DO GASOLINE PRICES RESPOND ASYMMETRICALLY TO CRUDE OIL PRICE CHANGES?*

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We test and confirm that retail gasoline prices respond more quickly to increases than to decreases in crude oil prices. Among the possible sources of this asymmetry are production/inventory adjustment lags and market power of some sellers. By analyzing price transmission at different points in the distribution chain, we attempt to shed light on these theories. Spot prices for generic gasoline show asymmetry in responding to crude oil price changes, which may reflect inventory adjustment effects. Asymmetry also appears in the response of retail prices to wholesale price changes, possibly indicating short-run market power among retailers.

I. INTRODUCTION

The 1990–1991 Persian Gulf crisis and other recent oil market disruptions have brought to attention the response of retail gasoline prices to fluctuations in world oil prices. Some observers have asserted that gasoline prices react more quickly to increases in crude oil prices than to decreases. In this paper we test for asymmetry in the speed of retail price responses and find supporting evidence. Although such a pricing pattern could indicate market power at some level of the distribution chain, the connection is not immediately apparent. Lags in the adjustment of price to input cost changes are not consistent with simple models of either competitive markets or monopoly.

The transmittal of a price change from crude oil to retail gasoline depends on the response in many intermediate margins. Most service stations and "jobbers" who handle intermediate transactions are not owned by refiners, and thus, they set prices independently of the upstream firms.[1] Even when the production

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1. Although a refiner cannot set prices at retail outlets that it does not own and operate, nonlinear wholesale pricing and and other incentives from refiners

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and distribution process occurs wholly within one firm, a company faces opportunity costs at every point in the process. Because market transactions occur and price data are available at most points in the production and distribution process, we observe measures of these direct or opportunity costs.

In the next section we describe the United States gasoline production and distribution process in greater detail and, in this context, discuss the sources and appropriateness of the data that we analyze. In Section III we test for and find that retail gasoline prices increase faster when the crude oil price rises than they decline when the crude price declines. In Section IV we present theories that could link such asymmetries to each of the distribution tiers.

By analyzing the price response at each level of distribution, in Section V we attempt to distinguish between the competing explanations for the asymmetric response. We find indication of an asymmetry in the transmission of crude oil price changes to the changes in the spot price for generic gasoline, although adjustments in both directions occur very quickly. At the next level of transmission, however, we find little evidence of asymmetry: wholesale gasoline prices respond about equally quickly to decreases as to increases in spot prices for generic gasoline. Combining these two transmissions, we find that wholesale gasoline prices respond significantly faster to crude price increases than to decreases. Finally, in the transmission of price changes from wholesale to retail, we find evidence of asymmetry: retail prices change more quickly in response to wholesale price increases than to wholesale price decreases.

II. THE PRODUCTION AND DISTRIBUTION OF GASOLINE

The production and distribution of gasoline in the United States is illustrated in Figure I. Motor gasoline is one of many products that can be made from refining crude oil, along with diesel fuel, kerosene, jet fuel, heating oil, and other products. The mix of outputs can be altered by changing refining processes, but the scope for such output substitution, while maintaining efficient production, is limited. During our sample period gasoline

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are commonly used in an effort to lessen the double marginalization problem. See Shepard [1993] for a detailed description of the contractual relationships between refiners and dealers and Temple, Barker, and Sloan, Inc. [1988] for a description of common distribution practices.

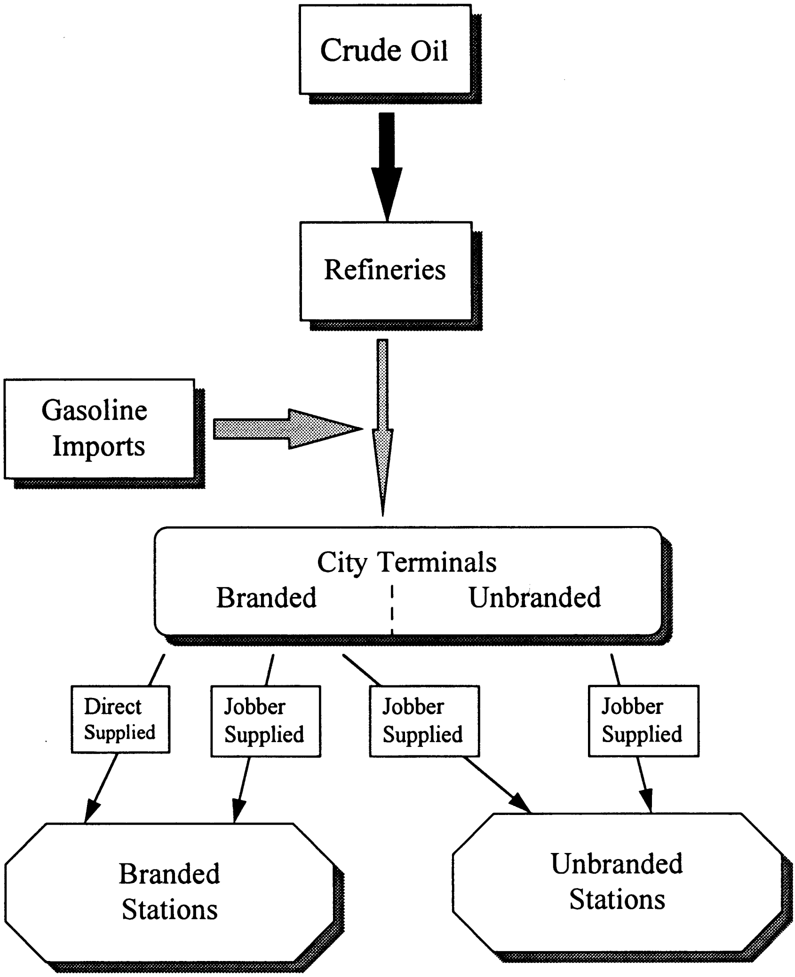

FIGURE I
Structure of the United States Gasoline Industry

averaged about 45 percent (by volume) of refined output at United States refineries [Energy Information Administration 1991, p. 16]. Gasoline is produced by over 100 United States refiners, with the largest company accounting for about 10 percent of United States production, and the four largest producing about 31 percent of the total [Dougher 1992, p. 80].

Gasoline produced at United States refineries, as well as the 5 percent of United States gasoline consumption that is imported, is distributed through many channels. Refiners often sell large quantities of generic gasoline directly from the refinery to distributors or other refiners in spot transactions. Gasoline may be shipped to the distribution terminal in a city and sold there as "branded" gasoline (with company-specific additives and with the right to use the refiner's name at resale) at a branded "terminal" (also known as branded "rack") price. Gasoline from a name-brand refinery may also be sold as generic gasoline at the terminal, without permission to use the refiner's name. Finally, "unbranded" refineries—those that do not operate their own chain of retail outlets—sell unbranded gasoline at their city terminals for resale at unbranded stations, i.e., stations that do not carry the name of a major refiner.

Once gasoline arrives at the city terminal, it can be distributed directly by the refiner ("direct-supplied") or through middlemen know as jobbers. About 55 percent of United States gasoline is distributed by jobbers or through other companies that are not controlled by refiners [Temple, Barker, and Sloan, Inc. 1988, p. 19]. A typical jobber supplies stations of many different brands and generally owns many of the stations it supplies. A jobber might, for instance, supply five Shell stations, three Chevron stations, and five unbranded stations, some of which the jobber owns and operates. All gasoline sold at the Shell stations must be purchased at the local Shell terminal by the jobber, and similarly for the Chevron stations. The unbranded stations can be supplied with the product of either Chevron or Shell, or gasoline from an unbranded refinery. At the margin the branded refiner competes with unbranded refiners, which only sell gasoline at the terminal for resale at unbranded stations. Unbranded gasoline prices discipline branded gasoline prices, which seldom differ by more than one cent per gallon at the terminal.[2]

Some gasoline is not purchased by jobbers, but is transported from the terminal to the retailer by the refiner. Most of these direct-supplied stations are operated by an independent franchisee, but some are owned and operated by the refiner. About 17 percent of United States gasoline is sold through refiner-operated stations [Temple, Barker, and Sloan 1988, p. 19]. For company-

2. Branded terminal prices exceed unbranded terminal prices by an average of about 1/4¢ in our data set.

operated stations no financial transaction occurs at the point of delivery, while franchisees purchase the delivered gasoline at a "dealer tankwagon" price.

At each point in the distribution process, many arm's-length transactions occur between companies. The prices of these exchanges indicate both the direct costs to the buyers and the shadow costs that vertically integrated firms face. Major refining companies, for instance, must frequently decide between refining additional crude oil or buying generic gasoline on the spot market, presumably equating the costs of these two sources on the margin. Thus, we use market transaction prices as indicators of the economic cost of the product at each stage of distribution.

The cost of crude oil can be represented by the daily spot market price of West Texas Intermediate (WTI) crude oil. More than 80 percent of oil traded worldwide is now traded at a spot price or under a contract with a price tied to the spot price [Razavi 1989]. WTI is the benchmark crude oil watched most closely in the United States. One criticism of using the spot price is that there is not an actual marketplace for spot crude oil transactions or real-time reporting of prices. Rather there are many independent trades that take place at different locations among well-informed traders. The price reported as the spot price is taken from a survey of traders each day, as reported by *Dow Jones International Petroleum Report* and published in the *Wall Street Journal.*[3] We have also constructed a price change series using nearest-contract futures prices for sweet crude oil, contracts that are traded on the New York Mercantile Exchange. This series has a correlation of 0.95 with the change in WTI spot prices. The results of our analysis are not altered by the use of futures prices instead of spot prices.

