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Efficiency of Trade Equilibria in the World Oil Market

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1. Introduction

This paper formulates a trading game in a productive natural resource like oil. Though simple, the model developed here will highlight the role of binding long-term agreements and will show that in their absence equilibria are inefficient. Clifford and Crawford (1987) have recently emphasized this point in the context of trade in natural resources. A related issue to which I draw attention here is that of the dynamic inconsistency or "subgame imperfection" of precommitment equilibria.

The construct considers interaction between two players: an oil-producing (or supplier) bloc (S) and an oil-consuming bloc (C). The model is assumed to be fully deterministic and its structure, including the values of all the parameters, common knowledge. Any issues associated with information acquisition and strategic signalling are therefore circumvented here.

The game is described by the following order of play and decision nodes: (i) S announces an oil price for next period; (ii) equipped with a faultless forecast of next period's oil price (equal to S's announcement if an enforceable price agreement obtains) C chooses - irreversibly - the next-period "vintage" (i.e., oil requirement) structure of its stock of productive capital on the basis of this forecast; (iii) S quotes a spot price for its oil (equal to the preannounced price if a binding agreement is in force); and (iv) C determines its oil purchases. Trade and production then take place, the players collect their payoffs, and the game ends.

In what follows C's optimization exercise is studied first in order to derive its "optimal response" (section 2). Throughout this paper, C is assumed to exhibit price-taking behaviour. It is then assumed that S endogenizes this response when formulating its pricing strategy. That is, S behaves as a Stackelberg leader in the spirit of Newbery's (1981) and Ulph and Folie's (1981) dominant resource supplier. It will transpire, however, that S is only able to display effective "leadership" to the extent that it is able to precommit itself to supply the resource at a given price in the future. I characterize the precommitment equilibrium in section 3. If, however, S has no recourse to a commitment mechanism, the appropriate equilibrium concept is that of a sequential, or perfect, equilibrium. Section 4 describes this equilibrium, and demonstrates that in the present context it is formally equivalent to the equilibrium that results if S takes C's demand structure for oil as given (I term the latter a Cournot-Nash equilibrium). The precommitment and Nash-Cournot (or sequential) equilibria, and in particular their respective welfare properties, are compared in section 5. Section 6 considers a variant of the model that meets one criticism of the analysis in the preceding sections. Section 7 contains some concluding remarks.

2. The Consumer Bloc's Response

Behaviourally, C is modelled as a single entity that takes the oil price as given. For the present, I assume that C has no oil of its own, and must therefore import all its requirements (I relax this assumption in section 6). C is assumed to possess a stock of productive capital of magnitude K_0, measured in physical units. In the initial state, a unit of capital must be combined with α units of oil in order to be productive. Thus if K', $0 < K' \leq K_0$, is productive, C's oil import bill is $p\alpha K'$, where p denotes the unit price - in terms of manufacturing output - at which oil is traded. Henceforth units of measurement are chosen such that $K_0 = \alpha = 1$. The associated manufacturing output is given by F(K'), where F(.) is assumed to display

(A.1) F(.) is twice-continuously differentiable with $F'(K') > 0$, $F''(K') < 0$, $0 < K' \leq 1$, and optionally the Inada condition $\lim_{K' \to 0} F'(K') = +\infty$.

C's manufacturing technology is thus assumed to exhibit diminishing returns.

However, before the resource is actually traded and used in the productive process, C has the option of expending an amount $A(\lambda)$ - measured in units of (future) manufacturing output - on enhancing the quality of a proportion λ, $0 \leq \lambda \leq 1$, of its capital stock. I shall suppose that the "improvement" comes in the dramatic form of releasing λ units of capital from any dependence on oil whatsoever for productivity. The remaining $(1-\lambda)$ units will subsequently be labelled as being of "inferior vintage". The choice of λ thus captures the extent to which substitution programmes are implemented, resource-saving devices introduced, and the like. The function A(.) is assumed to have the following properties:

(A.2) $A(.)$ is twice-continuously differentiable with $A'(\delta)>0$, $A''(\delta)>0$, $0 < \delta < 1$; $A(0)=A'(0)=0$ and $\lim_{\delta \to 1} A'(\delta)=+\infty$.

The cost of reducing C's dependence on oil thus rises at the margin, and a complete release is infinitely costly. Note that the possibility of fixed costs has been assumed away here.[1]

C's optimization problem at decision node (ii) of the game is now stated very simply as

(1) $\underset{\delta,\ R}{\text{maximize}} \quad F(\delta+R) - pR - A(\delta)$, subject to

(2) $0 \leq R \leq (1-\delta)$ and

(3) $0 \leq \delta \leq 1$,

where R is the volume of oil imported, and p is taken as exogenously given. Criterion (1) says simply that C seeks to maximize (an increasing function of) net manufacturing output, defined as gross output less the real import bill and real expenditure on substitution programmes. Constraint (2) captures the assumption that any purchases of oil exceeding the requirements of "inferior vintage" capital (of which there are $(1-\delta)$ units) are worthless, and therefore not concluded if $p > 0$.[2] The non-negativity restriction on R, as well as constraint (3), will prove redundant under (A.1) and (A.2). Note that C is modelled as choosing δ and R simultaneously. At this node of the game, the solution for R may be interpreted as "planned imports"; by virtue of the perfect foresight assumption these will always coincide with realized purchases.

