Online appendix
Closer to one great pool? Evidence from structural breaks in oil price differentials

Michael Plante[*] *and Grant Strickler*[**]

ABSTRACT

This online appendix contains additional information and results.
Keywords: crude oil price differentials, oil, structural breaks, refining

A. OIL PRICE DATA

Algerian Saharan - HAVER Mnemonic Q830AGS@OGJ. API gravity of 44.0 and sulfur content of 0.1, as reported in OPEC Annual Statistical Bulletins. HAVER reports the original source as OPEC.
Bonny Light - HAVER Mnemonic Q830NGBL@OGJ. API gravity of 36.7 and sulfur content of 0.1, as reported in OPEC Annual Statistical Bulletins.
Brent - Bloomberg Ticker EUCRBRDT. Bloomberg states the API gravity is greater than 35 while sulfur content is less than 1 percent. The paper reports API gravity and sulfur content from Platts. This price is FOB at Sullom Voe terminal in the Shetland Islands, UK.
Dubai - Bloomberg Ticker PGCRDUBA. API gravity of 31, sulfur content 1.7. This is FOB at Dubai, UAE.
Heavy Louisiana Sweet - Bloomberg Ticker USCRHLSE. API gravity of 33.7, sulfur content 0.39. This is a spot price at Empire, LA and is FOB.
Louisiana Light Sweet - Bloomberg Ticker USCRLLS. API gravity of 35.7, sulfur content 0.44. This is a spot price at St. James, LA and is FOB.
Mars - Bloomberg Ticker USCRHLSE. API gravity of 33.7, sulfur content 0.39. This is a spot price at Empire, LA and is FOB.
Maya - Bloomberg Ticker LACRMAUS. API gravity of 21.1, sulfur content 3.38. Price is derived from the formula for Maya sales to the U.S. Gulf Coast: [0.4*(WTS+3.5% Fuel Oil)] + [0.1*(LLS + Dated Brent)]. Price is FOB.
Oman - Bloomberg Ticker PGCROMAN. API gravity of 33, sulfur content 1.11. This is FOB at Muscat, Oman.
Saudi Heavy - Bloomberg Tickers PGCRAHUS, PGCRAHEU, and PGCRARHV for US, Europe and Asia, respectively. API gravity of 27, sulfur content 2.8. Asia price is FOB at Yanbu or Ras Tanura.
Tapis-Bloomberg Ticker APCRTAPI. API gravity of 44.6 and sulfur content of 0.028. Loading port is reported as Kertih, Malaysia.
Urals-HAVER Mnemonic is P922URL@INTDAILY for daily and Q830URU@OGJ for monthly. API gravity of 31.7, sulfur content 1.35. HAVER reports the original source for monthly data as OPEC.

[*]Corresponding author. Federal Reserve Bank of Dallas. Send correspondence to 2200 N Pearl Street, Dallas, TX 75201. E-mail: michael.plante@dal.frb.org.
[**]Federal Reserve Bank of Dallas.

WTI Cushing-Bloomberg Ticker USCRWTIC. API gravity of 39, sulfur content 0.34. This is a spot price at Cushing, OK and is FOB.
WTI Midland-Bloomberg Ticker USCRWTIM. API gravity of 39, sulfur content 0.34. This is a spot price at Midland, TX and is FOB.
West Texas Sour-Bloomberg Ticker USCRWTSM API gravity 34, sulfur content 1.9. This is a spot price at Midland, TX and is FOB.

B. SUMMARY STATISTICS FOR DAILY DATA

Table 1 shows some summary statistics for the series, based on a common sample starting from 1997 onwards.[1] In line with the previous literature, we find that the differentials are typically larger for those pairs of crude streams that are further apart in terms of API gravity and sulfur content.[2] For example, the mean differential between LLS and HLS was only 1.5 percent while it was almost 23 percent for the LLS-Maya differential.

We also find that the greater the differences in API gravity and sulfur content, the more volatile the differential tends to be. One potential explanation for this is that the degree of substitutability between any two grades of crude is inversely related to the quality differences of those crudes. For example, LLS and HLS are quite similar and as a result should be highly substitutable for each other in the refining complex in the USGC (and elsewhere). This should ensure that their prices generally do not deviate too far from one another, minimizing volatility in the percent-differential. On the other hand, LLS and Maya are very different from each other and refiners who prefer to process one over the other are likely to be hesitant to switch back and forth over short periods of time. This could require large price swings to clear the market, which would lead to volatile differentials.

Table 2 presents summary statistics for the across-area differentials. The upper panel shows the summary statistics for differentials between crudes of different types, the lower panel for same types. In general, the statistics are similar in nature to the within-area differentials. On average, we find that the means are greater for those pairs of crudes with larger differences in their API gravity and sulfur content. However, a few differentials do not exhibit this property. The LLS and HLS differentials with Brent are both positive while the two WTI-LLS differentials have negative means.

[1] Summary statistics for the full samples are available from the authors. They are generally not very different from the results in the table.
[2] See, for example, Bacon and Tordo (2005) and Giulietti et al. (2015).

Table 1: Oil price differentials within areas

Differential	API difference	Sulfur difference	Mean	Standard deviation
Midland, TX				
WTIM-WTS	5.0	-1.56	0.046	0.042
U.S. Gulf Coast				
LLS-HLS	2.0	0.05	0.015	0.016
LLS-Mars	6.8	-1.61	0.108	0.061
LLS-Maya	14.6	-2.94	0.227	0.109
HLS-Mars	4.8	-1.66	0.094	0.056
HLS-Maya	12.6	-2.99	0.212	0.102
Mars-Maya	7.8	-1.33	0.118	0.064
Europe / Atlantic Basin				
Brent-Urals	6.6	-1.03	0.043	0.036
Brent-SHE	11.1	-2.39	0.138	0.091
Urals-SHE	4.5	-1.36	0.078	0.060
Middle East / Asia				
Tapis-Oman	11.6	-1.07	0.093	0.053
Tapis-Dubai	13.6	-1.67	0.103	0.055
Tapis-SHA	17.6	-2.77	0.157	0.090
Oman-Dubai	2.0	-0.60	0.010	0.020
Oman-SHA	6.0	-1.70	0.063	0.058
Dubai-SHA	4.0	-1.10	0.053	0.056

Notes: These statistics are based on a sample from January 1997 to December 2018. For Brent-Urals, the sample runs from January 2002 to November 2013.

