# The Relation between Petroleum Product Prices and Crude Oil Prices

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## 1. Introduction

We study the short-run relations between the spot prices of Brent crude oil, gasoline (New York Harbor, Regular Conventional) and heating oil (New York Harbor, No. 2 Heating Oil). Two primary hypotheses regarding these relations have been presented in the literature. The first argues that the primary causal relation runs from oil prices to product prices. The alternative is that causality runs in the opposite direction, or potentially in both directions. The direction of causality has important implications for the regulation and organization of these markets and the facilitation of trade. We test for Granger causality between spot oil prices and spot petroleum product prices using reduced form Vector Autoregressive (VAR) models. We also explore how petroleum product prices respond to structural supply and demand shocks to the oil market through the medium of Structural VAR models of the spot crude oil and spot gasoline markets, and separately the spot crude oil and the spot heating oil markets. We study prices measured at the weekly frequency for the period 6/24/1988–4/26/2019.

Our empirical examination addresses the question of whether: a) petroleum product prices cause crude oil prices in a Granger causality sense (Granger, 1969), b) crude oil prices Granger-cause product prices, or c) bidirectional Granger causality is present between crude oil prices and petroleum product prices. Tests of Granger causality are tests of linear predictability rather than economic causality (see Kilian and Lütkepohl, 2017). While as originally formulated, Granger causality tests rely on the assumption of stationary time series, the tests we implement are robust to non-stationarity.

Whether there is a causal link running from product prices to oil prices has received limited attention with mixed results (Asche et al., 2003; Kaufmann et al., 2009; Kilian, 2010; Baumeister et al., 2018).[1] Nevertheless, much of the empirical literature begins with the assumption that the direction of causality runs from oil prices to product prices (survey of Frey and Manera, 2007; EIA, 2014). The focus of our study differs from and extends the discussion by formally testing whether in our case Granger causality runs from oil prices to petroleum product products or the reverse, including whether there is evidence of bidirectional Granger causality. We focus on spot U.S. petroleum product prices, but in light of recent evidence produced by the U.S. Energy Information Administration (EIA) (2014), Borenstein and Kellogg (2014), Kilian (2016) and others, we utilize Brent oil prices as a proxy for the global oil benchmark.

Our tests for Granger causality are based upon reduced form vector autoregression models and tests which are robust to nonstationarity (see, Toda and Yamamoto, 1995; Dolado and Lütkepohl, 1996). We find evidence of Granger causality running from oil prices to product prices for prices measured at the weekly frequency spanning roughly a 30-year period and for two subperiod where we divide the sample at the end of 2005. The results continue to hold when the model is extended to include variables measuring supply and demand conditions, which may themselves be jointly determined with prices. Conversely, we find no evidence that gasoline and heating oil prices Granger-cause oil prices when assessed over our full sample period. This result also holds for the period up until the end of 2005. Interestingly however, for the period following the end of 2005, while we continue to find that heating oil prices do not Granger-cause oil prices, we reject the null hypothesis that gasoline prices do not Granger-cause oil prices, while also rejecting the null hypothesis that oil prices do not Granger-cause product prices.

[1] See Ederington et al. (2019a, 2019b) for a review of this evidence and the characteristics of petroleum product prices.

The reduced form models estimated however do not allow us to say anything directly about how structural shocks to supply and demand conditions in the oil market impact real gasoline and heating oil prices. To address those questions we turn to recursively identified structural vector auto regressive models. We present an examination of gasoline and heating oil price responses to structural supply and demand shocks in the oil market based upon a structural VAR model that jointly characterizes the spot oil market and the spot gasoline market, and separately, the spot oil market and the spot market for heating oil.[2] Our results indicate that oil supply shocks have no short-run impact (over subsequent 15 week periods) on either spot gasoline or heating oil prices. In contrast, oil-specific demand shocks have a significant impact on both gasoline and heating oil prices. These results are in general agreement with results presented by Kilian (2010) in a study of retail gasoline prices measured at a monthly frequency indicating the conclusions apply both to short as well as intermediate term horizons.

The behavior of oil prices in recent years has attracted considerable attention and debate about whether this behavior is caused by fundamental supply and demand variables or by excess speculation and possibly manipulation. Researchers have debated whether trading in oil futures contracts by investment management funds has influenced the spot markets for oil and oil product prices.[3] A change in market investment philosophy near the end of 2005 resulted in oil futures being treated as a general investment option rather than a specialty investment belonging mainly to hedgers and speculators. Further, in early April of 2005 the Intercontinental Exchange (ICE)

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[2] "Spot" purchases refer to situations in which the commodity physically changes hands at a refinery gate or other major pricing hub for delivery on a pipeline or via barge or cargo.

[3] Fattouh, Kilian, and Mahadeva (2013) provide a review of the debate and conclude the evidence is more consistent with the hypothesis that fundamentals are the driving force. See also Hamilton and Wu (2014, 2015) and Singleton (2014). Boyd et al. (2018) survey the more recent literature and conclude "While speculation and financialization can theoretically destabilize commodity markets, the extant literature finds little evidence of destabilization and documents that speculators largely provide liquidity to hedgers. Moreover, recent concern that commodity index trading leads to price distortions has little support in the data." (pg. 91).

moved the trading of Brent oil futures to an electronic platform, after which there was an explosion in trading volume and open interest. To be conservative we use year-end 2005 as the date for demarcating the two subperiods we study. Our data span the period 06/24/1988 through 04/26/2019, which allows us to examine whether the relations between oil, gasoline, and heating oil prices changed before and after the end of 2005. Our tests reject the null hypothesis that oil prices do not Granger-cause product prices for both subperiods. We also do not reject the null that product prices do not Granger-cause oil prices during the first subperiod. However, we do reject the null that gasoline prices do not Granger-cause oil prices during the second subperiod, indicating bi-directional causality following 2005.

Section 2 of this study elaborates further on hypotheses regarding the causal direction between oil prices and petroleum product prices. The data we examine and descriptive statistics are discussed in Section 3. Section 4 presents the results of our tests for Granger causality. Section 5 introduces the SVAR models and presents an analysis of how petroleum product prices respond to shocks to oil supply, global commodity demand and oil-specific demand. We summarize the results and present our conclusions in Section 6.

## 2. Direction of causality between oil prices and petroleum product prices

The theme of a large body of research is that changes in petroleum product prices are driven by changes in oil prices and that a long-term equilibrium relation exists between oil prices and product prices. Indeed, many studies take this direction of causality as a given.[4] An alternative view is the hypothesis that demand for petroleum products and the resulting prices drive the price

[4] For instance, in a recent EIA report studying crude oil and gasoline prices (2014), the authors state that "While EIA recognizes that wholesale gasoline and crude oil prices are interdependent, because demand for crude oil is very highly related to the demand for refined products, this analysis focuses on the first order relationship between changes in crude oil price and wholesale gasoline price." Illustrative research that takes this view is reviewed in Frey and Manera (2007).

of oil. Verleger (1982) has argued that spot market prices for petroleum products are the primary determinants of crude oil prices. Baumeister at al. (2018) describe the economic dynamics of Verleger's hypothesis as follows: "A common view is that refiners view themselves as price takers in product markets and cut their volume of production when they cannot find crude oil at a price commensurate with product prices. In time, this reduction in the demand for crude oil will lower the price of crude oil and the corresponding reduction in the supply of products will boost product prices (see Verleger, 2011)" (p. 1). This hypothesis rests on the assumption that refiners wish to maintain margins and therefore adjust their demand for oil accordingly. In a study of oil price forecasting predicated on the Verleger thesis, Baumeister et al. (2018) find some evidence in support of the hypothesis, albeit for a model that deviates from the strict hypothesis. Most studies, however, have tended to emphasize the connection between changes in crude oil prices and gasoline (or product) prices, under the assumption that changes in oil prices drive changes in product prices. An example of the latter are investigations of the relation between gasoline prices and the two primary oil benchmark prices, the Brent price and the West Texas Intermediate (WTI) price (U.S. Energy Information Administration, 2014).

At a more fundamental level, crude oil is the main input in the production of distillate/heating oil and motor gasoline, thus oil supply disruptions can influence the price of oil as well as potentially the prices of the products refined from oil. Likewise changes in the demand for distillate/heating oil and gasoline as well as changes in the ability or capacity of refiners to process crude oil thus influencing the supply of these products, can influence the prices of these products independent of oil price changes, and consequently the price of oil through the demand for oil.[5]

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[5] A menu of variables include such events as an unexpected hurricane that interferes with refinery operations, colder-than-normal weather, and changes in environmental and other regulatory requirements.

Elaborating further, if the markets for crude oil, heating oil and gasoline were separate and subject to frictions both in trading and information flow, then a change in crude oil supply would potentially impact crude oil prices first and then product prices but longer run price levels would depend on how supply and demand respond to these prices. Likewise if such frictions were present one might expect a shock to gasoline or heating oil supply or demand to impact first gasoline or heating oil prices and then crude oil prices with a potential lag. Then, in the longer run, prices would depend on whether crude oil production increases so prices come back down or changes little so prices stay high.

We investigate whether Granger causality runs from oil prices to product prices, from product prices to oil prices, or in both directions using a reduced form Vector autoregression specification.[6] By approaching the question in this way, our study differs from those that begin with the premise that product prices are determined by oil prices. We explore not only the relations between the prices of oil, heating oil and gasoline in a model focused only on prices but also extend the analysis to a model that includes potential fundamental drivers of prices related to supply and demand conditions. An important part of that analysis involves the specification and estimation of a semi-structural vector autoregressive model and the assessment of how structural shocks related to supply and demand conditions in the oil market impact the behavior of prices.

[6] Research conducted by the U.S. EIA has found that changes in wholesale gasoline spot prices have a consistent effect on retail gasoline prices. Controlling for other variables, a $1-per-barrel change in the price of crude oil results in a $0.024-per-gallon change in the price of wholesale and retail gasoline. (One barrel contains 42 gallons, and 1/42 of $1 is $0.024.) The evidence suggests that the adjustment occurs with a lag and that about half of the change in crude oil price is passed through to retail prices within two weeks of the price change, all other market variables being equal (Gasoline Price Pass-Through (January 2003): http://www.eia.gov/petroleum/archive/gasolinepass.htm).

## 3. The sample data

### *3.1. Description*

We focus on U.S. spot petroleum product prices, but in light of recent evidence produced by the EIA (2014), Borenstein and Kellogg (2014), Kilian (2016) and others, we utilize Brent oil (FOB) prices as a proxy for the global oil benchmark.[7] We study data measured at the weekly frequency for the period 6/24/1988- 4/26/2019.[8] We present results based upon spot prices for Brent oil, henceforth referred to as oil, spot prices for gasoline (New York Harbor, Regular Conventional), henceforth referred to as gasoline, and spot prices for heating oil (New York Harbor, No. 2 Heating Oil), henceforth referred to as heating oil. Weekly averages of daily spot prices (henceforth weekly prices) are obtained from the archives of the U.S. Energy Information Administration (www.eia.gov).[9] Our empirical analysis is based upon the log of inflation adjusted and deseasonalized spot price series for gasoline and heating oil, and the log of inflation adjusted spot prices for Brent oil. We do not detrend prices. Nominal prices are converted to real prices using weekly extrapolated U.S. CPI data as described in the Appendix. Gasoline and Heating Oil prices are also deseasonalized using monthly dummies. In addition to an examination of results based upon the full sample period we also examine two subperiods, before and after the beginning of 2006.