Generic gasoline prices are reflected in the spot gasoline prices for delivery to New York and the Gulf Coast.[4] As with crude oil, gasoline spot prices are determined by a daily survey of major traders, as reported by *Oil Buyers' Guide* and published in the *Wall Street Journal.* We use the New York spot price for our analysis, but the results change very little if we instead use the Gulf Coast spot prices or a series constructed from nearest-contract

3. Ravazi [1989] discusses potential reporting errors. Support for the reliability of these spot prices, however, is evident from the fact that many long-term contracts are indexed by this price.

4. The two prices have a correlation of 0.99 over our sample period. The daily price changes have a correlation of 0.74.

futures prices of gasoline traded on the New York Mercantile Exchange.

The branded city terminal prices are averages of 33 cities east of the Rocky Mountains from weekly surveys conducted by Lundberg Survey, Inc. on Friday of each week. Spot markets are not as well established in the West, and the spot and futures commodity prices that we have are for delivery in the East, so we omit cities in the western United States from our analysis.

As mentioned above, there is often one more transaction point for gasoline, when the product is delivered and sold to the retailer at a dealer tankwagon price. Unfortunately, the data available on these transactions are incomplete—they cover only direct-supplied stations and are probably unreliable. Refiners admit that they frequently discount off of the posted dealer tankwagon price.

Retail gasoline prices present a number of data problems. The retail price we use is the average of unleaded regular self-service gasoline prices in 33 United States cities east of the Rocky Mountains collected semimonthly by Lundberg Survey on either the first and third or second and fourth Friday of each month. As with all prices in this study, the Lundberg prices are exclusive of excise or sales taxes, are in current dollars, and are for Friday. The first complication with the retail price data is that all but one of the cities are surveyed only once each month, either always in the first survey or always in the second survey of the month. The first survey average price for each month is the average of seventeen cities, and the second is the average of seventeen cities, with one city (Atlanta) appearing in both surveys. In the econometric analysis that includes retail prices, we include separate dummy variables for the second through twenty-fourth survey of the year. In addition to controlling for seasonal effects, these correct for the set of cities in the first survey possibly having a different mean price than the set of cities in the second surveys.[5] The second complication is caused by the irregular sampling period. About 85 percent of the surveys occur two weeks after the prior survey, but 15 percent occur three weeks later. Though the results we present do not include correction for irregularly observed time series, earlier attempts to do so, reported in our 1992 work-

5. The estimated difference in average prices was never statistically significant. Tests for changes in this difference over time did not indicate that it changed significantly within our sample.

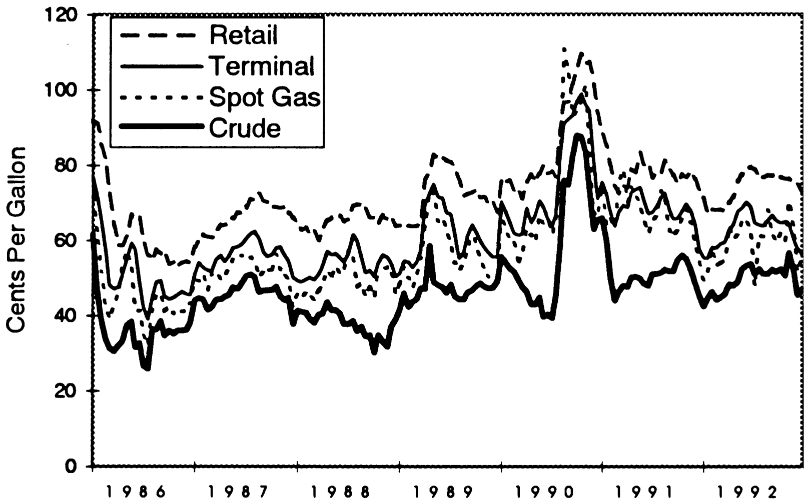

FIGURE II
Time Series of Gasoline and Crude Oil Prices

ing paper, indicate that this has little effect on our results. Further tests, reported in the Appendix, also lead to this conclusion.[6]

Figure II presents the semimonthly movements of prices for retail, terminal, and spot market unleaded gasoline, and spot WTI crude oil over our sample period from January 1986 to December 1992. This figure indicates that retail gasoline prices are less volatile than upstream gasoline prices or spot crude oil prices. The standard deviations of semimonthly changes in average retail, average terminal, spot market gasoline, and spot market crude oil prices are, respectively, 2.94¢, 3.77¢, 5.87¢, and 3.89¢. The smoother retail prices are indicative of the lags that we find in the adjustment of retail prices to changes in upstream prices and to the less-than-full adjustment that retail prices exhibit, e.g., a 1¢ increase in the spot price of gasoline or crude oil leads to a long-run increase in retail gasoline prices of less than

6. While weekly retail price data would be strongly preferred, the semimonthly Lundberg Survey data are the best available retail gasoline survey data. Other sources, in particular the *Oil and Gas Journal Database* employed in a number of studies, use wholesale prices to estimate approximate retail prices. Concerns about data reliability led to retail price data being dropped from the *Oil and Gas Journal Database* in 1992. Such data are clearly inappropriate for measuring the response of retail gasoline prices to changes in upstream prices.

1¢.[7] The much greater standard deviation for spot gasoline than for the other prices may reflect the rapid response of this price to both supply and demand shocks. Crude oil spot prices are more insulated from demand shocks. We find later that terminal and retail prices respond to supply shocks with significant lags.

III. Estimating the Response of Gasoline Prices to Oil Price Changes

A. A Simple Lag Adjustment Model

We begin the empirical analysis of gasoline pricing by testing the common belief that retail gasoline prices adjust more quickly to increases than to decreases in crude oil prices. To estimate the rate at which gasoline prices adjust to crude oil price changes, we start by assuming a simple linear long-run relationship between retail gasoline and crude oil prices, $R = \phi_0 + \phi_1 C + \varepsilon$, where R is the retail gasoline price per gallon, C is the price of crude oil per gallon, and ε is a normal and i.i.d. error term. We specify a relationship that is linear rather than log in nominal prices because the latter would imply that the crude-retail margin increases with the price of crude oil, which does not appear to be supported by the data.[8] The results we present, however, are very similar to those that obtain when the analysis is carried out with log values.[9]

We recognize that the adjustment of retail prices to changes in crude prices is not instantaneous, but we assume that the adjustment function is time-invariant during our sample period and is independent of the absolute magnitude of the crude oil price

7. This comparison of the standard deviation of *average* terminal and retail prices with the standard deviation of upstream prices is appropriate because the standard deviation of average terminal and retail prices are negligibly affected by idiosyncratic (city-specific) variation in each city's terminal and retail prices. Thus, these standard deviations for downstream prices are attributable almost entirely to nationwide effects. For instance, if all upstream price changes were passed through instantly and completely, we would expect the standard deviation of the *average* retail price to be about equal to the standard deviation of spot gasoline, but smaller than the standard deviation for retail price in any one city, which would include idiosyncratic city effects.

8. For instance, when the price of crude oil declined to about $12 per barrel in 1986, retail margins stabilized at about the same level as when crude was above $20 per barrel.

9. The linear specification has the drawback that it implies a constant nominal margin. We include a linear time trend in the final regression, which is a reasonably good approximation of the price index change over our sample period. Of course, in other periods of higher or more variable inflation, or over longer time periods, the linear model would not be tenable. We also have carried out the analysis using deflated prices (using the consumer price index or the producer price index) and have found very similar results.

change. Defining $\Delta C_t = C_t - C_{t-1}$ and $\Delta R_t = R_t - R_{t-1}$, the adjustment could be modeled as

(1)
$$\begin{aligned} \Delta R_t^t &= \beta_0 \Delta C_t \\ \Delta R_{t+1}^t &= \beta_1 \Delta C_t \\ &\vdots \\ \Delta R_{t+n}^t &= \beta_n \Delta C_t, \end{aligned}$$

where the superscript on ΔR indicates that it is solely the change resulting from the period t change in crude oil price and n is the number of periods it takes for retail prices to complete adjustment to the period t change in crude oil prices.

