) are the marginal productivities of \( K \) and \( L \). By (2), the following cost-min condition holds:

\[
\text{RTS} = \frac{q_K}{q_L} = \frac{r}{w} \quad \text{or} \quad \frac{q_L}{w} = \frac{q_K}{r}.
\]

By the first equation in (3), the rate of technical substitution (defined as \(-dL/dK\)) is equal to the price ratio \( r/w \); by the second equation, the marginal productivities per dollar are equalized between capital and labor\(^1\).

The rate of return on capital is defined as the ratio \((pq - wL)/K\), and the rate of return constraint is given by

\[
(pq - wL)/K \leq s,
\]

where \( s \) is the allowed rate or the ceiling imposed by regulators. Rearranging terms, (4) is equivalent to

\[^1\] The second interpretation is more appealing to students of intermediate microeconomics, because it has three advantages: (1) it saves the trouble of worrying whether the price ratio is \( w/r \) or \( r/w \); (2) it is similar to U-max: marginal utilities per dollar are equalized; (3) it implies the solution in linear cases.
(5) \( \pi(K, L) \leq (s-r)K. \)

Now, the regulated monopoly will choose \((K, L)\) to maximize its profits subject to the constraint (5). To be more precise, it solves the following constrained maximization problem:

(6) \[ \text{Max}\{ \pi(K, L) \mid K \geq 0, L \geq 0, \text{ and } \pi(K, L) \leq (s-r)K \}. \]

Let \( s_m \) be the unregulated monopoly’s rate of return, as implied by (2). For regulation to be effective, the rate \( s \) must be set between \( r \) and \( s_m \). For any \( s \in (r, s_m) \), Averch and Johnson (1962) showed that the solution of (6), \((K, L)\), satisfies the following inequality:

(7) \[ \frac{q_k}{q_L} < \frac{r}{w} \text{ or } \frac{q_k}{q_L} < \frac{q_L}{w}; \]

which leads to the A-J effects as summarized below:

**Proposition 1** (Averch and Johnson, 1962): Assume that the standard assumptions for profit-maximization hold. (i) A regulated monopoly uses more capital than the unregulated monopoly; and (ii) a regulated monopoly’s capital-labor ratio is higher than that required by cost-minimization.

By (7), labor has a higher productivity per dollar than capital. Therefore, a regulated monopoly’s output could be more cheaply produced by using more labor and less capital. This primary A-J effect, given in part (ii), motivated most of the subsequent debate and research about rate of return regulation.

The most rigorous demonstration of A-J effects are Baumol and Klevorick (1970) and Klevorick (1971). Zajac (1970) and Train (Ch. 1, 1991) provide simple geometric demonstrations. The next section of this paper provides a simple algebraic demonstration of the A-J effects without using a Lagrangian multiplier.

3. A Simple Demonstration of the A-J effects
In Peles and Stein’s 1976 study, the capital stock, K, is an ex ante choice variable, and labor is an ex post variable. In other words, decisions about K and L, respectively, are made before and after the realization of uncertain events. This was an important step forward in the applicability of ror analysis because the distinction between ex ante vs. ex post and long-term vs. short-term choices captures a fundamental feature of the utility industry in general and the recent energy crisis in particular. This section uses such a two-stage model to derive the A-J effects without using a Lagrangian multiplier.

For any fixed K decided in the first stage, the monopoly will in the second stage choose L to maximize (1) subject to (5). Define the assumptions A0, A1, and A2 as below:

**A0:** \( \pi(K, L) \) is twice-continuously differentiable, \( \pi_{KL} > 0 \), and \( \pi(K, L) \) is strictly concave (i.e., \( \pi_{KK} < 0 \), \( \pi_{LL} < 0 \), and \( (\pi_{KK} \pi_{LL} - \pi_{KL}^2) > 0 \)).