[7] Not all agree that Brent is the best benchmark (Pirrong, 2010; Fattouh, 2011; Mann and Sephton, 2016; Baumeister et al., 2018).
[8] Alquist, Kilian and Vigfusson (2013) document a structural break in the oil price series towards the end of 1973. The time period we study begins in 1988.
[9] While the front month futures price has been used as a substitute for the spot price in some studies, we chose to focus on spot prices. In this way we avoid any potential aberrations in futures prices that might have been caused by variables other than physical market supply and demand conditions. For a discussion of potential issues surrounding oil futures prices see Alquist and Kilian (2010).

### *3.2. Univariate comparisons and statistics*

Figure 1 presents plots of the nominal per barrel spot prices for Brent and WTI oil in $US. The graph shows the now-familiar similarity in the series but also the disconnect that occurred during the 2011-2014 period. As already mentioned, recent evidence supports the hypothesis that the Brent price is a better proxy for the world oil price.

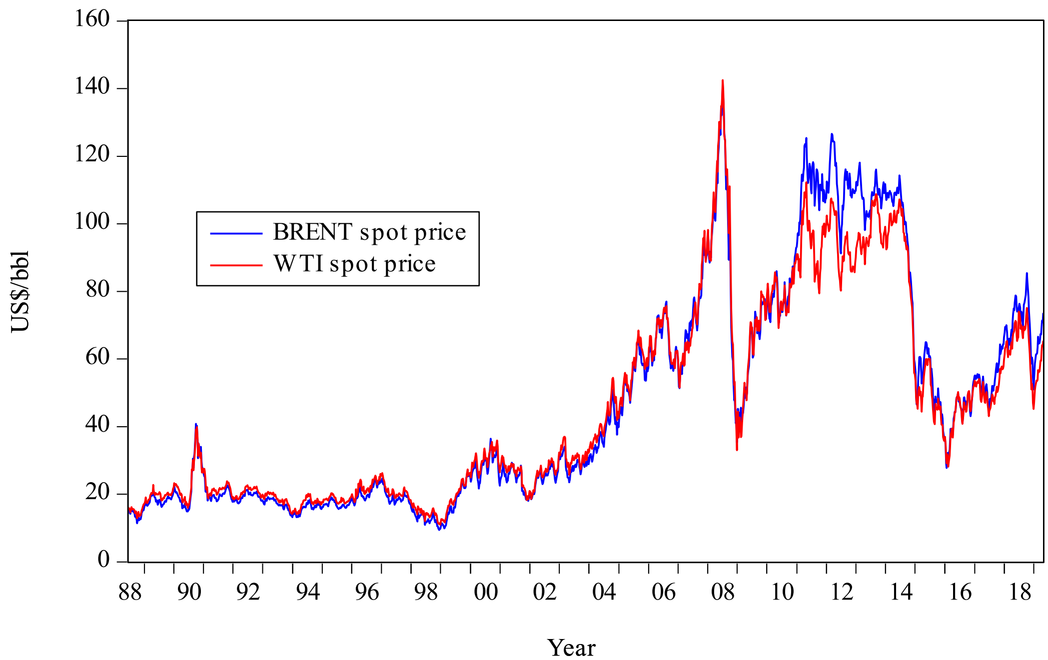


Fig. 1. Weekly average nominal per barrel spot prices, Brent Oil, WTI Oil, in $US, 6/24/1988-4/26/2019
Source: U.S. Energy Information Administration

Figure 2 presents plots of the per-barrel nominal spot price series for Brent oil in U.S. dollars as well as the per-gallon prices of gasoline and heating oil. The series displayed in Figure 2 tend to follow a similar pattern; however, it remains to assess the relation in more detail and in particular the direction of predictability between these prices.

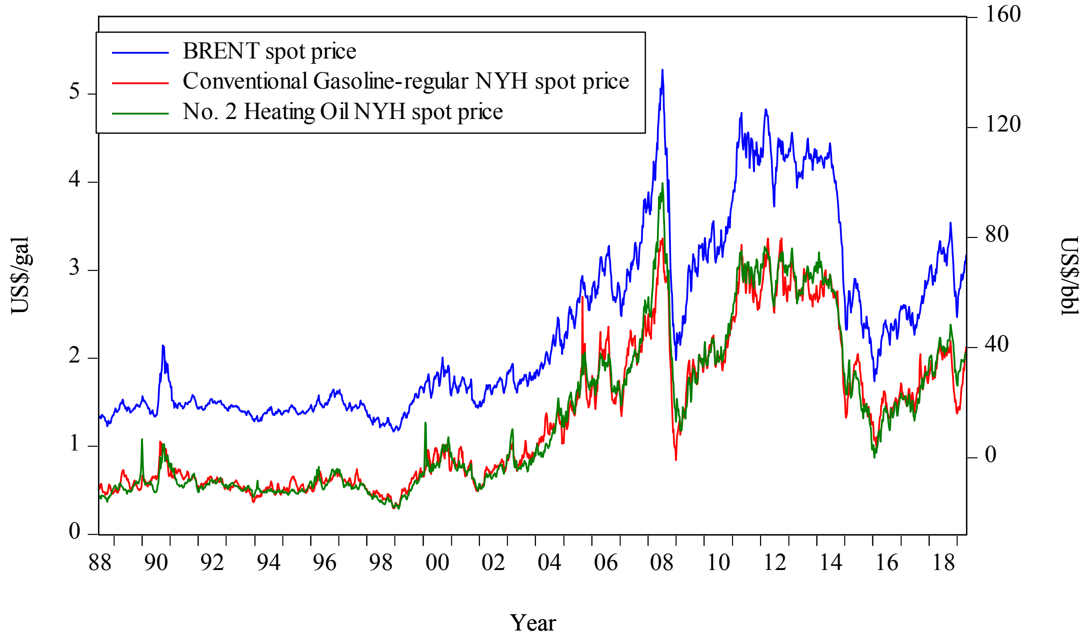


Fig. 2. Weely average nominal spot prices: Brent Oil, Regular Conventional Gasoline NYH, No. 2 Heating Oil NYH, 6/24/1988-4/26/2019
Source: U.S. Energy Information Administration

Descriptive statistics for the weekly average real spot prices (unlogged) are reported in Table 1. Panel A of the table reports statistics for the real spot price levels for the full sample period. Panel B reports data for the subperiod 6/24/1988–12/31/2005, and Panel C for the subperiod 1/6/2006–4/26/2019. Average and median real price levels were higher during the second subperiod for all three commodities.

We fit AR(p) models to each of the log price series suitably adjusted for inflation and seasonalities and examine the characteristics of the whitened errors. The Akaike Information Criterion (AIC) is used for determining lag length (Ivanov and Kilian, 2005). Standard deviation, skewness and excess kurtosis are presented for the computed errors. All three measures are fairly stable across the two subperiods for each adjusted price series. While skewness tends to be close to zero, each series exhibits excess kurtosis. Tests of the null hypothesis that the errors are drawings from a Normal distribution are rejected at the .01 level using the bootstrapping approach developed in Kilian and Demiroglu (2000) for the Jarque-Bera test.

**Table 1**
**Descriptive statistics for inflation-adjusted weekly averages of daily spot prices for crude oil (Brent, FOB), gasoline (New York Harbor, Conventional Gasoline-regular, FOB), and heating oil (New York Harbor, No. 2 Heating Oil, FOB), 6/24/1988-4/26/2019. Real prices are reported. Nominal prices are converted to real prices using weekly extrapolated U.S. CPI data (refer to the Appendix for details). Gasoline and Heating Oil prices are also deseasonalized. Std. Dev., Skewness and Excess Kurtosis are for errors generated from fitting AR(p) models to the log of real prices for Brent and the log of real deseasonalized prices for Gasoline and Heating Oil. AIC is used for determining optimal lag length for each AR(p) model.**

| | **Brent (per barrel)** | **Gasoline (per gallon)** | **Heating Oil (per gallon)** |
|---|---|---|---|
| **Panel A: Full period (6/24/1988–4/26/2019, N= 1610)** | | | |
| Mean | 27.38 | 0.78 | 0.78 |
| Median | 21.05 | 0.65 | 0.64 |
| Maximum | 76.41 | 1.82 | 2.16 |
| Minimum | 6.78 | 0.21 | 0.21 |
| Std. Dev. | 0.041 | 0.048 | 0.042 |
| Skewness | -0.191 | 0.148 | 0.110 |
| Excess Kurtosis | 5.843 | 6.641 | 8.473 |
| Jarque-Bera statistic | 548.752 | 889.498 | 1999.934 |
| **Panel B: 6/24/1988–12/30/2005 (N = 915)** | | | |
| Mean | 17.03 | 0.52 | 0.51 |
| Median | 16.09 | 0.50 | 0.48 |
| Maximum | 39.66 | 1.62 | 1.23 |
| Minimum | 6.78 | 0.21 | 0.21 |
| Std. Dev. | 0.043 | 0.050 | 0.047 |
| Skewness | -0.260 | 0.339 | 0.259 |
| Excess Kurtosis | 6.041 | 8.013 | 9.032 |
| Jarque-Bera statistic | 359.287 | 966.098 | 1383.498 |

**Table 1 (continued)**

| | Brent (per barrel) | Gasoline (per gallon) | Heating Oil (per gallon) |
|---|---|---|---|
| **Panel C: 1/6/2006–4/26/2019 (N = 695)** | | | |
| Mean | 41.01 | 1.11 | 1.14 |
| Median | 39.75 | 1.09 | 1.08 |
| Maximum | 76.41 | 1.82 | 2.16 |
| Minimum | 13.77 | 0.47 | 0.43 |
| Std. Dev. | 0.039 | 0.045 | 0.036 |
| Skewness | 0.005 | -0.109 | -0.139 |
| Excess Kurtosis | 5.114 | 4.453 | 3.998 |
| Jarque-Bera statistic | 128.129 | 61.884 | 30.763 |

Note: All reported Jarque-Bera statistics reject the null hypothesis of normality at the .01 level based upon the bootstrapping method developed in Kilian and Demiroglu (2000) for the Jarque-Bera test. Excess Kurtosis = Kurtosis minus 3.

