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Horizontal and vertical transmissions in the US oil supply chain

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ABSTRACT

Oil prices, inventory levels, and utilization rates are influenced by changes that are transmitted horizontally and/or vertically through the energy supply chain. We define horizontal transmissions as changes that are generated by linkages among fuels at a similar stage of processing while vertical transmissions are changes that are generated by upstream/downstream linkages in the oil supply chain. Here, we investigate vertical and horizontal transmissions by estimating vector error correction models (VECMs) that represent relationships among the price of crude oil, US refinery utilization rates, US stocks of crude oil, US stocks of motor gasoline, the US price of motor gasoline, and the US price of a substitute fuel, natural gas. Causal relationships estimated from both weekly and quarterly observations indicate that the price of crude oil is an important gateway for disturbances to the oil supply chain. Impulse response functions indicate that disturbances to crude oil prices ripple down the oil supply chain and affect inventory behaviors, refinery utilization rates, and the price of motor gasoline, and are transmitted laterally to the natural gas market.

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1. Introduction

Oil prices, inventory levels, and utilization rates are influenced by changes that are transmitted horizontally and/or vertically through the energy supply chain. We define horizontal transmissions as changes that are generated by linkages among fuels at a similar stage of processing. For example, the price for a particular crude oil may be influenced by the price of another crude oil or the price of a substitute fuel, such the wellhead price for natural gas. We define vertical transmissions as changes that are generated by upstream/downstream linkages in the oil supply chain. For example, the price of crude oil may be influenced by refining margins, stocks of crude oil or refined petroleum products, and/or the price of refined petroleum products.

Of these two transmission mechanisms, horizontal linkages have received greater scrutiny. Early investigations focus on the relationship between OPEC's official price for crude oil and prices for other crude oils. Starting in the 1970s and continuing through 1985, OPEC set an official price for oil, which implies that changes in OPEC's official price are transmitted to the price of other crude oils. This perception is invalidated by statistical analyses of the causal relationship between OPEC's official price for crude oil and crude oil prices in the spot market. Verleger (1982) finds no evidence that OPEC's official price "Granger causes" spot prices—rather he finds evidence that spot prices "Granger cause" OPEC's official price. This result is strengthened by Lowinger and Ram (1984).

Beyond OPEC's ability to influence the price of other crude oils, there is an extensive literature on the degree to which crude oil prices are synchronized across the world. Weiner (1991) investigates the degree to which the price of crude oils from various parts of the world are correlated. Results indicate that prices of crude oils produced within a region are highly correlated, but this correlation weakens when crude oil prices are compared across regions. Based on this result, Weiner (1991) argues that the crude oil market is regionalized. Conversely, Adelman (1984, 1992) argues that the crude oil market is unified based on the "Law of One Price". According to this notion, arbitrage opportunities will realign prices if crude oil prices diverge by amounts greater than differences implied by transportation costs and quality. Several studies find that crude oil prices from different parts of the globe cointegrate (Gulen, 1997, 1999; Ewing and Harter, 2000; Bachmeier and Griffin, 2006; Bentzen, 2007). The long-run relationship indicated by cointegration implies that the world oil market is unified—the world oil market is one big pool.

More recently, analysts examine price relationships between fuels at similar stages of processing. Several studies find that changes in crude oil prices are transmitted horizontally to natural gas prices (Villar and Joutz, 2006; Panagioides and Rutledge, 2007). Serletis and Rangel Ruiz (2004) find this coupling weakened between 1991 and 2001. Conversely, Bachmeier and Griffin (2006) find that changes in natural gas prices are transmitted horizontally to crude oil prices, albeit very slowly.

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Relatively few studies examine vertical price linkages. The transmission of price changes from the upstream sector to the downstream sector seems likely because crude oil is the "main ingredient" of refined petroleum products. This vertical transmission mechanism has been investigated in relation to an asymmetric relationship between the price of crude oil and motor gasoline. According to the so-called rockets and feathers effect (Bacon, 1991), rising crude oil prices cause motor gasoline prices to rise faster than motor gasoline prices decline in response to falling crude oil prices. This effect has been confirmed using observations from several nations at a variety of frequencies (Karrenbock, 1991; Borenstein et al., 1997; Galeotti et al., 2002; Eckert, 2002; Kaufmann and Laskowski, 2005; Grasso and Manera, 2007). This effect also is observed for the price of home heating oil in the US (Kaufmann and Laskowski, 2005).

The potential for vertical transmission in the other direction, from the so-called downstream sector to the upstream sector, has received less attention. Both market fundamentals and institutional arrangements may allow conditions in "downstream" sectors to affect crude oil prices. For example, Saudi Arabia instituted a net-back pricing scheme in 1986, by which crude prices were set in relation to supply/demand conditions in end-user markets.

