MANAGEMENT SCIENCE
Vol. 32, No. 7, July 1986
Printed in U.S.A.

INVENTORY OPTIMIZATION IN THE U.S. PETROLEUM INDUSTRY: EMPIRICAL ANALYSIS AND IMPLICATIONS FOR ENERGY EMERGENCY POLICY*

R. GLENN HUBBARD AND ROBERT J. WEINER
Center for Business and Government, Harvard University, Cambridge, Massachusetts 02138
Department of Economics, Northwestern University, Evanston, Illinois 60201
National Bureau of Economic Research, Cambridge, Massachusetts 02138
ICF, Inc., Washington, DC 20006
Energy and Environmental Policy Center, Harvard University, Cambridge, Massachusetts 02138

Much of the rapid increases in the price of crude oil during two of the last three supply shocks has been attributed to increased private inventory demand stimulated by the expectation of speculative profits. Government intervention in any future disruption is likely to take the form of releases from the Strategic Petroleum Reserve (SPR). Given that the SPR accounts for but a small fraction of U.S. oil inventories, the reaction of the private sector is critical in evaluating its impact. We incorporate inventory behavior in a model of the world oil market, which is then linked to a short-run macroeconometric model of the U.S. economy. Our model simulations support the view that substantial inventory accumulation accompanies a supply disruption. In the debate over whether the SPR is potentially a potent or impotent resource in an emergency, we lean toward potency. Our model suggests that public releases will not be absorbed in private stockpiles; indeed, their dampening price effects will serve, albeit slightly, to discourage speculative stock build.
(INDUSTRIES; PETROLEUM; INVENTORY POLICIES)

1. Introduction

Oil supply disruptions can inflict substantial damage on the U.S. economy. While consensus on specific remedies is lacking, few would argue against the idea of using the United States Strategic Petroleum Reserve (SPR) as an additional supply source.[1] There is little disagreement over whether the U.S. should be stockpiling oil. Estimates of the optimal size of the Reserve range from "more than we have now" to "much more than we have now."[2]

How to use the Reserve is a more difficult question. Several modeling issues arise; this paper focuses on the interaction between public and private stockpile decisions. The issue is important for two reasons. First, SPR drawdown is a form of government intervention, and the reaction of the private sector is critical in assessing its impact. The SPR constitutes but a small fraction of U.S. oil inventories; the bulk of the rest is controlled by the petroleum industry. Government stock policy will be effectively impotent if SPR releases are fully absorbed into private inventories.

Research in this area (Kuenne, Blankenship, and McCoy 1979; Teisberg 1981; Chao and Manne 1982) has largely ignored private inventory behavior. An exception is

*Accepted by Paul Gray; received June 22, 1983. This paper has been with the authors 3 months for 1 revision.

[1] U.S. official policy, as set out in U.S. Department of Energy (1981), is to confine government intervention in a disruption to using the SPR.

[2] The Reserve stood at about 500 million barrels at the start of 1986. National Petroleum Council (1981) lists 20 studies of SPR size, of which 17 recommend at least 500 million barrels.

0025-1909/86/3207/0773$01.25

Wright and Williams (1982), who employ stochastic dynamic programming. To do so, they have to assume that the oil market can be characterized by a small number of discrete states with probabilities given by a Markov transition matrix. Their assumptions that disruptions are anticipated and are very unlikely to extend for more than one period serve to exclude the behavior examined in this paper. A statistical investigation by Hamilton (1983) suggests that these disruptions were not anticipated.

The second reason for focusing on inventory decisions is the widely shared perception of the supply disruption price-spike "problem" as due as much to inventory accumulation as to loss of production capacity. Indeed, it has been claimed that the 1979 price increase stemmed largely from stock build by private companies, and that the stock draw which accompanied the disruption of similar size in late 1980 (due to the Iran-Iraq war) accounted for the very different outcome (Badger and Belgrave 1982).

The paper is organized as follows. §2 presents an optimizing model of private inventory behavior, discussing the influence of speculative stockpiling on market equilibrium in the presence of supply and demand fluctuations. The model considers both transitory and serially correlated shocks. For negative supply shocks, transitory shocks are accompanied by a drawdown, while speculative buildup may accompany a serially correlated shock. We estimate an equation for private oil inventory behavior in the U.S. and find evidence of a speculative motive.

In §3 we discuss public-private interaction in stockpiling. We focus on the impact of supply disruptions on inventories, and on the manner in which public reserves can influence these inventories through the market mechanism. Employing a simulation model of the world oil market and the U.S. economy, we examine the quantitative significance of inventory behavior in exacerbating the effects of a supply shock and the role of public-private stockpile interaction. Some conclusions and directions for future research are presented in §4.

2. An Optimizing Model of Inventory Behavior

A. *Private Stocks and Market Equilibrium*

The influence of private speculative stockpiling on commodity market equilibrium in the presence of supply and demand fluctuations has been recognized since the pioneering study by Muth (1961). Stockpiling smooths fluctuations in spot prices, while creating persistence of the impacts on prices of transitory shocks. Persistence may also be generated by the existence of contracts (see Hubbard and Weiner 1986). When shocks are serially correlated, the persistence problem is exacerbated.

Consider the following simple stylized model. Let production Q^S and consumption demand Q^D be responsive to the current period spot price P. Production and consumption are subject to random additive disturbances ϵ_{St} and ϵ_{Dt}, respectively, which are assumed to be independently and identically distributed with mean zero and variances σ_S^2 and σ_D^2, respectively. Total demand is the sum of consumption and speculative inventory demand.

Speculators trade in inventories on the spot market in anticipation of changes in price, and are assumed to be risk-neutral; i.e., they maximize expected profit. Let the objective of the speculators over the period $(t, t+1)$ be to

$$\max_{I_t} E_t\left\{\left((1+\delta)^{-1}P_{t+1} - P_t\right)I_t - \frac{h}{2}I_t^2\right\}, \tag{1}$$

where I represents the end-of-period stock level and δ is the discount rate. E_t denotes the expectation operator conditional on information available at time t. The first term represents speculative gains on the stock held, the second, holding costs. Holding stocks is assumed to be costly—in fact, increasingly costly—in the size of the stock due to payments to factors fixed in the short run, such as storage facilities, tankers, and pipelines. Thus, changes in price expectations cannot be fully acted upon instantaneously. We follow the literature (e.g., Sargent 1979) in modeling such costs as quadratic, the simplest specification of "diminishing returns"; these costs are indexed by the parameter h.

