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Time Series Analysis of Transatlantic Market Interactions: Evidence from Crude Oil and Gasoline Prices

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Abstract

This paper investigates the interactions of spot markets for crude oil and regular gasoline in a transatlantic context. A cointegrated vector autoregressive (VAR) system is estimated using weekly time series data for spot prices of representative crude oil and regular gasoline in Europe and the US. The cointegrated VAR analysis shows that the US crude oil plays the role of long-run price leadership, influencing the price determination of the other commodities in the VAR system. Cointegrating vectors are then normalized and restricted so that the underlying long-run market interactions may be interpreted in terms of causal chains. Finally, a parsimonious equilibrium correction system is estimated in order to reveal the short-run market interactions.

Key words: market interaction; long-run price leadership; crude oil, regular gasoline; cointegrated vector autoregressive model

JEL classification: C32; Q49; R19

1. Introduction

The objective of this paper is to investigate the interactions of representative spot markets for crude oil and regular gasoline in Europe and the US. A cointegrated vector autoregressive (VAR) system is estimated using weekly time series data for spot prices of representative crude oil and regular gasoline in the two areas. The introductory section briefly reviews a cointegrated VAR system, long-run price leadership, and several representative crude oil commodities. The most significant aspect of this paper is then described.

Time series data of economic variables tend to exhibit non-stationary behavior caused by the underlying common stochastic trends. A cointegrated VAR model, introduced by Johansen (1988, 1996), allows us to detect stationary linear combinations of non-stationary variables, so-called cointegrating relationships, as a

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result of removing the common stochastic trends. Cointegrating relationships may represent long-run economic relationships interpretable from economic theory and insight. A cointegrated VAR analysis, therefore, plays an important role in applied economic research. See Hendry and Juselius (2001), Burke and Hunter (2005), Juselius (2006), and Kurita (2007), inter alia, for theory and applications of cointegrated VAR models.

The notion of long-run price leadership, demonstrated by Burke and Hunter (2008), is closely associated with the presence of a single common trend in a cointegrated VAR system. Consider a set of prices interacting with each other, which are well fitted in a cointegrated VAR framework. The long-run price leadership corresponds to a case where one of the prices acts as the long-run driving force in the overall price determination. The driving force stems from a single common stochastic trend, which is synonymous with accumulated innovations for the leading price. Hence, as demonstrated below in this paper, the adjustment space for the leading price in the cointegrated VAR system is subject to a zero restriction such that the equation for the leading price is free from any equilibrium correction terms. The zero restriction on the adjustment space implies that the leading price is weakly exogenous for a set of parameters of interest in the system (see Engle et al., 1983; Johansen, 1996, Ch. 8).

Crude oil is used to produce various products such as gasoline and heating oil, and it is no doubt one of the most important fuel resources in the global economy. West Texas Intermediate (WTI) is known as a representative crude oil commodity, which is produced in Texas and southern Oklahoma in the US. There is another representative crude oil commodity, Brent crude oil, which is produced in the North Sea region in Europe. The quality of crude oil, in general, varies according to its content of sulfur and gravity. WTI and Brent are fairly similar in quality and therefore treated as comparable commodities. Both WTI and Brent serve as references or benchmarks for pricing a number of other crude oil streams.

Spot prices of these oil commodities should have strong pass-through effects on those of regular gasoline in Europe and the US. A question of interest that follows is how spot markets for crude oil and regular gasoline interact with each other. It is also of importance, in terms of the understanding of transatlantic causal chains, to identify which crude oil plays the role of long-run price leadership, affecting the price determination of the other crude oil and regular gasoline commodities. Price dynamics in crude oil and gasoline markets have been subjected to substantial empirical investigations; see Borenstein et al. (1997), Eltony (1998), Bachmeier and Griffin (2003), Chen et al. (2005), Blair and Rezek (2008), Wlazlowski et al. (2009), inter alia. The existing research, however, does not necessarily address such issues as described above in a transatlantic context. This paper therefore fills the gap in the literature.

With a view to shedding useful light on the transatlantic market interactions and long-run price leadership, this paper estimates a cointegrated VAR system consisting of logged spot prices of WTI and Brent as well as those of regular gasoline in two representative regional trading hubs: New York Harbor for the US and the Amsterdam-Rotterdam-Antwerp (ARA) area for Europe. Maximum likelihood estimation of the VAR system is performed using weekly time series data for these spot prices. The multivariate cointegration analysis shows that US crude oil plays the role of long-run price leadership, influencing the price determination of the other commodities in the VAR system. Cointegrating vectors are then normalized and restricted in such a way that the underlying long-run market interactions can be interpreted from the viewpoint of causal chains. Lastly, a parsimonious equilibrium correction system is estimated in order to investigate the short-run market interactions.

For the purpose of understanding regional market differences, whether long-run price leadership exists or not is a very important question to be answered. The analysis of this paper successfully reveals the long-run and short-run market interactions in a transatlantic context. It also lends weight to the validity of the Burke and Hunter (2008) approach to the description of long-run price determination in real-life markets. Although this paper provides useful information on the market interactions, there are some caveats in its interpretation and evaluation. The data simply refer to the primary wholesale markets in the relevant geographical areas, thus one may not draw a general conclusion on the price leadership in the overall global markets. The analysis, in addition, does not investigate the formation of gasoline prices at the retail level through strategic interactions among gasoline retailers. Addressing these issues is beyond the scope of the present paper but should be counted as a primary objective to be pursued in future research.

The organization of this paper is as follows. Section 2 reviews a cointegrated VAR system and long-run price leadership. Section 3 analyses weekly price data in order to reveal transatlantic market interactions. The overall conclusions are summarized in Section 4. All the empirical analysis and graphics in this paper use PcGive™ of OxMetrics™ (Doornik and Hendry, 2007).