Although net-back pricing allowed Saudi Arabia to capture market share relative to other OPEC producers, this pricing mechanism was short-lived. Soon after the 1986 price collapse, OPEC allocated its share of global demand (relative to non-OPEC production) via quotas for individual nations and allowed the market to establish prices for crude oil. Although this change eliminated the formal link between downstream conditions and crude oil prices, conditions in "downstream" sectors may still influence crude oil prices. For example, a cointegration and error correction model indicates that crude oil stocks and refinery utilization rates affect the price of crude oil (Kaufmann et al., 2004, 2008).

Here, we investigate vertical and horizontal transmissions by examining causal relationships among variables that represent different stages in the US oil supply chain. To identify these causal relationships, we estimate vector error correction models (VECMs) from both weekly and quarterly observations. In the vertical direction, disturbances generally move downstream, such that changes in crude oil prices affect inventory behaviors, refinery utilization rates, and the price of motor gasoline. In the horizontal direction, there is some evidence that disturbances are transmitted from the oil market to the natural gas market. These results and the methods used to obtain them are described in four sections. Section 2 describes the data and econometric techniques that are used to estimate VECMs from weekly and quarterly observations. Results are presented and discussed in Section 3. Section 4 concludes that crude oil prices are determined by a combination of upstream and downstream conditions.

2. Methodology

To investigate the direction of vertical and horizontal transmissions in the oil supply chain, we estimate a VECM that includes six variables; (1) the price of crude oil, (2) US refinery utilization rates, (3) US stocks of crude oil, (4) US stocks of motor gasoline, (5) the US price of motor gasoline, and (6) the US price of a substitute fuel, natural gas. These variables are chosen based on a simplified representation of the oil supply chain (for a more complete description, see Bornstein et al., 1997). According to our representation, the "upstream" sector is represented by the price for crude oil. Conditions in downstream sectors are represented by stocks of crude oil, refinery utilization rates, stocks of motor gasoline, and the price of motor gasoline. Horizontal linkages are represented using the wellhead price of natural gas because natural gas can be substituted for distillate and residual fuels in manufacturing, residential, and power sectors (for a more detailed description see Bachmeier and Griffin, 2006). The direction of vertical and horizontal transmissions is determined from the causal order of the cointegrating relationships.

2.1. Data

To determine causal order in the oil supply chain, the frequency of the data used to estimate the VECM must be shorter than the rate of potential adjustments. If the frequency of the data used to estimate the model is longer than the adjustment lag, estimates for the rate of adjustment are strongly biased (Maddala, 1977). To ensure that the frequency of the data does not bias our results, observations are compiled at two frequencies: weekly and quarterly.

We assemble a weekly data set from daily and weekly observations. Daily observations of the near month contract for crude oil (Cushing—dollars per barrel), natural gas (Henry Hub—dollars per thousand cubic feet (Tcf)), and motor gasoline (cents per gallon) as traded on the New York Mercantile Exchange (NYMEX) are converted to weekly values by averaging observations for Monday–Friday. For weeks with holidays that close the NYMEX, we average values for days on which contracts are traded. Weekly values for US refinery utilization rates (percent) and US stocks of crude oil and motor gasoline (million barrels) are obtained from the US Energy Information Administration.

Quarterly data are compiled from monthly observations as reported in the monthly energy review (Energy Information Agency, various years). The price of crude oil is measured at the wellhead (dollars per barrel)—similarly, the price of natural gas is measured at the wellhead (dollars per Tcf). Motor gasoline prices (cents per gallon) are measured by refiner prices to end users (excluding taxes). Stocks of crude oil (million barrels) are measured at month's end and exclude crude oil held in the strategic petroleum reserve. Similarly, stocks of motor gasoline (million barrels) are measured at month's end.

Stochastic trends in the time series invalidate the blind application of standard statistical techniques because they may generate spurious regression results (Granger and Newbold, 1974). To choose the proper estimation technique, we use test statistics (π_1, π_2, π_3, π_4, and $F\pi_3 \cap \pi_4$) developed by Hylleberg et al. (1990) that allow us to evaluate whether quarterly time series contain a unit root. Results generally are consistent with the hypothesis that the quarterly observations are non-stationary (Table 1). The failure to reject $\pi_1 = 0$ indicates that the variables contain a stochastic trend for the root 1. There are no seasonal unit roots, as indicated by results that reject $\pi_2 = 0$ and a joint test $F\pi_3 \cap \pi_4 = 0$. No comparable tests are available for weekly observations and so we assume that the weekly data also are non-stationary.