## 4. Granger causality tests

### *4.1. Model specification and Granger causality tests*

In a bivariate system with p lags, $x_t$ is said to Granger-cause $y_t$ if $y_t$ can be better predicted using the histories of both $x_t$ and $y_t$ than it can by using the history of $y_t$ alone (Lutkepohl (2005, pg. 42). The classical test of the hypothesis that no Granger causality is present is a test that the coefficients of the p lagged values of $x_t$ are jointly equal to zero (a Wald test statistic), and is based on the assumption that the series being studied are stationary (Granger, 1969; Sims, 1972). Extension to the trivariate case is straightforward. If the variables included in the statistical model are nonstationary, then the Wald test statistic in the test of the null hypothesis does not have the usual asymptotic chi-square distribution under the null hypothesis (Ohanian, 1988; Toda and Phillips, 1993).

It is well known that unit root tests have low power to reject the null of a unit root when the true root for a time series is close to but less than unity (Cochrane, 1991; DeJong et al., 1992). We employ tests for noncausality that are robust to the presence of unit roots in the level series being studied. The advantage of the level specification is that the VAR estimates remain consistent whether the variables in the system are integrated or not. Also, inference on impulse responses based on VAR models in levels will remain asymptotically valid. In addition, inference is asymptotically invariant to the possible presence of cointegration between the price series (Sims et al., 1990; Lutkepohl and Reimers, 1992).

The test for noncausality that we implement was developed by Toda and Yamamoto (1995) (TY) and Dolado and Lutkepohl (1996) (DL) and is robust to the level variables being nonstationary.[10] The test statistic is based upon a lag-augmented reduced form VAR specification. TY and DL have shown that a lag-augmented specification for a reduced form VAR overcomes nonsingularity problems with Wald tests of the estimated coefficients (tests of noncausality) that would be present if, for instance, one or more of the variables in the system exhibited nonstationarity. Henceforth we refer to the test as the TY/DL test.[11] Specifically, if the optimal lag length of the VAR is p, adding d additional lags of the variables in the system, where d represents the maximum order of integration of any variable in the system, results in a nonsingular covariance matrix for the coefficients of the first p lags, which are the coefficients of interest in the causality test.[12] The Wald test statistics will be asymptotically distributed chi-square with p degrees of freedom, under the null. Rejection of the null implies a rejection of no Granger causality. That is, a rejection allows us to infer the presence of Granger causality at the level of significance selected.

[10] For development of the Wald test see Lutkepohl (2005) and Kilian and Lutkepohl (2017).

[11] Although developed independently, the approaches to testing the null of no causality when the level variables are integrated of order 1 proposed by Toda and Yamamoto (1995) and Dolado and Lutkephohl (1996) are the same.

[12] The estimated lag-augmented VAR includes an intercept (Kilian and Lutkepohl, 2017, Ch. 2).

We estimate two alternative reduced form VAR specifications, the first (discussed in section 4.2) includes only the three adjusted price series described earlier, while the second (discussed in section 4.3) includes additional variables related to supply and demand conditions in the oil and petroleum products markets. We test the null hypothesis that oil prices do not Granger-cause gasoline and heating oil prices as well as the null hypothesis that gasoline and heating oil prices do not Granger-cause oil prices.

### *4.2. Do oil prices Granger-cause product prices or the converse?*

#### *4.2.1. Full sample period (6/24/1988–4/26/2019)*

The TY/DL test involves estimation of a lag augmented VAR. The logs of inflation adjusted and deseasonalized spot price series for gasoline and heating oil are labeled $\mathrm{gp_t}$ and $\mathrm{hp_t}$ respectively. The log of inflation adjusted spot prices for Brent oil is labeled $\mathrm{bp_t}$.

There are three equations in the first VAR system estimated, one for each of the prices. The choice of ordering will not influence the test statistic for noncausality. The equation for the Brent price has the following illustrative form.[13]

$$bp_t = \beta_{0b} + \sum_i^p \beta_{ib} bp_{t-i} + \sum_i^p \theta_{ib} gp_{t-i} + \sum_i^p \phi_{ib} hp_{t-i} + \left\{ \alpha_{1b} bp_{t-(p+1)} + \alpha_{2b} gp_{t-(p+1)} + \alpha_{3b} hp_{t-(p+1)} \right\} + u_{tb} . \quad (1)$$

The AIC is used to establish the lag length p of the VAR (see Ivanov and Kilian, 2005). The terms in curly brackets in equation (1) are the terms that augment the model per the test developments in TY and DL. As mentioned earlier, unit root tests have low power to reject the null when the true root is close to but less than unity. Equation (1) illustrates the model including 1 single additional

[13] The corresponding equations for heating oil and gasoline are

$$hp_t = \beta_{0h} + \sum_i^p \beta_{ih} bp_{t-i} + \sum_i^p \theta_{ih} gp_{t-i} + \sum_i^p \phi_{ih} hp_{t-i} + \left\{ \alpha_{1h} bp_{t-(p+1)} + \alpha_{2h} gp_{t-(p+1)} + \alpha_{3h} hp_{t-(p+1)} \right\} + u_{th}$$

$$gp_t = \beta_{0g} + \sum_i^p \beta_{ig} bp_{t-i} + \sum_i^p \theta_{ig} gp_{t-i} + \sum_i^p \phi_{ig} hp_{t-i} + \left\{ \alpha_{1g} bp_{t-(p+1)} + \alpha_{2g} gp_{t-(p+1)} + \alpha_{3g} hp_{t-(p+1)} \right\} + u_{tg}$$

lag of the endogenous variables. The system is estimated by least squares. The test that Brent prices are not Granger-caused by gasoline prices is for instance a test of the null hypothesis that the coefficients $\theta_i$ $i = 1,\ldots p$ in equation (1) are jointly equal to 0. This is a Wald test and the test statistic is distributed $\chi^2$ (chi-square) with p degrees of freedom under the null.[14] Table 2 presents the results of the tests for the full sample period. [15]

**Table 2**
**TY/DL test of noncausality, full sample period (6/24/1988–4/26/2019), weekly data**

| Null hypothesis: | $\chi^2$ | df | p-value |
|---|---|---|---|
| No Granger causality from oil prices to gasoline prices | 18.37 | 4 | 0.001 |
| No Granger causality from oil prices to heating oil prices | 13.72 | 4 | 0.008 |
| No Granger causality from gasoline prices to oil prices | 4.17 | 4 | 0.383 |
| No Granger causality from heating oil prices to oil prices | 3.45 | 4 | 0.485 |

Note: Lag length p for the VAR is determined by AIC and equals 4. VAR includes ln(real Brent spot price), ln(real gasoline spot price deseasonalized), ln(real heating oil spot price deseasonalized). Raw price variable definitions and sources are provided in Section 3.1 and the Appendix.

The results reported in Table 2 indicate that we can reject the null hypothesis that oil prices do not Granger-cause gasoline and heating oil prices at the 1% level. In contrast, we infer from the test results that we cannot reject the null of no causality from gasoline and heating oil prices to oil prices at the same significance level. Tests of the null hypothesis that gasoline prices do not

[14]For development of the Wald test see Lutkepohl (2005) and Kilian and Lutkepohl (2017).
[15]A tight significance level is important due to the large sample size (Alquist et al., 2013).

Granger-cause heating oil prices and separately that heating oil prices do not Granger-cause gasoline prices (not reported) do not reject the null in either case at the 1% level.

#### *4.2.2. Subperiod analyses*

A body of research in recent years has both debated and tested the question of whether spot oil prices have been influenced by excessive speculative and long-only investment activity in the oil futures market. Many authors have concluded that the behavior of spot prices is driven by fundamental supply and demand variables, but some contend that distortions in the futures market fed through excessive speculation and long-only investment activity have influenced spot prices.[16] In order to be prudent, we examine the periods before and after 2006, the point at which the historical record suggests that an appreciable increase in long-only investment activity in oil futures and hedge-fund activity occurred (see, for instance, Hamilton and Wu, 2014, 2015, and Singleton, 2014).

#### *4.2.3. The subperiod 6/24/1988 to 12/30/2005*

The TY/DL test results are reported in Table 3.

TABLE 3 IS PRESENTED ON THE FOLLOWING PAGE

[16] See Fattouh et al. (2013), Hamilton and Wu (2014, 2015) and Singleton (2014).

**Table 3**
**TY/DL test of noncausality, full sample period (6/24/1988–12/30/2005), weekly data**

| Null hypothesis: | $\chi^2$ | df | p-value |
|---|---|---|---|
| No Granger causality from oil prices to gasoline prices | 11.23 | 4 | 0.024 |
| No Granger causality from oil prices to heating oil prices | 10.10 | 4 | 0.038 |
| No Granger causality from gasoline prices to oil prices | 1.34 | 4 | 0.853 |
| No Granger causality from heating oil prices to oil prices | 3.97 | 4 | 0.410 |

Note: Lag length p for the VAR is determined by AIC and equals 4. VAR includes ln(real Brent spot price), ln(real gasoline spot price deseasonalized), ln(real heating oil spot price deseasonalized). Raw price variable definitions and sources are provided in Section 3.1 and the Appendix.

Our inferences from these results are similar to those drawn from the full sample period results. However the p-values for tests that oil prices do not Granger-cause product prices are weaker than those reported for the full sample period (.02 and .03 respectively). We do infer that the null is not rejected for the tests that gasoline and heating oil prices do not Granger-cause oil prices at the 1% level. Further, tests of the null hypothesis that gasoline prices do not Granger-cause heating oil prices and separately that heating oil prices do not Granger-cause gasoline prices do not reject the null at the 1% level.

#### *4.2.4. The subperiod 1/6/2006 to 4/26/2019*

The TY/DL test results are reported in Table 4. The estimated model again includes 1 additional lag of the endogenous variables. As with the prior results, we conclude that the null that oil prices do not Granger-cause gasoline prices is rejected at the 1% level, and a similar inference holds for heating oil prices. Likewise, we do not reject at the 1% level the null that gasoline prices do not cause oil prices. However the p-value for the test that gasoline prices do not cause oil prices is equal to .01. Finally, test results (not reported) of the null hypothesis that gasoline prices do not cause heating oil prices or vice versa during the subperiod indicate that the null is never rejected at the 1% level. In summary, the inference is that we can conclude causality runs from oil prices to product prices as in the overall sample period results and those for the period prior to January 2006. However, we also see that during the time period studied in Table 4 we do not reject the null hypothesis that gasoline prices did not cause oil prices, indicating there was bidirectional causality.

**Table 4**
**TY/DL test of noncausality, 1/6/2006–4/26/2019, weekly data**

| Null hypothesis: | $\chi^2$ | df | p-value |
|---|---|---|---|
| No Granger causality from oil prices to gasoline prices | 18.16 | 6 | 0.005 |
| No Granger causality from oil prices to heating oil prices | 17.59 | 6 | 0.007 |
| No Granger causality from gasoline prices to oil prices | 16.74 | 6 | 0.01 |
| No Granger causality from heating oil prices to oil prices | 9.00 | 6 | 0.173 |

Note: Lag length p for the VAR is determined by AIC and equals 6. VAR includes ln(real Brent spot), ln(real gasoline spot deseasonalized), ln(real heating oil spot deseasonalized). Raw price variable definitions and sources are provided in Section 3.1 and the Appendix.