Let $u, w \geq 0$ denote Kuhn-Tucker multipliers, such that $uR = 0$ and $w\{(1-\Delta) - R\} = 0$. Constraint (3) is always satisfied under (A.2). C's optimality conditions are given by

(4) $F'(\Delta+R) - A'(\Delta) = w$ and

(5) $F'(\Delta+R) - p = w - u$,

where $u > 0$ implies $R = 0$ and $w > 0$ implies $R = (1-\Delta)$. From (4) and (5)

(6) $p = A'(\Delta)$

when $R > 0$. Under (A.2), this gives a unique (interior) solution for Δ, independently of whether or not some inferior vintage capital is to lie idle. Write this solution as $\Delta = B(p)$. As expected, $B' = 1/A'' > 0$: the higher the oil price forecast, the greater the expenditure on substitution/conservation programmes. Substituting back into (5) yields that

(5') $F'(B(p)+R) - p = w$.

Thus if $0 < p \leq F'(1)$, $R = (1-\Delta)$. Over this price range, the price response of planned imports is given by

$$\frac{dR}{dp} = \frac{dR}{d\Delta}\frac{d\Delta}{dp} = -\frac{1}{A''} .$$

If, however, $p^c > p > F'(1)$, then R is determined such that

(5") $F'(B(p)+R) = p$;

where it is assumed for the moment that (in order to avoid losing sales) S sets p below that level (p^c say) at which demand would choke. Over this price range, the resource demand (that is, planned import) function has slope

$$\frac{dR}{dp} = \frac{1 - F''B'}{F''} = \frac{A'' - F''}{A''F''} .$$

To sum up: any price less than or equal to F'(1) always induces full capacity usage. However, any price above F'(1) means that certain units of inferior vintage capital will lie idle because oil is relatively expensive. Figure 1 illustrates C's *ex ante* or "long-run" oil demand function (that is, the demand function prior to the irreversible choice of vintage structure). The *ex ante* oil demand function is denoted R*(p).

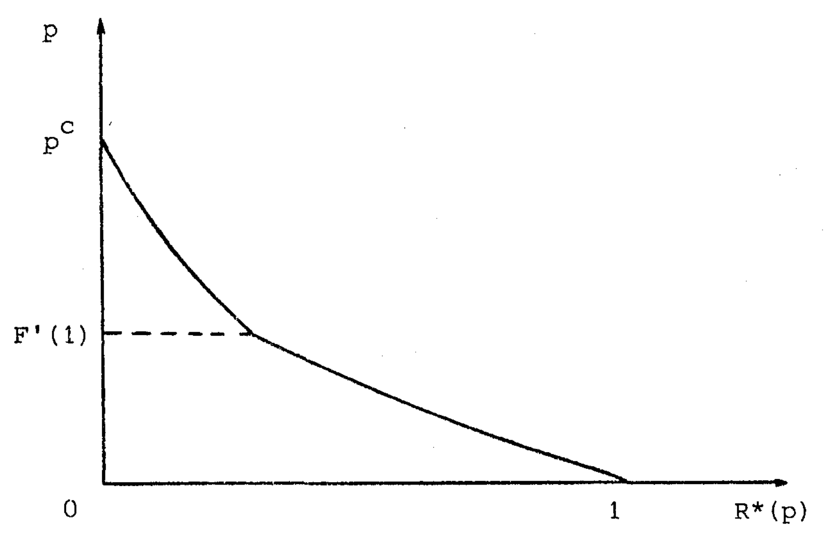

FIGURE 1

Finally, it is worth noting that C's value function (that is, the maximum attainable value of (1)), say V(p), is everywhere declining in p. This follows simply from Hotelling's lemma (see Varian, 1978, p. 31). For $p^c > p > F'(1)$,

$$\frac{d}{dp}\left\{ F(\Delta+R^*) - pR^* - A(\Delta) \right\}$$

$$= F'(\Delta+R^*)\left\{ \frac{d\Delta}{dp} + \frac{dR^*}{dp} \right\} - R^* - p\,\frac{dR^*}{dp} - A'(\Delta)\,\frac{d\Delta}{dp}$$

$$= -\,R^* < 0$$

since at the optimal solution $F' = p = A'$. Further, for $0 < p \leq F'(1)$, $R^* = (1-\Delta)$ and

$$\frac{d}{dp}\left\{ F(1) - p(1-\Delta) - A(\Delta) \right\} = -\,(1-\Delta) + [\,p - A'(\Delta)\,]\,\frac{d\Delta}{dp}$$

$$= -\,(1-\Delta) < 0$$

recalling that $p = A'$ at the optimal solution. Thus $V'(p) < 0$, as asserted. As is intuitive, C is unambiguously worse off the higher the oil price.