Table 1
Time series properties of the observations (quarterly data)

	Π_1	Π_2	Π_3	Π_4	$F\pi_3 \cap \pi_4$
Univariate tests (VECM)					
Crude oil price	−0.65	−6.43**	−5.42**	−2.95**	24.93**
Natural gas price	−1.44	−3.82**	−1.85	−3.55**	10.82**
Crude oil stocks	−3.58	−6.27**	−5.30**	−4.19**	35.20**
Motor gasoline stocks	−3.18	−2.04	−3.62*	−0.99	6.98*
Refinery utilization	−1.18	−2.58	−4.66**	−3.98**	31.19**

Univariate tests include a time trend and seasonal dummy variables.
Tests on the OLS residual include a constant only.
**Value exceeds $p < .01$, *$p < .05$, +$p < 0.10$.

2.2. Econometric methodology

To estimate statistically meaningful relationships among $I(1)$ variables, we focus on the presence of cointegration: a property displayed by variables that share a common stochastic trend. To determine whether two or more variables cointegrate and to identify and estimate cointegrating relationships, Johansen (1988) and Johansen and Juselius (1990) describe a full information maximum likelihood procedure to estimate a VECM:

$$\Delta\hat{y}_t = \Gamma_1\Delta y_{t-1} + \cdots + \Gamma_{k-1}\Delta y_{t-k+1} + \Pi y_{t-1} + \Phi d_t + \mu + \varepsilon_t \qquad (1)$$

in which Δ is the first difference operator (e.g. y_t–y_{t-1}), y is a vector of p variables whose behavior is being modeled (endogenous variables), k is the number of lags, Φ is a matrix of regression coefficients, μ is a vector of constants, ε_t is a vector of error terms each of which is normally, independently, and identically distributed (n.i.i.d.), and d_t is a vector of quarterly dummy variables and also possibly some stochastic variables that are found to be weakly exogenous (e.g. crude oil prices—see below). Because some variables may be weakly exogenous and therefore excluded from the left hand side, the dimension of the vector $\hat{y}_t$ may not be identical with y_t.

The term Πy_{t-1} is the error correction mechanism. If there are one or more cointegrating relationships, the error correction mechanism from Eq. (1) can be reformulated as follows:

$$\Pi y_{t-1} = \alpha\beta'[1, t, y_{t-1}] \qquad (2)$$

in which 1 represents a constant, t is a time trend, β' is the matrix of coefficients that creates a stationary combination of non-stationary variables, which is termed the cointegrating vector. Except as noted below, elements of β cannot be interpreted directly because their value depends on the variable used to normalize the cointegrating relationship and on the units used to measure the variable. This linear combination represents the long-run equilibrium relationship among variables (cointegrating relationship). α is a matrix of coefficients that indicates whether disequilibrium among the variables in a cointegrating relationship "loads into" or "Granger causes" a particular dependent variable. As such, estimated values of α are used to determine causal relationships in the oil supply chain. The number of cointegrating vectors, the variables that make-up a cointegrating relationship, the elements of the cointegrating vector, and the relationship between a cointegrating relationship and a dependent variable are evaluated using diagnostic statistics that are generated by the estimation process. For a more detailed description of the VECM, see Juselius (2006).

Decisions to include a time trend or constant in the cointegrating relationship are based on a method developed by Pantula (1989). The number of lagged first differences to include in Eq. (2), which is given by $k-1$, is determined by estimating VECMs with different lags and choosing the lag length associated with the smallest value for the Schwartz or Hannon-Quinn information criterion (Hansen and Juselius, 1995). Based on maximum lag lengths defined by an econometric "rule of thumb" $T^{1/3}$, the start date is adjusted so that VECMs with different lag lengths are estimated over the same sample period (1994:02:25–2006:09:15; 1987Q1-2006Q2). The number of cointegrating relationships in the VECM, which is equivalent to the rank of Π in Eq. (2), is chosen using λ_{trace} and λ_{max} statistics (Johansen, 1988; Johansen and Juselius, 1990).

Identifying the long-run structure of a VECM requires several types of restrictions (Pesaran and Shin, 2002). Greenslade et al. (2002) suggest that the efficiency of identifying the long-run structure can be improved by first attempting to reduce the number of endogenous variables. We evaluate whether variables can be excluded from $\hat{y}_t$ in Eq. (1) by testing restrictions that make all elements of α that are associated with a dependent variable equal to zero. Failure to reject $\alpha = 0$ for all cointegrating relationships for a given equation indicates that the dependent variable is weakly exogenous. We also test whether variables can be eliminated from cointegration space by assigning a value of zero to the β' coefficients associated with a given variable for all cointegrating relationships. Rejecting this restriction indicates that the variable must appear in one or more cointegrating relationships.