The summary statistics reported in Table 1 indicate that each individual price series is not Gaussian. This may be a manifestation of the presence of conditional heteroskedasticity. We also estimated a trivariate GARCH(1,1) constant conditional correlation model for the full sample period and each subperiod, in which the mean model includes lagged values of the endogenous variables. We justify the constant conditional correlation assumption based on the fact that gasoline and heating oil are both derived from oil. Tests of the estimated coefficients in the mean models yield inferences that are consistent with those presented in Tables 2, 3 and 4.[17]

### *4.3. A multivariate model including supply and demand variables*

#### *4.3.1. The variables of the reduced form model*

We begin this section by estimating a reduced form model which forms the basis for Granger causality tests similar to those presented earlier, but in which we allow for the influence of crude oil, gasoline and heating oil supply and demand variables, where the supply and demand variables are selected in the spirit of Kilian (2009, 2010), Kilian and Murphy (2014) and Kilian and Lee (2014). We emphasize that the model is in reduced form and that we are not enforcing any particular structure on the relations between the series studied. Our objective is to test whether real oil prices Granger-cause real gasoline and heating oil prices, or whether real gasoline and heating oil prices Granger-cause real oil prices within the framework of the extended reduced form model.

We follow Kilian and his coauthors and include the following variables in the model: 1) the percentage change in global crude oil production, 2) a measure of cyclical variation in global real economic activity which we proxy by the real detrended Baltic Dry Index, described more fully below, 3) the natural log of the spot real Brent oil price, 4) the natural log of the real deseasoned spot gasoline price, 5) the natural log of the real deseasoned spot heating oil price, 6) the percentage change in U.S. gasoline consumption, 7) the percentage change in U.S. distillate

[17] For brevity we do not report the tables.

consumption, 8) the change in world oil stocks deaseasonalized, 9) the change in U.S. gasoline stocks deseasonalized, and 10) the change in U.S. distillate stocks deseasonalized. The data are all measured at a weekly frequency. Nominal values are converted to real values using an interpolated U.S. CPI index. The data are deseasonalized by month. Due to data availability the sample period extends from 10/26/2009 through 4/26/2019. Details on the sources of the raw levels data and any transformations are provided in the Appendix.

Variable 2) described in the prior paragraph, oft referred to as the Kilian Index and first proposed in Kilian (2009), was designed "…to identify demand shifts in global commodity markets" (Kilian, 2019, pg. 109). The index was constructed using historic costs of oceanic shipping and was later extended using the Baltic Dry Index, a generally available index measuring these costs. As Kilian and Zhou (2018, pg. 58) point out, the index "…is an index of cyclical variation in global real economic activity", and "…the presumption is that variation in the volume of shipping of industrial commodities is proportionate to variation in this index".[18] We use weekly values of the Baltic Dry Index for our sample period. Because the Baltic Dry Index is a nominal index, we convert the index to real values and then detrend the series (Kilian, 2009, 2019).[19]

#### ***4.3.2. Granger causality tests***

The TY/DL test results are presented in Table 5. The sample period is 10/26/1990–4/26/2019 due to data availability. As our interest is in the relations between the three prices being investigated, we present only those results.[20] As Table 5 indicates, the extended model, which

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[18] Kilian and Zhou (2018) point out the following regarding the relation between bulk dry cargo rates and commodity demand: "Thus, sustained increases in bulk dry cargo shipping rates are commonly viewed as being indicative of aggregate demand pressures in global commodity markets. Likewise, a drop in global aggregate demand for commodities would be expected to lower bulk dry cargo shipping rates" (pg. 57), while also emphasizing that shifts in the index can also be driven by long-run supply of cargo shipping vessels that is itself driven by expected demand.
[19] Hamilton (2019) recommends using the two year first difference of the real BDI index in place of the detrended real BDI index. We select to focus on the real detrended index in our analysis per Kilian (2019).
[20] The full set of results are available from the authors upon request.

includes the supply and demand variables, yields conclusions similar to those already presented. Specifically, we do not reject at the 1% level the null hypothesis that gasoline prices and heating oil prices do not Granger-cause oil prices. In contrast, the hypothesis that oil prices do not Granger-cause gasoline and heating oil futures prices is rejected at the 1% level. In results not reported the null that gasoline prices do not cause heating oil prices, is not rejected at the 1% level, nor is the null that heating oil prices do not cause gasoline prices rejected.

**Table 5**
**TY/DL test of noncausality, extended VAR. Full sample period (10/26/1990–4/26/2019) using weekly data.**

| Null hypothesis: | $\chi^2$ | df | p-value |
|---|---|---|---|
| No Granger causality from oil prices to gasoline prices | 25.97 | 4 | 0.000 |
| No Granger causality from oil prices to heating oil prices | 16.97 | 4 | 0.002 |
| No Granger causality from gasoline prices to oil prices | 5.63 | 4 | 0.228 |
| No Granger causality from heating oil prices to oil prices | 3.85 | 4 | 0.427 |

Note: Lag length p for the VAR is determined by AIC and equals 4.The variables included in the system and the data sources are described in detail in the Appendix and include: 1) the percentage change in global crude oil production, 2) a measure of cyclical variation in global real economic activity which we proxy by the real detrended Baltic Dry Index, 3) the natural log of the spot real Brent oil price, 4) the natural log of the real deseasoned spot gasoline price, 5) the natural log of the real deseasoned spot heating oil price, 6) the percentage change in U.S. gasoline consumption, 7) the percentage change in U.S. distillate consumption, 8) the change in world oil stocks deaseasonalized, 9) the change in U.S. gasoline stocks deseasonalized, and 10) the change in U.S. distillate stocks deseasonalized. The data are all measured at a weekly frequency. Nominal values are converted to real values using an interpolated U.S. CPI index. The data are deseasonalized by month. Details on the sources of the raw levels data and any transformations are provided in the Appendix. The data are all measured at a weekly frequency. The sample period extends from 10/26/2009 through 4/26/2019.

We conclude, albeit within the context of a reduced form model, that the test results documented in Table 1 are not weakened by the inclusion of market supply and demand variables.

## 5. The response of petroleum product prices to structural shocks to the oil market

### *5.1. Introduction*

The results presented in Section 4.3.2 Indicate that we reject the null hypothesis that real oil prices do not Granger-cause real gasoline and heating oil prices within the context of a reduced form model that includes variables intended to measure supply and demand conditions in the oil market, the gasoline market and the heating oil market. The reduced form analysis presented in Section 4.3.2 however does not allow us to say anything directly about how structural shocks to supply and demand conditions in the oil market impact real gasoline and heating oil prices. To answer that question we turn to a recursively identified structural vector autoregressive model.

Kilian, (2009) has established how real oil prices respond to structural shocks to supply and demand in the oil market. We impose conditions on the relations between observed reduced form errors for measurable oil-related supply and demand variables and underlying structural shocks to oil market supply, aggregate demand, and oil-specific demand, acknowledging the results shown earlier that oil prices Granger-cause gasoline and heating oil prices. Our interest is in how gasoline and heating oil prices respond to these structural shocks and if those responses differ across shocks. In related analyses Kilian (2009), Kilian and Murphy (2014) and Kilian and Lee (2014) study oil market data measured at a monthly frequency and Kilian (2010) studies a model of the oil market and the retail gasoline market using monthly data. Our focus is on the short-horizon responses of gasoline and heating oil prices and so we continue to concentrate on data measured at a weekly frequency while attempting to stay faithful to the methods used by Kilian (2009, 2010), Kilian and Murphy (2014) and Kilian and Lee (2014).

We present impulse response graphs based upon the SVAR models estimated which we describe in more detail in the following sections. We present 95% confidence intervals for the impulse responses based upon Hall's percentile interval (Hall, 1992) and three alternative methods for constructing confidence intervals, which we denote as: (1) Residual Block Bootstrap with Block Size =150 per Bruggemann, Jentsch, and Trenkler (2016), (2) Residual iid Bootstrap under the assumption of iid errors, and (3) Residual Wild Bootstrap per Goncalves and Kilian (2004) (see Kilian and Lütkepohl, 2017, Ch. 12, for additional details on these methods). Our choice of block size for method (1) is based upon the suggestion by Bruggemann et al. (2016) of a block size equal to roughly 10% of the number of sample observations. This choice of block size is also roughly consistent with the illustration presented in Kilian and Lütkepohl (2017, Ch. 12). Method (1) has been shown to be preferred when the data exhibit conditional heteroskedasticity and so might be viewed as being more conservative than the other two alternatives.[21]

### *5.2. The response of real spot oil prices to structural oil supply and demand shocks*

We begin with an analysis of the oil market in isolation, as in Kilian (2009). This exercise allows us to establish whether the Kilian (2009) model estimated with our weekly data produces short-run real oil price responses to oil supply and demand structural shocks that are roughly consistent with those presented in Kilian (2009) based upon monthly data. We feel this is an important issue as the oil market 'block' will constitute part of the structural models that include the gasoline and heating oil markets. Our focus first is on the response of oil prices to structural supply and demand shocks in the oil market.

[21] We adapt the code available at https://drive.google.com/file/d/1K9ODDZa82m85ovpyvmaW6F5h1GVSyp57/view that was used to generate the graphs displayed in Figure 12.7 in Kilian and Lütkepohl (2017).

The model is recursive in nature and is built upon several conditions which identify the structure shown in equation (2).

$$\begin{bmatrix} u_t^{\%\Delta \text{ Global oil prod.}} \\ u_t^{\text{Gloval real activity}} \\ u_t^{\ln(\text{Real Brent spot price})} \end{bmatrix} = \begin{bmatrix} b_0^{11} & 0 & 0 \\ b_0^{21} & b_0^{22} & 0 \\ b_0^{31} & b_0^{32} & b_0^{33} \end{bmatrix} \begin{bmatrix} w_t^{\text{Oil supply shock}} \\ w_t^{\text{Aggregate demand shock}} \\ w_t^{\text{Oil mkt. specific demand shock}} \end{bmatrix} \tag{2}$$

The structural shocks represented in the model are first an oil supply shock, second a shock to aggregate demand which includes oil, and third an oil-specific demand shock, and, these shocks, in this model as well as the models proposed in the following two sections, are assumed to be uncorrelated.[22] The additional identifying assumptions are first that global oil production does not respond in the short run to demand shocks, either aggregate demand or oil-specific demand. That is, the price elasticity of oil supply is zero (Kilian, 2009), implying that global oil production does not respond to either demand shock. Hence, reduced form production errors are only related to structural shocks to supply. Since there are costs both to increasing as well as decreasing production, this condition is plausible especially at the weekly frequency. The condition is also reinforced by the observation that historically OPEC production is adjusted over long periods, not at a weekly frequency. Second, as described earlier, the real detrended BDI is our indicator of global real activity. Reduced form errors of this index are related to structural shocks to oil supply and to aggregate demand. Conversely, oil-specific structural demand shocks that impact oil prices,

[22] Bernanke (1986, pg. 52) provides a useful interpretation with the following regarding the structural innovations in the model he proposes which abstracting can be written as $y_t = Au_t$ . In his model $u_t$ is his notation for the structural innovations (note that we use the notation w to represent the structural innovations): "I think of the u's…as 'primitive' exogenous forces, not directly observed by the econometrician, which buffet the system and cause oscillations. Because these shocks are primitive, i.e., they do not have common causes, it is natural to treat them as approximately uncorrelated… However, one would not want to restrict individual u's to entering one and only one structural equation, in general; thus the matrix A is allowed to have arbitrary off-diagonal elements. Under this interpretation, then, the stochastic parts of individual structural equations are allowed to be contemporaneously correlated in an arbitrary way; however, the correlation between any two equations arises explicitly because the equations are influenced by one or more of the same fundamental shocks $u_t$ "

do not have an immediate impact on global real activity (Kilian and Zhou, 2018).[23] Third, reduced form oil price errors are however related to structural supply shocks, aggregate demand shocks, and oil-specific demand shocks. Kilian (2009) argues that oil-specific demand shocks are plausibly related to "…fluctuations in precautionary demand for oil driven by uncertainty about future oil supply shortfalls." (pg. 1059).