3. The Stackelberg Precommitment Equilibrium (SPE)

I begin by assuming that S has access to a device (enforceable long-term contracts, for example) that makes its price announcement a credible one. In any case, the optimization problem considered in this section characterizes S's best move at decision node (i). Conceptually, S gauges C's response - in accordance with the analysis of the preceding section - under every conceivable price announcement that it could make, and "leads" by choosing p to maximize the static profit function

(7) $\pi = pR - \lambda(R)$, subject to

(8a) $p = F'(B(p)+R)$ for $F'(1) < p < p^c$

(8b) $R = \{1 - B(p)\}$ for $0 < p \leq F'(1)$.

where the cost function $\lambda(.)$ displays $\lambda'(R)>0$, $\lambda''(R)>0$. Note that the optimization problem does not explicitly take an exhaustion constraint into account. This implies that S considers its reserves of oil to be "large", so that the user cost of the resource is very low. Alternatively, the cost function $\lambda(.)$ may be thought of as already incorporating the user cost of the resource.[3]

In general, the solution to the optimization problem described by (7) and (8) may lie on either segment of the demand function. If the optimal price announcement exceeds $F'(1)$, it will satisfy (8a) and

$$(9) \quad R + \{ p - \lambda'(R) \}\frac{(A''-F'')}{A''F''} = 0.$$

If there is no solution that simultaneously satisfies (8a) and (9), then S's optimal price announcement lies on the other segment of the *ex ante* demand curve and is no larger than $F'(1)$. In this case, the solution is given by (8b) and

$$(10) \quad R - \{ p - \lambda'(R)\} \frac{1}{A''} = 0.$$

I shall use (9) and (10) again later. For the moment define the profit function as

$$\pi(p) = pR^*(p) - \lambda(R^*(p))$$

where $R^*(p)$ is the implicit solution to $F'(B(p)+R) = p$, $F'(1) < p \leq p^c$, and $R^*(p) = 1 - B(p)$, $0 < p < F'(1)$. It is noteworthy that the profit function is continuous but has a kink at $F'(1)$, since

$$\lim_{p \to F'(1)^{+}} \pi(p) = \lim_{p \to F'(1)^{-}} \pi(p).$$

Figure 2 illustrates two possible shapes for the profit function. Panel (a) depicts a case where the solution is given by (8b) and (10), and panel (b) a case where (8a) and (9) characterize the solution. Naturally the second-order condition requires the profit function to be concave at the maximum point. The maximum point may also occur at the kink point.

At this point, it is easy to see that the SPE is not a subgame perfect, or sequential, equilibrium. This is so because once C is "locked in" with regard to its choice of technology (that is, once C has irreversibly committed itself to a particular value of λ at decision node (ii)), C's elasticity of demand for oil is lowered, and S typically has an incentive to raise the price above the level originally announced. That this is so will become apparent from the analysis in the sections that follow. As a consequence, unless S is truly bound to abide by its original price announcement (and C is truly confident thereof), the SPE price is not a credible one.

4. The Cournot-Nash Equilibrium (CNE) or Stackelberg Sequential Equilibrium (SSE)

One interpretation of the optimization problem and solution concept considered in this section is that C has already chosen λ and planned imports on the basis of S's original price announcement, but that S is now given the opportunity to revise the price at which trade is to take place. That is, this section characterizes S's best move at decision node (iii). An