Restrictions are required to identify the coefficients in the cointegrating vectors. Just identifying restrictions eliminate one variable from each cointegrating relationship. Additional restrictions, termed over-identifying restrictions, are needed to identify β and their standard errors. Because there are too many variables to identify the cointegrating relationships by testing every possible combination, we use a basic understanding of the oil market as a guide to identify the VECMs. More precisely, we test a series of restrictions that would create cointegrating vectors for individual variables. For example, theory suggests that motor gasoline prices are determined by the price for crude oil, refinery utilization rates, and/or stocks of motor gasoline and so efforts to identify one of the cointegrating relationships eliminates natural gas prices and stocks of crude oil from that cointegrating relationship.

3. Results

3.1. Weekly data set

Both the Hannon-Quinn and Schwartz criteria indicate that one lag should be used to estimate the VECM. Both the λ_{trace} and λ_{max} statistics indicate that assigning Π a rank of two or less is rejected strongly (Table 2). Based on this result, we estimate a VECM that has three cointegrating relationships.

Tests that restrict the three values of α (one for each cointegrating relationship) to zero generally are strongly rejected (Table 3). Notable exceptions include restrictions on equations for the first difference of crude oil prices ($\chi^2(3) = 0.38$, $p > .94$) and the first difference of natural gas prices ($\chi^2(3) = 2.65$, $p > .45$). Based on these results, we make these two variables exogenous (they are excluded from $\hat{y}_t$) and repeat the analysis with four endogenous variables. Again, results indicate that the VECM should be estimated with one lag. λ_{trace} and λ_{max} statistics indicate that the VECM contains four cointegrating vectors. Repeating restrictions on α and β indicate that the four remaining endogenous variables are endogenous and that none of the six variables can be excluded from cointegration space. Imposing four over-identifying restrictions ($\chi^2(4) = 6.77$, $p > .15$), identifies four cointegrating relationships (Table 4) that load into one or more of the equations for the four endogenous variables.

Table 2
Rank test for VECM

		Weekly model		Quarterly model	
H_o:r	P–r	λ_{max}	λ_{trace}	λ_{max}	λ_{trace}
0	6	104.53**	216.06**	142.30**	272.44**
1	5	45.56**	111.53**	50.20**	130.13**
2	4	36.02**	65.97**	43.24*	79.93**
3	3	15.97	29.95	26.28*	36.70*
4	2	10.96	13.98	7.84	10.41
5	1	3.02	3.02	2.58	2.58

**Values exceeds $p<.01$, *$p<.05$.
Critical values from Osterwald-Lennum (1992).

Table 3
Exclusion tests on VECM

	Weekly model		Quarterly model	
	Exogenous	Cointegration space	Exogenous	Cointegration space
Crude oil price	$\chi^2(3) = 0.38$	$\chi^2(3) = 27.98$	$\chi^2(4) = 6.94$	$\chi^2(4) = 42.60^{**}$
Natural gas price	$\chi^2(3) = 2.63$	$\chi^2(3) = 7.25^{+}$	$\chi^2(4) = 21.22^{**}$	$\chi^2(4) = 26.48^{**}$
Motor gasoline price	$\chi^2(3) = 13.94^{**}$	$\chi^2(3) = 26.19^{**}$	$\chi^2(4) = 46.50^{**}$	$\chi^2(4) = 44.69^{**}$
Crude oil stocks	$\chi^2(3) = 24.48^{**}$	$\chi^2(3) = 20.56^{**}$	$\chi^2(4) = 24.43^{**}$	$\chi^2(4) = 26.14^{**}$
Motor gasoline stocks	$\chi^2(3) = 74.13^{**}$	$\chi^2(3) = 24.81^{**}$	$\chi^2(4) = 38.81^{**}$	$\chi^2(4) = 33.34^{**}$
Refinery utilization	$\chi^2(3) = 23.71^{**}$	$\chi^2(3) = 88.83^{**}$	$\chi^2(4) = 101.67^{**}$	$\chi^2(4) = 36.05^{**}$

Tests of exogeneity $\alpha = 0.0$ for all cointegrating relationships for an equation in the VECM.
Tests of cointegration space $\beta_i = 0.0$ in all cointegrating relationships in the VECM.
**Values exceeds $p<.01$, $^{*}p<.05$, $^{+}p<0.1$.