Maximizing (1) with respect to I_t yields the following demand function for stocks:

$$I_t = h^{-1}\big((1+\delta)^{-1}E_tP_{t+1} - P_t\big). \tag{2}$$

As with most other specifications since the original development by Muth (1961), the holdings of risk-neutral speculators are a function of the expected increase in price, taking into account the cost of adjusting stock levels. Inventory demand (stock change) is just

$$I_t - I_{t-1} = h^{-1}\big[(1+\delta)^{-1}(E_tP_{t+1} - E_{t-1}P_t) - (P_t - P_{t-1})\big]. \tag{3}$$

The spot price solves the following equation for market equilibrium:

$$Q^D(P_t) + h^{-1}(1+\delta)^{-1}(E_tP_{t+1} - E_{t-1}P_t) - h^{-1}(P_t - P_{t-1}) + \epsilon_{Dt} = Q^S(P_t) + \epsilon_{St}. \tag{4}$$

Under simplifying assumptions of linear responses of supply and demand to price, we have

$$Q^D(P_t) = A - aP_t \quad \text{and} \tag{5}$$

$$Q^S(P_t) = B + bP_t. \tag{6}$$

Hence equation (4) can be rewritten as

$$A - aP_t + \epsilon_{Dt} + h^{-1}\big[(1+\delta)^{-1}E_tP_{t+1} - P_t - (1+\delta)^{-1}E_{t-1}P_t + P_{t-1}\big]$$
$$= B + bP_t + \epsilon_{St}, \quad \text{or} \tag{7}$$

$$\big[b + a + h^{-1}\big]P_t = A - B + \epsilon_{Dt} - \epsilon_{St}$$
$$+ h^{-1}\big[(1+\delta)^{-1}E_tP_{t+1} - (1+\delta)^{-1}E_{t-1}P_t + P_{t-1}\big]. \tag{8}$$

For simplicity, consider the case wherein $\delta = 0$. If we define the long-run average price obtained when expectations are realized ($E_tP_{t+1} = E_{t-1}P_t = P_t$) by $\hat{P}$, then it follows that

$$\hat{P} = \frac{A - B}{a + b}. \tag{9}$$

Let lower-case variables be defined in deviation form (i.e., $p_t = P_t - \hat{P}$). Under the assumption of rational expectations, we solve the second-order inhomogeneous difference equation (8) by standard methods to yield

$$p_t = \psi p_{t-1} + \frac{\epsilon_{Dt} - \epsilon_{St}}{a + b + 2h^{-1} - h^{-1}\psi}, \tag{10}$$

where ψ is the root within the unit circle of the quadratic equation $h^{-1}\psi^2 - (a + b + 2h^{-1})\psi + h^{-1} = 0$.

Hence, even transitory shocks exhibit persistence effects on the spot price because of the behavior of inventories. Moreover, the variance of the spot price increase with ψ, since

$$\sigma_p^2 = \frac{\sigma_D^2 + \sigma_S^2}{(a + b + 2h^{-1} - h^{-1}\psi)^2}. \tag{11}$$

Note that since $d\psi/da < 0$, the steeper is the demand curve for oil, the smaller is the initial increase in price and the lower is the persistence. Hence, policies such as oil import tariffs or certain types of buffer-stock stabilization policies (which effectively raise a) can mitigate both the impact and long-run effects of transitory shocks on prices. We return to this issue in §3.

We can easily extend the above analysis to the case of serially correlated quantity shocks. Suppose that demand and supply shocks follow first-order autoregressive processes (AR(1)):

$$\epsilon_{Dt} = \rho_D \epsilon_{Dt-1} + \nu_{Dt} \quad \text{and} \tag{12}$$

$$\epsilon_{St} = \rho_S \epsilon_{St-1} + \nu_{St}, \tag{13}$$

where ν_{Dt} and ν_{St} are white noise and $\sigma_{\nu_D \nu_S} = 0$.

Using equations (12) and (13) for the demand and supply shocks, we can rewrite equation (8) as

$$E_t\left\{p_{t+1}\left[h^{-1} - (a + b + 2h^{-1})L + h^{-1}L^2\right]\right\} = -(\epsilon_{Dt} - \epsilon_{St}), \tag{14}$$

where L denotes the lag operator. The solution to (14) given rational expectations is just

$$p_t = \psi_1 p_{t-1} + \psi_2^{-1}\left(1 - \psi_2^{-1}\rho_D\right)^{-1}\nu_{Dt} - \psi_2^{-1}\left(1 - \psi_2^{-1}\rho_S\right)\nu_{St}, \tag{15}$$

where ψ_1 is the root within the unit circle of the quadratic equation contained within the brackets in (14) (i.e., ψ from before), and ψ_2 is the root outside the unit circle.

Now persistence effects come also from the serial correlation parameters ρ_D and ρ_S. Equation (15) points up the need to consider the structural parameters determining ψ_1 (and ψ_2). As ψ_1 and ψ_2 tend toward unity, the existence of serial correlation amplifies the price effects of shocks. The variance of the spot price is also higher when the shocks are serially correlated. Finally, if the shocks are serially correlated, then changes in ψ_1 induced by policy changes have all the more impact.

It is clear from equation (2) that as long as supply shocks are purely transitory, inventories will be drawn down in response to a negative supply shock, since

$$\frac{dI_t}{d(-\epsilon_{St})} = \Omega(\psi - 1) < 0, \quad \text{where} \quad \Omega = h^{-1}\frac{dp_t}{d(-\epsilon_{St})}. \tag{16}$$

Speculative accumulation requires either serially correlated shocks or the expectation that the disruption will "get worse." An example would be an AR(2) process in which the first coefficient is greater than one and the second is negative.

Following this stylized model when shocks follow an AR(1) process, we note that the response of private stocks to a supply shock in the current period is

$$\frac{dI_t}{d(-\nu_{St})} = \Omega(\rho_S - (1 - \psi_1)). \tag{17}$$

For a negative shock ($\nu_{St} < 0$), equation (17) implies that private stocks will increase if $\rho_S > 1 - \psi_1$. That is, the likelihood of stock accumulation in response to a supply disruption is greater the higher is the serial correlation of the shocks (ρ_S) and/or the higher is the intertemporal correlation of price changes ψ_1.

B. *The Historical Record*

Although analysts have focused on oil consumption during disruptions, little attention has been devoted to a systematic investigation of private oil inventory behavior. Two exceptions are Danielsen and Selby (1980) and Verleger (1982). These accounts attribute much of the 1979–1980 price hike to increased inventory demand in response to expectations of higher prices in the future.