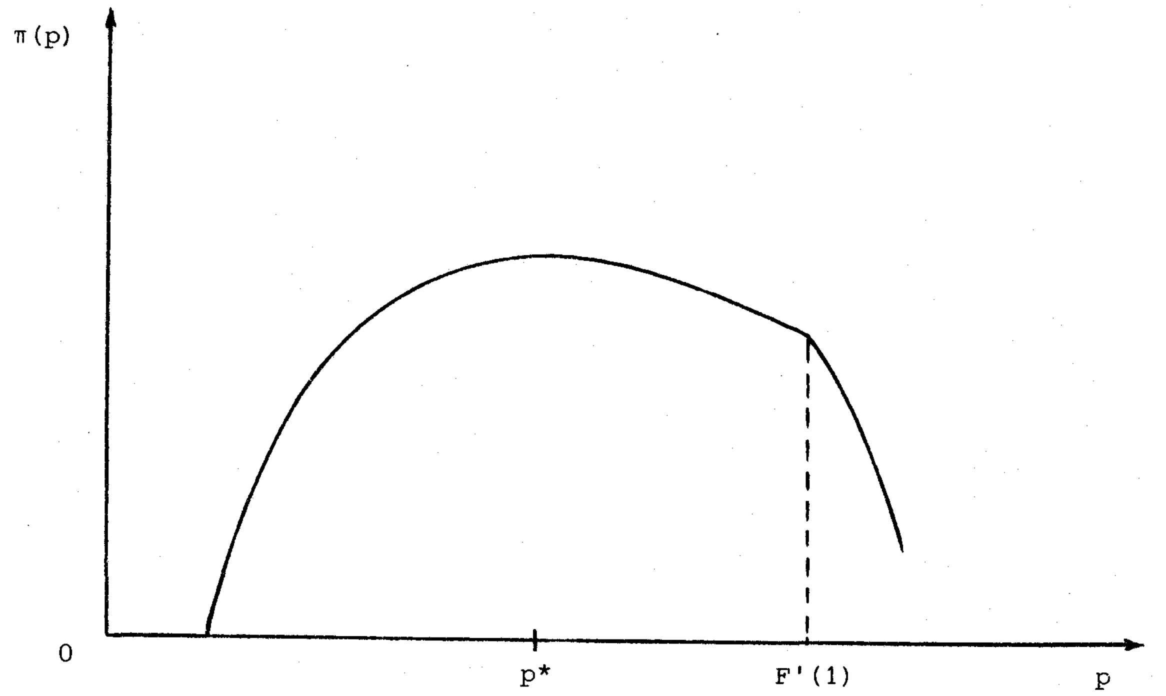

FIGURE 2(a)

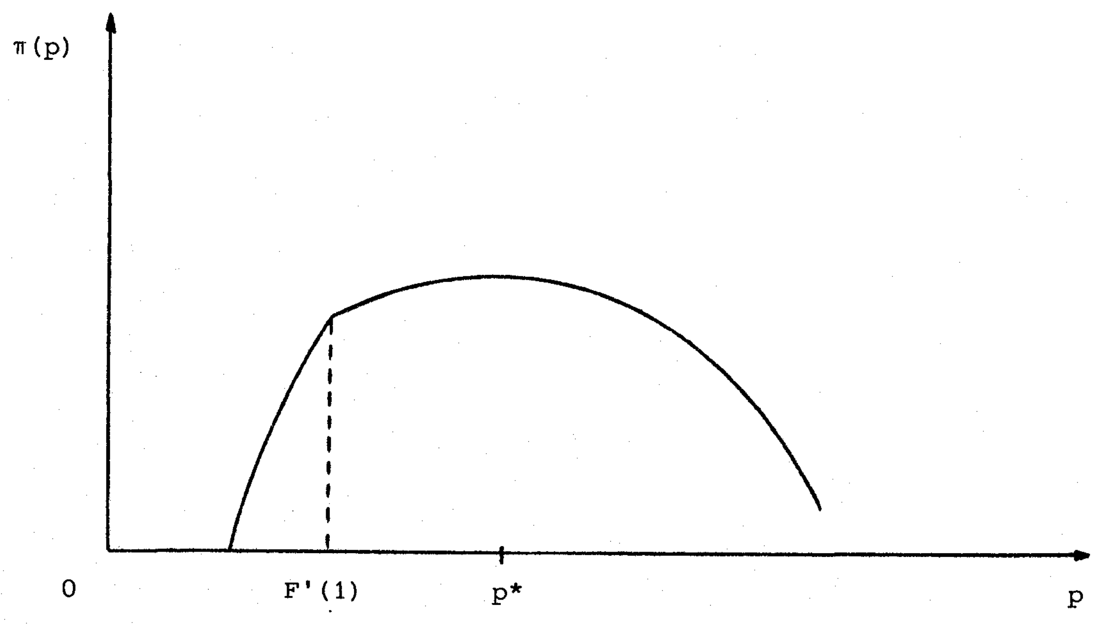

FIGURE 2(b)

alternative interpretation of the current formulation is that, at decision node (i), S behaves as a Cournot-Nash player in the following sense: S forms a perfect forecast of C's <u>ex post</u> demand for the resource and announces an oil price to maximize profits, <u>given</u> $\acute{\Delta}$. In other words, S emphatically fails to recognize the effect of its price announcement on C's choice of $\acute{\Delta}$.