Under these assumptions the total change in retail gasoline price in any period t will depend on the crude oil price changes in the previous n periods:

(2)
$$\begin{aligned} \Delta R_t &= \Delta R_t^t + \Delta R_t^{t-1} + \ldots + \Delta R_t^{t-n} \\ &= \sum_{i=0}^{n} \beta_i \Delta C_{t-i}. \end{aligned}$$

Equation (2), however, imposes symmetric responses to increases and decreases in crude oil prices. Recognizing that the adjustment process could be different for increases than for decreases, we instead assume that

(3a)
$$\begin{aligned} \Delta R_t^t &= \beta_0^+ \Delta C_t \\ \Delta R_{t+1}^t &= \beta_1^+ \Delta C_t \\ &\vdots \\ \Delta R_{t+n}^t &= \beta_n^+ \Delta C_t \end{aligned}$$

if $\Delta C_t > 0$, and

(3b)
$$\begin{aligned} \Delta R_t^t &= \beta_0^- \Delta C_t \\ \Delta R_{t+1}^t &= \beta_1^- \Delta C_t \\ &\vdots \\ \Delta R_{t+n}^t &= \beta_n^- \Delta C_t, \end{aligned}$$

if $\Delta C_t \leq 0$.[10]

Defining

10. The choice of assigning the $\Delta C_t = 0$ cases to the estimates of β^+ or β^- will have no effect on the parameter estimates, because no change due to the zero change in crude oil prices will be expected, by assumption.

$$(4) \qquad \Delta C_t^+ = \max\{\Delta C_t, 0\} \quad \text{and} \quad \Delta C_t^- = \min\{\Delta C_t, 0\},$$

a simple empirical model for the adjustment of retail gasoline prices to crude oil price changes, allowing for the possibility of asymmetric adjustment rates, would then be

$$(5) \qquad \Delta R_t = \sum_{i=0}^{n} (\beta_i^+ \Delta C_{t-i}^+ + \beta_i^- \Delta C_{t-i}^-) + \varepsilon_t,$$

where ε is assumed to be an i.i.d. error term.

A number of econometric issues must be addressed before proceeding with estimation. The issues that we discuss here arise in the estimation of all of the downstream price transmissions. They lead to specification of a model more general than (5).

B. Restrictions Imposed on the Lag Response Structure

The additive lag structure we use places few constraints on the adjustment path, allowing it to be even nonmonotonic. It also allows an intertemporal independence: if the price of crude oil increases by 10¢ per gallon in week t and decreases by the same amount in week $t + 1$, our model would not necessarily cause the direction of adjustment to reverse when the crude oil price does. The retail price could continue to rise in week $t + 1$.[11] This contrasts with a standard partial adjustment model, an approach that has been used by previous authors studying adjustments to oil price changes.

If the long-run equilibrium relationship is assumed to be $R = \phi_0 + \phi_1 C + \varepsilon$, then we could estimate a partial adjustment model such as

$$(6) \qquad R_t - R_{t-1} = \beta(\phi_0 + \phi_1 C_{t-1} - R_{t-1}) + \varepsilon_t.$$

Bacon [1991] tests for asymmetry in adjustment rates by including a quadratic term in the adjustment process,

$$(7) \quad R_t - R_{t-1} = \beta_1(\phi_0 + \phi_1 C_{t-1} - R_{t-1}) + \beta_2(\phi_0 + \phi_1 C_{t-1} - R_{t-1})^2 + \varepsilon_t,$$

so that the test of $\beta_2 = 0$ is the test of whether adjustment to increases and decreases in crude oil prices occurs equally quickly. The partial adjustment model, however, imposes equal proportional adjustments toward the new equilibrium in all periods after a shock to crude oil prices, a serious constraint. Furthermore, Bacon's method for diagnosing asymmetry with a quadratic

11. This would occur in (5) if $\beta_1^+ > \beta_0^-$.

term imposes a structure on the asymmetry, implying that the asymmetry becomes *proportionally* larger as the difference between the current retail price and the long-run equilibrium price increases.

C. Incorporating the Long-Run Relationship between Gasoline and Crude Prices

The principal advantage of the partial adjustment model over the lag adjustment model presented in (5) is that the partial adjustment model takes account of the long-run relationship between the prices of the upstream and downstream goods, and the tendency to revert toward that relationship. To address this, we estimate (5) with an error-correction term. The error-correction term is the one-period lagged residual from the relationship $R_t = \phi_0 + \phi_1 C_t$. The regression is then

$$(8)\quad R_t - R_{t-1} = \sum_{i=0}^{n}\left(\beta_i^{+}\Delta C_{t-i}^{+} + \beta_i^{-}\Delta C_{t-i}^{-}\right) + \theta_1\left(R_{t-1} - \phi_0 - \phi_1 C_{t-1}\right) + \varepsilon_t.$$

D. Accounting for the Joint Production of Gasoline and Other Petroleum Products

Due to joint production, the price of gasoline will depend to some extent on the demand for other refined products. The effect could be positive or negative; while some substitutability among outputs is possible, leading for instance to a positive effect of heating oil demand on gasoline prices, the scope for substitution is limited. If companies refine more crude oil in order to produce more heating oil, the output will include more gasoline, thus depressing the price of gasoline. The latter effect is thought to be more significant in the refining industry.[12]

Despite the role that prices of other petroleum products may play in determining the price of gasoline, it is unlikely that omitting other refined product prices in estimating the adjustment of gasoline to crude oil price changes will lead to significant bias. The exogenous determinants of changes in other refined product prices are principally demand shifts, which are not likely to be

12. The complex interdependence of supply and demand for petroleum products is reflected in the following observation from the *Petroleum Economist* [August 1988, p. 280]: "Gasoline is becoming increasingly tight and straining upgrading capacity, chiefly as a result of the increased proportion of low-lead or unleaded requirements, but this simply creates surplus problems for the other products and accounts for caution on throughput levels even with superficially attractive refining margins."

correlated over a one-to-ten week period with changes in the price of crude oil.

Nonetheless, we checked the sensitivity of our results to exclusion of other refined product prices by including the current and lagged changes in heating oil prices—the other major refined product and the one for which demand is probably most volatile—in regressions of downstream gasoline prices on crude oil prices. For the same reasons that heating oil prices are likely to influence gasoline price, gasoline prices are likely to influence heating oil prices, so we instrumented for heating oil prices with a measure of heating degree days in the northeastern region. Regressions in both levels and differences indicated that heating oil margins (the price of heating oil minus the price of crude oil) have a significantly negative impact on gasoline prices at each level of the distribution chain. This is consistent with the industry wisdom that gasoline and heating oil are production complements on the relevant margin.

Inclusion of heating oil margins in the adjustment functions had virtually no impact on the estimated asymmetries in the adjustment of gasoline products to crude oil price changes. This is not surprising, since changes in heating oil margins were not significantly correlated with crude prices over our sample period. Of course, the joint production issue does not arise in estimating the response of terminal or retail prices to changes in upstream *gasoline* prices.

E. Possible Endogeneity of Upstream Prices

There is reason for concern that crude oil prices could be correlated with the error term in an equation such as (8). Such a correlation could be present if unobserved determinants of the retail (downstream) price were also correlated with the crude (upstream) price. This would not arise from seasonal or cyclical variation in upstream and downstream prices since we control for seasonal effects directly and measures of economic or money supply growth are never statistically significant when included. Similarly, it seems unlikely that idiosyncratic location-specific shocks to retail demand would be correlated with the price of crude oil, which is determined over the long run in a world market. Nonetheless, local demand shocks could affect upstream prices in the short run if transportation lags caused a short-term severing of the connection between local crude (or other upstream) prices and the world price for the upstream product.

To control for this possible endogeneity, we have identified three valid identifying instruments. Two are spot crude oil prices in England, which reflect world oil prices, but presumably are not affected by idiosyncratic demand shocks in the United States.[13] The third instrument is the six-month-ahead crude oil futures price.[14] Since any disconnection between local upstream prices and world prices should be transitory, the six-month-ahead futures price for crude oil (New York delivery) should not be affected by such shocks.[15]

Using these instruments, we carried out Hausman-Wu tests for exogeneity of the contemporaneous change in the upstream price in all of the transmissions that we estimated.[16] We found significant evidence of endogeneity in all but one of the transmissions, and the one remaining case indicated that exogeneity could be rejected at the 15 percent level. Thus, we proceed with estimation by two-stage least squares. The estimated price adjustments and asymmetries are very similar, however, when the endogeneity is ignored and estimation is carried out using ordinary least squares.

F. The Estimated Model and Cumulative Adjustment Functions

We estimate by two-stage least squares the equation,

$$\text{(9)}\quad \Delta R_t = \sum_{i=0}^{n}\left(\beta_i^+ \Delta C_{t-i}^+ + \beta_i^- \Delta C_{t-i}^-\right) + \sum_{i=1}^{n}\left(\gamma_i^+ \Delta R_{t-i}^+ + \gamma_i^- \Delta R_{t-i}^-\right) + \theta_1\left[R_{t-1} - \left(\phi_0 + \phi_1 C_{t-1} + \phi_2 TIME_t + \sum_{j=2}^{P}\left(\eta_j SRVY_{j,t}\right)\right)\right] + \varepsilon_t,$$

where ΔC_t^+ and ΔC_t^- are treated as endogenous and the six instruments that identify the regression are the associated increase and decrease change variables created from Brent and Forties crude spot prices in England and the six-month ahead futures

13. These are Brent crude and Forties crude spot prices in Northwest Europe for main loading ports in England, as reported (in U. S. dollars) in the *Wall Street Journal.*

14. This is the price of the sixth-nearest light sweet crude oil futures contract on the New York Mercantile Exchange on the date of observation, as reported in the *Wall Street Journal.*

15. This is reflected in the fact that the week-to-week change in the six-month-ahead futures price has a standard deviation of only 1.92, compared with 3.03 for the week-to-week change in the spot price of crude oil.