Table 1 presents data on the crude oil inventory-to-sales ratio, where both numerator and denominator have been seasonally adjusted by using standard Bureau of the Census techniques based on moving averages, and the current-dollar and inflation-adjusted marginal cost of crude oil to U.S. refiners over the period from 1960 to 1981. The data in the first column of Table 1 can be interpreted as "days of consumption." An examination of the table shows a gradual decline in the inventory-to-sales ratio over the period 1960–1972, as stocks were not built as fast as demand increased. The almost flat nominal price indicates a declining real price over the period, and certainly a negative ex-post profit from holding speculative stocks when interest and physical carrying costs are taken into account. In the empirical work presented here, we have used the GNP deflator to express all prices in constant-dollar terms.

Stocks were built up both absolutely and relative to sales during the period of the Arab oil embargo, and again during the second oil shock (see Figures 1 and 2). The data for 1979–1981 point up difficulties in trying to isolate a speculative motive in oil inventory demand. It has frequently been stated that oil inventory levels were low prior to the interruption of oil supplies in Iran. Table 1 shows, however, that in 1978:3, the quarter before supplies were disrupted, inventory levels were not abnormal. The inventory-to-sales ratio did not fall to historically low levels until the end of 1979:1. This drawdown does not necessarily indicate that oil companies were unprepared for a disruption, but rather that inventories may have been used to offset the supply reduction during the initial months.

C. *Empirical Implementation*

As is often the case, the real world presents a considerable challenge to estimation. The oil market is characterized by short-run rigidities (e.g., contracts), which can be significant when prices change rapidly. As a result, more than one price can prevail in the market, even after quality adjustments. The price which comes closest to what we want is the marginal cost of crude oil to U.S. refiners. If we assume that the U.S. refinery industry is competitive, this is the appropriate price for valuing inventories. The U.S. refiners' acquisition cost, labeled P^{US}, is modeled as an average of spot and contract prices (plus transportation costs), and is assumed to adjust to the spot price P; i.e.,

$$P_t^{US} = a_0 + a_1 P_{t-1}^{US} + a_2(P_t - P_{t-1}^{US}). \tag{18}$$

The relationships among prices and the responses of prices to shocks are discussed in the Appendix A.

Rigidities can also cause inventory fluctuations for reasons unrelated to expected profits. For example, variation in sales due to unanticipated economic or climatic conditions will affect inventories if markets are not perfectly flexible. (Difficulty in finding *The New York Times* for sale late in the day is a familiar case of this phenomenon.) Thus, the decision by private companies to hold inventories of crude oil and petroleum products reflects two motives—a desire to hold sufficient work-in-process stocks to meet the expected level of sales as well as the previously described speculative demand for extra stocks (above those held as goods in process) because of an expectation of higher future prices (inclusive of carrying costs over the holding period).

TABLE 1
Quarterly Crude Oil Inventory-to-Sales Ratio and Prices
1960–1981

	$\frac{I}{S}$	P^{US}	P^{US}/P
1960:1	81	3.07	4.49
2	81	3.07	4.48
3	82	3.07	4.46
4	79	3.07	4 45
1961:1	85	3.07	4.46
2	83	3.08	4.45
3	82	3.08	4.43
4	83	3.09	4.44
1962:1	79	3.09	4.40
2	80	3.09	4.38
3	82	3.09	4.38
4	80	3.09	4.35
1963:1	77	3.08	4.31
2	81	3.08	4.31
3	78	3.08	4.30
4	78	3.07	4.28
1964:1	81	3.07	4.24
2	78	3.07	4.23
3	76	3.06	4.19
4	76	3.06	4.18
1965:1	75	3.06	4.15
2	75	3.06	4.13
3	73	3.06	4.10
4	72	3.06	4.08
1966:1	73	3.07	4.06
2	71	3.07	4.01
3	72	3.08	4.00
4	72	3.10	3.99
1967:1	75	3.11	3.97
2	73	3.12	3.97
3	75	3.14	3.96
4	74	3.15	3.93
1968:1	72	3.15	3.88
2	75	3.16	3.85
3	75	3.19	3.85
4	74	3.22	3.83
1969:1	72	3.26	3.84
2	72	3.29	3.82
3	68	3.33	3.81
4	68	3.36	3.80
1970:1	67	3.37	3.75
2	68	3.40	3.73
3	67	3.44	3.75
4	70	3.50	3.76
1971:1	69	3.58	3.79
2	68	3.64	3.80
3	70	3.67	3.80
4	68	3.67	3.77
1972:1	65	3.60	3.65
2	63	3.61	3.63
3	63	3.67	3.66
4	57	3.80	3.74

TABLE 1 (*Continued*)

	$\frac{I}{S}$	P^{US}	P^{US}/P
1973:1	56	3.72	3.61
2	58	3.84	3.67
3	56	4.25	3.99
4	60	5.87	5.40
1974:1	66	11.59	10.47
2	65	12.93	11.40
3	64	12.65	10.87
4	65	11.25	9.39
1975:1	72	10.62	8.64
2	68	10.73	8.62
3	69	11.10	8.83
4	71	11.76	9.12
1976:1	69	10.72	8.24
2	66	10.83	8.25
3	67	11.16	8.40
4	62	11.60	8.60
1977:1	64	11.48	8.39
2	68	11.36	8.17
3	69	12.02	8.52
4	73	12.45	8.69
1978:1	65	12.47	8.59
2	63	12.84	8.62
3	62	13.04	8.58
4	68	13.18	8.48
1979:1	59	13.65	8.61
2	64	15.90	9.82
3	66	21.48	13.01
4	70	26.03	15.49
1980:1	79	28.90	16.77
2	80	29.14	16.50
3	81	29.01	16.13
4	78	29.87	16.13
1981:1	88	38.72	20.38
2	84	37.76	19.55
3	78	35.95	18.22
4	84	35.86	17.79

Notes: I/S = inventory-to-sales ratio (of seasonally adjusted quantities).

P^{US} = marginal cost of crude oil to U.S. refiners in dollars per barrel.

P = GNP deflator (1972 = 1.000).

Various regulations have complicated the definition of P^{US}. A time series was constructed as follows. From the first quarter of 1960 (1960:1) to 1973:3, P^{US} equals the domestic crude oil prices, which was elevated by import quotas above the import price. From 1973:4 thorugh 1974:3, when domestic prices were kept below world levels by regulation, P^{US} is the import price less the value of crude oil entitlements, which served to reduce refiners' marginal costs. Beginning in 1976:4, domestically produced stripper oil was decontrolled; thus, we take P^{US} as the price of stripper oil to refineries less the value of crude oil entitlements. For details, see Kalt (1981). After price controls were lifted, P^{US} is just the refiners' acquisition cost of imported oil.