In either case, S chooses p to maximize

(7) $pR - \lambda(R)$, subject now to

(11a) $p = F'(\acute{\Delta}+R)$ for $F'(1) < p < p^c$

(11b) $R = (1-\acute{\Delta})$ for $0 < p \leq F'(1)$

treating $\acute{\Delta}$ as given. It is immediately apparent that the optimal price in this case will never be below F'(1). This is because, if $\acute{\Delta}$ is constant, the elasticity of demand is zero below a price of F'(1); sales are invariant to price over this range, so S trivially prefers a higher oil price to a lower one. Figure 3 depicts C's <u>ex post</u> (or "short-run") oil demand function. Let R(p) denote this demand function. (Note that $R(p) = R^*(p)$ when $\acute{\Delta} = B(p)$. (7) is thus maximized subject to (11a).) Assuming that a maximizing solution exists, it must satisfy

(12) $R + \left[\frac{p - \lambda'(R)}{F''} \right] = 0$

(where R is the implicit solution to (11a)), and $\acute{\Delta} = B(p)$ in equilibrium (recall that C is assumed always to form an exact forecast of the oil price). Note that the elasticity of demand at the maximum point must exceed unity in absolute value.

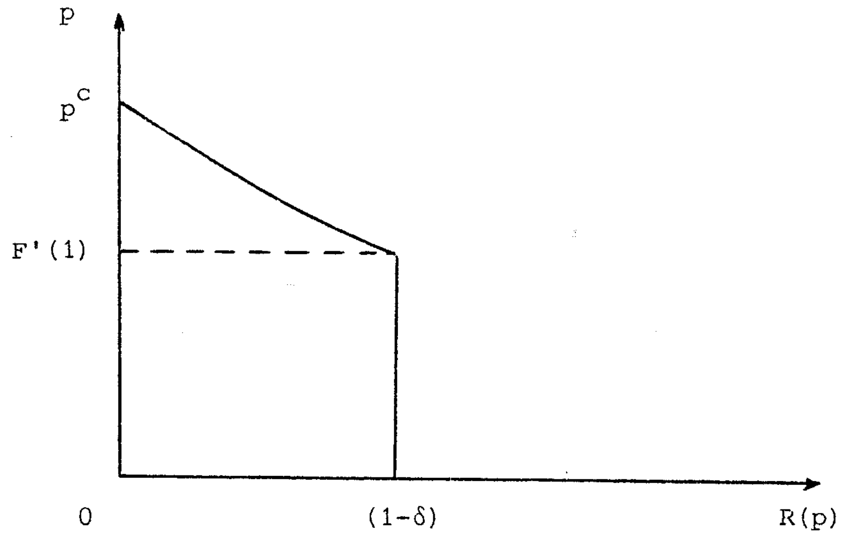

FIGURE 3

It is worth stressing the point that in this model, the CNE and the SSE are identical. Conceptually, the SSE differs from the SPE only in that S has no recourse to a precommitment mechanism in the former case. As a result, the only credible price announcement (equal by assumption to the price that C actually forecasts) is that which S would choose once Δ had already been irreversibly chosen. But this is precisely the premise on which the derivation of the CNE price is based. In the absence of a commitment mechanism, therefore, C correctly forecasts the CNE price - regardless of S's announcement - and chooses Δ accordingly. Once Δ is (irreversibly) fixed, S's optimal strategy is in fact to set the CNE price. The CNE is thus subgame perfect, and C's forecast is realized, as required.

5. A Comparison of the SPE and the CNE

In this section I show that under certain fairly weak conditions, the CNE oil price (p^N) exceeds the SPE price (p^*). If this is the case, both C and S are easily shown to be worse off in the CNE than in the SPE. That is, the CNE is Pareto inferior to the SPE. However, even in cases where p^N and p^* cannot be unambiguously ranked, it can still be demonstrated very simply that the CNE is Pareto inefficient.

I begin by discussing the conditions required for p^N to exceed p^*. Note first that if the SPE price is given by the simultaneous solution of (10) and (8b), then it is trivially the case that $p^* < p^N$. Next, suppose that the SPE is given by (9) and (8a). Recall that for an interior solution $F'(1) < p^N < p^c$, the CNE price is given by

$$R(p^N) + \frac{\{ p^N - \lambda'(R(p^N)) \}}{F''(B(p^N)+R(p^N))} = 0$$

(Recall that $R(p^N)$ is the implicit solution to (11a), for $\bar{A}$ fixed at the value $B(p^N)$.) Now because for $F'(1) < p < p^c$,

$$\frac{A''(B(p)) - F''(B(p)+R(p))}{A''(B(p))} > 1 ,$$

it follows that

$$R(p^N) + \{ p^N - \lambda'(R(p^N)) \} \frac{\{ A''(B(p^N)) - F''(B(p^N)+R(p^N)) \}}{F''(B(p^N)+R(p^N)) \ A''(B(p^N)} < 0.$$