Figure B.1 (Appendix B) presents figures displaying the impulse responses of the real oil price to each of the structural shocks, which we now summarize. We find that the impulse responses of real oil prices based upon the estimated SVAR for the oil market using our weekly data are largely consistent with the literature. The results indicate the following: 1) real oil prices do not respond to oil supply shocks during the 15 weeks following the shock and are within confidence limits which span zero for the 15 week horizon, 2) real oil prices respond positively to an aggregate demand shock but based upon the most conservative confidence limit estimates, we cannot confidently conclude that the response differs from zero after week 2, 3) real oil prices respond positively to an oil-specific demand shock and are confidently different from zero over the 15 week horizon examined. These results are largely consistent with those presented by Kilian (2009).[24] Comparable results presented in Kilian and Lütkepohl (2017, Ch. 12) suggest the following for the 3-4 month horizon responses based upon conservative confidence intervals and monthly data: 1) the response of the real oil price to a supply shock is consistently within a confidence interval that covers 0, 2) the response of the real oil price to an aggregate demand shock while positive, lies within a confidence interval that covers 0 out to a horizon of roughly 8 months, and 3) the response of the real oil price to an oil-specific demand shock is positive and is

[23] While a case can be made for the restriction $b_0^{21} = 0$ we chose to not impose this condition (Kilian and Zhou, 2018, 2020; Kilian and Lütkepohl, 2017).

[24] See also Kilian and Lütkepohl (2017, Ch. 12).

confidently different from zero out to 15 months. We therefore feel confident that our results, albeit where the data are measured at the weekly frequency, are largely in agreement with the longer frequency results presented elsewhere in the literature. Consequently we feel comfortable in analyzing models containing the oil market block of equations and blocks characterizing the petroleum product markets using our weekly data.

### *5.3. The response of real gasoline spot prices to structural oil supply and demand shocks*

We next turn to the response of real gasoline prices to structural oil supply and demand shocks. The model has two equation blocks and again is recursive. The first is the oil market block examined in the previous section. The second block includes conditions reflecting gasoline supply and gasoline demand. US refinery yields of finished motor gasoline and distillate fuel oil were relatively stable over the sample period we study, suggesting little if any substitution in terms of production: (https://www.eia.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_m.htm). This is consistent with conversations with refiners about short-run production substitution between gasoline and heating oil (distillate) and the technology of a typical U.S. based oil refinery. For this reason we do not include the heating oil market block in the model analyzed here, but specify a separate model in the following section that includes only the oil market block and a block for the heating oil market.

Kilian (2010) examines real retail gasoline prices within the context of a model focusing on monthly data. Our emphasis is on the spot price of gasoline and is focused on the short horizon response of the real spot price of gasoline. The model is recursive with the relations between reduced form errors for observables in the model and structural supply and demand shocks as shown in equation (3). The first three lines correspond to the oil market block examined in the prior section.

$$\begin{bmatrix} u_t^{\%\Delta \text{ Global oil prod.}} \\ u_t^{\text{Gloval real activiy}} \\ u_t^{\ln(\text{Real Brent spot price})} \\ u_t^{\ln(\text{Real gas spot price deseasonalized })} \\ u_t^{\%\Delta \text{ U.S.. gasoline consumption}} \end{bmatrix} = \begin{bmatrix} b_0^{11} & 0 & 0 & 0 & 0 \\ b_0^{21} & b_0^{22} & 0 & 0 & 0 \\ b_0^{31} & b_0^{32} & b_0^{33} & 0 & 0 \\ b_0^{41} & b_0^{42} & b_0^{43} & b_0^{44} & 0 \\ b_0^{51} & b_0^{52} & b_0^{53} & b_0^{54} & b_0^{55} \end{bmatrix} \begin{bmatrix} w_t^{\text{Oil supply shock}} \\ w_t^{\text{Aggregate demand shock}} \\ w_t^{\text{Oil-specific demand shock}} \\ w_t^{\text{Refinery shock}} \\ w_t^{\text{Gasoline demand shock}} \end{bmatrix} \tag{3}$$

The justification for the oil market block was presented in the prior section and will not be repeated here. The justification for the relations shown for the gasoline market block begin by first asserting that the reduced form errors for the real price of gasoline are impacted by all structural shocks in the oil market, and by a supply shock in the gasoline market. Refiners are price takers in the oil market and pass those costs along to the spot market. In addition refineries occasionally experience unanticipated shut downs (supply disruptions to the production of petroleum products) referred to in equation (3) as a refinery shock following Kilian (2010). These refinery shocks impact the supply of gasoline but not demand. Hence structural gasoline supply shocks are the primary channel through which prices are impacted beyond impacts that follow from the oil supply shocks, aggregate demand shocks, and oil-specific demand shocks. Finally gasoline consumption reduced form errors are impacted by all other structural shocks including a gasoline demand shock, implicitly also impacted by the price of gasoline through the channels impacting gasoline prices.[25] The structure reflected in equation (3) conforms overall to the full sample period causality results in that gasoline market structural shocks do not influence oil market variables in the short run for the full sample period, while oil market structural shocks impact

[25] Demand for gasoline has generally been regarded as being relatively price inelastic at least in the short run (Hughes et al., 2008; Pock, 2010; Small and Van Dender, 2007; Park and Zhou 2010). Recent evidence has however cast doubt on this conclusion, see the review by L. Kilian and X. Zhou, 6/16/2020, at https://www.dallasfed.org/research/economics/2020/0616?utm_source=cvent&utm_medium=email&utm_campaign=dfe . We do not impose any constraint on this elasticity.

gasoline market variables. The structure allows us to decompose the impact of oil demand and supply structural shocks on gasoline prices.

Figure 3 presents graphs of the impulse responses of the log of real deseasonalized spot gasoline price to (a) an oil supply structural shock, (b) an aggregate demand structural shock, and (c) an oil-specific demand structural shock. The results indicate that the response of the price of gasoline to an oil supply shock is reliably not different from zero. A similar conclusion is evident for the most conservative confidence limits for a shock to aggregate demand beyond week 2 of the horizon, suggesting a very short-term but not lasting response. Finally, the gas price responds positively to oil-specific demand shocks and is confidently different from zero over the 15 week horizon. These results are similar to the responses of oil prices to the three oil market structural shocks. Given the results presented earlier indicating that oil prices Granger-cause gasoline prices, the results shown in Figure 3 suggest that oil-specific demand shocks are the channel through which gasoline spot prices are impacted. By-and-large these results are not inconsistent with the results presented by Kilian (2010) based on monthly data for retail gasoline prices except the response to global commodity demand shocks. It should be noted however that we are drawing our conclusions based upon confidence limits that account for conditional heteroskedasticity, which would be a condition consistent with our finding that the price series are not distributed Gaussian.

