Location Basis Differentials in Crude Oil Prices

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Abstract

We examine the long-run pricing relationship among crude oil prices at the North Sea (Brent) and Cushing (WTI) delivery points. The Brent-WTI location basis differential is stable until December 2009, but it widens to record levels in the next two years. We report on recent changes in the crude oil market that causes the prices to move apart. Brent and WTI prices are cointegrated prior to this structural break, but not between 2010 and 2015. Since the U.S. lifted the crude oil export ban in December 2015, Brent and WTI prices have reintegrated. U.S. retail gasoline prices respond to Brent and WTI before January 2010 and then only to Brent afterwards.

Keywords: Brent, West Texas Intermediate, basis differential.

JEL Codes: G12, G14, G18, Q35, Q41

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1 Introduction

Crude oil still powers the engine of industrialized economies, and a vast international market exists for pricing and delivery of crude oil and its refined products. There are two international reference crude oil prices. The first is a U.S. benchmark called West Texas Intermediate (WTI), a low density (light), low sulfur (sweet) crude, which makes it more easily refinable into useful products. Cushing, Oklahoma was the crossroads of the U.S. crude oil pipeline infrastructure, and in 1983, the New York Mercantile Exchange (NYMEX) selected Cushing as the price settlement point for their WTI futures contract.

The traditional dominance in world markets of the WTI price has been challenged by other benchmarks. Saudi Arabia substituted the Argus Sour Crude Index (ASCI) for the WTI price in 2010 for its exports to the U.S. The primary challenger to WTI though has been the Brent price.

The Brent field is located in the North Sea, off the United Kingdom, and delivered by pipeline to a terminal at Sullom Voe, in the Shetland Islands, off Scotland. This delivery point was the original reference price. To help expand liquidity in the market, additional production locations were added, including the Ninian field in 1990, Forties and Oseberg in 2002, and Eofisk in 2007, each of which has a separate delivery point.¹

Because WTI is both lighter and sweeter, Brent has traditionally traded at a slight discount to WTI. Monthly crude oil prices at the Cushing and Brent delivery locations traded in a range of a $0.25 premium to -$5.76 discount between 1997 and 2004 as we show in Figure 1. Major changes in the global crude oil market disrupted these long term relationships in the subsequent decade.

[INSERT Figure 1 HERE]

Between 2004 and 2009, Brent traded at an average discount of –$1.48. Between 2010 and 2015, though, Brent traded at an average premium of $9.03. Brent reached a maximum premium of $27.31 in September 2011.

Our manuscript provides a formal statistical analysis of the differentials between the Brent and WTI crude prices. We identify a structural break in the differential in December 2009 when WTI was dropped from Saudi Arabian benchmark pricing. We also find that the

¹The settlement prices for Brent crude are complex and depend upon the quality of the production field and the delivery dates for oil in route to a hub. The Shell U.K. contract, “Agreement for the Sale of Brent Blend Crude Oil,” originally signed in 1990 and modified over the years, is the essential guidepost. Forties is the lowest grade and it typically sets the benchmark. Platts, a division of McGraw Hill, is an official Price Reporting Agency and produces a “Dated Brent” benchmark for physical delivery. The Intercontinental Exchange uses this price for settlement of Brent contracts. The settlement is based on trades occurring during the two-minute settlement period between 19:28 and 19:30 on each trading day.
prices re-integrate after the United States lifted the export ban on crude oil in December 2015. We then show that inventories can explain crude differentials before but not after the break. We also find that retail gasoline prices remain linked to Brent prices during this entire time period.

The academic literature has generally found that location does not prevent prices from moving in a synchronized manner as they would in an integrated world oil market. To model transitory fluctuations in the global market, Hammoudeh, Ewing and Thompson (2008), Fattouh (2010) and Mann and Sephton (2016) use a threshold cointegration model. Reboredo (2011) finds, using a copula model, that crude oil prices are closely linked.

A surge in U.S. production along with infrastructure constraints have led to periodic supply gluts at the Cushing delivery location. Kao and Wan (2012) and Büyüksahin, Lee, Moser and Robe (2013) emphasize that, starting in the late 2000s, the growing inventory of crude in Cushing has pushed the Brent prices to unusual surpluses relative to the WTI price.

Kao and Wan (2012) estimate a declining role in price discovery for WTI. Liu, Schultz and Swieringa (2014) still find an important role for WTI, and Elder, Miao, and Ramchander (2014) find more than 80% of price discovery is driven by WTI between 2007 and 2012.


Other economists such as Kilian (2009) and Hamilton (2009) have claimed that international demand is driving up global oil prices, particularly demand from the large and booming Chinese economy. Li and Lin (2011) note that demand from China and India has been impacting world oil prices since 2003.

We also address the impact of supply constraints on retail gasoline prices. Borenstein and Kellogg (2014) found that, for the period 2006 to 2011, the decline in WTI prices was not passed through to U.S. retail gasoline prices. We confirm a structural change in the relationship between retail gasoline prices and the crude oil benchmarks at the end of 2009. WTI prices, after January 2010, were no longer cointegrated with U.S. retail gasoline prices, while the link between Brent and U.S. retail gasoline was maintained. Muehlegger and Sweeney (2017) study the cost pass-through from crude oil prices to gasoline and diesel. Our results support their finding that the Brent price is the key determinant of the U.S. retail refined products pricing.

Derivative trading activity also reflects the decline and resumption of WTI’s influence. The majority of futures market trading was in Brent contracts between 2012 and 2014, but
in 2015, this reversed again.