Thus $\pi'(p) < 0$ at (and, by continuity, in a neighbourhood of) p^N. A minimal sufficiency condition for $p^N > p^*$ would therefore appear to be that $\pi'(p) \geq 0$, $F'(1) < p < p^*$. A stronger sufficiency condition is that $\pi''(p) \leq 0$, $F'(1) < p < p^*$; that is, that the profit function is concave between the kink point and its maximum point. To the right of the kink point, the profit function has slope

$$(13) \quad \pi'(p) = R + \{ p - \lambda'(R) \} \frac{\{ A''(\bar{A}) - F''(\bar{A}+R) \}}{A''(\bar{A}) \ F''(\bar{A}+R)}$$

where $\hat{\lambda} = B(p)$ and $F'(\hat{\lambda}+R) = p$. Thus (omitting arguments)

$$(14)\quad \pi''(p) = \frac{(A''-F'')}{A''F''}\left\{ 2 - \frac{\lambda''(A''-F'')}{A''F''} \right\} + \{ p - \lambda' \}\frac{d}{dp}\frac{(A''-F'')}{A''F''}.$$

The first term on the right-hand side of (14) is negative. Concavity thus requires the demand function to be concave or only mildly convex to the origin (so long as price exceeds marginal cost); that is,

$$\frac{d}{dp}\frac{(A''-F'')}{A''F''} = \frac{A'''}{(A'')^3} - \frac{F'''}{(F'')^3}$$

should not be a "large" positive number, $F'(1) < p < p^*$.

Panel (a) of Figure 4 depicts a case where the minimal sufficiency condition $\pi'(p) \leq 0$, $F'(1) \leq p \leq p^*$, is satisfied. Panel (b) depicts a case where the profit function is everywhere concave, $F'(1) < p < p^*$. It is clear that in both these cases, $p^N > p^*$. However, panel (c) of Figure 4 illustrates a case where neither of the above conditions is satisfied, and the possibility arises that $p^N < p^*$.

To sum up: there is a strong <u>prima facie</u> case for believing that p^* is likely to exceed p^N. If this is the case, C is worse off in the CNE than in the SPE (recall that C's value function V(p) is everywhere decreasing). Naturally S is also worse off in the CNE, since p^N is not a stationary point (recall that $\pi'(p^N) < 0$). Thus if $p^* < p^N$, the CNE is Pareto inferior to the SPE.

However, even if $p^* > p^N$, it is still immediate that the CNE is Pareto inefficient. To see this, consider the effects of a marginal reduction in p at p^N. Since $\pi'(p^N) < 0$, the reduction

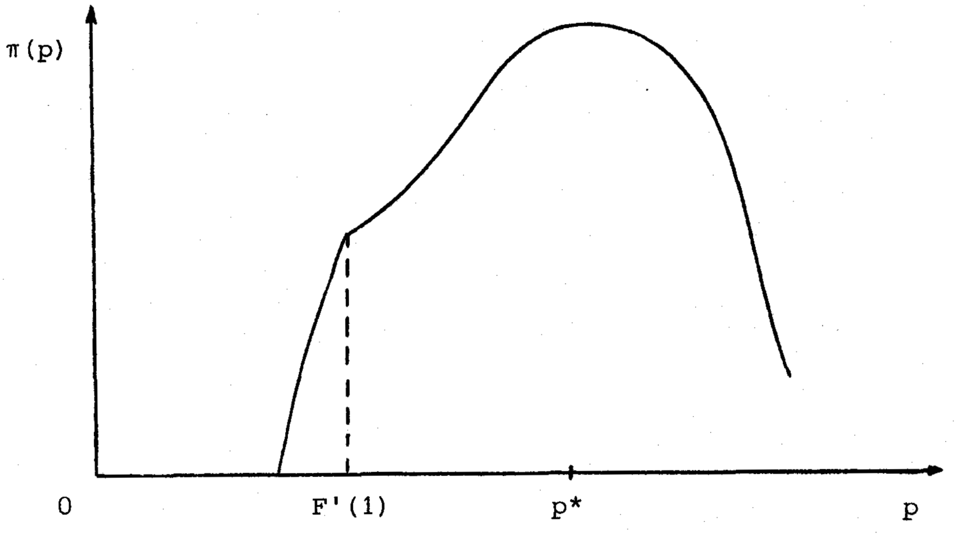

FIGURE 4(a)