16. To do this, we created "increase" and "decrease" variables for each of the identifying instruments, just as we did with the crude oil price. Thus, there were six excluded exogenous variables that identified the two contemporaneous crude oil change variables that were taken to be endogenous.

price.[17] This model additionally includes signed lagged changes in retail prices, necessary to ensure that the error term is white noise, and a richer specification of the long-run model. *TIME* is a time trend included because the data are levels of nominal prices, as discussed above. The *SRVY* variables are dummy variables for the particular survey of the year, with P equal to 24 for semimonthly data and equal to 52 for weekly data. These pick up seasonal influences, and the difference in the cities surveyed for the first versus second surveys of the month when retail data are used.

Model (9) can be rearranged to be linear in the variables, though not in the parameters:

$$(10)\quad \Delta R_t = -\theta_1\phi_0 + \sum_{i=0}^{n}\left(\beta_i^+\Delta C_{t-i}^+ + \beta_i^-\Delta C_{t-i}^-\right) + \sum_{i=1}^{n}\left(\gamma_i^+\Delta R_{t-i}^+ + \gamma_i^-\Delta R_{t-i}^-\right) - \sum_{j=2}^{P}\left(\theta_1\eta_j SRVY_{j,t}\right) + \theta_1 R_{t-1} - \theta_1\phi_1 C_{t-1} - \theta_1\phi_2 TIME_t + \varepsilon_t.$$

From estimation of this equation we can directly obtain estimates of the β's, γ's, and θ_1 necessary for construction of the cumulative adjustment function. To incorporate in the cumulative adjustment function the reversion toward a long-run relationship, we also need an estimate of ϕ_1. The coefficient on C_{t-1} divided by the coefficient on R_{t-1} is a consistent estimate of ϕ_1. Augmented Dickey-Fuller tests, presented in the Appendix, indicate that the price series are individually I(1) and pairwise cointegrated.

The specific procedure for determining the lag length to be used in the estimation and tests for white noise residuals are detailed in the Appendix. The lag length should be long enough to capture complete adjustment and ensure white noise residuals. We include *TIME* and the *SRVY* variables to guard against the possibility that our results are due to omitted trends or seasonal effects.[18]

Our empirical analysis is focused on the resulting cumula-

17. Since the six instruments are more than necessary to identify the two endogenous variables, we also tested sequentially the exclusion restriction on each of the identifying instruments by including in the regression the increase/decrease pair of variables from a given instrument. In each case, neither the increase variable, the decrease variable, nor the pair jointly were significant at the 10 percent level.

18. The *TIME* variable is significant at the 5 percent level in three of the five reported regressions, those in which crude oil is the upstream price. The survey variables are jointly significant at the 5 percent level in the same three regressions. For consistency, we include *TIME* and the *SRVY* variables in all five regressions, but the cumulative adjustment functions change little if they are excluded.

tive adjustment functions rather than on the parameter estimates. These measure the adjustment of retail gasoline (or other downstream) prices to a one-unit change in crude oil (or other upstream) prices. The cumulative adjustment function is a nonlinear function of the parameters, as the adjustment in the nth period after a change in the crude oil price will be the sum of the estimated response parameter from (10) (β_n^+ or β_n^-), the effects of the resulting changes in retail prices (γ_n^+ or γ_n^-), and the error correction effects over the n weeks. To arrive at an estimate of the full adjustment path, we construct cumulative adjustment functions for both increases and decreases in the price of crude oil, by methods explained in the Appendix. Standard errors for points on the cumulative adjustment function are derived using the delta method.[19]

G. Asymmetric Retail Price Responses to Crude Oil Price Changes

We estimate equation (10) by two-stage least squares using semimonthly retail and crude oil prices, both expressed in cents per gallon, from March 1986 through the end of 1992. The data used begin with March 1986 for all regressions so that the sample size can be standardized across regressions with different lag lengths. The procedure to determine lag length, presented in the Appendix, indicated that inclusion of two-period lagged changes in retail and crude prices was appropriate. The results of this estimation, excluding the 23 survey dummy variables, are shown in the first column of Table I.

The regression results indicate that the contemporaneous response of retail prices to crude oil price changes, the Upstream_0^+ and Upstream_0^- coefficients, is much greater for increases in crude prices than for decreases. To fully analyze later responses, however, one must include the indirect effects that would show up from lagged changes in retail prices and the effect of the reversion toward a long-run relationship.

The estimated cumulative adjustment functions are shown in Figure III. One period of a half-month is represented as two weeks on the graph. The line with plus signs is the estimated retail price response (in cents per gallon) to a one-time one cent

19. We have also estimated the 95 percent confidence bounds using a bootstrap method, similar to that described by Freedman [1984], with very similar results.

TABLE I
ESTIMATES OF PRICE ADJUSTMENT EQUATIONS

Downstream price:	Retail	Spot gas	Terminal	Terminal	Retail
Upstream price:	Crude	Crude	Spot gas	Crude	Terminal
Periodicity:	Semi-monthly	Weekly	Weekly	Weekly	Semi-monthly
Observations:	164	351	351	351	164
$\Delta Upstream^{+}_{0}$	0.549	0.888	0.593	0.558	0.623
	(0.084)	(0.135)	(0.075)	(0.063)	(0.069)
$\Delta Upstream^{+}_{-1}$	0.246	0.691	0.041	0.178	0.357
	(0.087)	(0.140)	(0.058)	(0.062)	(0.083)
$\Delta Upstream^{+}_{-2}$	0.022	−0.161	0.058		−0.101
	(0.088)	(0.136)	(0.048)		(0.079)
$\Delta Upstream^{+}_{-3}$					−0.024
					(0.076)
$\Delta Upstream^{-}_{0}$	−0.181	1.088	0.182	0.210	0.199
	(0.136)	(0.143)	(0.081)	(0.071)	(0.120)
$\Delta Upstream^{-}_{-1}$	0.236	−0.239	0.145	0.203	0.251
	(0.098)	(0.127)	(0.048)	(0.052)	(0.080)
$\Delta Upstream^{-}_{-2}$	0.028	−0.286	−0.001		0.065
	(0.100)	(0.116)	(0.040)		(0.080)
$\Delta Upstream^{-}_{-3}$					−0.133
					(0.070)
$\Delta Downstream^{+}_{-1}$	−0.314	−0.055	0.180	0.289	−0.507
	(0.123)	(0.096)	(0.090)	(0.077)	(0.109)
$\Delta Downstream^{+}_{-2}$	0.069	−0.009	−0.203		0.174
	(0.119)	(0.098)	(0.089)		(0.107)
$\Delta Downstream^{+}_{-3}$					0.004
					(0.095)
$\Delta Downstream^{-}_{-1}$	0.127	−0.070	0.310	0.332	−0.086
	(0.131)	(0.094)	(0.092)	(0.077)	(0.112)
$\Delta Downstream^{-}_{-2}$	0.396	0.279	0.042		0.271
	(0.119)	(0.091)	(0.081)		(0.087)
$\Delta Downstream^{-}_{-3}$					0.103
					(0.077)
$Upstream_{-1}$	0.141	0.131	0.229	0.081	0.278
	(0.040)	(0.037)	(0.034)	(0.020)	(0.054)
$Downstream_{-1}$	−0.175	−0.183	−0.254	−0.118	−0.262
	(0.045)	(0.037)	(0.039)	(0.024)	(0.054)
Time	0.225	0.326	0.011	0.165	−0.015
	(0.109)	(0.113)	(0.044)	(0.056)	(0.069)
R^2	0.663	0.589	0.646	0.630	0.916

Two-stage least squares estimates with $\Delta Upstream^{+}_{0}$ and $\Delta Upstream^{-}_{0}$ are treated as endogenous. Identifying instruments are positive and negative change variables from England crude oil spot markets and six-month-ahead crude oil futures market.

Asymptotic standard errors are in parentheses.

Fixed seasonal effects (described in the text) are not presented.

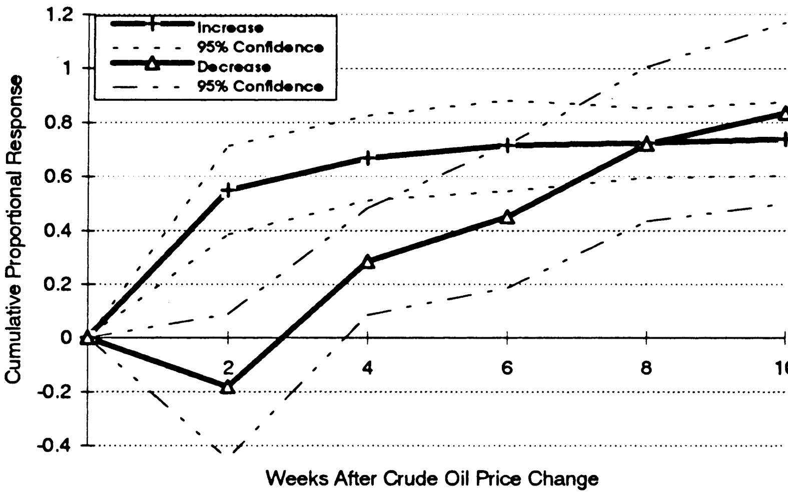

FIGURE III
Crude-to-Retail Cumulative Adjustments

per gallon increase in crude oil prices. Thus, a one cent increase in crude oil prices leads to a 0.55¢ increase in the first two weeks and a further 0.12¢ increase in the next two weeks, for a 0.67¢ increase after four weeks, and so on. The line with triangles is the estimated retail price response to a decrease in crude prices. The increases seem to be passed along faster than the decreases.