The paper comprises six sections. Following this introduction, Section 2 discusses the shale oil production boom and the changes in the crude oil infrastructure. Section 3 analyzes and identifies a structural break in the Brent-WTI spread. Section 4 tests for causal variables driving the Brent-WTI spread. Section 5 analyzes the link between Brent and retail gasoline prices in the U.S. and trading activity in crude oil derivatives. Section 6 provides some concluding remarks.

2 Structural Changes in the Crude Oil Market

Even as world oil prices surged prior to the financial crisis, with WTI prices peaking at almost $134 per barrel in June 2008, Brent and WTI prices moved in tandem. The price differentials at the peak were only a −$1.56 discount for Brent. As prices fell nearly $100 per barrel in just six months, with Brent bottoming at $39.95 in December 2008, the discount was −$1.17 for Brent. Major changes in the global crude oil market detached WTI prices from Brent in January 2009 and then re-integrated them in 2016. This section describes those changes.

2.1 The shale production boom

Crude oil production has surged in the U.S. with the use of horizontal drilling and modern well completion techniques in combination with hydraulic fracturing. Production reached a record high of 10.07 million barrels per day in November 2017. Since the shale markets revival in mid-2016, the Permian basin has led the surge in U.S. crude production.

The shale production boom led to a glut of inventory in Cushing. Before 2013, most of the crude from the Permian basin, which is located in West Texas and southeastern New Mexico, was transported to Cushing through the Basin and Centurion pipelines. From 2010 to 2015, the production of Permian doubled from just 900 thousand barrels to almost 2 million barrels per day. The gush of oil production quickly overwhelmed the capacity of the local refiners and the existing pipeline infrastructure taking oil to the Gulf coast (see Figure 2). Thus, the surplus barrels soon flooded the storage in Cushing.

2https://www.eia.gov/todayinenergy/detail.php?id=35632
3Refinery capacities of Permian Basin are of Big Spring and El Paso in Texas, and Navajo in New Mexico. The capacity of each refineries is available in EIA, Form EIA-820, Annual Refinery Report. https://www.eia.gov/petroleum/refinerycapacity/. The input volumes of these three refineries were estimated by multiplying the nominal capacity for the average capacity utilization rate of the refineries in Inland Texas. Over the period 2008 to 2016, this average capacity utilization was 93 percent. The pipeline takeaway capacities can be found in RBN Energy, Crude Oil Shuttle Pipelines and Gathering Systems in the Permian,
The cheapest route to the international markets is by ship, and oil in the Gulf of Mexico could, in principle, be exported to markets with higher prices. The legacy pipeline system, however, was not capable of moving the unprecedented amount of oil. Hence, producers and arbitrageurs have to rely on alternative, more expensive transportation options such as rail, tanker, and barge (see Figure 3).

Rail capacity for moving oil ten years ago was basically zero and grew to almost ten million barrels in 2013.4 Tanker and barge shipments from PADD 2 to PADD 3 also grew ten times to more than three million barrels in the same period. The widening of the Brent-WTI spread coincides with the increased usage of non-pipeline transportation modes between 2009 and 2015. Agerton and Upton (2019) suggest that pipeline capacity was the key factor in driving down WTI prices during this time period.

2.2 Expansion of pipeline capacity

Wider price differentials between Brent and WTI provide greater incentives to refiners and arbitrageurs to invest in pipelines to bring oil from Cushing and the Permian basin to the Gulf where refineries and export markets are. These infrastructure changes, we will show, have helped to reconnect the WTI and Brent prices.

Driven by the arbitrage opportunity, the market expanded pipeline capacity to bring more PADD2 production to the Gulf Coast. The Seaway Pipeline, originally intended to bring crude north from the Gulf of Mexico, was reversed in June 2012, bringing 4.5 million barrels per month to Freeport, Texas from Cushing.5 The capacity was increased to 12 million barrels in January 2013.

In early 2014, a second major pipeline project came online. The Gulf Coast portion of the TransCanada Keystone XL pipeline opened on January 22, 2014, with the potential to bring 24.9 million barrels per month to Port Arthur, Texas.6 A third route was opened through the Permian basin. Two old pipelines, Longhorn and Permian Express, and multiple new pipelines such as BridgeTex, Cactus, Permian Express


4The American Association of Railroads reported that U.S. Class I railroads originated a record 97,135 carloads of crude oil, up 166% from the 36,544 carloads in the first quarter of 2012. See http://www.aar.org/newsandevents/Freight-Rail-Traffic/Pages/2013-05-30-railtraffic.aspx

5http://seawaypipeline.com/

6http://www.gulf-coast-pipeline.com/about/questions-answers/
II, Permian Longview and Louisiana Extension have come on line since 2014. A total of 1.8 million barrels per day in takeaway capacity has been added in the last four years. By December of 2015, more than 90% of crude arriving in PADD3 from PADD2 was again by pipeline (see Figure 3).

These infrastructure changes are alleviating the oversupply in Cushing. As shown in Figure 4, Cushing inventories surged to 52.18 million barrels in January 2013.

Over the next 18 months, inventories fell to under 18 million barrels. McRae (2017) estimates that the elimination of pipeline constraints narrowed price differentials by between $6 and $11 per barrel.

### 2.3 Exporting crude

While the pipeline projects were able to reduce the inventory glut in Oklahoma, they were not able to reconnect the WTI price with Brent. The primary obstacle was a legal one. In 1975, the U.S. passed The Energy Policy and Conservation Act, a crude oil export ban designed to preserve the Alaskan oil supplies. As the world market changed though, pressure to reform the law grew, and in December of 2015, President Obama lifted the ban. Between November 2015 and October 2017, exports rose, as we show in Figure 4 to almost 50 million barrels per month.

In the next section, we test when the pricing relationship between WTI and Brent broke down and whether the lifting of the export ban has reintegrated the markets.