FIGURE 3 IS PRESENTED ON THE FOLLOWING TWO PAGES

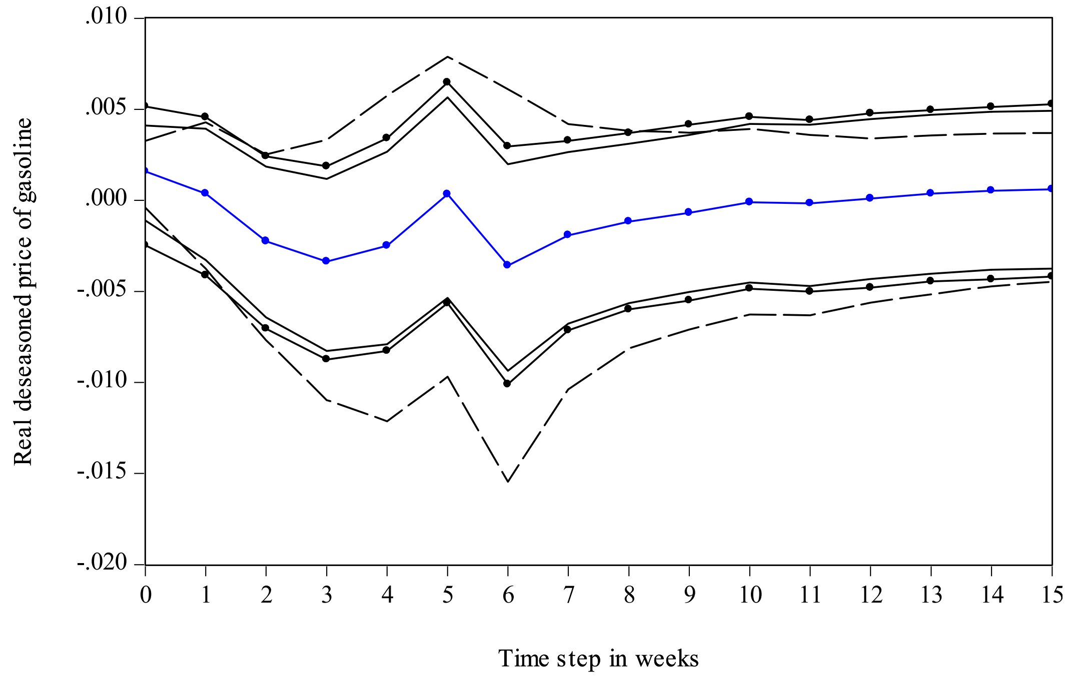



Fig. 3(a) Real deseasoned gasoline price response to an oil supply shock

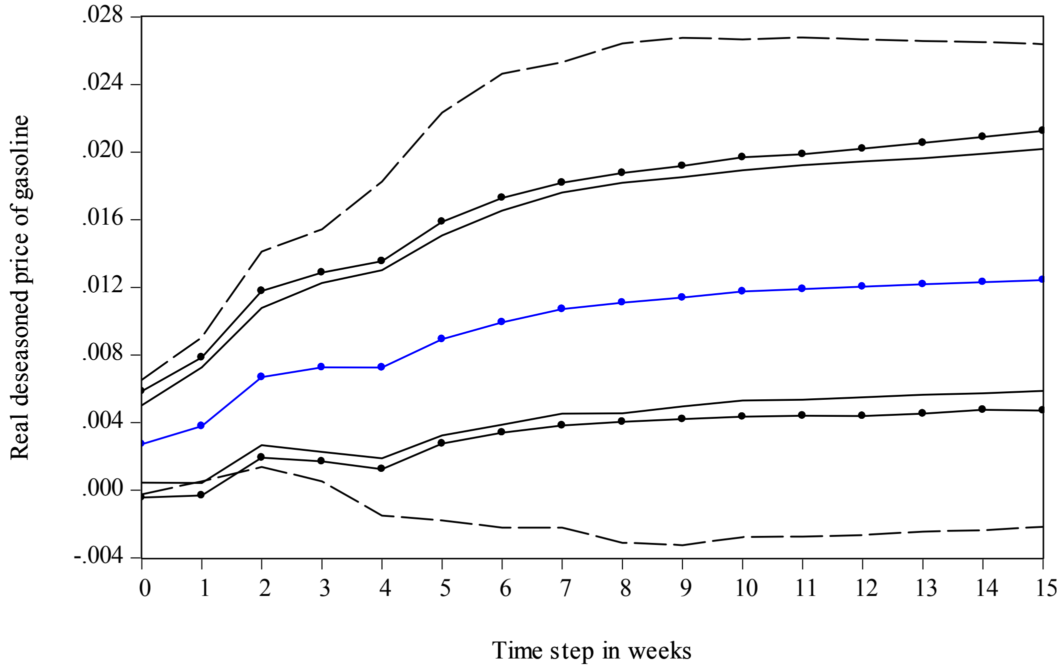



Fig. 3(b) Real deseasoned gasoline price response to an aggregate demand shock

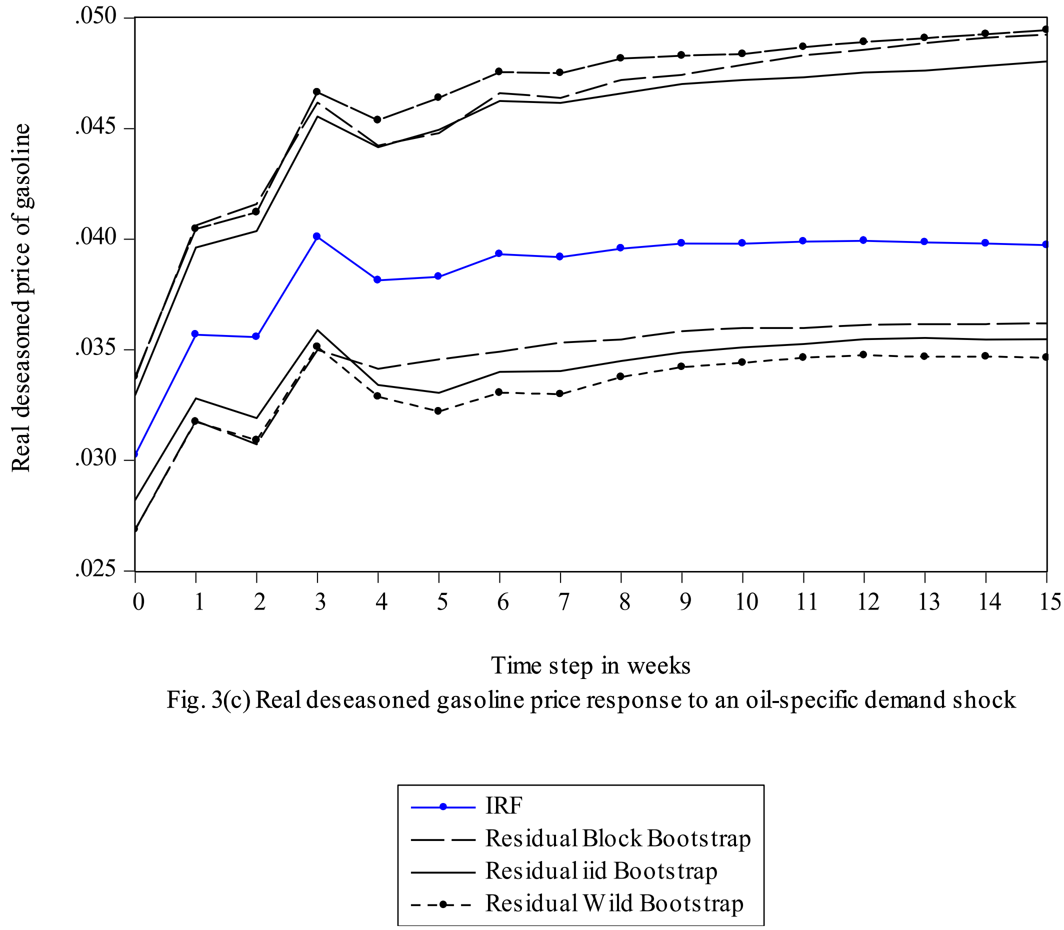



Fig. 3(c) Real deseasoned gasoline price response to an oil-specific demand shock

Fig. 3. Response of real deseasoned price of gasoline (IRF) to (a) An oil supply shock, (b) An aggregate demand shock, and (c) An oil-specific demand shock. 95% confidence intervals are displayed. Results are based upon Hall's percentile interval and three alternative confidence intervals which we denote as: 1) Residual Block Bootstrap with Block Size =150 per Bruggemann, Jentsch, and Trenkler (2016), 2) Residual iid Bootstrap under the assumption of iid errors, and 3) Residual Wild Bootstrap per Goncalves and Kilian (2004). See Kilian and Lütkepohl (2017, Ch. 12) for additional details.

### *5.4. The response of real heating oil spot prices to structural oil supply and demand shocks*

We now turn to the response of real heating oil prices to structural oil supply and demand shocks. Similar to the model in the prior section, the model has two equation blocks and is recursive. The first is the oil market block. The second block includes conditions reflecting heating oil supply and demand. For reasons provided in the prior section, that substitution between gasoline production and heating oil production is not likely in the short-run, we include only the oil market block and the heating oil market block in this model. The model is recursive with the relations between reduced form errors for observables and structural shocks as shown in equation (4).

$$\begin{bmatrix} u_t^{\%\Delta \text{ Global oil prod.}} \\ u_t^{\text{Global real activity}} \\ u_t^{\ln(\text{Real Brent spot price})} \\ u_t^{\ln(\text{Real heating oil spot price deseasonalized})} \\ u_t^{\%\Delta \text{ U.S. heating oil consumption}} \end{bmatrix} = \begin{bmatrix} b_0^{11} & 0 & 0 & 0 & 0 \\ b_0^{21} & b_0^{22} & 0 & 0 & 0 \\ b_0^{31} & b_0^{32} & b_0^{33} & 0 & 0 \\ b_0^{41} & b_0^{42} & b_0^{43} & b_0^{44} & 0 \\ b_0^{51} & b_0^{52} & b_0^{53} & b_0^{54} & b_0^{55} \end{bmatrix} \begin{bmatrix} w_t^{\text{Oil supply shock}} \\ w_t^{\text{Aggregate demand shock}} \\ w_t^{\text{Oil-specific demand shock}} \\ w_t^{\text{Refinery shock}} \\ w_t^{\text{Heating oil demand shock}} \end{bmatrix} \quad (4)$$

As with gasoline prices, refiners pass the cost of oil along to the spot market for heating oil, but supply disruptions from refinery shutdown shocks impact prices as well. Finally, heating oil consumption is impacted by all structural shocks, and implicitly by heating oil prices through the channels impacting those prices.[26] Structural heating oil demand shocks will largely be driven by weather shocks and hence the heating oil consumption reduced form error will be driven by such shocks, above and beyond structural shocks to the oil market and to heating oil supply.

The response results are presented in Figure 4. The results indicate that the response of the heating oil price to an oil supply shock is not different from zero based upon our estimated

[26] Empirical evidence, although limited, suggests that heating oil demand is inelastic, although we do not impose this as a constraint (Wade, 2003; Labanderia et al., 2017). This is supported by the observation that consumers of heating oil typically have fixed heating systems giving them limited ability to react to price increases without suffering a significant reduction in comfort.

confidence intervals. On the other hand, heating oil prices respond positively to a shock to aggregate demand but under the most conservative confidence interval assumptions we cannot conclude the response is different from zero past week 2. Finally, the real heating oil price responds positively to oil-specific demand shocks and is different from zero for the 15 week horizon displayed. These results are similar to those found for the responses of real gasoline prices and support the conclusion that the channel through which real heating oil prices are impacted is through structural shocks to oil market specific demand.