Table 2: Oil price differentials across areas

Crudes of different type				
Differential	API difference	Sulfur difference	Mean	Standard deviation
Light-medium differentials				
Tapis-Urals	13.1	-1.41	0.099	0.049
Tapis-Mars	15.7	-2.02	0.125	0.061
Brent-Oman	5.1	-0.69	0.040	0.044
Brent-Dubai	7.1	-1.29	0.050	0.047
Brent-Mars	9.2	-1.64	0.072	0.046
LLS-Oman	2.7	-0.66	0.078	0.066
LLS-Urals	4.2	-1.00	0.080	0.059
LLS-Dubai	4.7	-1.26	0.087	0.069
HLS-Oman	0.7	-0.71	0.062	0.062
HLS-Urals	2.2	-1.05	0.065	0.052
HLS-Dubai	2.7	-1.31	0.072	0.065
Light-heavy differentials				
Tapis-Maya	23.5	-3.35	0.244	0.098
Brent-Maya	17	-2.97	0.190	0.086
Medium-heavy differentials				
Oman-Maya	11.9	-2.28	0.150	0.075
Urals-Maya	10.4	-1.94	0.129	0.060
Dubai-Maya	9.9	-1.68	0.141	0.077
Crudes of similar type				
Light-light differentials				
WTIC-LLS	3.3	-0.10	-0.040	0.059
WTIM-LLS	3.3	-0.10	-0.057	0.076
LLS-Tapis	-8.9	0.41	-0.016	0.050
LLS-Brent	-2.4	0.03	0.037	0.045
HLS-Tapis	-10.9	0.36	-0.031	0.048
HLS-Brent	-4.4	-0.02	0.022	0.042
Medium-medium differentials				
Oman-Urals	1.5	-0.34	0.001	0.035
Oman-Mars	4.1	-0.95	0.032	0.049
Urals-Dubai	0.5	-0.26	0.011	0.034
Urals-Mars	2.6	-0.61	0.016	0.037
Dubai-Mars	2.1	-0.35	0.022	0.053

Notes: These statistics are based on a sample from January 1997 to December 2018.
For Urals differentials, the sample runs from January 2002 to November 2013.

C. UNIT ROOT TESTS USING DAILY DATA

In this section of the appendix we present a full set of results for the unit root tests that use daily data. Results for the unit root tests using monthly data are presented later.

Previous works in the literature have tested for the stationarity of oil price differentials using unit root tests, for example Fattouh (2010), Giulietti et al. (2015) and Agerton and Upton (2019). As discussed in Perron (1989) and many papers since then, the structural breaks identified in the paper can bias the results one gets from such tests. *A priori*, our expectation is that the differentials should be stationary once we have taken into account structural breaks. Our reasoning behind this expectation is similar to the logic of the previous literature (and the law of one price literature): arbitrage across locations and across types of oil should prevent a differential from becoming exceptionally large in either direction for significant periods of time. However, changes in the nature of that arbitrage could generate breaks of the type we have documented, and not taking them into account could lead to the appearance of non-stationarity.

Our procedure to test for unit roots is straight forward. We run an Augmented Dickey Fuller (ADF) test on each differential, considering cases where the optimal lag length is chosen using the SIC. We then perform an ADF breakpoint unit root test which searches for the break that minimizes the intercept break t-statistic, trimming 15 percent of the sample. A differential is flagged by us any time one of the tests fails to reject the null of a unit root at the 1 percent significance level.

The results are reported in Tables 3 and 4. We find that the null of a unit root is strongly rejected in all cases when using the breakpoint unit root test. Even when using the standard ADF test, we find only two quality differentials where the null is not rejected and both of those use the Urals data, for which we have a much smaller sample.

Table 3: Unit root test results for daily data

	SIC	
Differential	ADF	ADF (BP)
WTIM-WTS	-4.48	-9.80
	(<0.01)	(<0.01)
LLS-HLS	-9.34	-10.87
	(<0.01)	(<0.01)
LLS-Mars	-4.66	-8.14
	(<0.01)	(<0.01)
LLS-Maya	-3.51	-5.66
	(<0.01)	<(0.01)
HLS-Mars	-4.94	-7.82
	(<0.01)	<(0.01)
HLS-Maya	-4.14	-6.23
	(<0.01)	(<0.01)
Mars-Maya	-6.07	-8.83
	(<0.01)	<0.01
Brent-Urals	-4.11	-7.29
	(<0.01)	(<0.01)
Brent-SHE	-5.41	-8.20
	(<0.01)	(<0.01)
Urals-SHE	-8.54	-11.09
	(<0.01)	(<0.01)
Tapis-Oman	-7.06	-8.45
	(<0.01)	(<0.01)
Tapis-Dubai	-6.83	-8.47
	(<0.01)	(<0.01)
Tapis-SHA	-5.60	-6.39
	(<0.01)	(<0.01)
Oman-Dubai	-4.81	-6.83
	(<0.01)	(<0.01)
Oman-SHA	-5.33	-5.93
	(<0.01)	(<0.01)
Dubai-SHA	-5.67	-7.20
	(<0.01)	(<0.01)

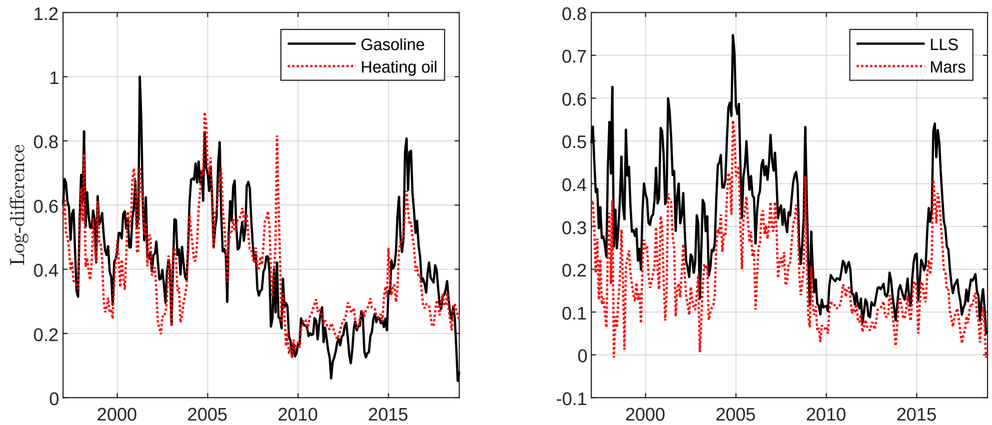
Notes: For each differential, the first row shows the test statistics for the Augmented Dickey-Fuller (ADF) and the ADF breakpoint (ADF BP) tests. The second row shows the p-value for the test. Bold text identifies a case where the null of a unit root would not be rejected at a one percent significance level.