### 3 Divergence in the Brent-WTI Spread

We begin our analysis in January 2004 because a number of series from the U.S. Energy Information Administration, including Cushing inventories, begin there. Our sample ends in December 2017. We utilize monthly data to emphasize longer run relationships. We analyze the data in levels because transportation costs are largely fixed costs. We define the

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<https://ihsmarkit.com/research-analysis/fixing-permian-mismatch/-upstream-growth-midstream-take-away-capacity.html>
location basis differential between Brent and WTI as

\[ S_t^{BW} = p_t^{Brent} - p_t^{WTI}, \]

and plot the differential in Figure 5.

[INSERT Figure 5 HERE]

### 3.1 Breakpoints

We hypothesize that the sample period consists of two regimes: one in which Brent and the WTI prices mean revert towards a long run equilibrium relationship and another in which they do not. Our dating of the breaks is motivated by major developments in the crude oil markets. Industry commentary about the isolation of the U.S. crude oil market from the global market began as early as 2007 (e.g. International Energy Agency (2007) and Morse (2009)).\(^8\)\(^9\) The isolation was acknowledged in December 2009, when WTI was dropped from the pricing formula in Saudi Arabia among other key oil exporting countries (Fattouh 2011). Saudi Aramco shifted from WTI to ASCI for pricing its U.S. sales.

Next, we predetermine a second break point linked to changes in the the U.S. that helped to reconnect WTI with international markets. We hypothesize that there have been two key frictions causing the U.S. market to be isolated from the global market: limited pipeline capacity sending crude oil from Cushing to the Gulf coast; and the crude oil export ban. By December 2015, both constraints were lifted, and we test the hypothesis that the U.S. crude oil market re-integrated with the global market in 2016.

Price differentials vary substantially between these regimes. The average spread in the two regimes are \(-$0.642\) and \(+$9.035\) respectively. A simple \(t\)-test easily rejects a stable mean Brent-WTI price differential. The corresponding \(t\) statistic is \(-10.372\) which rejects the null hypothesis at 1%.

We now turn to formal testing of these break points. We first confirm our predetermined structural break points with a Chow (1960) test.\(^{10}\) We conduct the test with the model

\[ S_t^{BW} = \theta + \lambda R_t + \phi S_{t-1}^{BW} + \varepsilon_t, \tag{1} \]

\(^8\)International Energy Agency (Oil Market Report, April, 2007): “The persistence of WTI's unusual weakness to other domestic and international crudes has raised questions about its viability as a regional benchmark.”

\(^9\)Morse (Financial Times, January 26, 2009): “West Texas Intermediate (WTI) crude oil traded on the NYMEX is the most commonly accepted benchmark for oil prices but the grade occasionally disconnects from global markets. ...WTI has not been a representative crude oil for the past eight weeks”

\(^{10}\)We also tried a purely data driven procedure for multiple break points, Bai and Perron (1998), and it identifies between zero and four breaks depending upon the specification.
where $TR_t$ is linear trend, $\theta$ is a constant term and $S_{t-1}^{BW}$ is a month lagged Brent-WTI spread.\textsuperscript{11} The unrestricted regressions that allow the coefficients to be different in the two regimes are

$$ S_{1,t}^{BW} = \theta_1 + \lambda_1 TR_{1,t} + \phi_1 S_{1,t-1}^{BW} + \varepsilon_{1,t} $$

and

$$ S_{2,t}^{BW} = \theta_2 + \lambda_2 TR_{2,t} + \phi_2 S_{2,t-1}^{BW} + \varepsilon_{2,t}. $$

Two subperiods are assumed to be under regime 1, the period dating from January 2004 to December 2009 and then from January 2016 to December 2017. The subperiod spanning from January 2010 to December 2015 is considered to be under regime 2. The null hypothesis to be tested is then $\theta_1 = \theta_2$, $\lambda_1 = \lambda_2$ and $\phi_1 = \phi_2$. The hypothesis can be tested with the $F$-test statistic

$$ (SSR - (SSR_1 + SSR_2)) / k \over (SSR_1 + SSR_2) / (N_1 + N_2 - 2k) $$

where $SSR$, $SSR_1$ and $SSR_2$ are sum of squared residuals from the restricted regression and the two unrestricted regressions respectively. $N_1$ and $N_2$ are the number of observations in each regime and $k$ is the number of coefficients.

The estimated restricted model, i.e. without breaks, is

$$ S_t^{BW} = 0.018 + 0.003TR_t + 0.934S_{t-1}^{BW} + \varepsilon_t, $$

\begin{align*}
(0.369) & \quad (0.028) & \quad (0.004)
\end{align*}$$

while the resulting estimates for the two regimes are

$$ S_{1,t}^{BW} = -0.953 + 0.018TR_{1,t} + 0.721S_{1,t-1}^{BW} + \varepsilon_{1,t} $$

\begin{align*}
(0.397) & \quad (0.007) & \quad (0.076)
\end{align*}$$

and

$$ S_{2,t}^{BW} = 1.669 - 0.023TR_{2,t} + 0.908S_{2,t-1}^{BW} + \varepsilon_{2,t} $$

\begin{align*}
(0.881) & \quad (0.018) & \quad (0.048)
\end{align*}$$

with standard errors reported in parentheses underneath each parameter estimate. The resulting $F$-test statistic is 2.927 with degrees of freedom 3 and 161. The corresponding $p$ value is 0.036. Therefore, we reject the null hypothesis at the 5% significance level, and we

\textsuperscript{11}The number of lags in the model is chosen by the Akaike Information Criteria (AIC) when we conduct unit root tests for Brent and WTI prices. As a robustness check, we conducted the break test with two and three lags finding the same result.
confirm the break points as being December 2009 and December 2015.\textsuperscript{12} We also cannot reject that the data after the crude export ban is drawn from the same regime prior to the structural break.\textsuperscript{13}

### 3.2 Cointegration

In the preceding section, we predetermined break points at December 2009 and December 2015, based on the critical events that affected the Brent-WTI pricing relationship, and confirmed them statistically with a Chow test. Our hypothesis is that during regime 1 (January 2004 - December 2009 and January 2016 - December 2017) WTI was connected to Brent, while during the regime 2 (January 2010 - December 2015) the U.S. benchmark decoupled from the global benchmark. This section utilizes the structural breaks identified by the Chow test and then tests for cointegration within the regimes.