**A1:** For each K, the monopoly’s labor choice in the second stage is unrestricted by the regulatory constraint.

**A2:** For each K, the monopoly’s labor choice in the second stage is restricted by the regulatory constraint.

Under A1, the monopoly’s optimal labor choice and its unconstrained maximal profits as functions of K are respectively given by

\[
L^*(K) = \text{Arg-Max}\{ \pi(K, L) \mid L \geq 0 \}, \text{ and } \\
\pi^*(K) = \pi(K, L^*(K)).
\]

Under A2, the above two functions become

\[
L(K) = \text{Arg-Max}\{ \pi(K, L) \mid L \geq 0, \pi(K, L) \leq (s-r)K \}, \text{ and } \\
\pi(K) = \pi(K, L(K)).
\]

As readers will see, A1 and A2 lead to the same outcome under certainty but will lead to
different outcomes under uncertainty. Under A0 and A1, the first order condition, \( \pi_L = MRq_L - w = 0 \), leads to \( dL^*/dK = -\pi_{LK}/\pi_{LL} > 0 \); and the envelope theorem implies

\[
\pi^*(K)' = \pi_K = MRq_K - r, \text{ and } \pi^*(K)'' = \pi_{KK} - \pi_{KL}^2/\pi_{LL} < 0.
\]

(Figure 1 about here)

Hence, \( \pi^* \) is strictly concave. Using the term “profit hill,” as coined by Zajac (1970), \( \pi^* \) is the profit hill’s projection onto the \( \pi-K \) plane. This is illustrated in Figure 1-a.

Let \( k_0 \) be the solution of \( \pi^*(K)' = 0 \). Then, \((k_0, L^*(k_0))\) is the unconstrained \( \pi\)-max solution determined by (2). Since the allowed rate, \( s \), is effective and the profit hill has a unique top point, there must exist \( k_1 < k_2 \) satisfying \( k_1 < k_0 < k_2 \) and

\[
\pi^*(K) = \begin{cases} 
(s-r)K & \text{if } k_1 < K < k_2 \\
= (s-r)K & \text{if } K = k_1 \text{ or } k_2 \\
< (s-r)K & \text{if } K < k_1 \text{ or } K > k_2.
\end{cases}
\]

Under A1 the monopoly will solve the following problem in the first stage:

\[
\max \{ \pi^*(K) \mid K \geq 0, \pi^*(K) \leq (s-r)K \}.
\]

By (11), and as shown in Figure 1-b, the feasible region for (12) is \( [0, k_1] \cup [k_2, \infty) \), and the maximal value of (12) is achieved at \( k_2 \). Hence, under A1 the optimal choice of a regulated monopoly is given by

\[
(K, L) = (k_2, L^*(k_2)).
\]

Now consider the monopolist’s behavior under A2. A comparison of (11) with (9) leads to

\[
\pi(K) = \pi(K, L(K)) = \begin{cases} 
(s-r)K & \text{if } k_1 \leq K \leq k_2 \\
\pi^*(k) & \text{if } K < k_1 \text{ or } K > k_2.
\end{cases}
\]

and
(15) \[ L(K) = \begin{cases} L(K), & \text{or } L(K)_{+} \quad \text{if } k_1 \leq K \leq k_2 \\ L^*(K) & \text{if } K < k_1 \text{ or } K > k_2 \end{cases} \]

where \( L(K) \) and \( L(K)_{+} \) are the two solutions\(^2\) of \( \pi(K, L) = (s-r)K \) for each \( K \in [k_1, k_2] \).

Under A2 the monopoly will solve \( \max \{ \pi(K) \mid K \geq 0 \} \) in the first stage. By (14) or Figure 1-a, \( \max \{ \pi(K) \mid K \geq 0 \} = \pi(k_2) \). In other words, under A2 the optimal choice of a regulated monopoly is the same as that given in (13).

Since \( k_0 \) is its unique maximum, the strict concavity of \( \pi^* \) and \( k_2 > k_0 \) lead to

\[ \pi^*(k_2)' = MRq_K - r < 0. \]

Substituting \( MR = w/q_L \) into the above expression, one gets \( q_K/q_L < r/w \), which is the A-J effect given by (7). This completes our elementary proof of the A-J effects.

4. The A-J Effects under Uncertainty

Following Peles and Stein (1976), let the inverse demand \( p(q, u) \) be affected by a random variable, \( u \), and let the monopoly be risk-neutral. The profit function now becomes \( \pi(K, L; u) = p(q(K, L), u)q(K, L) - rK - wL \). In order to evaluate whether a regulated monopoly is cost-efficient, we first provide characterizations of the unregulated monopoly’s behavior and of the cost-min condition under uncertainty, which have not yet been provided in the literature.