Table 4: Unit root test results for daily data

	SIC	
Differential	ADF	ADF (BP)
Tapis-Urals	-6.09	-7.97
	(<0.01)	(<0.01)
Tapis-Mars	-7.97	-11.42
	(<0.01)	(<0.01)
Brent-Oman	-9.04	-9.75
	(<0.01)	(<0.01)
Brent-Dubai	-7.92	-9.31
	(<0.01)	(<0.01)
Brent-Mars	-11.25	-12.05
	(<0.01)	(<0.01)
LLS-Oman	-5.42	-6.25
	(<0.01)	(<0.01)
LLS-Urals	**-3.02**	-8.36
	(0.03)	(<0.01)
LLS-Dubai	-4.93	-6.23
	(<0.01)	(<0.01)
HLS-Oman	-6.35	-10.85
	(<0.01)	(<0.01)
HLS-Urals	**-2.71**	-9.44
	(0.07)	(<0.01)
HLS-Dubai	-5.80	-10.78
	(<0.01)	(<0.01)
Tapis-Maya	-5.46	-7.12
	(<0.01)	(<0.01)
Brent-Maya	-5.14	-6.98
	(<0.01)	(<0.01)
Oman-Maya	-7.08	-8.43
	(<0.01)	(<0.01)
Urals-Maya	-6.03	-6.63
	(<0.01)	(<0.01)
Dubai-Maya	-6.88	-8.07
	(<0.01)	(<0.01)
WTIC-LLS	-3.91	-6.25
	(<0.01)	(<0.01)
WTIM-LLS	**-3.30**	-5.57
	(0.02)	(<0.01)
LLS-Tapis	-9.54	-12.56
	(<0.01)	(<0.01)
HLS-Tapis	-12.06	-13.66
	(<0.01)	(<0.01)
LLS-Brent	-4.95	-13.40
	(<0.01)	(<0.01)
HLS-Brent	-6.17	-14.45
	(<0.01)	(<0.01)
Oman-Urals	-8.44	-10.93
	(<0.01)	(<0.01)
Oman-Mars	-12.60	-13.04
	(<0.01)	(<0.01)
Urals-Dubai	-8.85	-9.59
	(<0.01)	(<0.01)
Urals-Mars	-6.46	-10.57
	(<0.01)	(<0.01)
Dubai-Mars	-9.18	-12.91
	(<0.01)	(<0.01)

Notes: For each differential, the first row shows the test statistics for the Augmented Dickey-Fuller (ADF) and the ADF breakpoint (ADF BP) tests. The second row shows the p-value for the test. Bold text identifies a case where the null of a unit root would not be rejected at a one percent significance level.

Figure 1: Residual fuel oil differentials



Notes: Figure plots log-differentials of spot prices for gasoline, heating oil, LLS and Mars relative to high sulfur fuel oil in the U.S. Gulf Coast using monthly data from January 1997 to December 2018.

D. RESIDUAL FUEL OIL DIFFERENTIAL CHART

We calculated differentials between the monthly average spot price of high-sulfur residual fuel oil and the following spot prices, all for delivery in the Gulf Coast: heating oil, gasoline, LLS and Mars. Since residual fuel oil is the low-quality product, its price is always in the denominator. Figure 1 plots the monthly time series of these differentials since 1997. The left panel shows the heating oil and gasoline differentials to fuel oil, while the right shows the differentials involving crude oil. There is remarkable similarity between these and many of the differentials plotted in the first figure of the paper. We note here that this is not just a Gulf Coast phenomenon: the chart looks very similar if one uses product prices for New York Harbor and replaces LLS and Mars prices with Brent and Dubai.

Table 5: Oil price series

Name	API gravity	Sulfur	API category	Sulfur category
Cushing, OK				
WTI Cushing (WTIC)	39.0	0.34	Light	Sweet
Midland, TX				
WTI Midland (WTIM)	39.0	0.34	Light	Sweet
West Texas Sour (WTS)	34.0	1.90	Light	Sour
U.S. Gulf Coast (USGC)				
Heavy Louisiana Sweet (HLS)	33.7	0.39	Light	Sweet
Louisiana Light Sweet (LLS)	35.7	0.44	Light	Sweet
Mars	28.9	2.05	Medium	Sour
Maya	21.1	3.38	Heavy	Sour
Saudi Heavy to US (SHU)	27.0	2.80	Medium	Sour
Europe/Atlantic Basin				
Algerian Saharan (Saharan)	44.0	0.10	Light	Sweet
Bonny Light (Bonny)	36.7	0.10	Light	Sweet
Brent	38.1	0.41	Light	Sweet
Saudi Heavy to Europe (SHE)	27.0	2.80	Medium	Sour
Urals	31.5	1.44	Medium	Sour
Middle East/Asia				
Dubai	31.0	1.70	Medium	Sour
Oman	33.0	1.10	Medium	Sour
Saudi Heavy to Asia (SHA)	27.0	2.80	Medium	Sour
Tapis	44.6	0.03	Light	Sweet

E. ADDITIONAL RESULTS USING MONTHLY DATA

In this section, we present results based on monthly data which includes a larger set of crude oil prices. Table 5 lists all of the crude oils considered plus their properties. The additional crude oils are Algerian Saharan, Bonny Light, and Saudi Arabian Heavy for the US. We only consider within-area differentials using the relevant Saudi Heavy price for each area. Summary statistics for the within-area and across-area differentials are presented in Tables 6 and 7, respectively.

We report breakpoint results for crude oils of different quality in Tables 8 and 9. For the breakpoint test we set the trimming parameter to 0.15, which sets the minimum regime length at roughly 3 years. The procedure used to estimate the long-run variance-covariance matrix is the same as with the daily data. We report results for a statistical significance of 5 percent. We have chosen to be somewhat less restrictive with the monthly data as we have significantly few observations but the results are not overly sensitive to choosing a more stringent level of significance. The evolution of the means can be found in Tables 10, 11, and 12. Summary statistics pre and post-break can be found in 13. Unit root test results are shown in Tables 14 and 15.

Table 6: Oil price differentials within areas

Differential	API difference	Sulfur difference	Mean	Standard deviation
Midland, TX				
WTIM-WTS	5.0	-1.56	0.046	0.040
U.S. Gulf Coast				
LLS-HLS	2.0	0.05	0.015	0.014
LLS-Mars	6.8	-1.61	0.110	0.059
LLS-SHU	8.7	-2.36	0.195	0.115
LLS-Maya	14.6	-2.94	0.230	0.107
HLS-Mars	4.8	-1.66	0.094	0.054
HLS-SHU	6.7	-2.41	0.180	0.109
HLS-Maya	12.6	-2.99	0.213	0.100
Mars-SHU	1.9	-0.75	0.086	0.069
Mars-Maya	7.8	-1.33	0.120	0.060
SHU-Maya	5.9	-0.58	0.032	0.056
Europe / Atlantic Basin				
Saharan-Brent	5.9	-0.31	0.009	0.015
Saharan-Bonny	7.4	0.00	-0.004	0.016
Saharan-Urals	12.5	-1.34	0.050	0.037
Saharan-SHE	17.0	-2.70	0.147	0.091
Brent-Bonny	1.4	0.31	-0.013	0.016
Brent-Urals	6.6	-1.03	0.040	0.035
Brent-SHE	11.1	-2.39	0.138	0.087
Bonny-Urals	5.2	-1.34	0.053	0.036
Bonny-SHE	9.7	-2.70	0.151	0.083
Urals-SHE	4.5	-1.36	0.098	0.070
Middle East / Asia				
Tapis-Oman	11.6	-1.07	0.093	0.049
Tapis-Dubai	13.6	-1.67	0.103	0.051
Tapis-SHA	17.6	-2.77	0.157	0.086
Oman-Dubai	2.0	-0.60	0.010	0.018
Oman-SHA	6.0	-1.70	0.063	0.056
Dubai-SHA	4.0	-1.10	0.053	0.053

Notes: These statistics are based on a sample from January 1997 to December 2018.