As Engle and Granger (1987) point out, when time series show non-stationary behavior, they may share a common stochastic trend, so linear combinations of the time series may be stationary. In other words, if the detrended series are found to be stationary, the series should be tested for cointegration.\textsuperscript{14} An advanced framework for testing cointegration in a multivariate system is given by Johansen (1988, 1991) and Johansen and Juselius (1990). The relationship can be examined by using the following $n$-dimensional vector error correction model (VECM):

$$\Delta p_t = \sum_{i=1}^{k} \Gamma_i \Delta p_{t-i} + \alpha (\beta' p_{t-1} + c) + \varepsilon_t$$

(2)

where $p_t$ is a $n \times 1$ vector of time series, each being integrated process of order 1, i.e. $I(1)$ process; $k$ is the number of lags; $\Gamma_i$ are $n \times n$ coefficient matrices measuring the short-run adjustment; $\alpha$ and $\beta$ are $n \times 1$ coefficient vector measuring long-run adjustment of the system to changes in $p_t$, respectively.

Johansen and Juselius recommended the trace test for the number $r$ of non-zero eigen-

\textsuperscript{12}We conducted robustness checks of our findings from Tables 1-4 against alternative break points. We test for $5 \times 5 = 25$ break point combinations i.e. [Oct 2009, Feb 2010] × [Oct 2015, Feb 2016] falling in a ±2 month window around our predetermined break. We confirmed that our conclusion holds for all 25 cases.

\textsuperscript{13}We test the null hypothesis that sub-period [2004 January – 2009 December] and sub-period [2016 January – 2017 December] are in the same regime. The Chow test does not reject the hypothesis at the 10% level. Moreover, the data from 2016 and 2017 strengthen our conclusions about the causality tests for both of our key hypotheses we examine in Sections 4 and 5. The additional data from January 2016 increases the statistical significance of causality tests for: (1) the Cushing inventory to the spread; (2) from retail gasoline to the Brent; (3) from retail gasoline to WTI; and (4) to retail gasoline from Brent. The retail gasoline results would not reach the conventional 95% confidence level without the data from after the export ban.

\textsuperscript{14}We conducted augmented Dickey-Fuller unit root tests on the three price series in the paper: Brent, WTI, and retail gasoline. None of the tests reject in levels, and all of the tests reject a unit root in first differences at the 5% level or better.
values in $\Pi = \alpha \beta'$,

$$H_0 : r \leq R \quad V.S. \quad H_1 : r > R, \quad (3)$$

$$Tr = -T \sum_{i=R+1}^{n} \ln(1 - \lambda_i). \quad (4)$$

Here, $r$ is the rank number. $T$ is the sample size and $n$ is the number of variables in the system. The eigenvalues of $\Pi$ are real numbers such that $1 > \lambda_1 > \cdots > \lambda_n \geq 0$. The trace test involves testing a sequence of alternatives $r = 0$ against $r > 0$, $r \leq 1$ against $r > 1$, $r \leq 2$ against $r > 2$ and so on. Critical values of the $Tr$ statistics are found in Johansen and Juselius (1990).

Our Johansen trace test statistics confirm two regimes (see Table 1). During the first regime, Brent and WTI are cointegrated, while in the second regime they are not. During the second regime, i.e. after Saudi Aramco dropped WTI from its pricing formula and before the lifting of the U.S. crude oil export ban, the U.S. and the North Sea benchmarks have failed to establish an equilibrium pricing relation. This indicates the isolation of the U.S. crude oil market from the international market. With the return to the first regime after December 2015, WTI and Brent have re-established the 2004-09 equilibrium pricing relation.

[INSERT Table 1 HERE]

Using Johansen’s procedure, we find a cointegrating vector in our first regime. The cointegrating vector, or the basis vector, provides the equilibrium pricing relation between Brent and WTI. The basis vector for Brent during the first regime, with estimates in Table 2, is

$$p_{t}^{Brent} = 0.976p_{t}^{WTI} - 0.757. \quad (5)$$

This implies that during the period when the U.S. market has been integrated to the global market, WTI has a premium of 76 cents, and that for every one dollar increase in WTI, Brent prices go up by 98 cents. The positive premium of WTI over Brent is in contrast to the observed large discount during the second regime.

While the basis vector estimates the long-run relationship between Brent and WTI, the speed of adjustment (or error correction) coefficients of the VECM tell us how the two prices adjust toward the equilibrium. If WTI (Brent) adjusts to Brent (WTI), $\alpha_2 (\alpha_1)$ has to be positive (negative). To maintain an equilibrium, at least one of the prices has to adjust. We indeed find $\alpha_2 > 0$, indicating the U.S. regional benchmark is adjusting to the global benchmark but not vice versa. The speed of adjustment of Brent is positive but insignificantly different from zero. Both estimates are reported in the first row of Table 2.