2. Long-Run Price Leadership

Let us introduce a vector of n prices $X_t = (p_{1,t}, \ldots, p_{n,t})'$. A cointegrated VAR(k) model for X_t, according to Johansen (1996), is given by:

$$\Delta X_t = \alpha(\beta', \gamma)\begin{pmatrix} X_{t-1} \\ t \end{pmatrix} + \sum_{i=1}^{k-1} \Gamma_i \Delta X_{t-i} + \mu + \varepsilon_t \ , \tag{1}$$

for $t = 1, \ldots, T$ where the sequence of innovations ε_t are independently and normal $N(0, \Omega)$ distributed conditional on the starting values $X_{-k+1}, \ldots, X_0$, $\alpha, \beta \in \Re^{n\times r}$ for $r < n$, $\gamma \in \Re^{r\times 1}$, $\mu \in \Re^{n\times 1}$, and $\Gamma_i \in \Re^{n\times n}$. Let $\beta^* = (\beta', \gamma')$ and $X^*_{t-1} = (X'_{t-1}, t)'$ for future reference. Johansen (1996) shows details of likelihood-based inference for these parameters. In equation (1) α is referred to as the adjustment vector, while β^* contains cointegrating vectors and $\beta^* X^*_{t-1}$ represents the cointegrating relationships. Note that linear trend t is restricted in the cointegrated space of (1); that is, X_t is subject to linear trend but excludes quadratic trend, so that ΔX_t has non-zero mean. See Johansen (1996, Ch. 5) for details. As discussed in the introduction, $\beta^{*\prime} X_{t-1}^{*}$ can be seen as describing the long-run economic relationships interpretable from economic theory and insight, while $\sum_{i=1}^{k-1}\Gamma_i \Delta X_{t-i}$ can represent short-run dynamics and interactions in the system. An orthogonal complement $\alpha_\perp$ is defined in such a way that $\alpha_\perp' \alpha = 0$ with the matrix $(\alpha, \alpha_\perp)$ is full rank. A series of shocks $\alpha_\perp' \varepsilon_t$ accumulates to the underlying common stochastic trends, which give rise to non-stationary trending behavior of X_t. Hence we are justified in looking upon $\alpha_\perp' \varepsilon_t$ as a permanent shock in the VAR system. A transitory shock may then be defined as $\alpha_\perp' \Omega^{-1} \varepsilon_t$, since the shock must be independent of the permanent one.

Let us then consider a case where $p_{n,t}$ plays the role of long-run leadership in (1). Burke and Hunter (2008) introduce a set of conditions required for the existence of long-run price leadership. According to Burke and Hunter (2008), the definition of long-run price leadership may be given as follows.

Definition of Long-Run Price Leadership

Suppose that $X_t = (p_{1,t}, \ldots, p_{n,t})'$ is generated by the process (1). The nth price $p_{n,t}$ is said to play the role of long-run leadership in (1) if the following conditions are fulfilled: <1> the number of cointegrating vectors is $n-1$, i.e., $r = n-1$, <2> the error process for $p_{n,t}$ corresponds to the permanent shock, i.e. $\alpha_\perp = (\mathbf{0}_{1\times n-1}, 1)'$, and <3> $n-1$ cointegrating relations can be expressed as:

$$\beta' X_{t-1} = \begin{pmatrix} 1 & 0 & \cdots & \cdots & -1 \\ 0 & 1 & 0 & \cdots & -1 \\ 0 & 0 & \ddots & \cdots & \vdots \\ 0 & 0 & \cdots & 1 & -1 \end{pmatrix} \begin{pmatrix} p_{1,\,t-1} \\ p_{2,\,t-1} \\ \vdots \\ p_{n,\,t-1} \end{pmatrix} = \begin{pmatrix} p_{1,\,t-1} - p_{n,\,t-1} \\ p_{2,\,t-1} - p_{n,\,t-1} \\ \vdots \\ p_{n-1,\,t-1} - p_{n,\,t-1} \end{pmatrix}. \tag{2}$$

According to the first condition above, there is a single common stochastic trend in the cointegrated VAR system, which corresponds to the long-run pushing force inside the system. The second condition then shows that the stochastic trend consists of accumulated innovations solely for $p_{n,t}$ rather than those of several prices. Finally, the third condition ensures that the stochastic trend shares a common loading parameter, thereby having an identical long-run impact on each variable in the VAR system. The concept of long-run price leadership defined above plays a critical role in the empirical analysis pursued in this paper.

Let us also note that long-run price leadership is closely related to the well-known concept of Granger-causality; see Granger (1969). The fact that $p_{n,t}$ plays the role of long-run leadership in the system implies that $p_{n,t}$ causes all the other variables in the system in the sense of Granger (1969), but not vice versa. That is, Granger-causality itself does not require such strict conditions as provided above for the establishment of long-run leadership. Thus, long-run leadership is perceived as more stringent than Granger-causality; the empirical validity of the former tells us more about the dynamic structure of an economy in question than does the latter.

The first condition above is testable using log likelihood ratio (*LR*) tests for the cointegrating rank (see Johansen, 1996, Ch. 6). The likelihood-based rank test statistics have non-standard limiting distributions; thus it is necessary to depend on tabulated quantiles for the purpose of conducting statistical inference. The second condition is synonymous with a set of zero restrictions on those elements of α which correspond to $p_{n,t}$, indicating that $p_{n,t}$ is weakly exogenous for β. The condition is testable as well using a log *LR* test statistic, which, once the cointegrating rank is given, is asymptotically χ^2-distributed. The third condition can also be tested using asymptotic χ^2-based inference. See Johansen (1996, Chs. 7 and 8) for details of restrictions on α and β.