FIGURE 4 IS PRESENTED ON THE FOLLOWING TWO PAGES

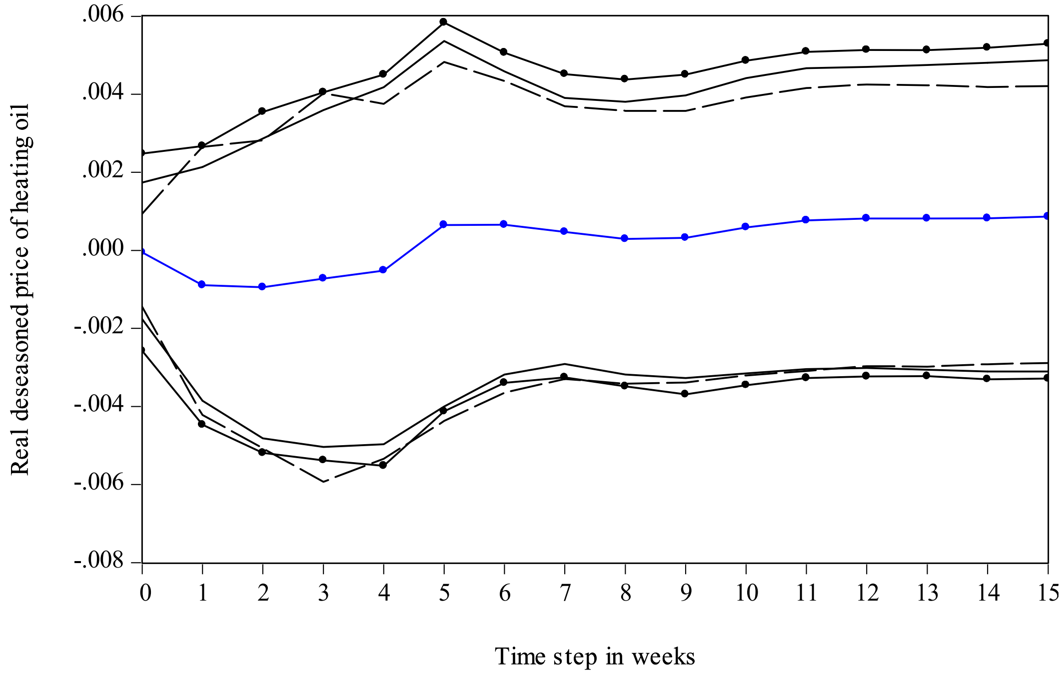



Fig.4(a) Real deseasoned heating oil price response to an oil supply shock

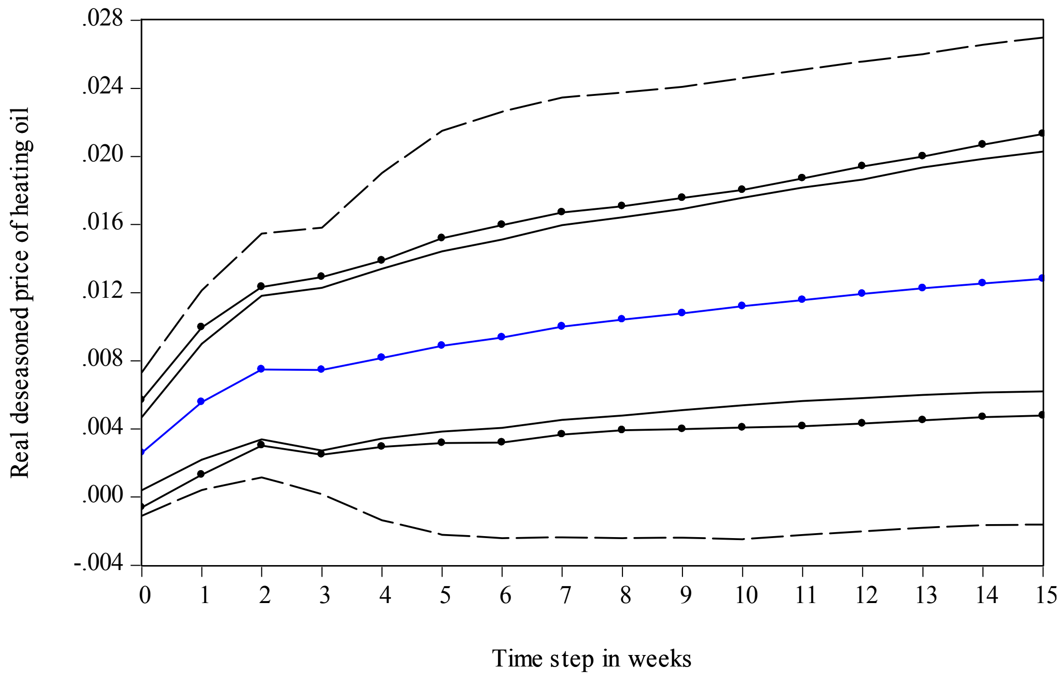



Fig. 4(b) Real deseasoned heating oil price response to an aggregate demand shock

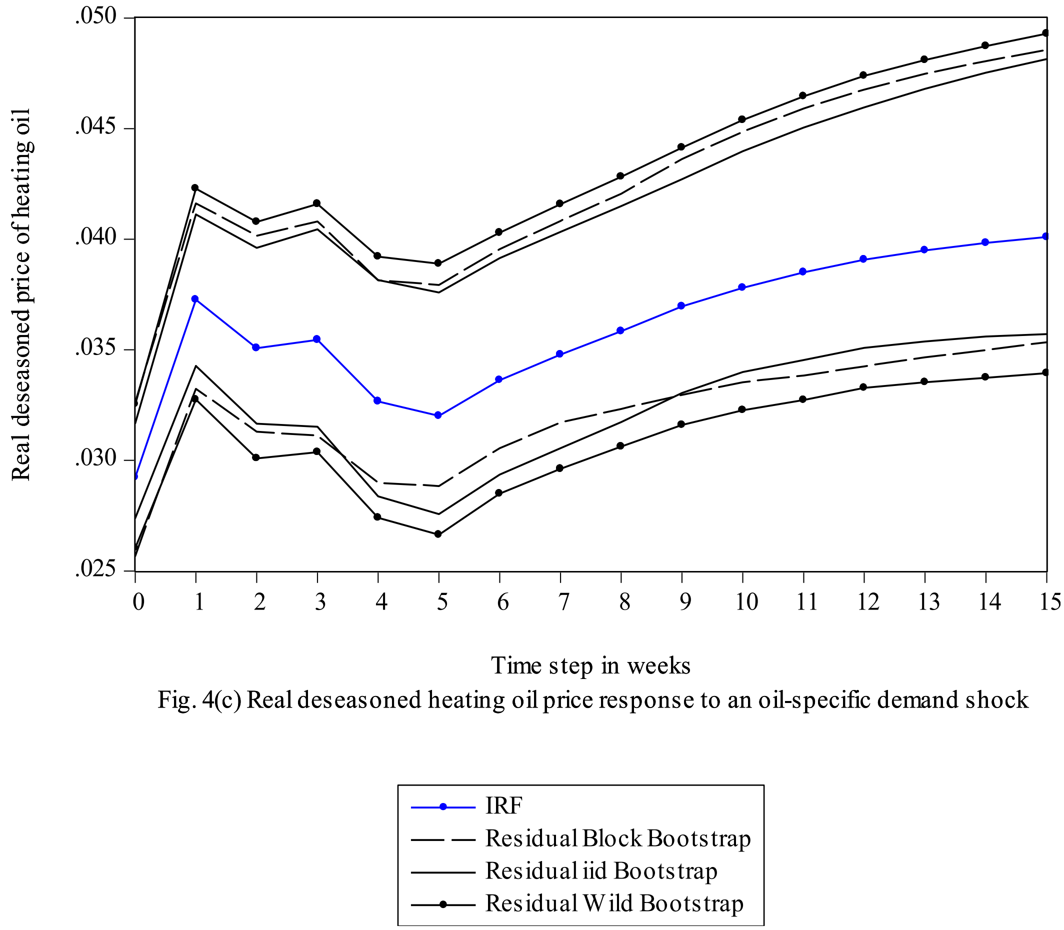



Fig. 4(c) Real deseasoned heating oil price response to an oil-specific demand shock

Fig. 4. Response of real deseasoned price of heating oil (IRF) to (a) An oil supply shock, (b) An aggregate demand shock, and (c) An oil-specific demand shock. 95% confidence intervals are displayed. Results are based upon Hall's percentile interval and three alternative confidence intervals which we denote as: 1) Residual Block Bootstrap with Block Size =150 per Bruggemann, Jentsch, and Trenkler (2016), 2) Residual iid Bootstrap under the assumption of iid errors, and 3) Residual Wild Bootstrap per Goncalves and Kilian (2004). See Kilian and Lütkepohl (2017, Ch. 12) for additional details.

## 6. Summary and conclusions

This study investigates the short-run relation between spot crude oil prices and the spot prices for gasoline and heating oil. Our emphasis is on the short-run relation between these prices and so we concentrate on prices measured at the weekly horizon. The evidence we present indicates that, in all periods studied, real spot oil prices Granger-cause real spot gasoline and real spot heating oil prices, where the base oil price is the Brent crude oil price. The analysis covers the period June 24, 1988, through April 26, 2019. We present evidence for the full sample period as well as for the two subperiods demarcated at the end of 2005, around the time that many observers believe there was a shift towards investing in futures as an asset class. While we find no evidence that gasoline or heating oil prices Granger-cause oil prices for the full sample period or for the period up to the end of 2005, we do find evidence that gasoline prices Granger-caused oil prices during the period following the end of 2005.

We then go on to evaluate an extended but reduced form model that includes the three price series plus potentially endogenous real market variables related to supply and demand in the oil market, the gasoline market and the heating oil market. We continue our investigation of whether oil prices Granger-cause product prices, whether product prices Granger-cause oil prices, or neither. Our tests support the conclusion that oil prices Granger-cause gasoline and heating oil prices but not the reverse.

The reduced form model analysis does not allow us to say anything directly about how structural shocks to supply and demand conditions in the oil market impact real gasoline and heating oil prices. Given the reduced form model results that oil prices Granger-cause gasoline and heating oil prices, we therefore specify and estimate recursively identified structural vector autoregressive models that specifically account for structural supply and demand shocks. The oil market block follows Kilian (2009). We find that real spot gasoline prices and real heating oil prices do not respond to structural oil supply shocks, respond briefly to aggregate demand shocks, but do respond to oil-specific demand shocks. We conclude the result that spot oil prices Granger-cause spot gasoline and heating oil prices largely occurs through the channel of oil-specific demand shocks.

## Appendix A: Descriptions and sources of the data

| Variable | Description | Source |
|---|---|---|
| % Δ World Oil Production | Weekly percentage change in estimated world oil production | Monthly oil production data for the U.S. are from the U.S. Energy Information Administration (https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm), Monthly World oil production data are from the Monthly Energy Review prepared by the U.S. EIA (Table 11.1b World Crude Oil Production: Persian Gulf Nations, Non-OPEC, and World, https://www.eia.gov/totalenergy/data/monthly/index.php); Weekly oil production data for the U.S. are from the, U.S. EIA, Weekly U.S. Field Production of Crude Oil (Thousand Barrels per Day) (https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=WCRFPUS2&f=W )<br><br>Weekly estimates are computed by a two-step process. First the relation between monthly U.S. production, and monthly world production is computed for each month in the sample period. Second, the relation for each month is applied to the U.S. weekly production data under the assumption that the ratio for each month holds for each week of the month. |
| Global Variation in Real Economic Activity | Baltic Dry Index, adjusted for inflation and detrended | Baltic Exchange (http://www.balticexchange.com/market-information/indices/). Nominal index adjusted to real using interpolated U.S. CPI index (Consumer Price Index for All Urban Consumers: All Items, Index 1982-1984=100, Monthly, Seasonally Adjusted, source FRED: https://fred.stlouisfed.org/series/CPIAUCSL ) |
| Real Brent Oil Spot Price | Weekly averages of daily spot prices adjusted for inflation | U.S. Energy Information Administration https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm Nominal index adjusted to real using interpolated U.S. CPI index (Consumer Price Index for All Urban Consumers: All Items, Index 1982-1984=100, Monthly, Seasonally Adjusted, source FRED: https://fred.stlouisfed.org/series/CPIAUCSL ) |
| Real Deseasonalized New York Harbor No. 2 Heating Oil Spot Price | Weekly averages of daily spot prices adjusted for inflation and deseasonalized | U.S. Energy Information Administration https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm Nominal index adjusted to real using interpolated U.S. CPI index (Consumer Price Index for All Urban Consumers: All Items, Index 1982-1984=100, Monthly, Seasonally Adjusted, source FRED: https://fred.stlouisfed.org/series/CPIAUCSL ) |
| Real Deseasonalized New York Harbor Conventional Regular Gasoline Spot Price | Weekly averages of daily spot prices adjusted for inflation and deseasonalized | U.S. Energy Information Administration https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm Nominal index adjusted to real using interpolated U.S. CPI index (Consumer Price Index for All Urban Consumers: All Items, Index 1982-1984=100, Monthly, Seasonally Adjusted, source FRED: https://fred.stlouisfed.org/series/CPIAUCSL ) |