[INSERT Table 2 HERE]
The WTI adjustment coefficient $\alpha_2 = 0.594$ indicates that when prices in the Brent market are high relative to their long-run value, WTI prices rise to meet Brent prices. The corresponding positive speed of adjustment for Brent, $\alpha_1 = 0.395$, suggests that Brent prices are not adapting to the WTI prices.

We do not find cointegration in the second regime indicating the isolation of the U.S. crude oil market from the global market.\(^{15}\) Our next section tries to answer why WTI has decoupled from Brent by examining the factors influencing the Brent-WTI price spread.

## 4 Factors Influencing the Spread

There have been a number of factors suggested as possible explanations for the divergence in the Brent-WTI spread. Both market participants and academics (e.g. Kao and Wan (2012)) have emphasized the glut of oil arriving in Cushing. As a delivery and settlement point of the WTI futures contract, excess supply at Cushing exerts downward pressure on the price. Therefore the increased inventory at Cushing leads to a wider Brent-WTI spread.

Crude oil data for the U.S. from the Energy Information Administration (EIA) are organized by Petroleum Administration for Defense Districts (PADD) which are mapped in Figure 6.

\[ \text{[INSERT Figure 6 HERE]} \]

Büyükşahin et al. (2013) found that greater Canadian crude oil shipments to the PADD 2 district increase the Brent-WTI spread. Macrae (2013) noted the Cushing buildup as part of the larger surge in domestic production. The ability to get oil into and out of Cushing was emphasized by Ederington, Fernando, Holland, Lee and Lin (2018). Ederington et al. highlighted that only Cushing inventories, and not PADD2 as a whole, respond to the futures-spot spread.

Figure 4 demonstrates the large buildup in PADD2 by plotting the end-of-month inventory. We turn to formal testing in the next section.

### 4.1 Causality Testing

We can analyze the causality between the Brent-WTI spread and potential drivers through Toda and Yamamoto (T-Y, 1995) modified Granger (1969) non-causality tests. Clarke and Mirza (2006) find that the practice of pretesting for cointegration can result in severe over

\(^{15}\)We applied the same analysis to Brent and an alternative U.S. gulf coast regional benchmark, Louisiana Light Sweet (LLS) crude. We find a similar result to the Brent-WTI relation, i.e. Brent-LLS cointegration also broke down during the period of 2010-2015.
rejections of the non-causal null, whereas over fitting results in better control of the Type I error probability with often little loss in power. Their simulation results suggest that the augmented lag method of T-Y (1995) exhibits consistent performance over the wide range of investigated data generating processes. On the face of it, if any of the variables are non-stationary (whether or not they are cointegrated), the usual Wald test statistic for will not have an asymptotic $\chi^2$ distribution.

Toda and Yamamoto recommend an analysis of the vector autoregression (VAR) model in levels, regardless of the orders of integration of the various time-series as indicated below.

1. Determine the appropriate maximum lag length $p$ for the variables in the VAR, using information criteria.
2. Add in $m$ additional lags of each of the variables into each of the equations.
3. Use the standard Wald test without the coefficients for the “extra” $m$ lags.

### 4.2 Results

Table 3 presents the T-Y bivariate Granger causality test results for the Brent-WTI spread. We utilize the two break points December 2009 and December 2015 confirmed by the Chow test in Section 3. The first regime is January 2004 - December 2009 and January 2016 - December 2017, and the second is January 2010 - December 2015. All diagnostic tests are validated by Wald test statistics, which are asymptotically $\chi^2$ distributed with $p$ degrees of freedom.

[INSERT Table 3 HERE]

Through the first regime, Granger causality between Cushing (PADD2) oil inventories and the Brent-WTI spread is bi-directional. As the delivery and settlement point of NYMEX futures contract, excess supply at Cushing has been the key determinant of the WTI price, which in turn affects the Brent-WTI spread. This is consistent with Ederington et al. (2018). In contrast, during the second regime, we cannot reject Granger non-causality from Cushing inventories to the Brent-WTI spread nor from the Brent-WTI spread to the Cushing inventory. The excess supply in Cushing has lost short-term predictive power for the Brent-WTI spread. The lack of a short-term lead-lag relation between the two variables demonstrates that the market has priced Brent and WTI as distinct goods in the second regime. In the next section, we will examine the impact on related markets.
5 Impacts on Related Markets

Between 2010 and 2015, U.S. oil production from shale formations rose from less than one million barrels per day to almost five million. We show in this section how markets linked to the crude oil prices adjusted to this supply shock. The first impact was that, during regime 2, retail gasoline prices lost their cointegration relationship with WTI crude. The second impact was in the futures market where the majority of trading activity temporarily shifted into Brent contracts.

5.1 Retail gasoline

In this section, we examine the link between the Brent and WTI crude oil benchmarks and retail gasoline prices by testing whether a stable long-run equilibrium relation has been maintained in the both regimes using Johansen’s cointegration test. We also test for causality from the global crude oil benchmarks to U.S. retail gasoline. Because of the structural breaks we have identified, we hypothesize that WTI has been a less effective benchmark for U.S. gasoline prices during the second regime than Brent. The literature includes several papers on cointegration analysis of refined products. Westgaard, Estenstad, Seim, and Fredenberg (2011) find that daily, short-term futures contracts for European gas oil and Brent crude futures are cointegrated over the period 1994-2009. Zavaleta, Walls and Rusco (2015) on the other hand find that cointegration among refined products is weaker than crude oil.

We conduct the Johansen’s test, using break dates of December 2009 and December 2015. Table 1 confirms the pricing link between Brent and retail gasoline in both regimes. The test rejects the hypothesis of no-cointegration between Brent and U.S. retail gasoline in both regimes, a finding in line with Muehlegger and Sweeney (2017). On the other hand, retail gasoline–WTI cointegration is weakly detected (10% significance level) only in the first regime. As hypothesized, during the period of Brent–WTI divergence between January 2010 - December 2015, WTI’s cointegration with retail gasoline vanishes completely, supporting the finding by Borenstein and Kellogg (2014).