These cumulative adjustment functions are estimated with an imperfect degree of confidence. In Figure III we also present estimates of the 95 percent confidence bounds for the cumulative adjustment functions. The lighter dotted lines are the bounds for responses to a unit increase and the lighter dashed lines are the bounds for response to a negative unit change. After ten weeks the functions are not significantly different from one another and are not significantly different from the estimated long-run adjustment factor of about 0.81. As one would expect, the estimates of these cumulative functions get noisier further away from the date of the crude oil price change. Still, the functions seem to be sufficiently different as to indicate an asymmetric adjustment speed.

One possible test of the symmetry of response is to compare the cumulative adjustment functions with one another at a given point after the crude oil price change. This is not particularly informative, however, about the underlying issue of how such an asymmetry affects consumer costs overall. Instead, we compare the gain to consumers from a given decrease in crude oil prices over the lifetime of the price adjustment with the loss to consumers over the adjustment process from an equal size increase in oil prices.

For instance, a one cent per gallon increase in the price of oil is estimated to increase gasoline prices by 0.55¢ at two weeks after the crude oil price increase, while a one cent per gallon decrease in the price of crude is estimated to *increase* gasoline prices by 0.18¢ at the same point. Thus, two weeks after a crude oil price change by one cent, a consumer's costs would have increased by 0.73¢ (= 0.55 − (−0.18)) more per gallon when crude prices increase than her costs would have decreased when crude prices decrease. Similarly, at week 4 the difference would be 0.67¢ − 0.28¢ = 0.39¢ per gallon. Integrating the differences in cumulative adjustments over the life of the adjustment yields an estimate of the asymmetry in cost to the consumer:

$$\text{(11)} \qquad \Delta \text{ Consumer Cost} = A_n = \int_{j=0}^{n} \left(B_j^+ - B_j^-\right) dj,$$

where B_j^+ and B_j^- are the estimated cumulative adjustments at time j to a one cent increase and decrease, respectively, in crude oil price. Under simple linear interpolation between estimated adjustment points, A_n is the difference in the areas under the two cumulative adjustment curves in Figure III from week 0 to week n.

Figure IV presents the estimated A_n and their 95 percent confidence bounds. It indicates that the total cost asymmetry rises to week 6 and then remains roughly constant around 2.6¢ per one cent crude price change per gallon bought each week. The asymmetry is significantly different from zero at the 5 percent level until after week 10. Thus, if a consumer uses ten gallons of gasoline per week,[20] a 5¢ per gallon increase in crude oil prices (equivalent to a $2.10 per barrel crude oil price increase) costs the consumer $1.30 more over the life of the adjustment than a 5¢ per gallon decrease saves her.[21] The asymmetry implies that variability in crude oil prices, even if there is no systematic increase or decrease in price, is costly to consumers.[22]

20. This is about the United States average per vehicle during our sample period [Energy Information Administration 1991, p. 7].

21. $1.30 is the 2.6 asymmetry multiplied by the 5 cent crude oil price change multiplied by ten gallons consumed per week.

22. When estimated in logs, the asymmetry also is significantly different from zero at the 5 percent level until after week 8. Retail price appears to adjust fully to increases in crude after four weeks (about a 0.6 percent long-run change

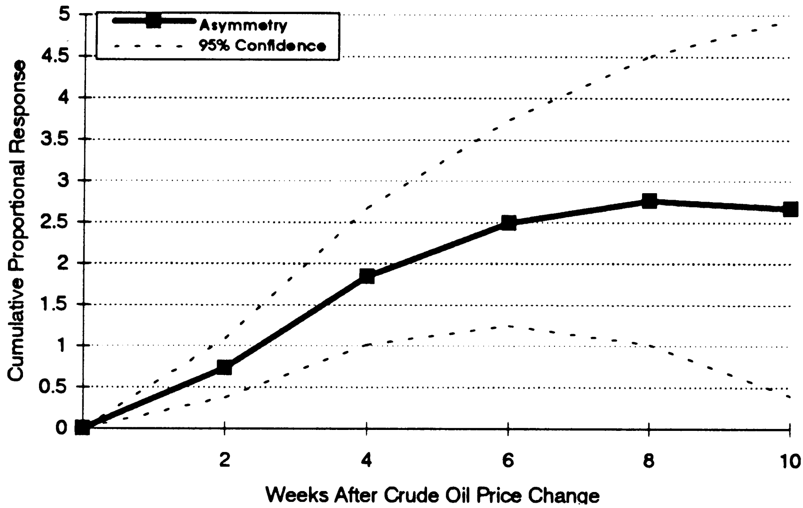

FIGURE IV
Crude-to-Retail Cumulative Adjustment Asymmetry

The fact that the asymmetric adjustment process indicates greater costs for consumers than would occur with symmetric adjustment does not imply either market power or supernormal profits among sellers at any point of the production process. Although two of the hypotheses discussed in the next section suggest that temporary market power could explain the asymmetry, other explanations consistent with competitive markets are also plausible.

Finally, it is worth commenting on the fact that the ten-week transmission of an x cent change in the price of a gallon of crude oil is less than x cents. This sort of "incomplete" adjustment over the ten weeks recurs in many of our subsequent estimates of price transmission through the points of distribution. In this case it could be attributed to the fact that there is substitution in inputs and outputs in the refining process. The scope for substitution is extremely small, however, in cases of upstream and downstream gasoline prices, e.g., the response of terminal prices to spot gasoline price.

in retail for a 1 percent change in crude oil price), but continues to adjust to decreases out to week 10. When the level regression is estimated by OLS rather than 2SLS, the asymmetry is significantly different from zero at the 5 percent level until after week 6. The total cost asymmetry rises to week 6 and then remains at about 1.6¢ per one cent crude price change per gallon bought each week.

At least two other explanations are possible. First, the transmission we observe could reflect only the short-run adjustment to the upstream cost change. If the short-run supply curve is upward sloping, we would expect only partial transmission of a price change over the period observed. For instance, an increase in oil prices might be partially passed along to terminal prices in the short run, but also lead to losses among some or all refiners. As refiners exit the market, price would rise farther in the long run, which we would not observe in a ten-week adjustment. Still, our estimate of the long-run relationship between the upstream and downstream prices, ϕ_1 would then reflect full passthrough. While the estimate of ϕ_1 is not significantly different from one in the crude-retail transmission, it is significantly below one in all of the transmissions that do not involve retail prices.

An alternative explanation, one consistent with $\phi_1 < 1$, is that the downstream industry under observation experiences industry diseconomies of scale, so that the industry supply curve downstream is upward sloping even in the long run. In that case the adjustment we observe in the first ten weeks could be all that actually occurs.

IV. Explanations for Asymmetric Retail Price Adjustments

We have identified three hypotheses that might explain departures from symmetric adjustments of retail gasoline prices to changes in crude oil prices. These hypotheses differ in the assumed degree of economic sophistication of the agents and in the incentives that the agents are assumed to face. They also differ in the competitive structure that is assumed at various points along the distribution chain. Most importantly, they differ in their implications for selling margins at different points in the distribution chain. These differences yield the predictions that could enable us to differentiate among them.

Hypothesis 1. Prices are sticky downward because when input prices fall the old output price offers a natural focal point for oligopolistic sellers.

In response to a negative cost shock, a firm might choose to maintain a prior price until demand conditions force a change. This is a variant of the "trigger price" model of oligopolistic coordination [Green and Porter 1984]. In that model each firm restricts its output to a level below the competitive (Nash) output if, and only if, the market price is above a threshold level. In the retail gasoline market each firm chooses its selling price with imperfect information about the prices charged by others. Firms may choose to maintain prices above competitive (Nash) levels if their sales remain above a threshold level. A drop in sales would indicate price cutting by rival firms and would justify a price reduction as an optimal competitive response. Tirole [1988] provides an analytical description of this "trigger sales" model.[23]

The model can explain asymmetric pricing behavior by retail gasoline outlets. A significant positive crude price shock would trigger retail price increases, otherwise, retail margins would become negative. Retail prices need not respond immediately to a negative crude price shock. However, over time, random shocks in demand would lead retailers to cut their prices in an equilibrium response to the threat of price cutting by rival firms.

While appealing, there are several deficiencies in this theory. A trigger sales model explains how retailers may sustain prices above competitive levels, but the model does not explain how retailers will coordinate on a particular price. There are multiple equilibria with prices above the competitive level. A price that firms charged before a shock lowers wholesale prices is a natural focal point for coordination, but that price is not a unique oligopoly equilibrium. An apparently troublesome aspect of the trigger sales model is that when coordination breaks down, retailers abruptly lower price to the competitive level. This is not inconsistent with a gradual reduction in *average* market prices, however, because the breakdown in coordination can begin locally and then spread to other retailers. With numerous clusters of interdependent firms, average prices can exhibit a gradual decline toward competitive levels following a negative cost shock.