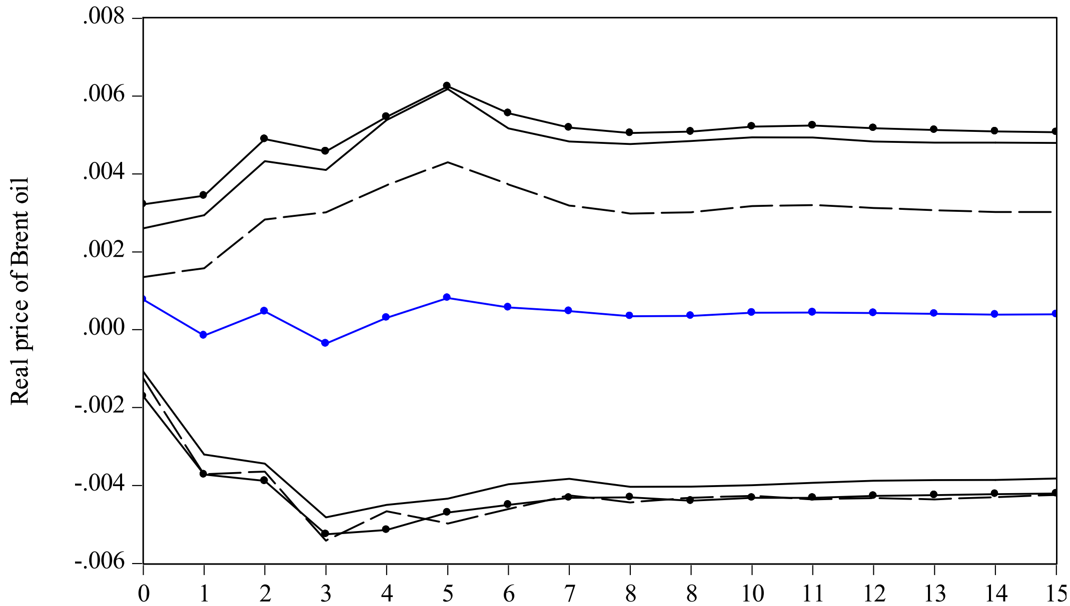
| | | |
|---|---|---|
| % Δ U.S. distillate consumption | Percent change Weekly U.S. Product Supplied of Distillate Fuel Oil. U.S. distillate consumption is deseasonalized and detrended. | U.S. Energy Information Administration<br>https://www.eia.gov/dnav/pet/pet_cons_wpsup_k_w.htm<br>From the EIA: "Measures the disappearance of petroleum products from primary sources; approximately represents consumption of petroleum products." Raw data in thousand barrels per day. |
| % Δ U.S. gasoline consumption | Percent change Weekly U.S. Product Supplied of Finished Motor Gasoline U.S. gasoline consumption is deseasonalized and detrended. | U.S. Energy Information Administration<br>https://www.eia.gov/dnav/pet/pet_cons_wpsup_k_w.htm<br>From the EIA website: "Measures the disappearance of petroleum products from primary sources; approximately represents consumption of petroleum products." Raw data in thousand barrels per day. |
| ΔWorld Oil Inventory | Weekly change in estimated World Stocks of Crude Oil (Thousand Barrels), deseasonalized | U.S. Energy Information Administration<br>https://www.eia.gov/dnav/pet/pet_stoc_wstk_dcu_nus_w.htm<br><br>Weekly estimates are computed by a two-step process. First the relation between monthly U.S. inventory, and monthly OECD inventory (obtained from the Monthly Energy Review of the U.S. EIA, https://www.eia.gov/totalenergy/data/monthly/) is computed for each month in the sample period. Second, the relation for each month is applied to the U.S. weekly inventory data under the assumption that the ratio for each month holds for each week of the month. |
| ΔU.S. Stocks of Distillate | Change in Weekly U.S. Ending Stocks of Distillate Fuel Oil (Thousand Barrels), deseasonalized | U.S. Energy Information Administration<br>https://www.eia.gov/dnav/pet/pet_stoc_wstk_dcu_nus_w.htm |
| ΔU.S. Stocks of Gasoline | Change in Weekly U.S. Ending Stocks of Total Gasoline (Thousand Barrels), deseasonalized | U.S. Energy Information Administration<br>https://www.eia.gov/dnav/pet/pet_stoc_wstk_dcu_nus_w.htm |

## Appendix B: Response of the real price of oil to an oil supply shock, a shock to global commodity demand and an oil-specific demand shock

Impulse response graphs for a three equation structural VAR of the oil market, in which the relation between reduced form errors and structural shocks is specified as

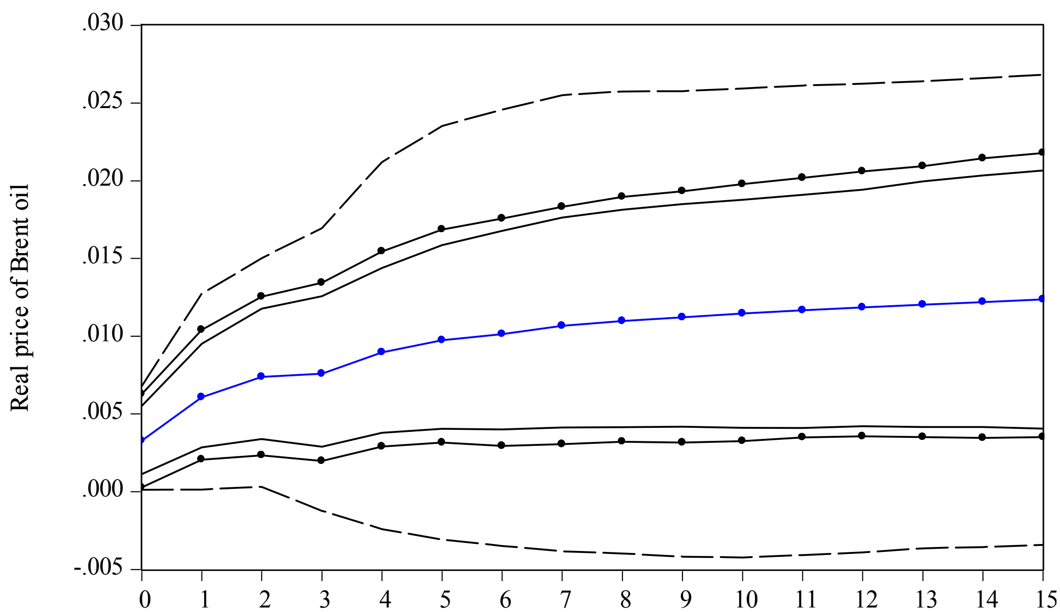
$$\begin{bmatrix} u_t^{\%\Delta \text{Global oil prod}} \\ u_t^{\text{Global\_real\_activity}} \\ u_t^{\text{Real\_Brent\_Spot\_Price}} \end{bmatrix} = \begin{bmatrix} b_0^{11} & 0 & 0 \\ b_0^{21} & b_0^{22} & 0 \\ b_0^{31} & b_0^{32} & b_0^{33} \end{bmatrix} \begin{bmatrix} w_t^{\text{Oil supply shock}} \\ w_t^{\text{Aggregate demand shock}} \\ w_t^{\text{Oil mkt specific demand shock}} \end{bmatrix} \quad \text{(B.1)}$$

FIGURE B.1 IS PRESENTED ON THE FOLLOWING TWO PAGES




Time step in weeks

Fig. B.1(a) Brent real oil price response to oil supply shock




Time step in weeks

Fig. B.1(b) Brent real oil price response to an aggregate demand shock

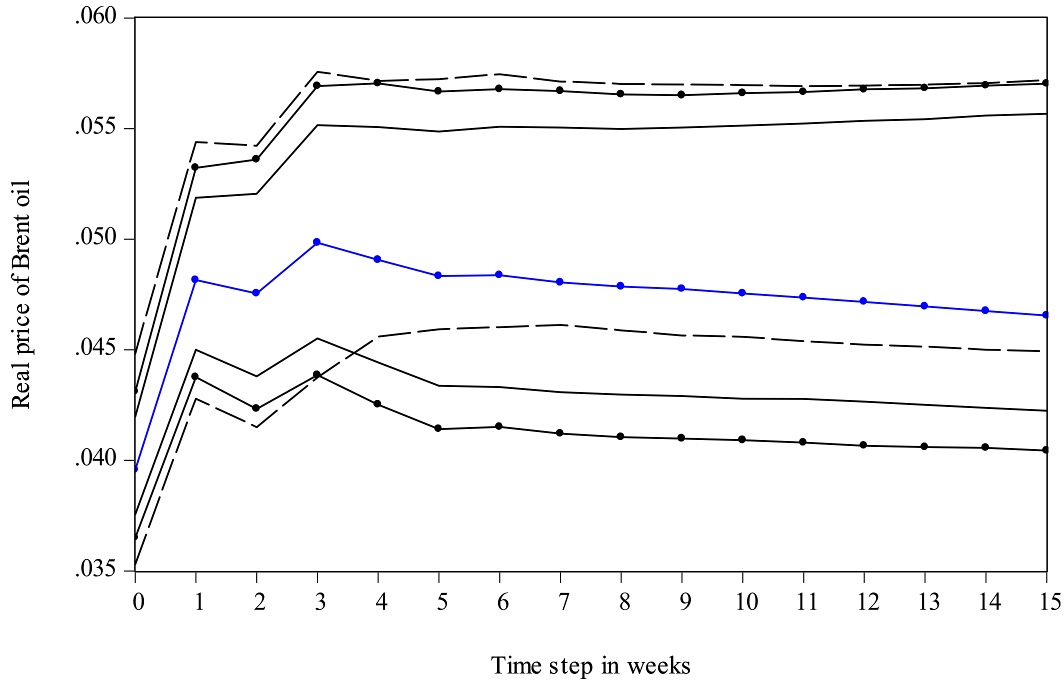



Fig. B.1(c) Brent real oil price response to an oil-specific demand shock

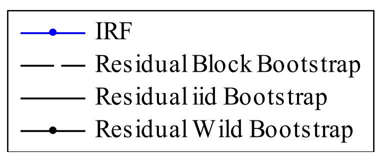



Fig. B.1 Response of real price of oil (IRF) to (a) An oil supply shock, (b) An aggregate demand shock, and (c) An oil-specific demand shock. 95% confidence intervals are displayed. Results are based upon Hall's percentile interval and three alternative confidence intervals which we denote as: 1) Residual Block Bootstrap with Block Size =150 per Bruggemann, Jentsch, and Trenkler (2016), 2) Residual iid Bootstrap under the assumption of iid errors, and 3) Residual Wild Bootstrap per Goncalves and Kilian (2004). See Kilian and Lütkepohl (2017, Ch. 12) for additional details.

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