We further examine the pricing relation between Brent and U.S. retail gasoline. Table 2

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16https://www.eia.gov/todayinenergy/detail.php?id=25372
17We use the the weekly retail gasoline all grades, conventional areas price available from the EIA: https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm
18The underlying for the Intercontinental Exchange futures contracts is diesel delivery on barges in Bel-

12
reports the Johansen maximum likelihood estimates of the basis equation

\[
p_{1,t}^{RG} = 0.022 p_t^{Brent} + 1.148 \\
p_{2,t}^{RG} = 0.022 p_t^{Brent} + 1.095
\]

for both regimes. In contrast to the WTI-retail gasoline relation, the basis coefficient of Brent-retail gasoline is highly stable at $0.022$ cents per $1$ change in a barrel of Brent. The estimate is in line with the $0.025$ rule of thumb used by Hamilton (2013).

The error correction coefficient estimates of the VECM allow us to examine how the U.S. retail gasoline price adjusts to the equilibrium basis equation. As documented by Muehlegger and Sweeney (2017), the cost pass-through goes from the Brent price to the U.S. retail gasoline, so we expect gasoline prices to adjust to Brent. If that is the case, the price adjustment coefficient \( \alpha_1 \) should be negative. Table 1 confirms a stable adjustment coefficient for both regimes. During the periods of Brent-WTI cointegration in January 2004 - December 2009 and January 2016 - December 2017, \( \alpha_1 = -0.551 \). During the Brent-WTI divergence period of January 2010 - December 2015, \( \alpha_1 = -0.471 \). We do not reject the null hypothesis that the two adjustment coefficients are equivalent at the conventional 5% level.

Table 2 also reports the adjustment coefficient estimates for U.S. retail gasoline-WTI in the first regime. During the period where the Brent-WTI spread has been stable, retail gasoline prices did adjust to WTI prices, \( \alpha_1 = -0.383 \), a statistically significant result at the 1% level. However, during the period of Brent-WTI divergence, the pricing link between WTI crude oil and retail gasoline is no longer significant. These results help explain the finding of Borenstein and Kellogg (2014) that cheap WTI crude did not lower retail gasoline prices in the U.S. during regime 2.

We now extend our Granger causality analysis to retail gasoline prices, \( p_t^{RG} \). Hamilton (2013) contends that during regime 2, Brent drove gasoline prices because the U.S. could only sell refined products at the international price.\(^{19}\) The T-Y causality test in Table 4, in a tri-variate VAR with both benchmark prices, confirms Hamilton’s view.

As suggested in Table 4, the U.S. retail gasoline prices did not follow the U.S. benchmark WTI during either regime; instead, they tracked the path of European Brent prices. During the second regime, the causality from retail gasoline to WTI disappeared, confirming the

\(^{19}\) Hamilton (2013): “The average retail price of gasoline in the United States historically has tracked the price of crude oil pretty closely...the fact that the U.S. can sell refined petroleum markets at the world price means that for purposes of using that rule of thumb today, you’d want to look at the price of Brent rather than the price of WTI.”
cointegration test. Further, the Granger causality tests provide support to our estimates of retail gasoline - Brent error correction coefficients, i.e. $\alpha_1 < 0$ and $\alpha_2 < 0$, which indicate the adjustment is only from retail gasoline to Brent. Both the adjustment coefficients and the lead-lag relations corroborate the view of Hamilton (2013).

5.2 Derivatives markets

Futures contracts linked to the Brent benchmark and to WTI are traded on the Intercontinental Exchange (ICE) and the NYMEX division of the Chicago Mercantile Exchange (CME), respectively. Annual trading volumes from 2006 to 2017 are reported in Table 5.

In 2006, the ICE Brent trading volume was 44.345 million contracts, while the figure for WTI was 71.053 million. Over the next six years, the ICE Brent trading tripled to 147.385 million. While WTI trading nearly doubled over that time frame, ICE Brent surpassed CME WTI for the first time in 2012, taking a 51% market share. Brent’s market share continued to edge up in 2013 and 2014, reaching a 52.50% market share in 2014.

During the time frame reflected in this paper, the spot and derivative markets were sending a clear message: when there are impediments to reaching global markets, WTI is a less useful market signal about the scarcity of crude oil.

As differentials narrowed in 2015, perhaps in anticipation of the export ban being lifted, WTI resumed its majority role in the futures market. Its market share reached 52% in 2015, and WTI continued to rise, reaching over 56% in 2017.

6 Conclusions

This paper provides a comprehensive empirical analysis of the co-movement of benchmark crude oil prices at the Brent and WTI delivery locations. Since 2010, Brent and WTI prices detached from one another. After reaching a spread of more than $27 per barrel in September 2011, a variety of forces have combined to reintegrate WTI and Brent prices.

We hypothesize and test that structural breaks divide the sample period in two regimes: the first regime in which Brent and the WTI prices mean revert towards their long run equilibrium relation; and a second regime in which they do not. We date these regimes around two critical events in the global crude oil market: December 2009, when WTI was dropped from the pricing formula by Saudi Arabia; and the termination of the crude oil export ban by the U.S. government in December 2015. During the first regime, i.e. jointly
between 2004 and 2009 and between 2016 and 2017, we show that Brent and WTI prices were cointegrated, and an error correction relationship kept the two prices closely in alignment. Whereas during the second regime, i.e. between 2010 and 2015, Brent and WTI prices failed to retain their long-run equilibrium relation.