For each \( K \) and each observed \( u \), the unregulated monopoly’s labor choice in the second stage and its profit as functions of \( (K, u) \) are

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\(^2\) By continuity and by the above definitions, one has

\[ \lim_{K \to k_i} L(K)_{-} = \lim_{K \to k_i} L(K)_{+} = L^*(k_i) \]

holds for \( i = 1, \) and 2.
\[(16) \quad L^*(K, u) = \text{Arg-Max}\{ \pi(K, L; u) \mid L \geq 0 \}, \text{ and} \]
\[\pi^*(K, u) = \pi(K, L^*(K, u); u).\]

Note that \(L^*(K, u)\) is defined by \(\pi_L(K, L; u) = MR q_L - w = 0\). By arguments similar to (10), one has \(\frac{\partial^2 \pi^*}{\partial K^2} < 0\). Hence, \(\pi^*(K, u)\) is strictly concave in \(K\). Let
\[(17) \quad \tilde{\pi}(K) = E\pi^*(K, u) = \int \pi^*(K,u)f(u)du\]
denote the expectation of the unconstrained profits, where \(f(u)\) is the probability density function of \(u\). Then \(\tilde{\pi}(K)\) is strictly concave because \(\frac{\partial^2 \pi^*}{\partial K^2} < 0\).

Let \(K_0\) denote the unregulated optimal choice of capital given by \(\tilde{\pi}(K)' = 0\), and note the (expected) optimal choice of labor is given by \(\tilde{L} = E[L^*] = \int L^*(K_0, u)f(u)du\). Using the envelope theorem and \(MR = w/q_L\), \(\tilde{\pi}(K)' = 0\) becomes
\[\tilde{\pi}(K)' = \int \frac{\partial \pi^*}{\partial K}f(u)du = \int (MRq_L - r)f(u)du = w\int (q_K/q_L)f(u)du - r = 0.\]

The discussion above is summarized in the following Proposition 2:

**Proposition 2:** Under A0, the unregulated optimal choice \(K_0\) and \(L^*(K_0, u)\) satisfy:
\[(18) \quad MR(K_0, L; u) q_L = w, \quad \text{and} \quad E[\frac{q_K}{q_L}] = \frac{r}{w}.\]

In other words, the unregulated monopoly will maximize its expected profits by equating its marginal revenue product of labor to the wage rate, \(w\), for each \(u\) and by equating its expected rate of technical substitution to the input price ratio.\(^3\)

Now, consider the cost-min condition under uncertainty. To stay as close to our monopoly analysis as possible, let the cost-min problem be defined as:

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\(^3\) Peles and Stein (1976) did not provide such an interpretation on the cost efficiency, their equation (9) is the first step to derive (18).
Min\{ rK + wL \mid K, L ≥ 0, \text{ and } q(K, L) ≥ Q(p, u) \},

where Q is the monopoly’s demand function, whose inverse is p(q, u). Assume the price is fixed at some given p. Let L(K, Q(u)) be the firm’s optimal labor choice in the second stage for each K and u, which is defined by q(K, L) = Q(p, u). Then, one has dL/dK = - qK/qL < 0. The minimal cost as a function of (K, u) and its expectation are given by

C(K, u) = rK + wL(K, Q(u)), \text{ and } \bar{c}(K) = \int C(K, u)f(u)du.

Using the chain rule and dL/dK = - qK/qL, \bar{c}(K)' = 0 becomes

\bar{c}(K)' = r - w \int (qK/qL)f(u)du = 0,

which leads to the cost-min condition summarized as Proposition 3 below:

Proposition 3: Under standard assumptions about the production function, the optimal condition for cost minimization under uncertainty is given by

E[qK/qL] = \frac{r}{w}.

It is clear that the π-max condition (18) implies the cost-min condition (22). Therefore, the unregulated monopoly’s output is cost-efficient.

Let us now turn to the behavior of a regulated monopoly. A1 and A2 correspond to the two types of regulations: under A1, the expected rate of return is regulated (type I); under A2, the rate of return in every state of nature is regulated (type II). Future welfare analysis and empirical studies are necessary to determine which type of regulation is socially more efficient and which type of regulation is used in practice. In the rest of this section, we characterize the regulated monopoly’s behavior under A1 and A2, focusing in particular on whether it is cost-efficient.

First, consider the monopoly’s behavior under A1. In this case, the monopoly’s second
stage labor choice, $L^*(K, u)$, its maximal profits, $\pi^*(K, u)$, and its expected profit, $\bar{\pi}(K)$, are the same as in (16-17). Given an effective rate, $s$, there exist $K_1 < K_2$ satisfying $K_1 < K_0 < K_2$ and

$$\bar{\pi}(K) > (s-r)K \text{ if } K_1 < K < K_2; \text{ and } \leq (s-r)K \text{ if } K \leq K_1 \text{ or } \geq K_2,$$

where $K_0$ is the unconstrained maximal solution given by $\bar{\pi}(K)' = 0$.