Table 7: Oil price differentials across areas

Differential	API difference	Sulfur difference	Mean	Standard deviation
Crudes of different type				
Light-medium differentials				
Tapis-Urals	13.1	-1.41	0.093	0.053
Tapis-Mars	15.7	-2.02	0.126	0.053
Saharan-Oman	11.0	-1.00	0.049	0.043
Saharan-Dubai	13.0	-1.60	0.059	0.045
Saharan-Mars	15.1	-1.95	0.081	0.046
Brent-Oman	5.1	-0.69	0.040	0.038
Brent-Dubai	7.1	-1.29	0.050	0.041
Brent-Mars	9.2	-1.64	0.072	0.041
Bonny-Oman	3.7	-1.00	0.053	0.039
Bonny-Dubai	5.7	-1.60	0.063	0.041
Bonny-Mars	7.8	-1.95	0.085	0.041
LLS-Oman	2.7	-0.66	0.077	0.062
LLS-Urals	4.2	-1.0	0.077	0.066
LLS-Dubai	4.7	-1.26	0.087	0.065
HLS-Oman	0.7	-0.71	0.062	0.057
HLS-Urals	2.2	-1.05	0.062	0.059
HLS-Dubai	2.7	-1.31	0.072	0.060
Light-heavy differentials				
Tapis-Maya	23.5	-3.35	0.244	0.094
Saharan-Maya	22.9	-3.28	0.199	0.089
Brent-Maya	17.0	-2.97	0.191	0.084
Bonny-Maya	15.6	-3.28	0.204	0.082
Medium-heavy differentials				
Oman-Maya	11.9	-2.28	0.151	0.070
Urals-Maya	10.4	-1.94	0.151	0.070
Dubai-Maya	9.9	-1.68	0.141	0.072
Crudes of similar type				
Light-light differentials				
WTIC-LLS	3.3	-0.10	-0.040	0.058
WTIM-LLS	3.3	-0.10	-0.057	0.074
LLS-Tapis	-8.9	0.41	-0.016	0.043
LLS-Saharan	-8.3	0.34	0.028	0.040
LLS-Brent	-2.4	0.03	0.037	0.041
LLS-Bonny	-1.0	0.34	0.024	0.047
HLS-Tapis	-10.9	0.36	-0.031	0.040
HLS-Saharan	-10.3	0.29	0.014	0.036
HLS-Brent	-4.4	-0.02	0.022	0.037
HLS-Bonny	-3.0	0.29	0.009	0.042
Medium-medium differentials				
Oman-Urals	1.5	-0.34	0.000	0.034
Oman-Mars	4.1	-0.95	0.032	0.039
Urals-Dubai	0.5	-0.26	0.010	0.036
Urals-Mars	2.6	-0.61	0.032	0.044
Dubai-Mars	2.1	-0.35	0.022	0.044

Notes: These statistics are based on a sample from January 1997 to December 2018.

Table 8: Breakpoint test results for crudes of different qualities

Part 1: Within-area differentials

Differential	Break 1	Break 2	Break 3	F-statistic 0 vs. 1	1 vs. 2	2 vs. 3
Midland, TX						
WTIM-WTS	11/2007	02/2013	-	115.19	10.22	-
U.S. Gulf Coast						
LLS-Mars	01/2009	12/2001	-	43.47	23.30	-
LLS-SHU	05/2006	09/2009	02/2002	32.53	17.98	15.45
LLS-Maya	05/2007	-	-	61.36	-	-
HLS-Mars	04/2008	12/2001	-	37.87	15.62	-
HLS-SHU	05/2005	02/2009	02/2002	31.53	31.28	14.01
HLS-Maya	05/2007	-	-	63.43	-	-
Mars-Maya	04/2007	-	-	41.97	-	-
SHU-Maya	09/2000	-	-	9.11	-	-
Europe/Atlantic Basin						
Saharan-Urals	06/2008	-	-	46.03	-	-
Saharan-SHE	06/2007	-	-	14.93	-	-
Brent-Urals	06/2008	-	-	31.96	-	-
Brent-SHE	02/2007	-	-	16.43	-	-
Bonny-Urals	10/2007	01/2004	-	33.93	13.27	-
Bonny-SHE	07/2007	-	-	14.97	-	-
Middle East/Asia						
Tapis-Oman	04/2008	-	-	14.01	-	-
Tapis-Dubai	04/2008	-	-	21.03	-	-
Tapis-SHA	02/2009	-	-	10.07	-	-

Part 2: Across-area differentials

Differential	Break 1	Break 2	Break 3	F-statistic 0 vs. 1	1 vs. 2	2 vs. 3
Light-medium						
Tapis-Urals	05/2008	07/2012	-	30.10	11.68	-
Tapis-Mars	01/2008	04/2011	-	15.37	10.93	-
Saharan-Oman	04/2008	-	-	15.67	-	-
Saharan-Dubai	04/2008	-	-	21.93	-	-
Saharan-Mars	01/2002	-	-	11.72	-	-
Brent-Oman	04/2008	-	-	11.10	-	-
Brent-Dubai	04/2008	-	-	12.95	-	-
Brent-Mars#	01/2008	08/2013	-	7.02	32.04	-
Bonny-Oman#	06/2004	04/2008	-	7.18	15.96	-
Bonny-Dubai	06/2008	-	-	10.67	-	-
Bonny-Mars#	04/2008	07/2013	-	5.88	19.94	-
LLS-Oman	11/2008	-	-	47.92	-	-
LLS-Urals	05/2009	-	-	51.09	-	-
LLS-Dubai	12/2008	04/2005	-	45.17	13.59	-
HLS-Oman	10/2008	-	-	48.43	-	-
HLS-Urals	03/2007	04/2012	-	57.55	16.50	-
HLS-Dubai	10/2008	03/2005	-	48.57	16.74	-
Light-heavy						
Tapis-Maya	05/2007	-	-	34.67	-	-
Saharan-Maya	07/2007	-	-	29.95	-	-
Bonny-Maya	07/2007	-	-	26.37	-	-
Brent-Maya	05/2007	-	-	31.47	-	-
Medium-heavy						
Oman-Maya	05/2007	-	-	23.18	-	-
Dubai-Maya	03/2002	-	-	13.30	-	-
Urals-Maya	02/2002	-	-	14.53	-	-

Notes: Dates refer to the last month of a given regime. The order of the breaks is determined by the test. The critical values are 8.58, 10.13 and 11.14 for tests of 0 or 1 break, 1 or 2 breaks, and 2 or 3 breaks, respectively. These reflect a significance level of 5 percent. #: The test rejects the null of 1 break vs. 2 but fails to reject the null of 0 vs. 1.