3. Econometric Analysis of Spot Price Data

This section, using a comprehensive cointegrated VAR analysis, investigates various time series properties of weekly spot price data for the representative crude oil and regular gasoline introduced above. This section is composed of six sub-sections. Section 3.1 presents an overview of the data and then estimates an unrestricted VAR model. Section 3.2 investigates the cointegrating rank of the VAR model. Section 3.3 conducts tests for weak exogeneity and Section 3.4 then explores restrictions on the cointegrating space. Based on the preceding findings, Section 3.5 reveals interpretable long-run structure, and Section 3.6 achieves a parsimonious equilibrium correction model of the data.

3.1 Data Overview and Unrestricted VAR Model

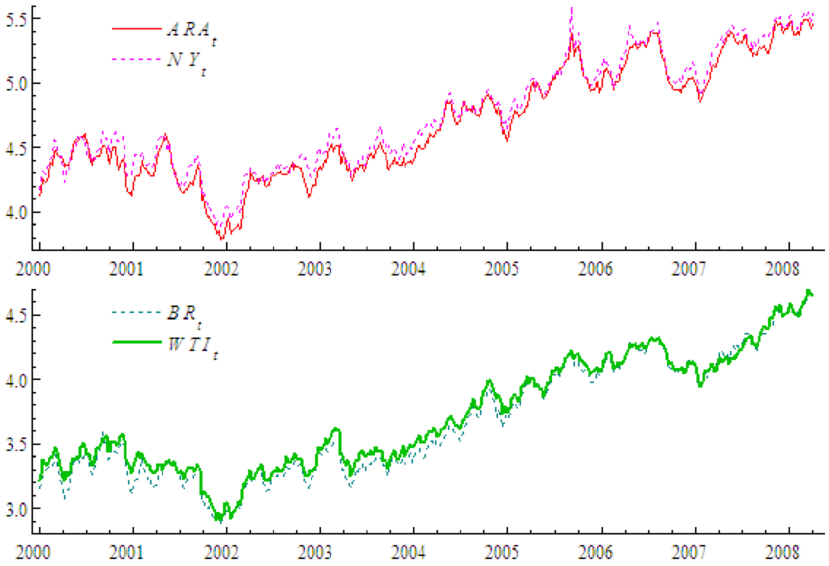
Figure 1 presents an overview of logged weekly price data for the four commodities. In the figure, ARA_t and NY_t identify logged spot prices for conventional regular gasoline (cents per gallon) in ARA and New York Harbor, respectively. Similarly, BR_t and WTI_t denote logged spot prices for Brent and WTI (dollars per barrel), respectively. The sample period runs from the 1st week in 2000 to the 13th week in 2008. The end point of the sample period is determined by the availability of the gasoline price data. All data are collected from the webpage of the US Energy Information Administration.

According to the figure, all prices exhibit non-stationary trending behavior, wandering around in a very similar fashion with no clear mean-reversion. These price series seem to be cointegrated, but it is not necessarily clear how many cointegrating relations are embedded in the data. Furthermore, judging from the figure, it is not evident which price series plays the role of long-run leadership. These issues need to be addressed using a formal cointegrated VAR analysis.

Proceeding to maximum likelihood estimation of a VAR system, a general unrestricted VAR model is estimated for X_t:

$$X_t = (ARA_t, NY_t, BR_t, WTI_t)'.$$

Figure 1. An Overview of Weekly Data of Various Spot Prices



The lag-order of the unrestricted VAR model is chosen to be 4 based on F-tests for the lag-length selection. The number of observations available for estimation is therefore 426, which is large enough that asymptotic theory for cointegration should hold. The unrestricted VAR(4) model is a purely statistical representation, so that the estimated coefficients are not necessarily subject to economic interpretation. Identifying cointegrating relationships enables us to pursue such interpretations. The unrestricted VAR(4) model should provide a basis for the subsequent modeling and therefore needs to pass various diagnostic checks on its residuals. The estimated VAR(4) model, however, suffers from several outliers, thus the following dummy variables are incorporated in the VAR(4) model:

$$D_{1,t} = 1(\text{39th week of 2001})$$

$$D_{2,t} = 1(\text{3rd week in 2002})$$

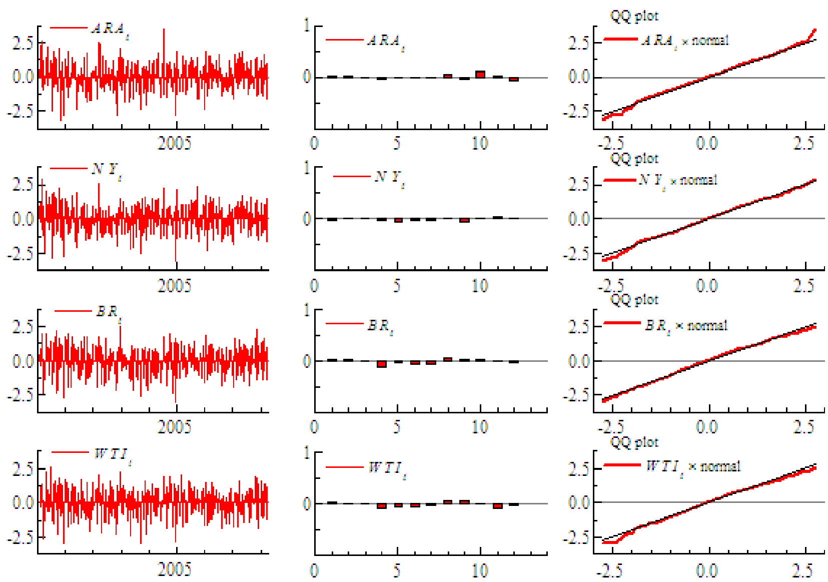
$$D_{3,t} = 1(\text{12th week in 2003})$$

$$D_{4,t} = 1(\text{35th week in 2005}), -1(\text{36th week in 2005}),$$

where $1(\cdot)$ is the standard indicator function. These dummy variables are deemed to correspond to volatile markets around 2001 and 2002 after the September 11 attacks, the outbreak of the Iraq war in 2003, and the attack of Hurricane Katrina in 2005, respectively. The second dummy variable seems to be a bit distant from September 2001, but the crude oil markets continued to be rather unstable until the end of the first quarter of 2002; thus the second dummy variable is required to model an outlier observed in this period. All of these dummy variables are included in the VAR model unrestrictedly, following Doornik et al. (1998).