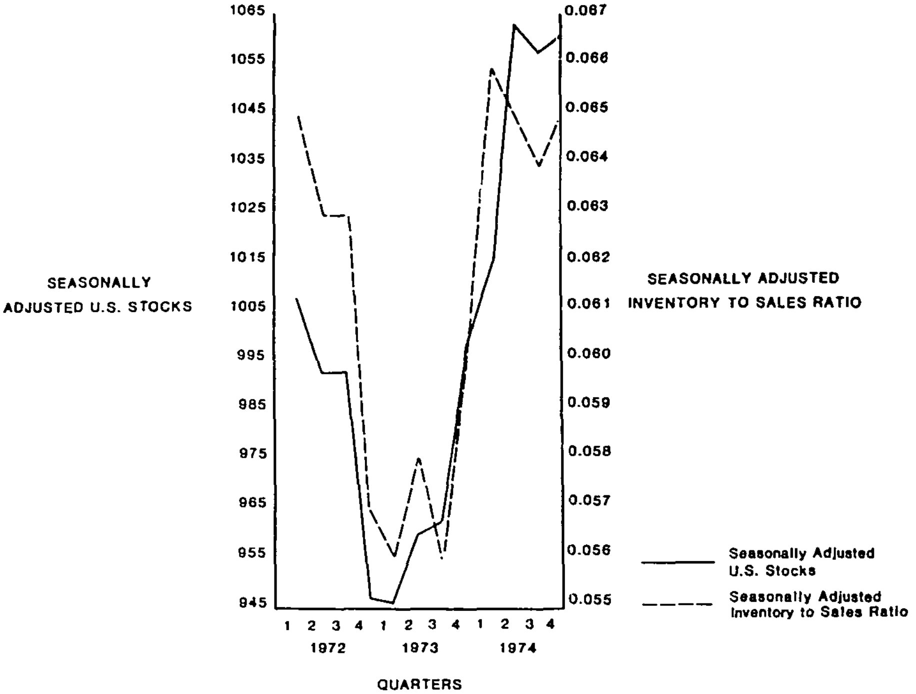

FIGURE 1

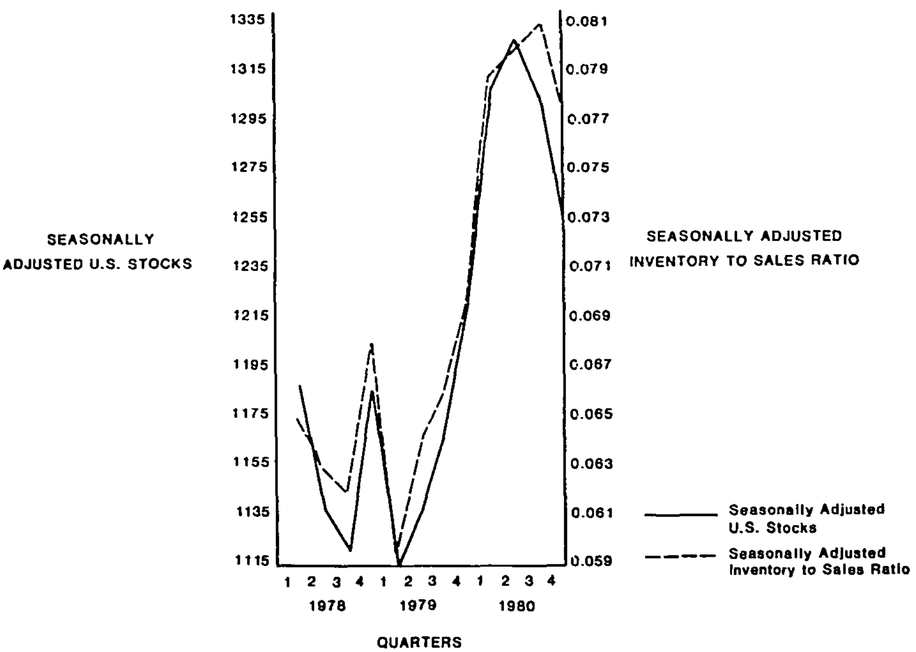

FIGURE 2

Isolating the impact of the speculative motive underlying private oil inventory behavior is important for two reasons. First, it will help us to understand more fully the price dynamics of the oil market during a supply disruption. Second, if the impact of speculation is important, announced *future* strategies (such as an SPR release or the imposition of a tariff on imported oil) can affect oil inventory behavior and hence, oil prices today.

We take the quarter as our time unit, since higher frequency data are unavailable for some variables, and of dubious quality for others. Further, the time required to transport oil from field to inventory makes the interpretation of monthly data difficult. On the other hand, annual data are likely to be insufficient for capturing short-run market dynamics. We use seasonally adjusted data throughout.

Assuming that work-in process stocks are unit-elastic with respect to sales, a specification for private inventory behavior is:

$$I_t^* - I_{t-1} = S_t^* - S_{t-1} + \gamma\left[(1+\delta)^{-1} E_t P_{t+1}^{\mathrm{US}} - P_t^{\mathrm{US}}\right] \tag{19}$$

where I^* represents desired inventories, S^* represents expected sales, δ is represented by the three-month Treasury bill rate, and variables are in logarithmic form. That is, the expected return variable is $\ln(E_t P_{t+1}^{\mathrm{US}}/(1+\delta)P_t^{\mathrm{US}})$. The amount by which the desired and actual stocks differ

$$I_t^* - I_t = \alpha(S_t - S_t^*) + \beta\left[(I/S)_{t-1} - (I/S)_{t-1}^*\right]. \tag{20}$$

The first term captures "sales surprises" in the current period. Given the above assumptions of desired work-in-process inventory as a fixed fraction of sales and costly adjustment, the second term is designed to model movements in the inventory-to-sales ratio in response to past disturbances. These measures are admittedly crude, but in the absence of both a detailed theory of short-run rigidity and the necessary data, they must suffice as proxies for the channels of inventory fluctuation unrelated to the speculative motive.