Table 4
Results for the vector error correction models estimated from the weekly and quarterly data sets

	Cointegrating relationship 1	Cointegrating relationship 2	Cointegrating relationship 3	Cointegrating relationship 4
Weekly model				
Cointegrating vector				
Crude oil price	-2.76^{**}	-0.054^{*}	0.864^{**}	
Natural gas price				
Motor gasoline price	1.00^{*}			1.00^{*}
Crude oil stocks			-0.583^{**}	
Motor gasoline stocks			1.00^{*}	3.67^{**}
Refinery utilization	-0.072^{+}	1.00^{*}		-6.99^{**}
Constant		-94.33^{**}		
Loadings (α)				
Motor gasoline price	-0.12^{**}	0.032	−0.012	−0.003
Crude oil stocks	0.013	-0.297^{**}	0.016	−0.009
Motor gasoline stocks	0.009	−0.046	−0.013	-0.013^{**}
Refinery utilization	0.022^{*}	-0.191^{**}	-0.029^{**}	−0.004
Quarterly model				
Cointegrating vector				
Crude oil price	-3.08^{**}			-0.14^{**}
Natural gas price				1.00^{**}
Motor gasoline price	1.00^{**}	1.00^{**}		
Crude oil stocks		-1.31^{**}	1.00^{**}	
Motor gasoline stocks		2.51^{**}		
Refinery utilization	-0.50^{**}		5.48^{**}	
Constant			-944.23^{**}	
Loadings (α)				
Natural gas price	0.030^{*}	0.008^{*}	0.003	-0.407^{**}
Motor gasoline price	-0.869^{**}	-0.079^{*}	−0.007	0.787
Crude oil stocks	-0.391^{+}	0.039	−0.005	4.408^{*}
Motor gasoline stocks	0.404^{**}	-0.165^{**}	-0.134^{**}	1.054
Refinery utilization	0.045	-0.042^{**}	-0.068^{**}	0.012

**Value exceeds $p<.01$, $^{*}p<.05$, and $^{+}p<.10$.
Statistical significance of elements that are used to normalize the cointegrating vector ($\beta = 1.0$) is determined by imposing the same over-identifying restrictions but normalizing the cointegrating vectors by a different variable.

The first cointegrating relationship, which includes the price of crude oil, refinery utilization rates, and the price of motor gasoline, can be interpreted as a cointegrating relationship for the price of motor gasoline and refinery utilization rates because this cointegrating relationship loads into the equations for the first difference of motor gasoline prices and refinery utilization rates. The second cointegrating relationship includes the price of crude oil, refinery utilization rates, and a constant. It loads into the equations for the first difference of refinery utilization rates and crude oil stocks. The third cointegrating relationship includes the price of crude oil and stocks of crude oil and motor gasoline, and loads into the equation for the first difference of refinery utilization rates. The fourth cointegrating relationship includes the price of motor gasoline, stocks of motor gasoline, and refinery utilization rates. This cointegrating relationship loads into the equation for the first difference of motor gasoline stocks.

3.2. *Quarterly data set*

As with the weekly data set, both the Hannon-Quinn and Schwartz criteria indicate that one lag should be used to estimate the VECM. Both λ_{trace} and $\lambda_{\max}$ statistics indicate that assigning Π a rank of three or less is rejected strongly (Table 2). Based on this result, we estimate a model that has four cointegrating vectors.

Tests that restrict the four values of α (one for each cointegrating relationship) to zero generally are strongly rejected (Table 2). Restrictions that impose $\alpha = 0$ on the crude oil price equation are not rejected ($\chi^2(4) = 6.94$, $p > .14$). Based on this result, crude oil prices are removed from $\hat{y}$ and the analysis is repeated with five endogenous variables. Again, results indicate that the VECM should be estimated with one lag. Both λ_{trace} and $\lambda_{\max}$ statistics indicate that the VECM contains four cointegrating vectors. Restrictions on α and β indicate that the five remaining variables in $\hat{y}$ are endogenous and none of the six variables can be excluded from cointegration space. Imposing five over-identifying restrictions ($\chi^2(5) = 9.20$, $p > 0.10$), identifies four cointegrating relationships (Table 4).

As with the weekly data set, the first cointegrating relationship, which includes the price of crude oil, refinery utilization rates, and the price of motor gasoline, appears to be a cointegrating relationship for the price of motor gasoline. This cointegrating relationship loads into the equation for the first difference of motor gasoline prices. As with the weekly VECM, elements of the cointegrating vector indicate that motor gasoline prices are positively related to refinery utilization rates and the price of crude oil. The first cointegrating relationship also loads into the equation for the first difference of motor gasoline stocks and natural gas prices.

The second cointegrating relationship includes the price of motor gasoline, stocks of crude oil, and stocks of motor gasoline, while the third cointegrating relationship includes stocks of crude oil, refinery utilization rates, and a constant. Both cointegrating relationships load into equations for the first difference of motor gasoline stocks and refinery utilization rates. The second cointegrating relationship also loads into the equation for the first difference of natural gas and motor gasoline prices. Signs on the elements of the cointegrating vectors indicate that there is a negative relationship between motor gasoline prices and stocks of motor gasoline—as motor gasoline prices rise, stocks of motor gasoline fall. Conversely, rises in stocks of crude oil tend to increase refinery utilization rates.