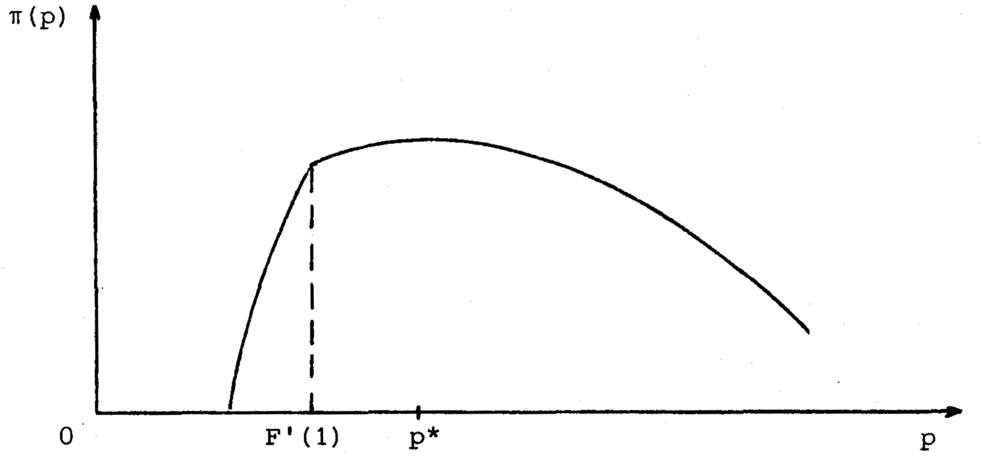

FIGURE 4(b)

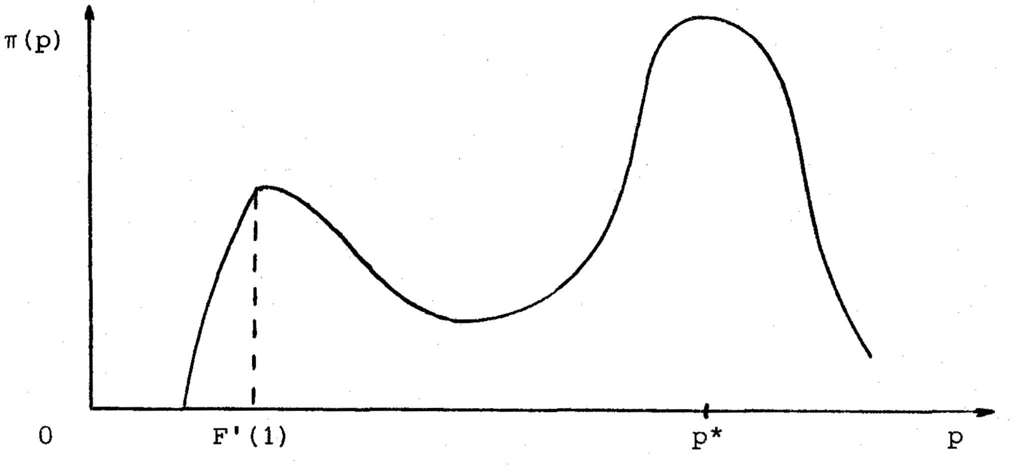

FIGURE 4(c)

makes S better off. Likewise, because $V'(p) < 0$ everywhere, C is better off the lower is p.

6. A Variant of the Model

One unattractive feature of the model is that demand is required to be elastic at the SPE and CNE prices. This may be an eminently reasonable requirement to impose on the *ex ante* (or "long-run" demand elasticity. However, the *ex post* (or "short-run") elasticity of demand for most resources cannot in general be expected to exceed unity. For example, available estimates of short-run elasticities for energy and individual energy carriers, including crude oil and petroleum products, are consistently below unity.[4]

In the model considered here, it is clear that if both the *ex ante* and *ex post* elasticities lie everywhere below unity in absolute value, the optimal strategy for S in both the SPE and the CNE is to set p marginally below the choke price p^c and supply a negligible amount of oil. To make such a scenario slightly more palatable, I modify the model as follows: C is now assumed to have domestic oil stocks, exploitable at constant unit cost $\bar{p} < p^c$ (recall that $p^c \leq +\infty$ is the solution to $F'(B(p)) = p$. Then in the case where both the *ex post* and the *ex ante* elasticities are less than unity below $\bar{p}$, $\bar{p}$ is both the SPE price and the CNE price.[5]

One interesting case that strengthens the argument of the preceding section, however, arises where the *ex post* elasticity is everywhere less than unity but the *ex ante* elasticity exceeds unity. I illustrate the point through the following simple, though extreme, example.

<u>Example</u>. Assume, contrary to what is postulated in (A.1), that C has a fixed coefficients technology, such that manufacturing output is proportional to utilized capital. Thus $F(\lambda+R) = \beta(\lambda+R)$, $\beta > 0$. From (5), it is immediate that $p < \beta$ implies $R = (1-\lambda)$. Now suppose that $\bar{p} < \beta$. Then so long as S sets the price at (strictly, marginally below) or below $\bar{p}$, C imports $(1-\lambda)$ units of oil. It then follows from this that the CNE always features S setting the ceiling price $\bar{p}$. This is because the CNE price is calculated on the premise that λ is exogenously given; S's perception in the CNE is therefore that demand is completely inelastic up to $\bar{p}$. By analogous reasoning, it is easily checked that the SSE price is also the ceiling price $\bar{p}$.