In our estimation we take changes in the inventory-to-sales ratio, rather than the inventory level itself, as the variable to be explained. This ratio is widely used in the industry literature, which characterizes inventories in terms of "days of consumption." Substituting (20) into (19) and expressing inventories as a fraction of sales yields the specification:

$$\left(\frac{I}{S}\right)_t - \left(\frac{I}{S}\right)_{t-1} = -(1+\alpha)(S_t - \bar{S}_t) - \beta\left[\left(\frac{I}{S}\right)_{t-1} - \left(\frac{\bar{I}}{S}\right)_{t-1}\right]$$
$$+\gamma\left[(1+\delta)^{-1} E_t P_{t+1}^{\mathrm{US}} - P_t^{\mathrm{US}}\right], \tag{21}$$

where a bar over a variable indicates a four-quarter moving average, which we use to proxy for expectations of sales and the inventory-to-sales ratio.

The equation was estimated in two stages. Price expectations are taken from the world oil market model described in the Appendix; detailed information on the construction of the profit term and the estimation procedures used therein are in Hubbard and Weiner (1983a). Equation (21) was then estimated by ordinary least squares over the period 1974:4–1981:4; coefficient estimates (t-statistics in parentheses) are as follows:

$$\alpha = 0.44\ (5.5), \quad \beta = 0.54\ (4.0), \quad \gamma = 0.16\ (2.0), \quad \bar{R}^2 = 0.54,$$
$$\text{D.W.} = 1.24, \quad \text{S.E.E.} = 0.045.$$

Several comments on the estimation results are in order. First, the post-1974 interval was chosen for data considerations with respect to the subsidiary price expectations model.[3] Second, the assumption of unit sales elasticity could not be rejected over this sample period. Finally, the low value of the Durbin–Watson statistic led us to examine the residuals for autocorrelation (although the model is already in first-difference from, making autocorrelation difficult to interpret). Low order (up to four quarters) autoregressive and moving average alternative models yielded insignificant results.

The results imply that stocks are accumulated when sales (a) are unexpectedly low, (b) when inventory-to-sales ratios are below historical levels, and (c) when prices are expected to increase in percentage terms by more than the interest rate. The coefficients, which are all significant at the 95% level, can be interpreted as elasticities. For example, a 1% rise in expected profit during a quarter leads to a 0.16% increase in the ratio of inventories to sales. Under current conditions, this amounts to roughly 21,000 barrels per day in additional demand (ratio of 80 days × 0.16% × 15.2 million barrels per day sales = 2 million barrels during the quarter, or about 21,000 barrels per day).

It is too simplistic to think of inventory accumulation as "procyclical" or "anticyclical" per se, as has sometimes been asserted (see Danielsen and Selby 1980; Frankel 1982). Stock build, stock draw, or both, can accompany the evolution of a supply disruption.

3. Oil Shocks and Inventories: Public-Private Interaction

A. *Public Stockpile Behavior*

The analysis in §2 illustrated the role of private inventory speculation in assessing the impact of supply shocks on oil prices. In this section, we turn to the questions of the impact of shocks on private stocks and the influence of government stockpiling policy on private stockpiling.

Public stockpile policy can influence private responses to serially correlated supply shocks through three channels. First, the stockpile authority (Strategic Petroleum Reserve) could offset part of a contemporaneous supply shock. By reducing the effective magnitude of the shock, private inventory response is reduced for a given shock. Public and private stock movements would be complementary in such a world; public stockpile releases would discourage private speculative stockpiling. Nothing is being said here about optimal public stockpiling, in which the public authority trades off intertemporally the benefits of stockpile use (see Hubbard and Weiner 1986).

A second type of stockpile policy would make stockpile releases Δ a function of deviation of prices from trend, i.e.,

$$\Delta_t = \omega p_t, \qquad \omega > 0. \tag{22}$$

Adding the public stockpiling rule in equation (22) to equation (8) for market equilibrium and solving as before, we see that the price responsiveness of demand is effectively heightened, reducing the mean and variance of the price as well as the persistence effects of the shocks. To the extent that such a stockpile rule reduces persistence (ψ_1), equation (16) reveals that the private inventory response will be reduced.

A third strategy would be to use forward or future sales of public stocks in the event of a crisis. The link between expected future prices and speculative hoarding provides an opportunity for policy intervention if the government can manipulate price expectations. The announcement of an SPR drawdown strategy for the future means more oil will be available at the future date, which lowers the expected future price and,

[3]When (21) was estimated over the period from 1960 to 1973, the estimate of γ was positive, but insignificantly different from zero. That there has been a change of regime over the two periods is clear, and the variance of prices (not considered in the empirical work) increased dramatically.

therefore, expected future profits from speculation. This, in turn, reduces inventory demand and spot prices today.[4]

B. *The Model in Practice: Simulating a Disruption*

To investigate the importance of stock accumulation in a disruption, we need to incorporate consumption demand into the model. Since an increase in the price of oil has a significant effect on the economy, in turn affecting oil demand, it is inappropriate to take income as exogenous. Instead, we generate income figures by solving an econometric model of the U.S. macro-economy simultaneously with the oil-market model detailed above in the Appendix A. Descriptions of the complete model may be found in Hubbard and Fry (1982, 1984) or Hubbard and Weiner (1983b). A schematic diagram is given in Figure 3.

Our simulations cover the four-year period 1983 through 1986 (the current version of the model is initialized in the fourth quarter of 1982). We take our assumptions about monetary and fiscal policy (tax rates, monetary base growth, etc.) from the Stanford Energy Modeling Forum 7 Study, "Energy Shocks, Inflation, and Economic Activity" (Hickman and Huntington 1982). For this study, we have set U.S. and foreign crude oil tariffs to zero and assumed the current Windfall Profits Tax schedule with no mechanism for recycling the additional funds collected.

In the "control scenario," no further disruption takes place. Combined Iranian and Iraqi production recovers throughout the interval. U.S. oil production is projected to drop slowly throughout the interval, although it is more than offset by increases outside OPEC. We expect a relatively "loose" market (i.e., low output relative to capacity production) in the absence of further deliberate restrictive actions by OPEC, with oil prices first falling, then rising as the economy recovers from recession. The endogenous (fourth-quarter to fourth-quarter) growth rates for real income are 1983—4.3%, 1984–4.2%, 1985—4.4%, 1986—3.5%. We assume that the SPR is filled at a rate of 200,000 barrels per day, a figure consistent with historical data.

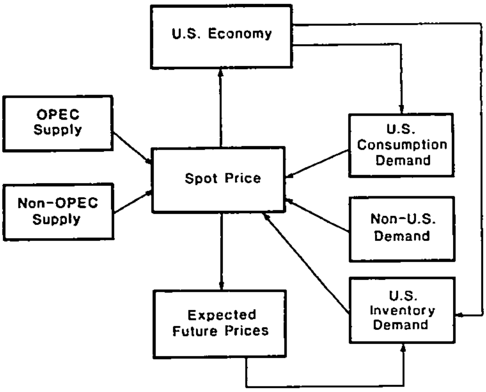

FIGURE 3. A Model of the World Oil Market and the U.S. Economy.