Table 9: Breakpoint test results for crudes of similar type

Part 1: Within-area differentials

Differential	Break 1	Break 2	Break 3	Break 4	F-statistic 0 vs. 1	1 vs. 2	2 vs. 3	3 vs. 4
U.S. Gulf Coast								
LLS-HLS	01/2011	06/2014	-	-	11.80	14.65	-	-
Mars-SHU	02/2002	12/2009	-	-	25.76	31.48	-	-
Europe/Atlantic Basin								
Saharan-Brent	05/2000	-	-	-	27.93	-	-	-
Saharan-Bonny	12/2001	-	-	-	64.88	-	-	-
Brent-Bonny	03/2005	07/2014	-	-	18.77	32.24	-	-
Urals-SHE	01/2001	-	-	-	13.55	-	-	-
Middle East / Asia								
Oman-Dubai	-	-	-	-	-	-	-	-
Oman-SHA	-	-	-	-	-	-	-	-
Dubai-SHA	-	-	-	-	-	-	-	-

Part 2: Across-area differentials

Differential	Break 1	Break 2	Break 3	Break 4	F-statistic 0 vs. 1	1 vs. 2	2 vs. 3	3 vs. 4
Light-light								
WTIC-LLS	04/2010	11/2006	04/2001	07/2013	10.92	100.91	22.73	14.05
WTIM-LLS	01/2011	10/2006	04/2014	04/2001	14.58	243.76	30.84	12.53
LLS-Tapis	01/2005	-	-	-	35.71	-	-	-
LLS-Saharan	12/2010	02/2005	-	-	45.90	18.70	-	-
LLS-Brent	05/2011	12/2004	-	-	50.11	22.28	-	-
LLS-Bonny	02/2005	03/2011	-	-	56.57	16.17	-	-
HLS-Tapis	04/2004	-	-	-	38.41	-	-	-
HLS-Saharan	12/2004	07/2013	-	-	52.33	19.68	-	-
HLS-Brent	12/2004	07/2013	-	-	45.47	33.25	-	-
HLS-Bonny	01/2005	-	-	-	87.49	-	-	-
Medium-medium								
Oman-Mars#	01/2002	08/2013	-	-	8.58	26.69	-	-
Urals-Mars	07/2013	01/2002	10/2005	-	- 17.50	11.38	11.67	-
Dubai-Mars	08/2013	-	-	-	11.92	-	-	-
Oman-Urals	06/2010	-	-	-	10.97	-	-	-
Urals-Dubai	-	-	-	-	-	-	-	-

Notes: Dates refer to the last month of a given regime. The order of the breaks is determined by the test. The critical values are 8.58, 10.13, 11.14 and 11.83 for tests of 0 or 1 break, 1 or 2 breaks, 2 or 3 breaks, and 3 or 4 breaks, respectively. These reflect a significance level of 5 percent. #: The test rejects the null of 1 break vs. 2 but fails to reject the null of 0 vs. 1.

Table 10: Regression constant across regimes for crudes of different types

Within-area differentials

<table>
<tr><th>Differential</th><th>97</th><th>98</th><th>99</th><th>00</th><th>01</th><th>02</th><th>03</th><th>04</th><th>05</th><th>06</th><th>07</th><th>08</th><th>09</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>Change</th></tr>
<tr><td>WTIM-WTS</td><td colspan="11">0.080</td><td colspan="5">0.025</td><td colspan="6">0.003*</td><td>-0.077</td></tr>
<tr><td>LLS-Mars</td><td colspan="5">0.179</td><td colspan="7">0.126</td><td colspan="10">0.062</td><td>-0.117</td></tr>
<tr><td>HLS-Mars</td><td colspan="5">0.161</td><td colspan="6">0.108</td><td colspan="11">0.055</td><td>-0.106</td></tr>
<tr><td>LLS-Maya</td><td colspan="10">0.312</td><td colspan="12">0.151</td><td>-0.161</td></tr>
<tr><td>HLS-Maya</td><td colspan="10">0.292</td><td colspan="12">0.142</td><td>-0.150</td></tr>
<tr><td>LLS-SHU</td><td colspan="5">0.343</td><td colspan="4">0.240</td><td colspan="4">0.167</td><td colspan="9">0.102</td><td>-0.241</td></tr>
<tr><td>HLS-SHU</td><td colspan="5">0.325</td><td colspan="3">0.223</td><td colspan="4">0.168</td><td colspan="10">0.095</td><td>-0.230</td></tr>
<tr><td>SHU-Maya</td><td colspan="4">-0.018*</td><td colspan="18">0.043</td><td>0.061</td></tr>
<tr><td>Mars-Maya</td><td colspan="10">0.158</td><td colspan="12">0.083</td><td>-0.075</td></tr>
<tr><td>Saharan-Urals</td><td colspan="11">0.073</td><td colspan="11">0.023</td><td>-0.050</td></tr>
<tr><td>Saharan-SHE</td><td colspan="10">0.208</td><td colspan="12">0.091</td><td>-0.117</td></tr>
<tr><td>Brent-Urals</td><td colspan="12">0.061</td><td colspan="10">0.018</td><td>-0.043</td></tr>
<tr><td>Brent-SHE</td><td colspan="10">0.198</td><td colspan="12">0.087</td><td>-0.111</td></tr>
<tr><td>Bonny-Urals</td><td colspan="7">0.055</td><td colspan="4">0.103</td><td colspan="11">0.035</td><td>-0.020</td></tr>
<tr><td>Bonny-SHE</td><td colspan="11">0.204</td><td colspan="11">0.101</td><td>-0.103</td></tr>
<tr><td>Tapis-Oman</td><td colspan="11">0.117</td><td colspan="11">0.069</td><td>-0.048</td></tr>
<tr><td>Tapis-Dubai</td><td colspan="11">0.131</td><td colspan="11">0.074</td><td>-0.057</td></tr>
<tr><td>Tapis-SHA</td><td colspan="12">0.195</td><td colspan="10">0.109</td><td>-0.086</td></tr>
</table>

Notes: Change is the difference between the final regime and the first regime for each regression equation. A * means the coefficient is not statistically different from 0 at a 5 percent confidence level. In the table, breaks that occur from July to December in a particular year are assigned to the following year.