Consider now the SPE. For any price below $\bar{p}$, $R^* = (1-\lambda)$, and the elasticity of demand is given by

$$\frac{dR^*}{dp}\frac{p}{R^*} = -\frac{1}{A''(\lambda)}\frac{A'(\lambda)}{(1-\lambda)} \equiv \eta(\lambda) \text{ say,}$$

(recall that $p = A'(\lambda)$, $0 < \lambda < 1$). I shall suppose that $\eta(\lambda) = \eta < -1$. A functional form with the required property is

$$(15)\quad A'(\lambda) = \phi\,\{-\eta(1-\lambda)\}^{1/\eta}$$

where $\phi > 0$ is a constant. Note that

$$A'(0) = \phi(-\eta)^{1/\eta} > 0 \quad \text{and} \quad \lim_{\lambda\to 1} A'(\lambda) = +\infty.$$

Equating (15) with p yields, for $\lambda > 0$,

$$(16)\quad (1-\delta) = -\frac{1}{\eta}(p/\phi)^{\eta},$$

provided that

$$p \geq \phi\,(-\eta)^{1/\eta} \equiv \underline{p} \quad \text{say},$$

where it is understood that $p \leq \underline{p}$ implies $\delta = 0$ in equilibrium. It is clear that for given $\eta < -1$, the interval $(\underline{p},\bar{p})$ is non-degenerate provided ϕ is not prohibitively large. Finally, using (16) in (10) and solving for p^* yields that

$$(17)\quad p^* = \phi^{\eta/(\eta-1)}\,\{-(1+\eta)/2\lambda\}^{1/(\eta-1)}$$

where the functional form $\lambda(R) = \lambda R^2$, with $\lambda > 0$ constant, has been used. It is easily checked that under the present functional forms $\pi(p)$ is strictly concave on $(\underline{p},\bar{p})$. Thus if the values of the parameters are such that $\underline{p} \leq p^* \leq \bar{p}$, (17) gives the SPE price. If $p^* < \underline{p}$, it is clear that the SPE will be $\underline{p}$ (recall that $\delta = 0$ in equilibrium for any price below $\underline{p}$). If $p^* > \bar{p}$, the optimal SPE price is the ceiling price, and the SPE and CNE prices coincide in this case.

From (17), it can be seen that if ϕ and λ are relatively "small" for given η and $\bar{p}$, p^* lies below $\bar{p}$ (perhaps at $\underline{p}$). This conforms broadly with intuition: if S's marginal production cost rises very slowly (that is, λ is small), it is reasonable to expect that optimally supply should be larger and price lower than otherwise. Similarly, the lower is the marginal cost of introducing substitution programmes that C faces (that is, the smaller is ϕ), the lower is the SPE price chosen by S to deter their implementation to a given extent in order to avoid losing sales of oil. In sum, provided that S's marginal production cost and the marginal cost of implementing substitution and resource-saving programmes are sufficiently small relative to the unit cost of domestic oil production in C, the SPE price lies below the CNE price. Following the argument in the preceding section, the absence of a precommitment mechanism in this case results in an equilibrium that is Pareto-inferior to the SPE.

7. Concluding Remarks

This essay has elucidated one aspect of the rudiments of Consumer-Producer relationships in the World Oil Market. Although the construct I have used is overly simplistic, I have tried to capture the mechanics of pre-emptive strategies by oil users and long-term pricing considerations by producers. In particular, I have sought to demonstrate in this context that credible strategies sustain Pareto-inefficient equilibria. It has also been shown under fairly weak conditions that the absence of long-term agreements results in equilibria that are Pareto-inferior to the equilibria when such agreements do obtain. If one gives the result a slightly different interpretation, it may appear somewhat counterintuitive that under precommitment more "aggressive" leadership behaviour by the producer bloc (Stackelberg versus Cournot behaviour) should typically benefit the consumer bloc as well as the producer bloc.

This said, I have abstracted from a number of aspects that are likely to be of importance. These include repercussions on capital markets, feedback effects on oil demand due to the maladjustment and adverse income effects following periods of high oil prices (see Marquez, 1983, Chs. 2 and 5 for a discussion). Perhaps most importantly, I have restricted the analysis to what is essentially a two-period model, and thus automatically excluded any possibility of "tacit cooperation" between the producer and consumer blocs in the absence of binding agreement mechanisms. In spite of these omissions, however, it seems safe to conjecture that the principal results in this paper would generalize.

Notes

1. I relax this in section 6 below.

2. Issues associated with strategic stockpiling or speculation are ignored here.

3. That is, the cost function imposes a penalty on current extraction that captures the value of having an extra unit of the resource still available for extraction once the game is finished. The drawback here is that players' behaviour in any future game must be taken as given.

4. See Kouris (1983) for a survey. Geroski, Ulph and Ulph (1986) report estimates of short- and long-run demand elasticities for crude oil.

5. This is identical to the problem where a monopolist faces inelastic demand for a resource below a limit price (see Dasgupta and Heal, 1979, pp. 340-45).

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