[4]Of course, the success of this intervention depends on how credible the announced SPR drawdown strategy is. If firms suspect that the government may not release the oil in the future, they will continue to hold speculative stocks. By selling futures contracts, however, the government can guarantee that a specified amount of SPR oil will be available at a certain time in the future. Thus, instead of its traditional risk sharing role, the futures contract here plays the role of a credible guarantor of the government's SPR drawdown policy. For a more detailed theoretical and empirical discussion of these points, see Devarajan and Hubbard (1983).

TABLE 2

Comparison of Control and "Base Case" Disruption

C—Control D—Disruption Quarter	Spot Price U.S. $/Barrel		Refiner Acq. Cost U.S. $/Barrel		U.S. Private Stock Change (1000 b/d)	
	C	*D*	*C*	*D*	*C*	*D*
1983:1	28.40	39.00	31.70	34.90	− 1780	−1510
2	25.50	45.00	30.70	38.80	150	370
3	22.60	48.00	29.00	42.40	60	260
4	23.90	59.70	28.30	43.60	− 200	66
1984:1	24.90	53.40	28.10	51.10	− 740	−800
2	26.30	48.20	28.30	51.40	230	290
3	28.20	43.60	29.10	50.20	430	460
4	30.80	39.40	30.40	48.00	− 280	−380
1985:1	31.16	34.30	31.50	45.00	− 890	− 1040
2	31.90	30.40	32.50	41.60	300	190
3	33.00	27.50	33.50	38.30	470	340
4	35.20	25.60	34.90	35.50	− 230	−400
1986:1	35.20	23.20	36.00	32.70	− 860	− 1030
2	35.60	22.10	36.80	30.40	300	170
3	36.60	22.20	37.70	28.80	460	340
4	38.80	24.00	39.00	28.20	− 210	−300

The disruption is modeled by reducing OPEC capacity unexpectedly by 7 mmb/d (million barrels per day) for one year, starting in 1983:1. It should be noted that "disruption size" is not a well-defined concept, since a loss in capacity leads nondisrupted OPEC members to produce more, depending on the extent of spare capacity available, and to stock changes. In the 7 mmb/d disruption, OPEC is producing about 1.4 mmb/d less by 1983:4, and the U.S. is importing about 0.8 mmb/d less than in the control case. The 7 mmb/d figure was chosen to be roughly comparable to past disruptions. In comparison, the Iranian disruption led to a capacity loss of about 6 mmb/d, and a short-term production decline of about 2 mmb/d. Much of the loss here is made up (albeit at higher prices) because of the substantial excess capacity at the outset of the disruption. The growth rate of real income is initially lowered by the

TABLE 3

Effects of Using the SPR in a Disruption

Small Draw: 0.5 mmb/d during 1983 (180 mmb total)

Large Draw: 1.5 mmb/d during 1983:1, 2 (270 mmb total)

Quarter	Spot Price ($/bbl) No Draw	Changes Due to Small Draw	Changes Due to Large Draw
1983:1	39.00	− 2.90	− 5.70
2	45.00	− 4.10	− 9.60
3	48.00	− 5.20	− 7.10
4	59.70	− 5.30	− 5.00
1984:1	53.40	− 4.30	− 3.90
2	48.20	− 3.40	− 3.10
3	43.60	− 3.50	− 2.00
4	39.40	− 1.70	− 1.10
1985:1	34.30	− 1.00	− 0.60
2	30.40	− 0.40	− 0.30
3	27.50	0.20	0.90
4	25.60	0.70	1.40

TABLE 4

Effects of Using the SPR in a Disruption

Small Draw: 0.5 mmb/d during 1983 (180 mmb total)

Large Draw: 1.5 mmb/d during 1983:1, 2 (270 mmb total)

U.S. Private Stock Change (mb/d), "−" indicates additional draw			
Quarter	No Draw	Change Due to Small Draw:	Change Due to Large Draw:
1983:1	−1510	−70	−150
2	370	−50	−110
3	260	−40	40
4	66	−30	30
1984:1	−800	−20	10
2	290	−10	−30
3	460	−20	30
4	−380	10	40
1985:1	−1040	20	50
2	190	20	20
3	340	20	20
4	−400	20	30

shock, with new growth rates of 3.3% in 1983, 4.1% in 1984, 4.5% in 1985, and 3.6% in 1986. A disruption occurring in a period of high capacity utilization would cause substantially larger price increases than those reported below.

Table 2 presents quarterly results for spot prices, refiner's acquisition costs, and changes in private inventories. Although capacity is restored by 1984:1, spot prices do not decline to pre-disruption levels until 1985:1, refiner's acquisition costs until the end of 1985. By the middle of 1985, the spot price is actually lower than in the control due to demand reduction associated with the drop in economic activity. U.S. private inventories are built relative to the control, rapidly at first (roughly 90 million barrels in 1983), more slowly thereafter. Starting in 1984:4, private inventories are reduced relative to the control.

We have simulated many SPR drawdown rates, and here present two: one "small" (0.5 mmb/d) and one "large" (1.5 mmb/d). The 1.5 mmb/d release causes the SPR to "run dry" after two quarters. Tables 3 and 4 present the results for spot prices and private inventory behavior. The resulting changes are probably understated, since we held foreign inventory fluctuations constant throughout. We found that the SPR releases were relatively successful in blunting the spot price increase. They also reduced private inventory accumulation, albeit slightly, in the early stages of the shock. As the model system had returned to equilibrium, results for 1986 are not reported in Tables 3 and 4.

4. Conclusions

Movements in private oil inventories can exacerbate oil price increases, magnifying the economic costs of oil shocks. We have analyzed oil inventory behavior in terms of an optimization model, in which firms hold stocks both to meet expected future sales and to make a speculative profit when expected future prices are high. By modeling the change in the inventory-to-sales ratio as a function of a "sales surprise," a "target adjustment," and an expected profit, we have documented the role of expected future prices in influencing inventory demand (and oil prices) today. That channel suggests policy innovation in the form of announced changes in future *public* stockpiling policy.

We assumed that inventories are held by firms, not consumers. A richer version of the model would include consumers holding stocks for portfolio reasons, especially since returns on stockpiling and other assets are likely to be negatively correlated.