Table 11: Regression constant across regimes for crudes of different types

Across-area: Light-medium

<table>
<tr><th>Differential</th><th>97</th><th>98</th><th>99</th><th>00</th><th>01</th><th>02</th><th>03</th><th>04</th><th>05</th><th>06</th><th>07</th><th>08</th><th>09</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>Change</th></tr>
<tr><td>Tapis-Urals</td><td colspan="11">0.122</td><td colspan="5">0.074</td><td colspan="6">0.055</td><td>-0.067</td></tr>
<tr><td>Tapis-Mars</td><td colspan="11">0.150</td><td colspan="3">0.080</td><td colspan="8">0.110</td><td>-0.040</td></tr>
<tr><td>Saharan-Oman</td><td colspan="11">0.067</td><td colspan="11">0.029</td><td>-0.038</td></tr>
<tr><td>Saharan-Dubai</td><td colspan="11">0.082</td><td colspan="11">0.035</td><td>-0.047</td></tr>
<tr><td>Saharan-Mars</td><td colspan="5">0.121</td><td colspan="17">0.069</td><td>-0.052</td></tr>
<tr><td>Brent-Oman</td><td colspan="11">0.055</td><td colspan="11">0.024</td><td>-0.031</td></tr>
<tr><td>Brent-Dubai</td><td colspan="11">0.069</td><td colspan="11">0.030</td><td>-0.039</td></tr>
<tr><td>Brent-Mars</td><td colspan="11">0.088</td><td colspan="6">0.033</td><td colspan="5">0.080</td><td>-0.008</td></tr>
<tr><td>Bonny-Oman</td><td colspan="8">0.048</td><td colspan="4">0.099</td><td colspan="10">0.040</td><td>-0.008</td></tr>
<tr><td>Bonny-Dubai</td><td colspan="12">0.080</td><td colspan="10">0.045</td><td>-0.035</td></tr>
<tr><td>Bonny-Mars</td><td colspan="11">0.098</td><td colspan="6">0.054</td><td colspan="5">0.089</td><td>-0.009</td></tr>
<tr><td>LLS-Oman</td><td colspan="12">0.117</td><td colspan="10">0.030</td><td>-0.087</td></tr>
<tr><td>LLS-Urals</td><td colspan="12">0.121</td><td colspan="10">0.020</td><td>-0.101</td></tr>
<tr><td>LLS-Dubai</td><td colspan="8">0.143</td><td colspan="4">0.100</td><td colspan="10">0.035</td><td>-0.108</td></tr>
<tr><td>HLS-Oman</td><td colspan="12">0.098</td><td colspan="10">0.021</td><td>-0.077</td></tr>
<tr><td>HLS-Urals</td><td colspan="10">0.108</td><td colspan="5">0.047</td><td colspan="7">0.003*</td><td>-0.105</td></tr>
<tr><td>HLS-Dubai</td><td colspan="8">0.124</td><td colspan="4">0.083</td><td colspan="10">0.027</td><td>-0.097</td></tr>
</table>

Across-area: Light-heavy

<table>
<tr><th>Differential</th><th>97</th><th>98</th><th>99</th><th>00</th><th>01</th><th>02</th><th>03</th><th>04</th><th>05</th><th>06</th><th>07</th><th>08</th><th>09</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>Change</th></tr>
<tr><td>Tapis-Maya</td><td colspan="12">0.308</td><td colspan="10">0.189</td><td>-0.119</td></tr>
<tr><td>Saharan-Maya</td><td colspan="11">0.258</td><td colspan="11">0.146</td><td>-0.112</td></tr>
<tr><td>Brent-Maya</td><td colspan="11">0.246</td><td colspan="11">0.141</td><td>-0.105</td></tr>
<tr><td>Bonny-Maya</td><td colspan="11">0.255</td><td colspan="11">0.156</td><td>-0.099</td></tr>
</table>

Across-area: Medium-heavy

<table>
<tr><th>Differential</th><th>97</th><th>98</th><th>99</th><th>00</th><th>01</th><th>02</th><th>03</th><th>04</th><th>05</th><th>06</th><th>07</th><th>08</th><th>09</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>Change</th></tr>
<tr><td>Oman-Maya</td><td colspan="10">0.192</td><td colspan="12">0.113</td><td>-0.079</td></tr>
<tr><td>Dubai-Maya</td><td colspan="5">0.209</td><td colspan="17">0.119</td><td>-0.089</td></tr>
<tr><td>Urals-Maya</td><td colspan="5">0.219</td><td colspan="17">0.130</td><td>-0.089</td></tr>
</table>

Notes: Change is the difference between the final regime and the first regime for each regression equation. A * means the coefficient is not statistically different from 0 at a 5 percent confidence level. In the table, breaks that occur from July to December in a particular year are assigned to the following year.

Table 12: Regression constant across regimes for crudes of the same type

<table>
<tr><td colspan="24">Light-light differentials</td></tr>
<tr><td>Differential</td><td>97</td><td>98</td><td>99</td><td>00</td><td>01</td><td>02</td><td>03</td><td>04</td><td>05</td><td>06</td><td>07</td><td>08</td><td>09</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>Change</td></tr>
<tr><td>WTIC-LLS</td><td colspan="4">0.008*</td><td colspan="6">-0.005</td><td colspan="3">-0.038</td><td colspan="4">-0.139</td><td colspan="5">-0.055</td><td>-0.050</td></tr>
<tr><td>WTIM-LLS</td><td colspan="4">-0.005</td><td colspan="6">-0.011</td><td colspan="4">-0.042</td><td colspan="3">-0.164</td><td colspan="5">-0.097</td><td>-0.092</td></tr>
<tr><td>LLS-HLS</td><td colspan="14">0.019</td><td colspan="4">-0.002*</td><td colspan="4">0.012</td><td>-0.007</td></tr>
<tr><td>LLS-Tapis</td><td colspan="8">0.015</td><td colspan="14">-0.035</td><td>-0.050</td></tr>
<tr><td>LLS-Saharan</td><td colspan="8">0.062</td><td colspan="6">0.029</td><td colspan="8">-0.008*</td><td>-0.070</td></tr>
<tr><td>LLS-Brent</td><td colspan="8">0.074</td><td colspan="6">0.039</td><td colspan="8">-0.005*</td><td>-0.079</td></tr>
<tr><td>LLS-Bonny</td><td colspan="8">0.070</td><td colspan="6">0.015</td><td colspan="8">-0.018*</td><td>-0.088</td></tr>
<tr><td>HLS-Tapis</td><td colspan="7">-0.002*</td><td colspan="15">-0.045</td><td>-0.043</td></tr>
<tr><td>HLS-Saharan</td><td colspan="8">0.044</td><td colspan="9">0.008</td><td colspan="5">-0.022</td><td>-0.066</td></tr>
<tr><td>HLS-Brent</td><td colspan="8">0.056</td><td colspan="9">0.017</td><td colspan="5">-0.019</td><td>-0.075</td></tr>
<tr><td>HLS-Bonny</td><td colspan="8">0.051</td><td colspan="14">-0.015</td><td>-0.066</td></tr>
<tr><td>Saharan-Brent</td><td colspan="3">0.024</td><td colspan="19">0.006</td><td>-0.018</td></tr>
<tr><td>Brent-Bonny</td><td colspan="8">-0.004*</td><td colspan="10">-0.023</td><td colspan="4">-0.007</td><td>-0.003</td></tr>
<tr><td colspan="24">Medium-medium differentials</td></tr>
<tr><td>Differential</td><td>97</td><td>98</td><td>99</td><td>00</td><td>01</td><td>02</td><td>03</td><td>04</td><td>05</td><td>06</td><td>07</td><td>08</td><td>09</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>Change</td></tr>
<tr><td>Mars-SHU</td><td colspan="6">0.166</td><td colspan="8">0.086</td><td colspan="8">0.039</td><td>-0.127</td></tr>
<tr><td>Oman-Mars</td><td colspan="5">0.053</td><td colspan="12">0.014</td><td colspan="5">0.052</td><td>-0.001</td></tr>
<tr><td>Oman-SHA</td><td colspan="22">0.063</td><td>–</td></tr>
<tr><td>Urals-Mars</td><td colspan="5">0.053</td><td colspan="4">-0.010*</td><td colspan="8">0.020</td><td colspan="5">0.060</td><td>+0.007</td></tr>
<tr><td>Urals-SHE</td><td colspan="4">0.189</td><td colspan="18">0.077</td><td>-0.112</td></tr>
<tr><td>Dubai-Mars</td><td colspan="17">0.014</td><td colspan="5">0.046</td><td>+0.032</td></tr>
<tr><td>Dubai-SHA</td><td colspan="22">0.053</td><td>–</td></tr>
</table>