The fourth cointegrating relationship includes the price of crude oil and natural gas and appears to be a cointegrating relationship for natural gas prices. Elements of the cointegrating vector indicate that natural gas prices are positively related to crude oil prices and that disequilibrium in this relationship affects natural gas prices. Disequilibrium in this cointegrating relationship also affects stocks of crude oil.

4. Discussion

4.1. Vertical transmissions in the oil supply chain: implications for OPEC behavior

The hypothesis that the oil supply chain transmits conditions from downstream sectors to crude oil prices is evaluated by imposing restrictions on α in Eq. (2) that makes crude oil prices exogenous. For the VECMs estimated from both the weekly and quarterly data set, we fail to reject restrictions $\alpha = 0$ for the crude oil price equation. This implies that none of the four cointegrating relationships identified from either data set "Granger cause" the price of crude oil. Failure to reject restrictions $\alpha = 0$ for the crude oil price equation implies that disequilibrium in the cointegrating relationships in the VECM estimated from the weekly or quarterly data sets cannot account for changes in the price of crude oil. This indicates that cointegrating relationships, which include wellhead prices of natural gas, stocks of crude oil or motor gasoline, refinery utilization rates, and/or the price of motor gasoline, cannot account for stochastic trends in the real price of crude oil.

Conversely, crude oil prices are part of the cointegrating relationships that load into the equations for variables that represent downstream conditions, such as stocks of crude oil, stocks of motor gasoline, refinery utilization rates, and motor gasoline prices. This implies that changes in the price of crude oil are transmitted vertically through the oil supply chain, from the upstream sector to the downstream sector. From this perspective, crude oil prices serve as a "gateway" for innovations to the oil supply chain.

The finding that disturbances to the oil supply chain generally move "downstream" can be used to evaluate competing hypotheses regarding OPEC's ability to influence oil prices. Several analysts argue that OPEC decisions accommodate downstream conditions (Verleger, 1982; Fitzgerald and Pollio, 1984; Lowinger and Ram, 1984; Loderer, 1985). If correct, such decision-making implies that OPEC has no real power over oil prices. But this hypothesis is inconsistent with results that indicate downstream conditions, such as stocks, refinery utilization rates, and end-user prices for refined petroleum products, and potential substitutes cannot account for stochastic trends in the price for crude oil. Instead, results that indicate crude oil price are exogenous to downstream conditions are consistent with the hypothesis that there is an exogenous component of OPEC behavior concerning quotas, production rates, and additions to installed capacity, at least since 1986 (Smith, 2005; Kaufmann et al. 2004, 2008; Wirl and Kujundzic, 2004). This implies that OPEC decisions enter the oil supply chain as exogenous shocks to oil prices.

4.2. Crude oil and refined product prices

Causal order in the oil supply chain implies that the price of crude oil has a long-term effect on the price of refined petroleum products. The nature of this effect can be evaluated by imposing additional restrictions on the cointegrating vector. If crude oil prices are related to motor gasoline prices on a one-to-one Btu basis, the element of the cointegrating vector associated with crude oil prices in the first cointegrating relationship for both the weekly and quarterly model would be −2.38 (100 cents per dollar/42 gal per barrel). We assess this possibility by imposing a value of −2.38 on the element of the cointegrating vector that is associated with the price of crude oil in the first cointegrating relationship. For both data sets, this restriction is rejected—for the quarterly data set the restriction is rejected $\chi^2(1) = 37.58$ ($p < .01$) and for the weekly data set, the restriction is rejected $\chi^2(1) = 9.71$ ($p < 0.01$). Estimated values are −2.76 (weekly data set) and −3.08 (quarterly data set). These values imply that increases in crude oil prices raise the price of motor gasoline relative to crude oil on a Btu basis even after accounting for the costs of refining (refinery utilization rates are in the first cointegrating relationship). This result is consistent with studies by Kaufmann and Laskowski (2005) and Bachmeier and Griffin (2003), who find that a $1 increase in crude oil prices increases the retail price of motor gasoline by more than $1. Conversely, Bornstein et al. (1997) are not able to reject a one-to-one relationship between the price of crude oil and the retail price of motor gasoline.

4.3. Horizontal transmission: connections between crude oil and natural gas prices

The fourth cointegrating relationship in the VECM estimated from quarterly data identifies a long-run relationship between the wellhead price of crude oil and natural gas. Values of α indicate that innovations in crude oil prices "Granger cause" natural gas prices, but innovations in natural gas prices do not "Granger cause" crude oil prices. This result would imply that price changes in US energy markets move horizontally from oil markets to natural gas markets. The direction of these transmissions is similar to that found by Villar and Joutz (2006).