With a view to checking if the VAR model incorporating the dummy variables fits the data well, Figure 2 displays various graphs on the residuals of the model: scaled residuals (the first column), residual correlogram (the second column), and residual quantile-quantile plots based on the normal distribution (the third column). According to the figure, there is no strong evidence against the assumption of normality and temporal independence. The overall evidence allows us to proceed to a likelihood-based cointegrated VAR analysis.

Figure 2. Mis-Specification Tests for the VAR Model



3.2 Determination of the Cointegrating Rank

The cointegrated VAR analysis is primarily interested in the question of whether or not long-run leadership exists in the price data. It is therefore necessary, at the first stage of the analysis, to check whether the cointegrating rank is three $(r = n - 1 = 3)$, in line with the first condition for long-run price leadership given in the previous section.

Table 1 presents log-likelihood ratio (log *LR*) test statistics for cointegrating rank, in addition to the modulus of the six largest roots of the companion matrix. The log *LR* tests in the first panel strongly reject the null hypotheses $r = 0$, $r \leq 1$, and $r \leq 2$, while the hypothesis $r \leq 3$ has p-value 0.13. The second panel provides two types of modulus (denoted *mod*) of the six largest eigenvalues of the companion matrix, unrestricted and restricted with $r = 3$. There is no modulus greater than 1.0, suggesting that the model should not include any explosive root. The restricted case includes only a single unit root, which corresponds to the number of the common trend, therefore indicating the absence of $I(2)$ roots. Furthermore, Figure 3 displays a set of recursive eigenvalues derived from the VAR system. In line with Table 1, the first three eigenvalues hold much larger values than the fourth one, which stays low throughout the sample period.

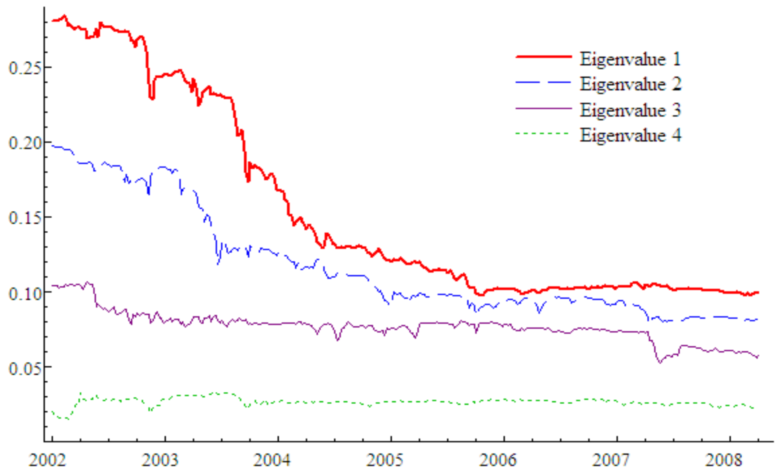
Table 1. Determination of the Cointegrating Rank

	$r=0$	$r\le 1$	$r\le 2$	$r\le 3$
$\log LR(H(r)\mid H(p))$	116.39 [0.00]**	71.71 [0.00]**	35.48 [0.00]**	10.02 [0.13]

***mod* (unrestricted)**	0.97	0.87	0.87	0.76	0.76	0.62
***mod* ($r=3$)**	1.00	0.87	0.87	0.75	0.75	0.62

Notes: Figures in the square brackets are p-values according to the limiting distribution. ** denotes significance at the 1% level.

Figure 3. Recursive Eigenvalues of the VAR System



All of these results support the validity of an $I(1)$ cointegrated VAR system with $r=3$; thus, the first condition for long-run price leadership is judged to be satisfied. The subsequent cointegrated VAR analysis is conducted with the restriction $r=3$.

3.3 Testing Weak Exogeneity

The determination of the cointegrating rank $(r=3)$ allows us to conduct hypothesis testing on α and β. For the purpose of checking the second condition for long-run price leadership, it is necessary to identify which error process corresponds to the permanent shock in the cointegrated VAR system. This identification problem is translated into the question of which variable is weakly exogenous with respect to β. This is due to the fact that testing weak exogeneity corresponds to checking zero restrictions on α, thereby identifying $\alpha_\perp$ given $r = n - 1 = 3$.

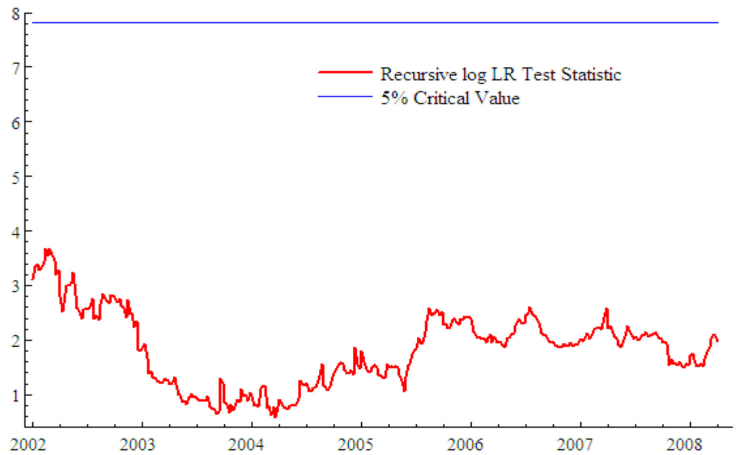
Table 2 provides a set of log *LR* test statistics for the null hypothesis of weak exogeneity with respect to each variable in the system. The null hypothesis is rejected for ARA_t, NY_t, and BR_t at the 5% significance level, whereas the hypothesis is not rejected for WTI_t at the same level. The p-value for WTI_t is 0.58, suggesting that the adjustment coefficients for WTI_t are very likely to be zero. In order to check its stability over the sample period, the log *LR* test statistic is recursively calculated and its plots are presented in Figure 4. The test statistic stays at much lower level than the 5% critical value, evidence in favor of the validity of the restriction.