As an example, consider the case with two states of nature as illustrated in Figure 2. The top (bottom) curve is the unconstrained profit with high (low) demand $\pi^*(K, u_H)$ ($\pi^*(K, u_L)$), and the middle one, a convex combination of the other two, is the expected profit, $\bar{\pi}(K) = E\pi(K)$. The feasible areas for $\text{Max}\{ \bar{\pi}(K) \big| K \geq 0, \bar{\pi}(K) \leq (s-r)K \}$ are marked as the two thick pieces of $E\pi(K)$. The constrained maximum is clearly $K_2$. By using the same arguments as at the end of Section 3, or by examining Figure 2, we obtain

$$\text{(24)} \quad MR(K_2, L; u) q_L = w, \quad \text{and } E\left[q_L \right] < \frac{r}{w},$$

which lead to the following A-J effects under uncertainty:

(Figure 2 about here)

**Proposition 4:** Under $A_0$ and $A_1$, a regulated monopoly uses more capital than an unregulated monopoly, and its expected rate of technical substitution (defined by $-dL/dK$) is less than that required for cost minimization.

Since (22) is violated, a regulated monopoly’s production is not cost-efficient. Therefore, the A-J effects hold under uncertainty for a regulated monopoly under $A_1$.

Finally, consider the monopoly’s behavior under $A_2$. For each given $(K, u)$ in the second stage, the monopoly’s labor choice and its maximal profit as functions of $(K, u)$ are given by

$$\text{(25)} \quad L(K, u) = \text{Arg-Max}\{ \pi(K, L; u) \big| L \geq 0, \pi(K, L; u) \leq (s-r)K \}, \quad \text{and}$$
\[ \pi(K, u) = \pi(K, L(K, u); u); \]

and its expected profit as a function of \( K \) is

\[
(26) \quad \bar{\pi}(K) = \mathbb{E}[\pi(K, u)] = \int \pi(K, u) f(u) du.
\]

The monopoly’s choice, \( K \), in the first stage is the solution of \( \max \{ \bar{\pi}(K) \mid K \geq 0 \} \). The previous A-J effects or anti-AJ effects were incorrectly obtained by treating \( K \) as the solution of \( \bar{\pi}(K)' = 0 \), because \( \bar{\pi}(K)' \) in general does not exist at \( K \). The appendix shows how the anti-AJ effects were incorrectly derived in Peles and Stein (1976 and 1979), and the remaining part of this section illustrates the nonexistence of \( \bar{\pi}(K)' \).

Recall that the constrained profit function, \( \pi(K) \), under certainty has two kinks (see (11) or Figure 1-a). With any finite number of states, kinks will clearly existence on the curve \( \bar{\pi}(K) \) because it is a finite convex combination of kinked curves. To see this geometrically, consider the two states case of Figure 2, which is reproduced in Figure 3. The constraint is effective in both states, i.e., the line \( \pi = (s-r)K \) cuts both the high and low demand profit curves. Denote its intersection points with \( \pi^*(K, u_H) \) as \( K_{1H} < K_{2H} \), and those with \( \pi^*(K, u_L) \) as \( K_{1L} < K_{2L} \). It is straightforward to see, as shown in Figure 3-a, that \( \bar{\pi}(K) = \mathbb{E}[\pi(K)] \) is below both \( \pi = (s-r)K \) and the unconstrained profit \( \bar{\pi}(K) = \mathbb{E}[\pi(K)] \). More precisely, one has

(Figure 3 about here)

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4 With a continuum of states, the kinks might be smoothed out. Hence, \( \pi(K)' \) could exist with a continuum of states under some technical conditions. However, such conditions have not been provided in the previous studies, and they are beyond the interests of this note.
\[ \bar{\pi}(K) = E\pi(K) = \begin{cases} = \bar{\pi}(K) & \text{if } K \leq K_{1H} \text{ or } K \geq K_{2H} \\ < \bar{\pi}(K) & \text{if } K \in [K_{1H}; K_{1L}] \cup [K_{2L}; K_{2H}] \\ = (s-r)K & \text{if } K \in [K_{1L}; K_{2L}] \end{cases} \]

which is clearly not differentiable.