An oligopolistic coordination equilibrium of the kind described here is consistent with a rapid response of prices to positive cost shocks and a slow response to negative shocks. The response to cost shocks would be asymmetric because retailers would refrain from cutting prices in response to a negative shock and would instead rely on prevailing prices as a focal point for oligopolistic coordination. Retailers would not exercise similar restraint after a positive cost shock. Given the typically thin margins in gasoline distribution, retailers would operate at a loss if

23. See Tirole [1988, p. 264]. See our working paper [1992] for an application of the Tirole model to the gasoline retailing market.

they did not raise prices after a significant positive cost shock. Thus, a price increase after a significant positive cost shock is profit maximizing without regard to the pricing behavior of other retailers.

The theory is sufficiently general that it might describe the price change transmission mechanism from spot crude oil to spot gasoline, from spot gasoline to gasoline sold at the city terminals, or from terminal gasoline to final retail sale. Upon closer scrutiny, however, the theory is unlikely to describe the transmission of crude oil price changes to changes in the spot gasoline market. The spot gasoline market is supplied to some extent by nearly all of the United States refiners.[24] Concentration in the gasoline refining industry is quite low nationally, and sales in the spot market are for generic gasoline, so it seems unlikely that tacit collusion could persist among those who produce gasoline sold in the spot market.

The oligopolistic coordination theory could possibly explain asymmetric terminal price movements in response to spot gasoline or crude oil price changes, if such an asymmetry exists. In fact, this seems to be the implication of complaints that the major oil refining companies collude to slow passthrough of oil price decreases. There is, however, an important check on oligopolistic coordination in the sale of even branded product at the terminals. If a refiner's branded price at the terminal gets too high relative to the spot price from gasoline, the refiner will quickly see two effects: (1) it will lose most or all sales for use other than branded resale, i.e., marginal sales on which it competes with unbranded gasoline; and (2) branded resellers of the refiner's product, jobbers and retailers, will suffer reduced margins or reduced sales and will pressure the refiner to lower its price.[25]

The theory seems most likely to describe the reaction of retail prices to changes in the wholesale or terminal price. Sellers are spatially and otherwise differentiated. They face many competitors, only some of which can be monitored at low cost. If stations in an area are operating at competitive margins and then the wholesale price of gasoline declines, it seems plausible that each

24. Although transaction prices are not posted per se, they are constantly monitored, and they necessarily track the prices for gasoline futures, which are traded on the New York Mercantile Exchange, quite closely. See Ng and Pirrong [1992].

25. See Borenstein and Gilbert [1993] for a more thorough analysis of competition among refiners on a national and local level.

station might maintain its retail price until it sees convincing evidence (in the form of lower sales) that competing stations have lowered price. The sellers are certainly not price takers, and the buyers are not completely informed about the price of each seller.[26]

HYPOTHESIS 2. Production lags and finite inventories of gasoline imply that negative shocks to the future optimal gasoline consumption path can be accommodated more quickly than positive shocks.

If half of all world oil reserves suddenly disappeared, the long-run competitive price of gasoline would increase greatly, and consumption would decrease greatly. Oil companies could accommodate that change quickly by raising gasoline prices. Since refinery production schedules cannot be adjusted immediately—such responses generally take at least two to four weeks to implement—the result would be a short-run building up of finished gasoline inventories. In contrast, if world oil reserves doubled overnight, the short-run response in the gasoline market would be limited by available supplies of finished gasoline.

Essentially, this argument relies on an asymmetry between the short-run cost of decreasing inventories versus increasing inventories. While it is clear that inventories must be nonnegative so the cost of decreasing inventories must increase substantially at some point, the elasticity of the marginal cost of increasing inventories is less clear. If, for instance, storage adjustment marginal costs were decreasing at low levels of reserves and constant at all higher levels, as would be the case if refiners had substantial excess storage capacity, then the asymmetry in storage adjustment costs would exist. These asymmetric adjustment costs also could be a local or regional phenomenon since there can be significant transportation bottlenecks, and pipelines carry oil products in only one direction.

Reagan and Weitzman [1982] present such a model with asymmetric inventory adjustment costs due to the nonnegativity constraint on inventories. They find that in the short run prices should respond more to situations of excess demand than to excess supply, because the ability and incentive for competitive

26. See Shepard [1991], Borenstein [1991], and Borenstein and Shepard [1996a] for evidence of price discrimination and local market power among retail gasoline sellers.

firms to respond with inventory (quantity) adjustments is greater in the case of excess supply. Bresnahan and Spiller [1986] develop a related theoretical model that explains "backwardation," the premium of spot prices over futures prices. They note that arbitrage constrains the amount by which futures prices can exceed current spot prices (known as a "contango" condition, the opposite of backwardation), because all current consumption can be shifted into the future. By contrast, the only future consumption that can be shifted to the current period—the arbitrage that would limit backwardation—is the current inventories that would otherwise be held to the next period. Borenstein and Shepard [1996b] examine the role of production lags and inventory adjustment costs in explaining the lagged response of wholesale gasoline prices to crude oil price changes. Using futures market and terminal price data, they find evidence that these factors play an important role in the lagged response of wholesale gasoline prices.

This inventories theory could explain asymmetry in the adjustment of spot gasoline prices to spot crude oil prices or in the adjustment of terminal prices to the upstream spot prices. It is unlikely to be relevant to an asymmetry that could occur between terminal price and retail price changes, because service stations do not generally set price in order to ration scarce inventories. Service stations can almost always order and receive delivery of gasoline on less than 48 hours notice.[27]

HYPOTHESIS 3. Volatile crude oil prices create a signal-extraction problem for consumers that lowers the expected payoff from search and makes retail outlets less competitive.

When a consumer knows that crude oil prices or retail gasoline prices are currently volatile, he or she may be more likely to believe that an increase in one station's retail price reflects crude oil price changes, rather than a change in the station's relative price in the retail market. Thus, the expected gain from search in reaction to a retail price increase may be smaller when crude oil prices are known to be volatile than when they are fairly stable. Each retailer realizes that this implies a temporary de-

27. At least two major refiners we have spoken with say that they set no minimum quantity for delivery to their branded stations, although one does require that the stations to which it delivers have underground storage tanks of at least a minimum size, and it is customary for a station to order sufficient quantity to fill its tanks. The most active stations receive deliveries every day or two, while those selling less volume may get supplied only once every one to two weeks.

cline in the elasticity of demand it faces and thus increases its margin. This temporarily increased market power of retailers may dampen the rate of passthrough of upstream price decreases and exacerbate the rate of passthrough of upstream price increases, possibly even resulting in temporary "overshooting" on increases. Since this is a theory of costly search, it applies to retail margins, but has little to say about refiner or wholesaler margins.

Bénabou and Gertner [1993] formalize a theory of costly endogenous search and conclude that common cost shocks among competing firms (or economywide inflation) can increase or decrease the equilibrium amount of consumer search, and thus increase or decrease competition among sellers. They find that search is more likely to decrease due to common cost shocks if the cost of search is high to begin with.

These three hypotheses do not exhaust the possible explanations for the asymmetric response of retail gasoline to crude oil prices. Still, variations on these theories have been suggested either directly in the context of gasoline pricing, as is the case for Hypotheses 1 and 2, or more broadly, but with obvious application to the gasoline market, e.g., Hypothesis 3. Recognizing that we will not in this study be able to identify the single model that describes the actual transmission process from crude oil to retail gasoline prices, we seek instead to narrow the field by ruling out common explanations that are not supported by a more detailed analysis of the data.

V. Identifying the Asymmetric Transmission of Price Adjustments

To shed light on the asymmetry hypotheses, we consider in turn the following transmissions: crude oil to spot gasoline, spot gasoline to city terminal (wholesale) gasoline, crude oil to city terminal gasoline, and city terminal to retail gasoline. Two-stage least squares estimates of (10) (with the appropriate upstream and downstream variables) using data from March 1986 to the end of 1992 are presented in columns 2 to 5 of Table I. The first three of these transmissions are estimated using weekly data, and the last using semimonthly data.

The first price transmission we investigate for asymmetry is from changes in crude oil prices to changes in the commodity price for generic gasoline. The spot and futures gasoline markets are used by independent refiners and marketers of gasoline to obtain and sell gasoline, as well as by firms interested in hedging risk or speculating on future shocks to gasoline demand or supply. They are also used by the major refiners to balance excess supply or demand for their branded product. With the proper additives and the appropriate insignia on the side of the delivery truck, generic gasoline bought in the spot market can be marketed by a major refiner as its own namebrand gasoline.

The large number of participants in the gasoline spot and futures markets, and the generic nature of the product, make these markets quite competitive. Since the refined gasoline product is traded in these markets, price will reflect not only the cost of inputs in making gasoline, particularly the cost of crude oil, but also the short-run constraints on delivery due to production or transportation bottlenecks, refinery outages, and the availability of gasoline inventories. If asymmetric production and inventory adjustment costs, as explained in Hypothesis 2, are responsible for the asymmetry of retail price adjustment to crude oil price changes, one might expect this to be evident in the relationship between the spot gasoline price and spot crude oil prices. Hypotheses 1 and 3 would not be supported by an asymmetry in spot gasoline price adjustment, because of the low search costs and competitiveness in the spot gasoline market.