Notes: Change is the difference between the final regime and the first regime for each regression equation. A * means the coefficient is not statistically different from 0 at a 5 percent confidence level. In the table, breaks that occur from July to December in a particular year are assigned to the following year.

Table 13: Summary statistics pre and post-break

Part 1: Within-area differentials

Differential	Pre-break Mean	Pre-break Standard deviation	Post-break Mean	Post-break Standard deviation	Ratio of mean (Post/pre)	Ratio of std. dev. (post/pre)
Midland, TX						
WTIM-WTS	0.076	0.028	0.01	0.016	0.13	0.57
U.S. Gulf Coast						
LLS-Mars	0.149	0.048	0.062	0.028	0.42	0.58
LLS-SHU	0.270	0.102	0.105	0.040	0.39	0.39
LLS-Maya	0.299	0.086	0.141	0.054	0.47	0.63
HLS-Mars	0.128	0.049	0.054	0.022	0.42	0.45
HLS-SHU	0.250	0.100	0.097	0.033	0.39	0.33
HLS-Maya	0.279	0.083	0.133	0.049	0.48	0.59
Mars-Maya	0.151	0.056	0.079	0.038	0.52	0.68
Europe/Atlantic Basin						
Saharan-Urals	0.070	0.035	0.023	0.020	0.33	0.57
Saharan-SHE	0.195	0.092	0.089	0.046	0.46	0.50
Brent-Urals	0.058	0.036	0.018	0.017	0.31	0.47
Brent-SHE	0.183	0.088	0.084	0.044	0.46	0.50
Bonny-Urals	0.070	0.038	0.033	0.017	0.47	0.45
Bonny-SHE	0.194	0.085	0.099	0.039	0.51	0.46
Middle East/Asia						
Tapis-Oman	0.114	0.053	0.069	0.031	0.61	0.58
Tapis-Dubai	0.128	0.053	0.074	0.031	0.58	0.58
Tapis-SHA	0.196	0.091	0.110	0.049	0.56	0.54

Part 2: Across-area differentials

Differential	Pre-break Mean	Pre-break Standard deviation	Post-break Mean	Post-break Standard deviation	Ratio of mean (Post/pre)	Ratio of std. dev. (post/pre)
Light-medium						
Tapis-Urals	0.119	0.058	0.063	0.022	0.53	0.38
Saharan-Oman	0.065	0.045	0.029	0.031	0.45	0.69
Saharan-Dubai	0.079	0.046	0.035	0.030	0.44	0.65
Brent-Oman	0.053	0.042	0.024	0.025	0.45	0.60
Brent-Dubai	0.067	0.045	0.030	0.024	0.45	0.53
Bonny-Oman	0.065	0.044	0.039	0.025	0.60	0.57
Bonny-Dubai	0.079	0.046	0.044	0.024	0.56	0.52
LLS-Oman	0.116	0.049	0.030	0.037	0.26	0.76
LLS-Urals	0.121	0.049	0.023	0.037	0.19	0.76
LLS-Dubai	0.130	0.050	0.035	0.037	0.27	0.74
HLS-Oman	0.097	0.048	0.021	0.035	0.22	0.73
HLS-Urals	0.101	0.046	0.015	0.033	0.15	0.71
HLS-Dubai	0.111	0.050	0.027	0.035	0.24	0.70
Light-heavy						
Tapis-Maya	0.296	0.089	0.181	0.052	0.61	0.58
Saharan-Maya	0.248	0.082	0.141	0.057	0.57	0.70
Brent-Maya	0.236	0.078	0.136	0.053	0.58	0.68
Bonny-Maya	0.236	0.078	0.151	0.050	0.64	0.64
Medium-heavy						
Oman-Maya	0.183	0.072	0.112	0.045	0.61	0.63

Notes: The pre-break sample runs from Jan. 1997 to Dec. 2008. The post-break sample runs from Jan. 2009 to July 2018.

Table 14: Unit root test results for monthly data

	SIC	
Differential	ADF	ADF (BP)
WTIM-WTS	**-2.90**	-6.76
	(0.05)	(<0.01)
LLS-HLS	-6.09	-7.03
	(<0.01)	(<0.01)
LLS-Mars	**-2.53**	-5.27
	(**0.11**)	(<0.01)
LLS-SHU	**-2.51**	-4.29
	(**0.11**)	(<0.01)
LLS-Maya	**-2.96**	-5.62
	(0.04)	<(0.01)
HLS-Mars	**-2.15**	-5.69
	(0.23)	<(0.01)
HLS-SHU	**-2.42**	-6.11
	(0.14)	<(0.01)
HLS-Maya	**-3.02**	-5.77
	(0.03)	(<0.01)
Mars-Maya	-4.68	-7.77
	(<0.01)	<0.01
SHU-Maya	-5.21	-5.16
	(<0.01)	<0.01
Saharan-Urals	-3.99	- 5.79
	(<0.01)	(<0.01)
Saharan-SHE	-3.55	-4.76
	(<0.01)	(<0.01)
Brent-Urals	-4.23	-5.77
	(<0.01)	(<0.01)
Brent-SHE	-3.70	-5.00
	(<0.01)	(<0.01)
Bonny-Urals	-4.89	-6.23
	(<0.01)	(<0.01)
Bonny-SHE	-3.85	-5.00
	(<0.01)	(<0.01)
Tapis-Oman	- 3.72	- 6.75
	(<0.01)	(<0.01)
Tapis-Dubai	-5.74	-7.01
	(<0.01)	(<0.01)
Tapis-SHA	-4.74	-5.54
	(<0.01)	(<0.01)
Oman-Dubai	-5.09	-4.68
	(<0.01)	(<0.01)

Notes: For each differential, the first row shows the test statistics for the Augmented Dickey-Fuller (ADF) and the ADF breakpoint (ADF BP) tests. The second row shows the p-value for the test. Bold text identifies a case where the null of a unit root would not be rejected at a one percent significance level.