Our simulations support the view that a supply disruption is accompanied by substantial inventory accumulation. In the debate over whether drawing down the SPR is potentially a potent or impotent policy in an emergency, we lean toward potency. Public releases were not absorbed in private stockpiles; indeed, their dampening price effects served, albeit slightly, to discourage speculative stockpiling.[5]

Appendix A

This appendix provides a brief description of the econometric model used in the simulations in the text; detailed documentation is in Hubbard and Weiner (1983a). The model is designed to quantify the short-term economic costs of oil supply disruptions and to pinpoint the general equilibrium impacts of policy responses. Domestic economic aggregates are linked to a model of the world oil market by a core macroeconomic model with real and financial sectors. Solution of the models is fully simultaneous and is accomplished through iteration. The government has at its disposal a set of fiscal and monetary policy instruments, with which it can influence aggregate demand and supply. The basic output of the model consists of a set of relevant oil prices accompanied by endogenous OPEC output projections and a set of macroeconomic variables dealing primarily with inflation, unemployment, financial variables, and income.

The World Oil Market

Be it explicit or implicit, a model of the world oil market is crucial to any discussion of stocks policy. Essential to our analysis is a rigorous notion of market "tightness"; we abstract from much of the rich institutional detail of the oil trade in order to focus on this aspect. We employ two prices as proxies for the many prevailing in the market at any given time. Crude oil is sold under term contracts at the contract price. The spot price (labeled P below) is paid for oil purchased on a single-cargo basis. We used data on Mideast Light, since it makes up the largest fraction of crude oil trade internationally. Our results will thus be biased to the extent that the behavior of spot-contract price differentials differs systematically across grades of crude oil. For further discussion, see Verleger (1982).

The contract price is set by OPEC in accord with its production decisions and demand estimates. This description of the short run is consistent with several view of medium- to long-term behavior, and we are thus agnostic on the question of OPEC internal structure, whether it be a cartel, a dominant-country oligopoly, or something else. Given the difficulty in forecasting demand and the numerous minor shocks inherent in any market, the contract price will not in general equate supply and demand. The spot market serves to satisfy the excess, and thus acts as a signal of market disequilibrium in OPEC, which adjusts the contract price. The process is then repeated.

The spot price increases when the market tightens. Two forms of "tightening" are possible: demand can increase due to changes in consumption or stock buildup and supply can decrease due to disruption in a

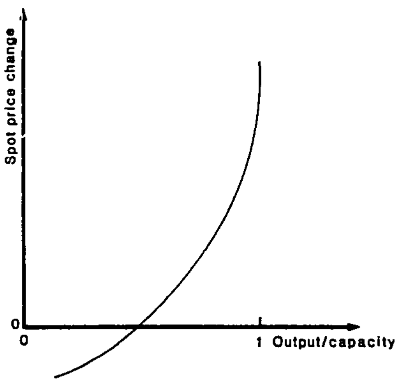

FIGURE A1. OPEC Price-Reaction Function.

[5]An earlier version of this paper was presented at the TIMS/ORSA MEETING in Chicago in April 1983. We thank Shantayanan Devarajan, James Hamilton, Jerry Hausman, William Hogan and an editor and two anonymous referees for comments. Financial support from the U.S Department of Energy is acknowledged. Opinions expressed, as well as any errors, are solely ours.

producing country, or deliberate production cuts. In order to capture both effects, we employ a form of price reaction function (see Figure A1) following Nordhaus (1980) and Hubbard and Fry (1982).

When a disruption occurs, capacity is removed from the market, and the output-to-capacity ratio of the nondisrupted producers rises. At higher prices, these producers are willing to accelerate output, thereby bumping up against their own capacity constraints. When excess capacity no longer exists (output/capacity = 1), even large increases in the spot price can elicit little further supply response, hence the nonlinearity of the curve. "Price-reaction functions" such as this are widely used in dynamic oil-market models. See Energy Modeling Forum (1982) for a survey. We assume that capacity decisions are governed by long-term considerations outside the scope of the model, and take them as exogenous. We expect the spot price to rise sharply as capacity utilization nears 100%. Quadratic and cubic specifications were tried for f, with similar results; we chose the latter based on monotonicity. Estimation results are in Hubbard and Weiner (1983).

TABLE A1

Variables in the Model

Variable	Determination	Definition
<u>Oil Supply</u>		
CAP	Exogenous	Available capacity of "nondisrupted" OPEC members
OUTPUT	Endogenous	OPEC production from "nondisrupted" members
DISRUP	Exogenous	Production from "disrupted" countries
NONOPEC	Exogenous	Non-OPEC production
<u>Oil Demand</u>		
USCON	Endogenous	US oil consumption
FCON	Endogenous	Free-world oil consumption outside the US
USSPR	Exogenous	US Strategic Petroleum Reserve demand
USSTCH	Endogenous	US private sector oil inventory demand
FSTCH	Exogenous	Free world oil inventory demand outside the US
<u>Prices</u>		
P	Endogenous	Spot price of Mideast light crude oil
P^{US}	Endogenous	US refiner acquisition cost
P^{F}	Endogenous	Foreign refiner acquisition cost
<u>Other</u>		
Y	Endogenous	Gross national product
X	Endogenous	Vector of structural variables used in calculating consumption demand

In equation form (Table A1 collects the variable names for convenience):

$$P_t = \psi P_{t-1} + f(\text{OUTPUT/CAP})_t \tag{A1}$$

where t indexes are time period, f is the function graphed in Figure A1 ($f > 0$), CAP denotes capacity, and OUTPUT and CAP refer to OPEC.

OUTPUT is obtained from the conditions that supply and demand be equal:

$$(\text{USCON} + \text{FCON}) + (\text{USSPR} + \text{USSTCH} + \text{FSTCH}) = \text{OUTPUT} + \text{DISRUP} + \text{NONOPEC}, \tag{A2}$$

where US stands for United States, F for foreign, CON for consumption, STCH for (non-SPR) stock change, SPR for Strategic Petroleum Reserve fill or draw, OUTPUT for the production of non-disrupted OPEC producers, DISRUP for the (reduced) output from the disrupted country, and NONOPEC for non-OPEC production.