The estimates, represented in Figure V, exhibit an asymmetry in the adjustment of gasoline spot prices to changes in crude oil spot prices. The asymmetry rises to almost 2.0¢ (per 1¢ change in crude oil spot price). Due to the noisy estimates, however, the asymmetry is never significantly different from zero at the 5 percent level, although it is nearly so at week 4.[28]

The adjustment of generic gasoline prices to changes in crude oil prices appears to occur very quickly, and the cumulative adjustment is fairly symmetric at the end of week 1. At two weeks, however, there is a noticeable asymmetry. One might wonder, however, whether this might be an artifact of the spot price data collection.[29] To check this, we compared the results with those using the nearest-contract futures price series and found very similar results.

28. We also have estimated this adjustment function using daily data and have found very similar results.

29. Ng and Pirrong [1992] find that new information in refined petroleum product markets generally affects prices in the futures market before it appears in the spot market. The lag they find, however, is only about two days.

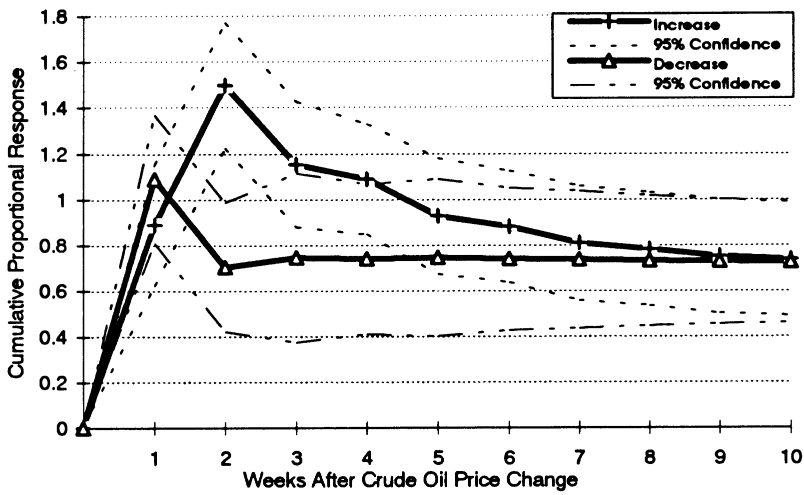

FIGURE V
Crude-to-Spot Gasoline Cumulative Adjustments

These results appear to violate weak form efficiency in the spot (or futures) unleaded gasoline markets. It appears that the change in today's crude oil price can be used to predict next week's change in the unleaded gasoline commodity price. Although this interpretation is correct, it may not be possible to trade profitably on this information. The reason again relates to the level of inventories and the marginal cost of changing inventory levels. If gasoline inventories are low, then a decrease in crude oil prices might not be immediately transmitted downstream because the very short-run scarcity value of the gasoline exceeds its eventual replacement cost. Arbitraging may not be possible because the higher short-run price reflects the temporary scarcity.[30]

The asymmetry in the gasoline commodity price adjustment to crude oil price changes is probably part of the cause for the asymmetric adjustment of retail prices to crude oil price changes. It is consistent with the theory that production and inventory adjustment costs explain part of the asymmetric retail price adjust-

30. Bresnahan and Suslow [1985] demonstrate the presence of similar predictable price changes in the copper market. More recently, Deaton and Laroque [1992] have found similar results in studying price series for thirteen commodities.

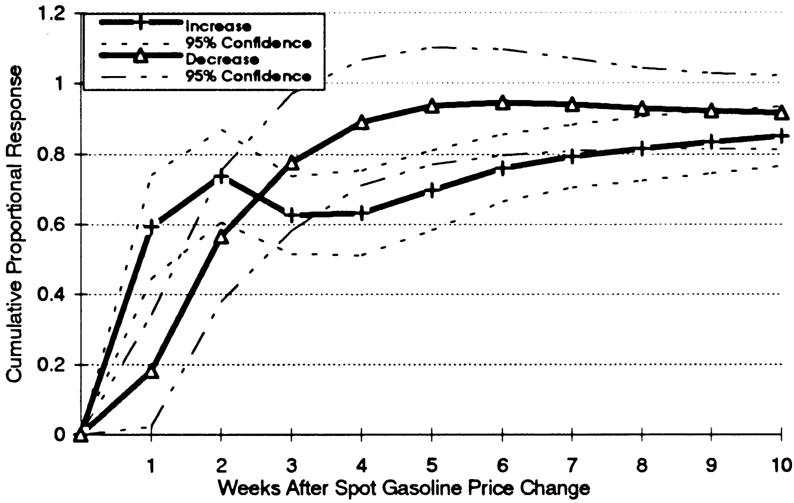

FIGURE VI
Spot Gasoline-to-Terminal Cumulative Adjustments

ment. There are other possible interpretations, but in any case, this component of the explanation probably cannot be attributed to Hypotheses 1 or 3.

Figure VI indicates that the transmission of gasoline prices from the spot gasoline market to the city terminals displays some evidence of asymmetry in the first few weeks, but then the speed of negative adjustment becomes greater causing the asymmetry to decline and possibly reverse. After three weeks, however, the asymmetry is not statistically significant. Even at its peak (week 3), however, this cumulative asymmetry is only about 0.5, a small part of the overall asymmetry. This result conflicts with Hypothesis 1 to the extent that it might explain an asymmetry in the price-adjusting behavior of the major branded refiners. If crude oil price decreases facilitated coordination among the major refiners of gasoline that induce the retail price asymmetry described in Section III, then transmission of changes from the generic spot gasoline market—for which production is very competitive—to branded terminal prices would be expected to exhibit that asymmetry.

The net result in the transmission of crude oil prices to branded city terminal gasoline prices is shown in Figure VII. This figure indicates an asymmetry out to city terminals that is statis-

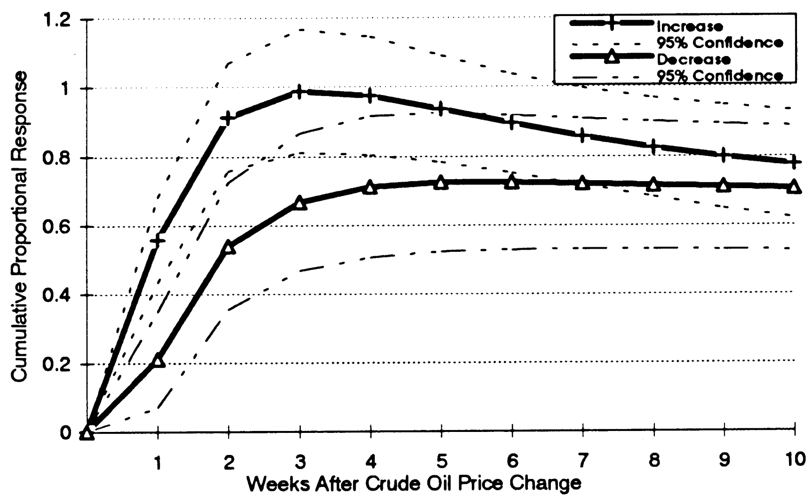

FIGURE VII
Crude-to-Terminal Cumulative Adjustments

tically significant for at least ten weeks and is of the same sign as we found in the crude-to-retail asymmetry, but not quite so large. It climbs gradually to about 2.0¢ by week 10, although it is barely significant at the 5 percent level by then.

The transmission process from terminal to retail prices appears to be a smaller, but also significant, source of the asymmetry in retail price response to spot crude oil price changes. Figure VIII indicates that terminal price increases are transmitted to retail prices significantly more quickly than terminal price decreases over the first four weeks. The cost asymmetry is estimated to be about 1¢ at four or six weeks for every 1 cent change in the terminal price, but it is not statistically significant after four weeks. The estimated asymmetry then declines somewhat, and the estimates become much noisier. The pattern of the terminal-retail asymmetry is similar to the crude-retail asymmetry, and it is about two-fifths as large at its peak.

The estimated terminal-retail asymmetry is consistent with Hypothesis 1, as it relates to the retail gasoline market, and Hypothesis 3, that the consumers' signal-extraction problem resulting from noisy common input prices temporarily lowers the elasticity of demand faced by retail outlets. This may result in retailers increasing prices more quickly and decreasing prices

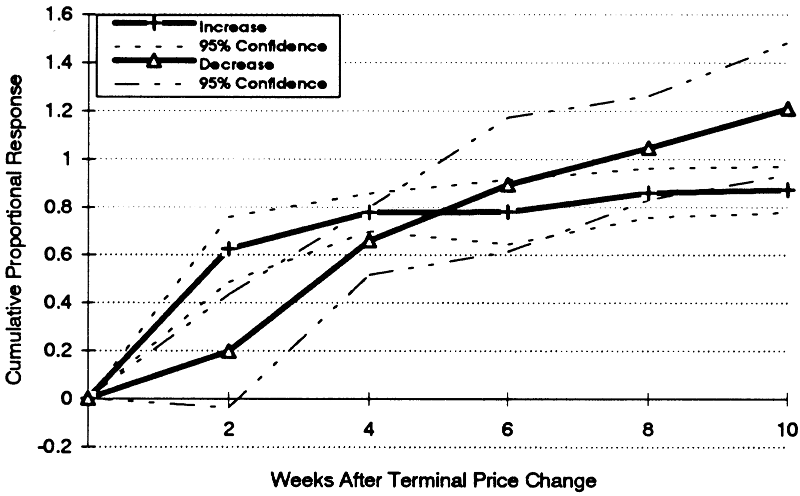

FIGURE VIII
Terminal-to-Retail Cumulative Adjustments

more slowly in response to input price changes than would occur if consumers were perfectly informed.