Table 2. Testing Weak Exogeneity

	ARA_t	NY_t	BR_t	WTI_t
log *LR*	8.25 [0.04]*	15.11 [0.00]**	8.24 [0.04]*	1.98 [0.58]

Notes: Figures in the square brackets are p-values according to $\chi^2(3)$. ** and * denote significance at the 1% and 5% levels, respectively.

Figure 4. Recursive log LR Test Statistic for Weak Exogeneity of WTI_t



These results allow us to judge that WTI_t is weakly exogenous with respect to β. Accordingly, the orthogonal complement of α can be given by $\alpha_\perp = (0,0,0,1)'$. Hence, the second condition is fulfilled, indicating that the permanent shock in the VAR system solely consists of the error process for WTI_t. This finding paves the way for the conjecture that WTI_t plays the role of long-run price leadership in the crude oil and gasoline markets. This is in line with the accepted view that WTI_t serves as a benchmark for pricing a number of other crude oil commodities, thereby influencing the price determination of such products as regular gasoline.

3.4 Restrictions on the Cointegrating Space

We are now in a position to investigate whether the third condition for long-run price leadership is satisfied. The third condition is embodied in a set of restrictions on the cointegrating space. It is thus necessary to check if the cointegrating space can be expressed as (2), under the restriction of WTI_t being weakly exogenous with respect to β, or $\alpha_\perp = (0,0,0,1)'$, as investigated above. A set of restricted estimates of β are provided below:

$$\hat{\beta}^{*\prime} X_{t-1}^{*} = \begin{pmatrix} \underset{(-)}{1} & \underset{(-)}{0} & \underset{(-)}{0} & \underset{(-)}{-1} & \underset{(0.00014)}{0.00013} \\ \underset{(-)}{0} & \underset{(-)}{1} & \underset{(-)}{0} & \underset{(-)}{-1} & \underset{(0.00011)}{0.00014} \\ \underset{(-)}{0} & \underset{(-)}{0} & \underset{(-)}{1} & \underset{(-)}{-1} & \underset{(0.0000475)}{-0.00014} \end{pmatrix} \begin{pmatrix} ARA_{t-1} \\ NY_{t-1} \\ BR_{t-1} \\ WTI_{t-1} \\ t \end{pmatrix},$$

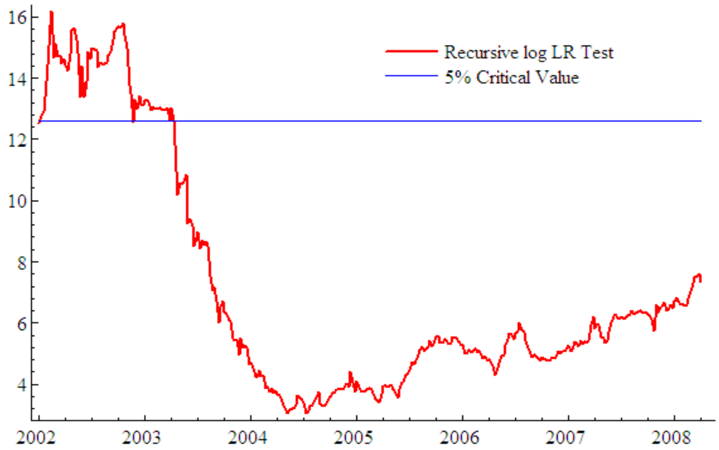
where the figures in parentheses correspond to standard errors. These estimates are obtained with the weak exogeneity restriction imposed on WTI_t. The log *LR* test statistic for the joint restrictions is 7.32, with an associated p-value 0.29 according to $\chi^2(6)$. Thus the cointegrating space is represented as (2), satisfying the third condition for long-term leadership. All the conditions being fulfilled, we conclude that WTI_t plays the role of long-run price leadership, influencing the price determination of the other commodities in the VAR system.

In order to check the stability of the revealed price leadership, the log *LR* test statistic for the joint restrictions is recursively calculated and its plots are displayed in Figure 5. According to the figure, the test statistic lies well below the 5% critical value mid-2003 onwards, suggesting that the price leadership led by WTI_t has been stable for a very long period of time. The recursive test, however, rejects the null hypothesis of stability prior to 2003, indicating the possibility that WTI_t previously played a less significant role in the long-run price determination in international crude oil and gasoline markets.

3.5 Revealing the Underlying Hierarchical Structure

Motivated by the finding above, this section aims to reveal a hierarchical structure embedded in the crude oil and gasoline price data. The revealed structure may allow us to interpret the long-run linkages of the data from the viewpoint of causal chains. A battery of restrictions on the adjustment and cointegrating spaces, allowing for the long-run price leadership discussed above, leads to the following identified structure:

Figure 5. Recursive log LR Test Statistic for the Joint Restrictions



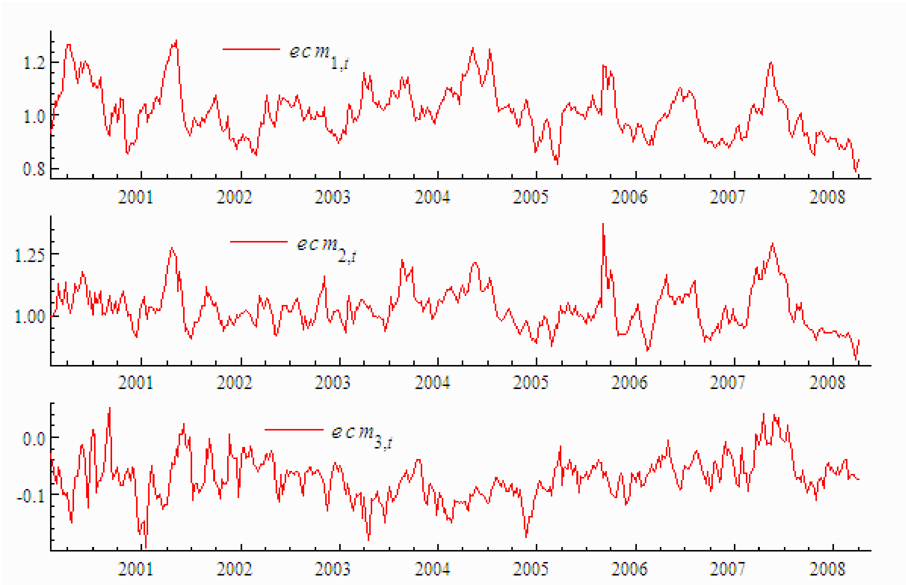
$$\hat{\alpha}\hat{\beta}^{*\prime}X^{*}_{t-1}=\begin{pmatrix} \underset{(0.02)}{-0.08} & \underset{(-)}{0} & \underset{(0.04)}{-0.20} \\ \underset{(0.03)}{0.07} & \underset{(0.03)}{-0.21} & \underset{(-)}{0} \\ \underset{(-)}{0} & \underset{(-)}{0} & \underset{(0.03)}{-0.17} \\ \underset{(-)}{0} & \underset{(-)}{0} & \underset{(-)}{0} \end{pmatrix}\begin{pmatrix} \underset{(-)}{1} & \underset{(-)}{0} & \underset{(-)}{-1} & \underset{(-)}{0} & \underset{(-)}{0} \\ \underset{(-)}{0} & \underset{(-)}{1} & \underset{(-)}{0} & \underset{(-)}{-1} & \underset{(-)}{0} \\ \underset{(-)}{0} & \underset{(-)}{0} & \underset{(-)}{1} & \underset{(-)}{-1} & \underset{(0.0000389)}{-0.00012} \end{pmatrix}\begin{pmatrix} ARA_{t-1} \\ NY_{t-1} \\ BR_{t-1} \\ WTI_{t-1} \\ t \end{pmatrix}, \qquad (3)$$

where the figures in parentheses are standard errors. The log *LR* test statistic for the joint restrictions is 18.84, with its p-value 0.09 according to $\chi^2(12)$. Thus the joint hypothesis is not rejected again at the 5% level. The restricted cointegrating relationships given in (3) act as equilibrium correction terms in the VAR system. These relationships defined as follows:

$$\begin{aligned} ecm_{1,t-1} &= ARA_{t-1} - BR_{t-1} \\ ecm_{2,t-1} &= NY_{t-1} - WTI_{t-1} \\ ecm_{3,t-1} &= BR_{t-1} - WTI_{t-1} - 0.00012t\ . \end{aligned}$$

The first two relations indicate that the markups of the gasoline prices over the crude oil prices in both Europe and the US are judged to be stationary. The third relation, in contrast, suggests that the markup of the representative crude oil price in Europe over that in the US is a stationary process augmented with deterministic trend. The presence of linear trend in the cointegrating combination, with a very small coefficient, may indicate that the Brent-WTI spread is gradually widening. Figure 6 displays time series plots of $ecm_{1,t-1}$, $ecm_{2,t-1}$, and $ecm_{3,t-1}$, none of which appears to be non-stationary.

Figure 6. Plots of the Restricted Cointegrating Relations



The logic behind these long-run specifications lies in a conceivable hierarchical structure in which the common stochastic trend in WTI_{t-1} is transmitted to BR_{t-1} and NY_{t-1} then passed to ARA_{t-1} by way of BR_{t-1}. All of these markups work as attractor sets or equilibrium correction mechanisms, playing a key role in accounting for the major dynamics of the VAR system.

Next, we proceed to the inspection of the adjustment structure in terms of the equations for ΔARA_t, ΔNY_t, and ΔBR_t in the cointegrated VAR system. First, according to (3), the equation for ΔARA_t is expressed as:

$$\Delta ARA_t = -0.08(ARA_{t-1} - BR_{t-1}) - 0.2(BR_{t-1} - WTI_{t-1} - 0.00012t) + \dots, \qquad (4)$$

where $\dots$ represents a set of omitted short-run dynamics. The adjustment of ARA_t towards the first cointegrating relation agrees with its normalization; thus, the interpretation of its role as equilibrium correction appears to be reasonable. The second cointegrating combination, in contrast, stems from the international crude oil market, therefore indicating the presence of direct influences of the oil market on the European regular gasoline market. Its adjustment coefficient is estimated as -0.2 using the weekly data, hence suggesting that, other things being equal, it takes five weeks for the influence of the oil market's disequilibrium errors to disappear in the European gasoline market.

Turning to ΔNY_t, one finds in (3) that ΔNY_t reacts to both $ecm_{2,t-1}$ and $ecm_{1,t-1}$:

$$\Delta NY_t = -0.21(NY_{t-1} - WTI_{t-1}) + 0.07(ARA_{t-1} - BR_{t-1}) + \dots . \tag{5}$$

Note that the first cointegrating linkage is normalized for NY_{t-1}; thus, its presence in (5) implies a stable reversion of NY_t to its long-run equilibrium given by WTI_{t-1}. The adjustment coefficient for the second cointegrating relation, in contrast, is small but positive, indicating some spill-over influences of the European gasoline market on the US counterpart; a hypothetical explanation for this is that an increase in the European gasoline price over the corresponding crude oil price may generate the expectation that the US gasoline price will also go up, thereby having an actual positive impact on ΔNY_t.