The nature of this horizontal transmission can be evaluated by testing the hypothesis that natural gas prices are related to crude oil prices on a one-to-one Btu basis. In this case, a value of −0.19 $\left[\frac{1.104*10\ \mathrm{Btu/Tcf}}{5.8*10^6\ \mathrm{Btu/Bbl}}\right]$ is imposed on the element of β associated with crude oil prices in the fourth cointegrating relationship of the quarterly model. This restriction is strongly rejected $\chi^2(1) = 36.63$ ($p<.001$). The estimated value -0.14 is smaller (in absolute terms) than -0.19, which implies that the increases in the price of crude oil reduce the relative price of natural gas per Btu. This result is similar to those described by Villar and Joutz (2006), who find that a 20 percent increase in the price of crude oil generates a 16 percent increase in the price of natural gas.

The long- and short-term relationships between the wellhead prices for crude oil and natural gas in the VECM estimated from quarterly data are absent from the VECM estimated from weekly data. The presence/absence of a relationship between crude oil and natural gas prices may be associated with the frequency of the data. Analyses of monthly data indicate that changes in crude oil prices are transmitted horizontally to natural gas prices (Villar and Joutz, 2006; Panagiotidis and Rutledge, 2007). But an analysis of daily data (Bachmeier and Griffin, 2006) finds a small long-run relationship that transmits prices horizontally from natural gas to crude oil very slowly (0.6–2.2 percent per period) as opposed to the long-run relationship from the price of crude oil to natural gas that adjusts relatively rapidly (41 percent rate of adjustment implied by the value of α) in the quarterly VECM.

The lack of evidence for horizontal linkages between oil and natural gas prices in high frequency data may be caused by short-term noise that obfuscates the cointegrating relationship. Daily and weekly prices for crude oil and natural gas may respond to short-term innovations that are unique to the fuel. For example, crude oil prices declined sharply during the Asian financial crisis in 1998 due to the international nature of the oil market (Bachmeier and Griffin, 2006). This international demand shock had relatively little effect on US natural gas markets, which tend to be more regional. Over longer periods, natural gas prices may be related to crude oil prices due to ample opportunities for interfuel substitution in the manufacturing and residential sectors. For example, in 2002, US manufacturers could substitute 18.8 percent of their natural gas use, 20.1 percent of their distillate oil use, and 41.4 percent of their residual oil use with alternative fuels (EIA, 2002).

Alternatively, results that show horizontal price linkages may be caused by the techniques used to estimate the relationship. For example the relationship between crude oil and natural gas prices reported here and that reported by Villar and Joutz (2006) use a cointegration/error correction approach. Bachmeier and Griffin (2006), who find little relationship, do not use techniques that are designed to estimate long-run relationships among $I(1)$ variables while Serletis and Rangel-Ruiz (2004) use techniques that are designed to identify common cycles rather than causal order.

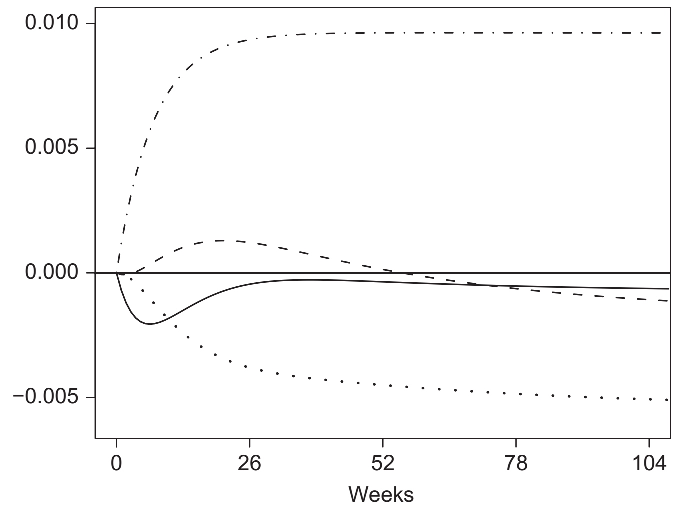

Fig. 1. The impulse response functions for the price of motor gasoline (dash–dot line), refinery utilization rates (solid line) stocks of crude oil (dashed line), and stocks of motor gasoline (dotted line), generated by the VECM estimated from the weekly data set.