U.S. retail gasoline price have adapted to the Brent price in both regimes, but only to the WTI price in the first regime. This indicates that the European benchmark has been the consistent key determinant of the U.S. retail refined products.

New oil production technologies provided a massive supply shock to the U.S. domestic crude oil market. Wider Brent-WTI spreads led to major adjustments in infrastructure, but policy action by the U.S. government completed the re-integration. What we have witnessed in the U.S. crude oil market during 2004-2017 is a vivid example of how the market mechanism can recover its equilibrium in long-run.
References


We report Johansen trace test results for cointegration between Brent and WTI crude prices. The first regime is January 2004 to December 2009 and January 2016 to December 2017. The second regime runs from January 2010 to December 2015. One lag is selected using the Akaike Information Criteria (AIC). ***Indicates that the null hypothesis can be rejected at the 1% level, ** the 5% level, * the 10% level.

<table>
<thead>
<tr>
<th></th>
<th>H₀</th>
<th>Regime 1</th>
<th>Regime 2</th>
<th>Regime 1</th>
<th>Regime 2</th>
<th>Regime 1</th>
<th>Regime 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Brent-WTI</td>
<td>Brent-Retail Gasoline</td>
<td>WTI-Retail Gasoline</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r = 1</td>
<td></td>
<td>6.64</td>
<td>0.64</td>
<td>5.55</td>
<td>0.79</td>
<td>4.13</td>
<td>0.83</td>
</tr>
<tr>
<td>r = 0</td>
<td>20.16**</td>
<td>6.76</td>
<td>30.14***</td>
<td>23.79**</td>
<td>19.43*</td>
<td>14.86</td>
<td></td>
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</tbody>
</table>

Critical values

<table>
<thead>
<tr>
<th></th>
<th>H₀</th>
<th>10pct</th>
<th>5pct</th>
<th>1pct</th>
</tr>
</thead>
<tbody>
<tr>
<td>r = 1</td>
<td>7.52</td>
<td>9.24</td>
<td>12.97</td>
<td></td>
</tr>
<tr>
<td>r = 0</td>
<td>17.85</td>
<td>19.96</td>
<td>24.6</td>
<td></td>
</tr>
</tbody>
</table>
Table 2: Vector Error Correction Model Estimation Results

<table>
<thead>
<tr>
<th></th>
<th>$\beta$</th>
<th>$c$</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brent-WTI Basis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regime 1</td>
<td>-0.976***</td>
<td>-0.757</td>
<td>0.395</td>
<td>0.594**</td>
</tr>
<tr>
<td></td>
<td>(0.029)</td>
<td>(1.895)</td>
<td>(0.278)</td>
<td>(0.269)</td>
</tr>
<tr>
<td>Response of Retail Gasoline to Brent</td>
<td>-0.022***</td>
<td>-1.148***</td>
<td>-0.551***</td>
<td>-12.543***</td>
</tr>
<tr>
<td>Regime 1</td>
<td>(0.002)</td>
<td>(0.100)</td>
<td>(0.105)</td>
<td>(3.641)</td>
</tr>
<tr>
<td>Regime 2</td>
<td>-0.022***</td>
<td>-1.095***</td>
<td>-0.471***</td>
<td>-10.227**</td>
</tr>
<tr>
<td></td>
<td>(0.001)</td>
<td>(0.144)</td>
<td>(0.092)</td>
<td>(3.874)</td>
</tr>
<tr>
<td>Response of Retail Gasoline to WTI</td>
<td>-0.020***</td>
<td>-1.233***</td>
<td>-0.383***</td>
<td>-7.747*</td>
</tr>
<tr>
<td>Regime 1</td>
<td>(0.002)</td>
<td>(0.147)</td>
<td>(0.097)</td>
<td>(3.214)</td>
</tr>
</tbody>
</table>

We estimate Brent-WTI, Retail Gasoline-Brent and Retail Gasoline-WTI basis vectors using maximum likelihood.

Brent - WTI Basis:
\[ \Delta p_{t}^{\text{Brent}} = \alpha_1(p_{t-1}^{\text{Brent}} + \beta p_{t-1}^{\text{WTI}} + c), \quad \Delta p_{t}^{\text{WTI}} = \alpha_2(p_{t-1}^{\text{Brent}} + \beta p_{t-1}^{\text{WTI}} + c) \]

Response of Retail Gasoline to Brent:
\[ \Delta p_{t}^{\text{RG}} = \alpha_1(p_{t}^{\text{RG}} + \beta p_{t}^{\text{Brent}} + c), \quad \Delta p_{t}^{\text{Brent}} = \alpha_2(p_{t-1}^{\text{RG}} + \beta p_{t-1}^{\text{Brent}} + c) \]

Response of Retail Gasoline to WTI:
\[ \Delta p_{t}^{\text{RG}} = \alpha_1(p_{t}^{\text{RG}} + \beta p_{t}^{\text{WTI}} + c), \quad \Delta p_{t}^{\text{WTI}} = \alpha_2(p_{t-1}^{\text{RG}} + \beta p_{t-1}^{\text{WTI}} + c) \]

***Indicates that the null hypothesis can be rejected at the 1% level, ** the 5% level, * the 10% level.
Table 3: Causality Tests for Brent-WTI Spread

<table>
<thead>
<tr>
<th></th>
<th>Regime 1</th>
<th>Regime 2</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>to spread</td>
<td>from spread</td>
<td>to spread</td>
<td>from spread</td>
</tr>
<tr>
<td>PADD2 Inventory</td>
<td>4.216**</td>
<td>4.560**</td>
<td>0.018</td>
<td>1.159</td>
</tr>
<tr>
<td></td>
<td>(0.040)</td>
<td>(0.033)</td>
<td>(0.894)</td>
<td>(0.282)</td>
</tr>
<tr>
<td>Cushing Inventory</td>
<td>19.676***</td>
<td>7.605***</td>
<td>0.249</td>
<td>0.127</td>
</tr>
<tr>
<td></td>
<td>(0.000)</td>
<td>(0.006)</td>
<td>(0.618)</td>
<td>(0.721)</td>
</tr>
</tbody>
</table>