It is then found that the equation for ΔBR_t exclusively reacts to $ecm_{3,t-1}$:

$$\Delta BR_t = -0.17(BR_{t-1} - WTI_{t-1} - 0.00012t) + \dots , \tag{6}$$

which suggests a stable reversion of BR_t to its long-run equilibrium value. Also note that all the adjustment coefficients for the ΔWTI_t equation are set to be zero in (3), in line with Section 3.3, where WTI_t is judged to be weakly exogenous for β. Thus, WTI_t plays the role of the pushing force in the system, as discussed in Section 3.4.

The structure of long-run interactions, demonstrated in (4), (5), and (6) above, is schematically expressed as follows:

$$\begin{tikzcd} WTI_t \arrow[r] \arrow[dr] & BR_t \arrow[r] & ARA_t \arrow[dl] \\ & NY_t & \end{tikzcd}$$

The arrows indicate the existence of a long-run influence of one variable on another. The hierarchical structure is clearly revealed; that is, the common stochastic trend in WTI_t is communicated to BR_t and NY_t, then transmitted to ARA_t via BR_t. Furthermore, it should be noted that the European gasoline market has a spill-over effect on the US counterpart ($ARA_t \to NY_t$), possibly through the expectation channel as described above. The influence of WTI_t on BR_t, coupled with that of ARA_t on NY_t, may be perceived as evidence for long-run transatlantic market interactions.

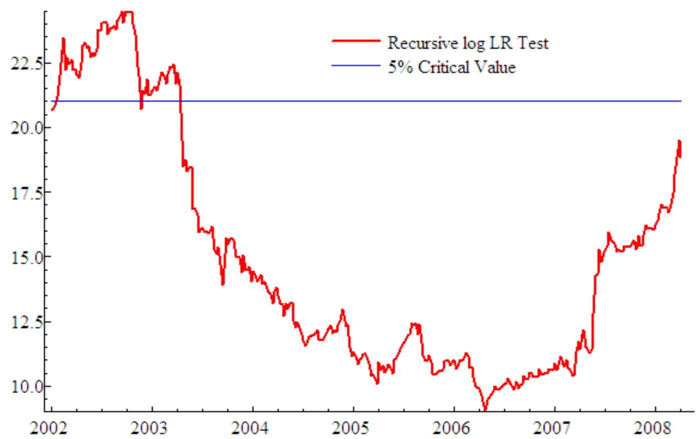
Furthermore, calculating the product $\hat{\alpha}\hat{\beta}^{*\prime}$ or the long-run matrix in (3) would also be helpful for clarifying the hierarchical structure:

$$\hat{\alpha}\hat{\beta}^{*\prime} X_{t-1}^{*} = \begin{pmatrix} \underset{(0.02)}{-0.08} & \underset{(-)}{0} & \underset{(0.04)}{-0.12} & \underset{(0.04)}{0.20} & \underset{(0.00000471)}{0.0000230} \\ \underset{(0.03)}{0.07} & \underset{(0.03)}{-0.21} & \underset{(0.03)}{-0.07} & \underset{(0.03)}{-0.21} & \underset{(-)}{0} \\ \underset{(-)}{0} & \underset{(-)}{0} & \underset{(0.03)}{-0.17} & \underset{(0.03)}{0.17} & \underset{(0.00000339)}{0.0000191} \\ \underset{(-)}{0} & \underset{(-)}{0} & \underset{(-)}{0} & \underset{(-)}{0} & \underset{(-)}{0} \end{pmatrix} \begin{pmatrix} ARA_{t-1} \\ NY_{t-1} \\ BR_{t-1} \\ WTI_{t-1} \\ t \end{pmatrix}, \qquad (7)$$

where the figures in parentheses are standard errors. The upper diagonal form found in (7) represents the hierarchical structure underlying the data.

Again, the log *LR* test statistic for the joint restrictions is recursively calculated and its plots are presented in Figure 7. In line with Figure 5, the test statistic goes beyond the 5% critical value in the period of 2002, but stays below the critical value mid-2003 onwards. The figure indicates, together with Figure 5, that the revealed structure was established around 2003 and has been stable since then.

Figure 7. Recursive log *LR* Test Statistic for the Joint Restrictions



3.6 A Simultaneous Vector Equilibrium Correction System

Finally, a simultaneous vector equilibrium correction system for the price data is estimated in order to investigate the short-run market interactions. Mapping the data to the $I(0)$ space by differencing and using the restricted cointegrating relations, we obtain an $I(0)$ vector equilibrium correction system. Checking the presence of contemporaneous correlations in the system and then removing insignificant regressors from it step by step, we arrive at a parsimonious simultaneous equations system representing the data as follows:

$$
\begin{aligned}
\Delta ARA_t &= -\underset{(0.02)}{0.07}(ARA_{t-1} - BR_{t-1}) - \underset{(0.04)}{0.19}(BR_{t-1} - WTI_{t-1} - 0.00012t) \\
&\quad + \underset{(0.03)}{0.23}\,\underline{\Delta NY_{t-1}} + \underset{(0.03)}{0.14}\,\underline{\Delta NY_{t-3}} + \underset{(0.09)}{0.22}\,\Delta BR_{t-2} - \underset{(0.1)}{0.25}\,\underline{\Delta WTI_{t-2}} + \underset{(0.02)}{0.06} \\
\Delta NY_t &= \underset{(0.03)}{0.08}(ARA_{t-1} - BR_{t-1}) - \underset{(0.03)}{0.21}(NY_{t-1} - WTI_{t-1}) + \underset{(0.04)}{0.2}\,\Delta NY_{t-1} \\
&\quad + \underset{(0.04)}{0.1}\,\Delta NY_{t-3} + \underset{(0.1)}{0.28}\,\underline{\Delta BR_{t-2}} - \underset{(0.11)}{0.32}\,\Delta WTI_{t-2} + \underset{(0.02)}{0.13} \\
\Delta BR_t &= \underset{(0.1)}{0.57}\,\underline{\Delta WTI_t} - \underset{(0.03)}{0.17}(BR_{t-1} - WTI_{t-1} - 0.00012t) + \underset{(0.04)}{0.16}\,\Delta BR_{t-1} \\
&\quad - \underset{(0.04)}{0.09}\,\Delta BR_{t-3} + \underset{(0.04)}{0.17}\,\underline{\Delta WTI_{t-3}} - \underset{(0.002)}{0.01} \\
\Delta WTI_t &= \underset{(0.06)}{0.12}\,\Delta NY_t + \underset{(0.03)}{0.07}\,\Delta NY_{t-3} + \underset{(0.03)}{0.16}\,\underline{\Delta BR_{t-1}} + \underset{(0.07)}{0.34}\,\underline{\Delta BR_{t-2}} \\
&\quad - \underset{(0.07)}{0.46}\,\Delta WTI_{t-2} + \underset{(0.002)}{0.003},
\end{aligned} \tag{8}
$$