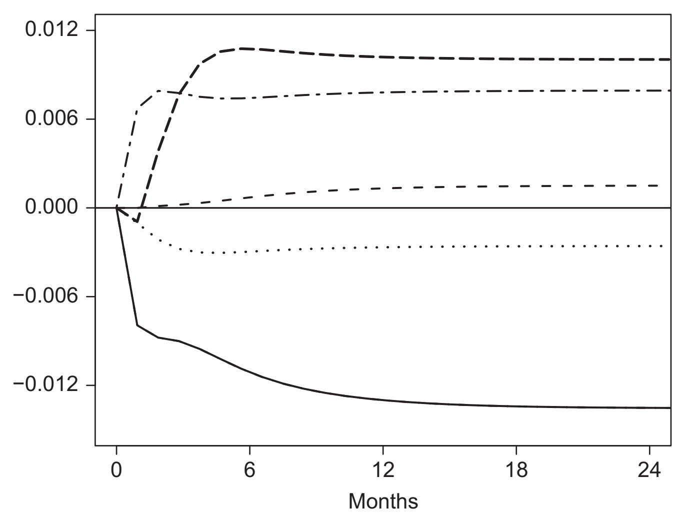

Fig. 2. The impulse response functions for the price of natural gas (dashed line), motor gasoline (dash–dot line), refinery utilization rates (short dashed line), stocks of crude oil (dotted line), and stocks of motor gasoline (solid line), generated by the VECM estimated from the quarterly data set of an increase of 1 percent of crude oil price.

4.4. *Vertical transmission of crude oil prices: inventory management*

Crude oil prices are present in cointegrating relationships that load into equations for the stock of crude oil, the stock of motor gasoline, and refinery utilization rates. Because of this high degree of interconnectedness, the effects of changes in crude oil prices on stocks and refinery utilization rates are evaluated using impulse response functions. To generate impulse response functions, weekly and quarterly models are run to equilibrium based on the last observation for the wellhead price of crude oil [September 15, 2006 ($64.69 per barrel); second quarter 2006 ($62.20 per barrel)]. After the model comes to equilibrium, the price of crude oil is exogenously increased by 1 percent, and the simulation is continued so that the endogenous variables move towards their new equilibrium. To ease comparisons among variables and between weekly and quarterly models, values are measured by their fractional change relative to the equilibrium value that prevailed just before the price of crude oil price was increased by 1 percent (0.01).

Figs. 1 and 2 indicate that the downstream effects of a crude oil price increase are similar across the weekly and quarterly models. A 1 percent increase in the price of crude oil raises the price of motor gasoline and natural gas (in the quarterly model). Motor gasoline prices increase by slightly less than 1 percent because a Btu of motor gasoline is more expensive than a Btu of crude oil. Conversely, natural gas prices rise by slightly more than 1 percent because a Btu of natural gas at the wellhead is less expensive than a Btu of crude oil at the wellhead.

Both simulations indicate that higher prices for crude oil and refined petroleum products change the management of oil inventories. Higher prices for crude oil reduce stocks of crude oil and motor gasoline and increase refinery utilization rates in the long run (the weekly model shows a slight decline in refinery utilization rates). Higher prices for crude oil and ultimately motor gasoline raise the cost of holding stocks, which tends to reduce inventories. To offset this reduction, refinery utilization rates rise slightly in the long term. These effects can be viewed as a change in inventory management towards "just-in-time" practices. Increasing refinery utilization rates increase the real-time production of motor gasoline, which offsets the reduction in stocks of motor gasoline.

5. Conclusion

This analysis indicates that vertical transmission in the oil supply chain run from the "upstream sector" crude oil prices to the downstream sector, as represented by stocks, refinery utilization rates, motor gasoline prices, and horizontally, from crude oil prices to the price of a potential substitute, natural gas. As expected, crude oil prices are an important determinant of motor gasoline prices. Crude oil prices also affect inventory management practices, such that higher prices reduce inventories and offset this reduction by increasing refinery utilization rates. This change may explain the general decline in crude oil inventories held in OECD nations over the last twenty years, as measured by days of forward consumption (Kaufmann et al., 2004).

VECMs estimated from weekly and quarterly data indicate that downstream conditions alone cannot account for changes in crude oil prices since 1986, including the rapid rise since 2004. This result has two possible interpretations; (1) the price of crude oil is unaffected by downstream conditions or (2) downstream conditions affect the price of crude oil, but the VECMs do not include all of the relevant variables therefore, there are no cointegrating relationships that can represent the long-run determinants of crude oil prices in a statistically meaningful fashion. Of these two possibilities, it seems unlikely that downstream conditions have no effect on crude oil prices. Kaufmann et al., (2004) establish a causal relationship from stocks of crude oil to crude oil prices. Similarly, Kaufmann et al. (2008) find that crude oil prices are affected by both upstream factors (e.g. OPEC capacity utilization rates) and downstream factors (i.e. refinery capacity utilization).

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