US consumption is assumed to depend on the domestic refiner's acquistion cost (P^{US}), income (Y^{US}), and a vector of structural variables, including past prices (X^{US}). Foreign consumption is defined similarly:

$$\text{USCON} = g^{\text{US}}(P^{\text{US}}, Y^{\text{US}}(P^{\text{US}}), X^{\text{US}}), \tag{A3}$$

$$\text{FCON} = g^{\text{F}}(P^{\text{F}}, Y^{\text{F}}(P^{\text{F}}), X^{\text{F}}). \tag{A4}$$

The US refiner's acquisition cost is taken to be an average of spot and contract price (plus transport costs), and to adjust to the spot price. The domestic price abroad is defined similarly:

$$P_t^{\text{US}} = j_0 + j_1 P_{t-1}^{\text{US}} + j_2(P_t - P_{t-1}^{\text{US}}), \tag{A5}$$

$$P_t^{\text{F}} = k_0 + k_1 P_{t-1}^{\text{F}} + k_2(P_{t-1} - P_{t-1}^{\text{F}}). \tag{A6}$$

In general, the j's and k's will be different for institutional as well as tax reasons. For the moment, we take the other variables as exogenous.

To obtain OUTPUT in terms of consumption, stock change, and production by other countries, rearranged equation (A2):

$$\text{OUTPUT} = (\text{USCON} + \text{FCON}) + (\text{USSPR} + \text{USSTCH} + \text{FSTCH}) - (\text{DISRUP} + \text{NONOPEC}). \tag{A7}$$

We are interested in the effect of SPR releases on the spot price. In this model, there are three such effects: direct, feedback, and international interaction. The direct effect is to ease pressure as the SPR release reduces demand for OPEC output. The feedback effect occurs because holding down the spot price serves to hold down domestic prices at home and abroad as well, thus reducing the cutbacks in US and foreign consumption. The feedback effect clearly works against the direct effect. The international interaction effect depends on the reaction of foreign stocks to SPR releases. Cooperation implies that the SPR and foreign stockpiles are drawn down simultaneously. Under competition, foreign stocks may be built up as the US government draws down the SPR. In equation form:

$$\begin{aligned}\frac{dP}{d\text{USSPR}} &= \frac{f'}{\text{CAP}}\frac{d\text{OUTPUT}}{d\text{USSPR}} \\ &= \frac{f'}{\text{CAP}}[(d\text{USCON}/dP^{\text{US}})(dP^{\text{US}}/dP) \\ &\quad \times (dP/d\text{USSPR}) + (d\text{FCON}/dP^{\text{F}})(dP^{\text{F}}/dP)(dP/d\text{USSPR}) \\ &\quad + (1 + d\text{FSTCH}/d\text{USSPR})].\end{aligned} \tag{A8}$$

Substituting equations (5) and (6) into equation (8) and labeling the international interaction effect, $d\text{FSTCH}/d\text{USSPR}$, as Ω yields:

$$\frac{dP}{d\text{USSPR}} = \frac{\underbrace{\underbrace{\frac{f'}{\text{CAP}}}_{\text{direct effect}}\underbrace{\left[1 - \frac{f'}{\text{CAP}}\left(j_2\frac{d\text{USCON}}{dP^{\text{US}}} + k_2\frac{d\text{FCON}}{dP^{\text{F}}}\right)\right]^{-1}}_{\text{feedback effect}}}_{\text{domestic effect}}}{} \times \underbrace{\left[(1 + \Pi)\right]}_{\text{interaction effect}}. \tag{A9}$$

The sign of the direct effect is positive. The term in brackets is larger than one, so inverting it yields a number less than one—the feedback effect partially offsets the direct effect. The effect of international interaction depends on the sign of Π. Cooperation ($\Pi > 0$) serves to magnify the benefits of the SPR release, while competition ($\Pi < 0$) serves to mitigate them. In the extreme case, when foreign stocks are built barrel-for-barrel as the SPR is realized ($\Pi = -1$), the net effect on the oil market is nil. It is important to realize that the magnification (or mitigation) effect is more than proportional, due to the nonlinearity of the price reaction function. Thus for a given SPR drawdown, a higher value of Π not only affects the spot price proportionally through the interaction effect, but also works through the direct effect (by lowering the argument of f') to exert additional downward pressure. In this paper, we ignore the international aspects of stockpile policy (effectively setting $\Pi = 0$) in order to focus on public-private interaction.

Macroeconomic Model

The transmission of an oil shock is modeled through a set of structural linkages. A sudden increase in the price of oil lowers the economy's potential output, reducing aggregate supply. Aggregate demand effects come through several channels. Personal consumption spending depends on permanent income and consumer wealth; an oil shock would lower consumption both by reducing the value of the existing capital stock (wealth effect) and by reducing current output (income effect). Business fixed investment depends on expected output and on the cost of capital services, which includes the cost of borrowed and equity funds as well as considerations of depreciation, investment tax credits, and the corporate income tax. Oil price increases influence capital spending through their impact on these channels. Housing and inventory investment decisions are also modeled. Oil shocks also affect the economy through the current account, though this impact is much larger in the short run than the long run in the model because of the difference in short-run and long-run price elasticities of the demand for oil, the propensity to import of oil-producing countries, and exchange rate movements. Shocks affect unemployment through their impact on real output in conjunction with their impact on real unit labor costs.

The model also emphasizes the determination of wages and prices as an important transmission mechanism. A common problem in many macroeconometric models is the simultaneity of the determination of wages and prices. Increases in unit labor costs are certainly a factor in inflation, but workers presumably consider inflation when making nominal wage demands. The growth of (nominal) wages in the model depends on inflationary expectations and on the unemployment rate. Labor compensation depends on wages, fringe benefits, and the employer's contribution to payroll tax programs (like social security and unemployment insurance).

Inflationary expectations depend on lagged inflation and on money growth. Hence, while oil price shocks may ultimately affect wage demands through their inflationary impact, the stance of monetary policy (i.e., whether or not to accommodate the shock) is important for the path of nominal and real wages after the shock. The implicit price deflator for the gross national product is determined from information about unit labor costs, the cost of capital services, and the aggregate price of energy (determined from the world oil market model and from assumptions about the prices of coal and natural gas).

The macroeconomic model also contains a model of the domestic money market, focusing on the supply of and demand for money. Short-term interest rates from that model in conjunction with a term structure equation (influenced by the financing of government debt) yield long-term interest rates (which influence business fixed investment) and mortgage rates (affecting housing demand). Central bank decisions on the growth of the monetary base also affect inflationary expectations, with resulting impacts on wage rate and exchange rate determination.

The government can also affect the outcomes of the variables in the model through changes in fiscal policy (taxes and spending). Changes in payroll taxes affect labor compensation and the price of output; changes in corporate income taxes, the investment tax credit, or allowable depreciation rates affect investment. In analyzing the impact of fiscal policy, the model focuses on:

(i) the timing of the revenue and expenditures changes;

(ii) the components of aggregate demand affected (and their feedbacks to the rest of the model);

(iii) the inflationary consequences of the changes; and the way in which the change is financed.

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