where the figures in parentheses correspond to standard errors, and all the dummy variables are omitted for the sake of simplicity of exposition. A log *LR* test for over-identifying restrictions in (8) is 41.37, where the p-value is 0.41 according to $\chi^2(40)$. Terms indicating a short-run transatlantic influence are underlined in (8).

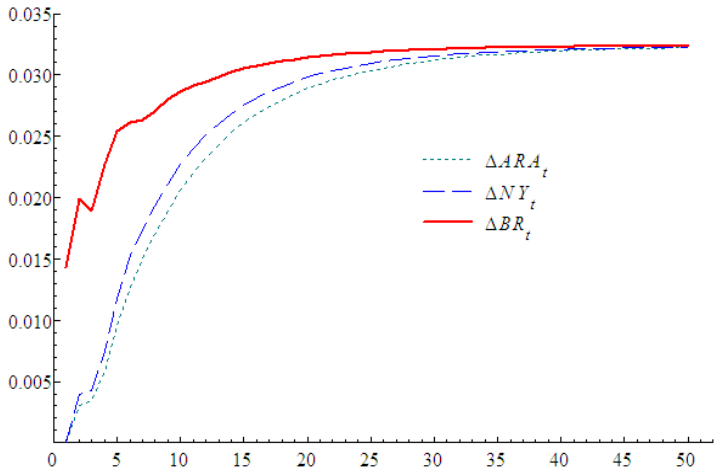
Taking a closer look at the structure of short-run dynamics in (8), with regard to the equation for ΔARA_t, it should be noted that the coefficients of ΔNY_{t-1} and ΔNY_{t-3} are both large and highly significant, suggesting the presence of strong short-run impacts of the US gasoline price on that in Europe. The equation for ΔNY_t, in contrast, does not include any short-run dynamic terms associated with the past values of ΔARA_t. As far as the short-run transatlantic interactions in the gasoline markets are concerned, ΔNY_t plays a more important role than ΔARA_t, possibly reflecting the dominant position of the US in the global economy as compared with other countries and regions.

Turning to the equation for ΔBR_t, one finds that ΔWTI_t and ΔWTI_{t-3} play major roles in accounting for the short-run dynamics of the equation. The presence of ΔWTI_t in the equation may be seen as additional evidence for the price leadership of the US crude oil price. Regarding the equation for ΔWTI_t, the short-run dynamics of the European crude oil price, ΔBR_{t-1} and ΔBR_{t-2}, play a critical role in the equation. This evidence indicates that there is a strong interdependent relationship between the two crude oil prices, although it is WTI_t that works as a long-run pushing force in the system.

Furthermore, ΔNY_t and ΔNY_{t-3} are significant in the ΔWTI_t equation, with positive coefficients, which is in contrast to the equation for ΔBR_t; the evidence indicates that a rise in the US gasoline price leads to an increase in the US crude oil price. This finding is noteworthy in that the underlying financial markets should serve as a catalyst for connecting the crude oil and gasoline markets. As a result, the price of gasoline has a significant impact on the price-setting in the crude oil market, in spite of the fact that gasoline is a product of crude oil and therefore located downstream in the production process from crude oil.

Finally, Figure 8 displays accumulated responses of ΔARA_t, ΔNY_t, and ΔBR_t to an impulse in the ΔWTI_t equation. As expected from the common long-run pushing force WTI_t, the accumulated responses converge to the same long-run value. Note that ΔBR_t is more responsive to the impulse than ΔNY_t and ΔARA_t. This is in support of the view that the crude oil markets are internationally integrated; thus, shocks are more quickly transmitted within the global oil markets rather than to the outside markets such as those for regular gasoline.

Figure 8. Accumulated Responses to an Impulse in the ΔWTI_t Equation



4. Summary and Conclusions

Spot prices of crude oil such as Brent and WTI should have strong pass-through influences on those of regular gasoline in Europe and the US. It then seems to be natural to ask how spot markets for crude oil and regular gasoline interact with each other. It is also of great interest, in terms of the understanding of transatlantic cause-effect chains, to find out which crude oil plays the role of long-run price leadership, influencing the price determination of the other crude oil and regular gasoline commodities. Price dynamics in these markets have been subjected to substantial empirical investigations, but the existing research does not necessarily focus on addressing the issues above in a transatlantic context. For the purpose of shedding useful light on the transatlantic market interactions and long-run price leadership, this paper estimates a cointegrated VAR system comprising logged spot prices of Brent and WTI as well as those of regular gasoline in two representative regional markets in Europe and the US. A likelihood-based multivariate cointegration analysis reveals that the US crude oil plays the role of long-run price leadership, affecting the price determination of the other commodities in the VAR system. Cointegrating vectors are then normalized and restricted in such a way that the underlying long-run market interactions may be interpreted in terms of causal chains. Finally, a parsimonious equilibrium correction system is estimated to explore the short-run market interactions. This paper's analysis successfully reveals the transatlantic long-run and short-run market interactions, contributing to deeper understanding of the structure of crude oil and gasoline markets.

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