Since the maximum, \( K_0 \), of \( \bar{\pi}(K) \) is in general one of its kink points, it is impossible to find robust characterizations for the A-J or anti-AJ effects at \( K_0 \). Given \( K_0 \) as the unique maximum of \( \bar{\pi}(K) \) or the unregulated capital choice, there exists an A-J (anti-AJ) effect at \( K_0 \) if \( K > K_0 \) (\( K < K_0 \)). Part (a) of Figure 3 illustrates an A-J effect at a kink point, \( K = K_{2L} \), and part (c) illustrates an anti-AJ effect at a kink point, \( K \). With some luck, one might have an A-J effect (as shown in part (b)) or an anti-AJ effect at a differentiable point \( K \). This discussion is summarized in Proposition 55(5,5),(993,991) given below:

**Proposition 5:** Under A0 and A2, a regulated monopoly has an irregular maximization problem in the first stage, and there exists no robust characterization of A-J or anti-AJ effects at its optimal choice.

As already discussed, A2 is equivalent to imposing rate of return regulation in every state of nature. Although the firm bears the costs of risk, type II regulation forbids the firm from harvesting any of the benefits. Therefore, type II regulation seems to be socially less efficient than regulating the expected rate of return, as under A1. Whether this is true and whether A2 is ever used in practice needs to be investigated in future studies.

**5. Discussions and Conclusions**

This paper has provided a simple illustration of A-J effects under certainty. It has characterized the difference between type I (expected ror) and type II (ror in every states)
regulations under uncertainty. There are AJ effects under type I regulation, but no general predictions can be made under type II regulation. It will be useful to investigate which type of regulation is socially more efficient and which type is used in practice in future studies.

This paper has also discovered that all of the previous results of ror studies were incorrectly obtained. Indeed, Chang (1991) observes the irregularity in Peles and Stein (1976), their response (1979) to Rau (1979), and in Das (1980), but fails to get to the bottom of the problem: there are two types of regulations, and expected profit functions under type II regulation have been incorrectly assumed to be differentiable.

Although the anti-AJ effects in Peles and Stein (1976) were incorrectly obtained, future work should build on their two-stage model rather than Das’ simultaneous model (1980), because the distinction between long-term and short-term input choices is fundamental to the utility industry. New insights will be obtained by adding to the Peles-Stein model each of the following features: multiple short-term inputs (Courville, 1974), cost uncertainty (Pint, 1992), dynamics (Gilbert and Newbery, 1994), peak-load pricing, and the incentive mechanisms developed during the past two decades.

In conclusion, the importance of the recent energy crisis provides a challenge for economists to provide better policy recommendations based on a better understanding of a regulated monopoly’s behavior. Further studies will be necessary before economists can say anything that might help in resolving the crisis, but the author hopes that these problems will attract the attention of more scholars.
Appendix

This appendix points out two areas in which previous studies have made incorrect derivations. For each fixed $K$, partition the states into $S = S(K) = \{ u \mid \bar{\pi}(K, u) < (s-r)K \}$, and $T = T(K) = \{ u \mid \bar{\pi}(K, u) \geq (s-r)K \}$, and let $Pr[u \in S] = \int_{u \in S} f(u)du$, and $Pr[u \in T] = \int_{u \in T} f(u)du$.

Then, $Pr[u \in S] + Pr[u \in T] = 1$, and $\bar{\pi}(K)$ becomes (Peles and Stein, 1979):

$$\bar{\pi}(K) = \int_{u \in S} \pi_\ast(K, u)f(u)du + (s-r)K Pr[u \in T].$$

In both Rau (1979, p191) and Das (1980, p456), $S$ and $T$ are given as closed intervals.

All derivations so far are correct. At this point, previous studies made two incorrect assumptions: that $dPr[u \in S]/dK$ exists, and $dPr[u \in T]/dK$ could be ignored. Since $\bar{\pi}(K)'$ does not exist at its kinks, $dPr[u \in S]/dK$ clearly will not exist (otherwise, $\bar{\pi}(K)'$ will always exist).
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Figure 1. (a) The constrained profit is not differentiable; (b) feasible region is disconnected.

Figure 2. The unconstrained expected profit curve and the feasible region.
Figure 3. (a) AJ Effect at $K = K_2 > K_0$, $E\pi(K)'$ does not exist; (b) AJ Effect at $K > K_0$, $E\pi(K)' = 0$; (c) Anti-AJ Effect at $K = K_2 < K_0$, $E\pi(K)'$ does not exist.