VI. CONCLUSION

The evidence we have gathered supports the common belief that retail gasoline prices respond more quickly to increases in crude oil prices than to decreases. Establishing the points in the distribution chain at which the asymmetries occur could be a powerful tool in distinguishing between possible explanations for the phenomenon. The adjustment of spot gasoline markets to changes in crude oil prices appears to be responsible for some of the asymmetry. This asymmetry also is reflected in the adjustment of terminal prices to crude oil price changes. In the response of branded terminal prices to changes in spot gasoline prices—the transmission over which branded refiners are likely to have the most control—there is very little asymmetry, and it dissipates quickly. The asymmetry in adjustment of retail gasoline to terminal price changes contributes significantly, but explains less than half of the overall adjustment asymmetry.

The response of spot and terminal gasoline prices is possibly due to asymmetries in the cost of inventory adjustment. Terminal gasoline prices should fully incorporate information about inventories, however, so the explanation for the asymmetry in retail adjustment to changes in wholesale gasoline prices must be found elsewhere. This result is consistent with the theoretical work of Bénabou and Gertner [1993], which demonstrates that consumers may search less when the common input prices of all retailers become more variable, causing short-run decreases in the elasticity of demand that each retailer faces. It is also consistent with a model of sticky downward price adjustment in an oligopoly with imperfect monitoring.

Appendix

We consider four price series: spot crude oil (crude), spot gasoline (spot gas), branded city terminal gasoline (terminal), and retail gasoline (retail). The first three price series are weekly, and the fourth is semimonthly. All are measured in cents per gallon exclusive of taxes and are observed on a Friday. Five transmission mechanisms are analyzed: crude-retail, crude-spot gasoline, spot gasoline-terminal, crude-terminal, and terminal-retail. The two mechanisms involving retail are analyzed with semimonthly data, while the other three use weekly data. The analysis estimates models from 3/7/86 to 11/20/92 (weekly data) or 12/18/92 (semimonthly data). Analysis of the weekly data only goes to 11/20/92, because no data were available for 11/27/92. We estimate equation (10) for each of these relationships.

Unit Root Tests. The price series data y_t are expected to trend upward with overall inflation in the sample period. The price index is about linear in time during our sample, so the natural null hypothesis is a unit root process with positive drift, a stochastic trend, while the alternative is a deterministic time trend. The augmented Dickey-Fuller (ADF) test [1979], which corrects for possible autocorrelation of order p in y_t, is based on the usual ordinary least squares (OLS) t-ratio for the coefficient of y_{t-1} in the regression of Δy_t on a constant, time trend, y_{t-1}, $\Delta y_{t-1}, \ldots,$ Δy_{t-p+1}. The lag length p is eight periods for weekly data and four periods for semimonthly data. The 5 percent critical value is given in, for example, Hamilton [1984], Table B.6, Case 4. For crude, spot gas, and terminal the t-statistics are, respectively, -4.29, -2.96, and -2.39, compared with a 5 percent critical value of -3.66, while for the semimonthly retail data the t-

statistic is −3.53, compared with a 5 percent critical value of −3.68. At significance level 5 percent the null hypothesis—that the coefficient on y_{t-1} is zero—is not rejected for spot gasoline, terminal, and retail, and is rejected for crude. While the evidence for a unit root is mixed, in all cases the coefficient of y_{t-1} lies between −0.10 and zero, close enough to zero that we assume a unit root and treat all prices as first difference trend stationary.

Cointegration Tests. Cointegration was tested by an ADF test using the t-ratio on the coefficient of u_{t-1} in an OLS regression of Δu_t on a constant, u_{t-1}, $\Delta u_{t-1}, \ldots, \Delta u_{t-m}$, where the lag length is that used in the stationarity tests and u_t is the residual from OLS regression of the downstream price on the upstream price, a constant, and a time trend. Critical values of MacKinnon [1991] were obtained using the CDF procedure in PC-TSP. If the null hypothesis of a unit root is rejected, we conclude that the series are cointegrated. For crude-spot gasoline, spot gasoline-terminal, and crude-terminal, the test statistics were, respectively, −3.51, −5.99, and −3.33, compared with a 5 percent critical value of −3.81. Using semimonthly data for crude-retail and terminal-retail, the test statistics were −4.53 and −6.40 compared with a 5 percent critical value of −3.84. The null hypothesis of no cointegration is easily rejected at 5 percent for three of the five transmissions (including crude-retail), is rejected at 10 percent for crude-spot gas, and is rejected at 15 percent for crude-terminal. We treat all the transmissions as cointegrated.

Lag Length Tests. A conservative test procedure for lag length was adopted to ensure that the chosen lag length was sufficiently long to capture the adjustment process. We restricted $m_c = m_r = m$, and progressively added lags, choosing $m = m^*$ such that we could not reject by conventional F-tests at 10 percent against the model with $m = m^* + 1$. Relaxing the restriction $m_c = m_r$ makes very little difference to the results. Our reported results use lag lengths of one period for crude-terminal, three periods for terminal-retail, and two periods for all others.

Autocorrelated Error Tests. The analysis assumes that the errors are white noise. We tested for this by the Breusch-Godfrey LM test for autocorrelated errors in models with lagged dependent variables. The test was applied to the residuals from model (10). The null hypothesis of no serial correlation against serial correlation up to third order could not be rejected at the 10 percent level of significance in any of the regressions. For the time series of residuals from all models, the first four autocorrelation coefficients for the residuals were less than 0.08 in absolute value.

Cumulative Adjustment Function. In a fully symmetric version of (10), the k-period cumulative response B to a one-time 1 cent change in the price of crude oil is given by

$$
\text{(A1)}\quad
\begin{aligned}
B_0 &= \beta_0 \\
B_1 &= B_0 + \beta_1 + \theta_1(B_0 - \phi_1) + \gamma_1 B_0 \\
B_2 &= B_1 + \beta_2 + \theta_1(B_1 - \phi_1) + \left[\gamma_1(B_1 - B_0) + \gamma_2 B_0\right] \\
&\vdots \\
B_k &= B_{k-1} + \beta_k + \theta_1(B_{k-1} - \phi_1) + \sum_{i=1}^{k}(B_{k-1} - B_{k-i-1}).
\end{aligned}
$$

The cumulative adjustment after t periods is the sum of (1) the adjustment through period $t - 1$, (2) the impact this period of contemporaneous changes in the upstream price, (3) the effect of being away from the long-run response (the error correction term), and (4) the effects of lagged changes in retail.

For an initial crude price increase in the asymmetric model (10), all of the β_i on the right-hand side of (A1) are replaced by β_i^+, and the γ_i are replaced by γ_i^+ or γ_i^- depending on the sign of the term they multiply. The result is

$$
\text{(A2)}\quad
\begin{aligned}
B_0^+ &= \beta_0^+ \\
B_1^+ &= B_0^+ + \beta_1^+ + \theta_1(B_0 - \phi_1) + \gamma_1^+ MAX(0,B_0) + \gamma_1^- MIN(0,B_0) \\
B_2^+ &= B_1^+ + \beta_2^+ + \theta_1(B_1 - \phi_1) + \gamma_1^+ MAX(0,B_1 - B_0) \\
&\quad + \gamma_1^- MIN(0,B_1 - B_0) + \gamma_2^+ MAX(0,B_0) + \gamma_2^- MAX(0,B_0) \\
&\vdots \\
B_k^+ &= B_{k-1}^+ + \beta_k^+ + \theta_1(B_{k-1} - \phi_1) \\
&\quad + \sum_{i=1}^{k}\Big(\gamma_i^+ MAX\big(0,(B_{k-i} - B_{k-i-1})\big) \\
&\quad + \gamma_i^- + MIN\big(0,(B_{k-1} - B_{k-i-1})\big)\Big).
\end{aligned}
$$

Similar adjustments are made for an initial decrease. The figures provided in the text are offset from this by one unit, as it is more natural to think of the response beginning in period 1 rather than in period 0.

Inccnsistent Periodicity of the Retail Price Data. We do not attempt to adjust the terminal-retail or crude-retail adjustment regressions for the inconsistent periodicity of the observations. Instead we treat the data as biweekly, even though one-sixth of the observations lag the previous observation by three weeks instead of two. Our 1992 working paper implemented a correction for the longer and inconsistent periodicity of the retail data and found it had little effect on the parameter estimates and no effect on the conclusions.

To further explore the possible effect of the retail data, we reestimated the adjustments for which we have weekly data—spot gasoline-crude, terminal-crude, and terminal-spot gasoline—using only the observations for dates on which we also have retail price. The cumulative adjustment functions from these estimates were very similar to those from estimates using weekly data. In all three cases the estimated asymmetry from the inconsistent periodicity data had the same sign and basic shape as we found using the weekly data series. In all three cases the asymmetry point estimates using the semimonthly data fell completely within the 95 percent confidence bounds of the estimates using weekly data.

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