This table reports Toda and Yamamoto (1995) tests for causality between the spread and the listed factors. *To spread* indicates the test that a variable does not cause the spread, and *from spread* is the test for whether the spread does not cause the inventory measure. The first regime is January 2004 to December 2009 and January 2016 to December 2017. The second regime runs from January 2010 to December 2015. We use $m = 1$, as the unit root test results indicate order of integration = 1 for all the variables in question. The $\chi^2$ statistic is on the first line, and the asymptotic $p$-value is on the next line in parentheses. The data are monthly and were obtained from the U.S. Energy Information Administration (EIA). *** Indicates that the null hypothesis of non-causality can be rejected at the 1% level, ** the 5% level, * the 10% level.
Table 4: Causality Tests for Retail Gasoline

<table>
<thead>
<tr>
<th></th>
<th>Regime 1 from gasoline</th>
<th>Regime 1 to gasoline</th>
<th>Regime 2 from gasoline</th>
<th>Regime 2 to gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brent</td>
<td>4.109**</td>
<td>5.708**</td>
<td>1.960</td>
<td>8.835***</td>
</tr>
<tr>
<td></td>
<td>(0.043)</td>
<td>(0.017)</td>
<td>(0.161)</td>
<td>(0.003)</td>
</tr>
<tr>
<td>WTI</td>
<td>4.096**</td>
<td>0.443</td>
<td>0.693</td>
<td>0.257</td>
</tr>
<tr>
<td></td>
<td>(0.043)</td>
<td>(0.505)</td>
<td>(0.405)</td>
<td>(0.612)</td>
</tr>
</tbody>
</table>

This table reports Toda and Yamamoto (1995) tests for causality between retail gasoline prices, and Brent and WTI crude. *To gasoline* indicates the test that crude oil prices do not cause the gasoline price, and *from gasoline* is the test for whether the gasoline price does not cause the crude oil prices. We use $m = 1$, as the unit root test results indicate order of integration = 1 for all the variables in question. The $\chi^2$ statistic is on the first line, and the asymptotic $p$-value is on the line below in parentheses. The first regime is January 2004 to December 2009 and January 2016 to December 2017. The second regime runs from January 2010 to December 2015. The data are monthly and were obtained from the EIA. ** Indicates that the null hypothesis of non-causality can be rejected at the 1% level, * the 5% level, * the 10% level.
Table 5: Futures Market Shares

<table>
<thead>
<tr>
<th>Year</th>
<th>Brent</th>
<th>WTI</th>
<th>Brent %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>44.345</td>
<td>71.053</td>
<td>38.43%</td>
</tr>
<tr>
<td>2007</td>
<td>59.728</td>
<td>121.525</td>
<td>32.95%</td>
</tr>
<tr>
<td>2008</td>
<td>68.368</td>
<td>134.674</td>
<td>33.67%</td>
</tr>
<tr>
<td>2009</td>
<td>74.137</td>
<td>137.428</td>
<td>35.04%</td>
</tr>
<tr>
<td>2010</td>
<td>100.022</td>
<td>168.652</td>
<td>37.23%</td>
</tr>
<tr>
<td>2011</td>
<td>132.045</td>
<td>175.036</td>
<td>43.00%</td>
</tr>
<tr>
<td>2012</td>
<td>147.385</td>
<td>140.531</td>
<td>51.19%</td>
</tr>
<tr>
<td>2013</td>
<td>159.093</td>
<td>147.690</td>
<td>51.86%</td>
</tr>
<tr>
<td>2014</td>
<td>160.425</td>
<td>145.147</td>
<td>52.50%</td>
</tr>
<tr>
<td>2015</td>
<td>183.853</td>
<td>202.202</td>
<td>47.62%</td>
</tr>
<tr>
<td>2016</td>
<td>210.561</td>
<td>276.768</td>
<td>43.21%</td>
</tr>
<tr>
<td>2017</td>
<td>241.544</td>
<td>310.052</td>
<td>43.79%</td>
</tr>
</tbody>
</table>

This table reports annual spot screen-traded contract volumes (million contracts) in Brent (North Sea) crude on the Intercontinental Exchange and West Texas Intermediate (Cushing) crude on the CME/NYMEX. The source is the Futures Industry Association Annual Reports.
Source: Energy Information Administration (EIA). WTI is the spot price freight on board (FOB) at Cushing, Oklahoma. Brent is the Europe Brent Spot Price FOB.
Figure 2: Permian Production and Takeaway Capacity

Source: Production is the EIA’s Permian Basin region’s production. Refinery capacities of the Permian Basin are of Big Spring and El Paso in Texas, and Navajo in New Mexico. Both are from the EIA. The pipeline takeaway capacities of local refineries are from RBN Energy.
Figure 3: Crude Transportation Modes from PADD2 to PADD3

Source: The percentages are based on EIA data on Movements of Crude Oil and Selected Products by Pipeline, Tanker, and Rail.
Figure 4: Monthly Inventory and Exports

Source: Inventory and Export data are from the EIA. The dotted vertical lines represent the two breakpoints we identify.
Figure 5: Brent-WTI Differentials

Source: Brent-WTI differentials are based on the spot FOB prices from Figure 1. The dotted vertical lines represent the two breakpoints we identify.
Figure 6: PADD Map

Source: EIA