Table 15: Unit root test results for monthly data

	SIC	
Differential	ADF	ADF (BP)
Tapis-Urals	-3.75	-8.75
	(<0.01)	(<0.01)
Tapis-Mars	- 6.62	-7.61
	(<0.01)	(<0.01)
Saharan-Oman	-5.81	-6.63
	(<0.01)	(<0.01)
Saharan-Dubai	-5.49	-6.56
	(<0.01)	(<0.01)
Saharan-Mars	-5.87	-6.75
	(<0.01)	(<0.01)
Brent-Oman	-5.79	-6.44
	(<0.01)	(<0.01)
Brent-Dubai	-5.12	-5.91
	(<0.01)	(<0.01)
Brent-Mars	-6.15	-6.81
	(<0.01)	(<0.01)
Bonny-Oman	-6.68	-7.08
	(<0.01)	(<0.01)
Bonny-Dubai	-6.17	-6.85
	(<0.01)	(<0.01)
Bonny-Mars	-7.00	-7.49
	(<0.01)	(<0.01)
LLS-Oman	-3.88	-5.74
	(<0.01)	(<0.01)
LLS-Urals	**-2.97**	-5.08
	(0.04)	(<0.01)
LLS-Dubai	-3.58	-5.49
	(<0.01)	(<0.01)
HLS-Oman	-4.61	-6.48
	(<0.01)	(<0.01)
HLS-Urals	-3.50	-7.24
	(<0.01)	(<0.01)
HLS-Dubai	-4.26	-6.17
	(<0.01)	(<0.01)
Tapis-Maya	-4.69	-6.39
	(<0.01)	(<0.01)
Saharan-Maya	-4.47	5.98
	(<0.01)	(<0.01)
Brent-Maya	-4.37	-5.95
Bonny-Maya	-4.34	-5.60
	(<0.01)	(<0.01)
Oman-Maya	-5.58	-6.98
	(<0.01)	(<0.01)
Urals-Maya	-5.67	-6.87
	(<0.01)	(<0.01)
Dubai-Maya	-4.88	-5.94
	(<0.01)	(<0.01)
WTIC-LLS	**-2.35**	-4.29
	(**0.16**)	(<0.01)
WTIM-LLS	**-2.32**	-4.63
	(**0.17**)	(<0.01)
LLS-Tapis	-6.73	-8.49
	(<0.01)	(<0.01)
LLS-Saharan	**-3.17**	7.51
	(0.02)	(<0.01)
LLS-Brent	**-2.82**	-6.67
	(0.06)	(<0.01)
LLS-Bonny	**-2.62**	-5.77
	(0.09)	(<0.01)
HLS-Tapis	-7.94	-9.77
	(<0.01)	(<0.01)
HLS-Saharan	-3.87	-8.56
	(<0.01)	(<0.01)
HLS-Brent	**-3.45**	-7.46
	(0.01)	(<0.01)
HLS-Bonny	**-2.70**	-9.45
	(0.08)	(<0.01)
Oman-Urals	-8.77	-9.25
	(<0.01)	(<0.01)
Oman-Mars	-8.03	-8.47
	(<0.01)	(<0.01)
Urals-Dubai	-8.58	-8.57
	(<0.01)	(<0.01)
Urals-Mars	-7.41	-7.71
	(<0.01)	(<0.01)
Dubai-Mars	-6.99	-7.37
	(<0.01)	(<0.01)

F. ADDITIONAL DETAILS ON SULFUR CONTENT REGULATIONS

We begin by defining the different grades of fuel in regards to sulfur content. We then provide more details on the sources of data used in our analysis. Finally, we provide additional details in regards to the time line and coverage of the regulations.

F.1 Definitions

Sulfur content is often reported in parts per million (ppm). During the distillation process, there is a tendency for sulfur to settle into the denser petroleum products. As a result, sulfur content is typically lowest in light distillates, such as gasoline, and highest in residual fuel oil. Sulfur content of middle distillates tends to be in between light distillates and residual fuel oil. Because of these differences, the use of the terms such as low sulfur and ultra-low sulfur have different meanings across the fuels in regards to sulfur content in ppm.

For diesel, there is a well-defined nomenclature in use and we follow standard terminology. Low sulfur diesel (LSD) is defined as having a sulfur content of 500 ppm or less while ultra-low sulfur diesel (ULSD) has 15 ppm or less. European standards define ULSD as having 10 ppm or less.

Unlike diesel, there does not appear to be a well-accepted nomenclature for defining grades of gasoline by sulfur content. We define low sulfur gasoline (LSG) as having sulfur content of 150 ppm or less while ultra-low sulfur gasoline (ULSG) has 10 ppm or less. These line up with the category 2 and category 4 specifications for unleaded gasoline found in Worldwide Fuel Charter Committee (2013).

For residual fuel oil, we define low sulfur fuel oil (LSFO) as having a sulfur content of 10,000 ppm or less. Very-low sulfur fuel oil (VLSFO) is defined as having a sulfur content of 5,000 ppm or less. Ultra-low sulfur fuel oil (ULSFO) is defined as having 1,000 ppm or less.

F.2 Data sources

Determining what share of global consumption is covered by the regulations requires identifying regulations across countries and having country-level consumption data across products.

It is possible to put together an accurate time line of the implementation of these regulations for the OECD countries, China, and India. For other countries, snapshots of their regulations can be put together. The United Nations Partnership for Clean Fuels and Vehicles provides maps of diesel regulations (http://www.airqualityandmobility.org/gfeitoolkit/sulphur.html). These maps provided important information for coverage in 2007 and 2018. Stratas Advisors, through their Global Fuel Specifications service, produce annual reports on gasoline sulfur content regulations (see, for example, https://stratasadvisors.com/Insights/2019/072519-Fuels-Top-100-Gasoline-Sulfur-Ranking). This provided information on 2018 coverage. Information for 2007 coverage came from a map produced by the International Fuel Quality Center. For the OECD countries, additional sources include various government documents, industry reports, Wikipedia entries and media sources. Please contact the author for specific references, if interested. For a summary on China, see International Council on Clean Transportation (2014). For India, see International Council on Clean Transportation (2016) and the Wikipedia entry on the Bharat stage emissions standards (https://en.wikipedia.org/wiki/Bharat_stage_emission_standards).

Consumption data are from the International Energy Agency. For 2007, see International Energy Agency (2019a). For 2018, see International Energy Agency (2019b). These reports provide a breakdown across different products for the OECD countries, both as a whole and for individual countries. The reports also provide an aggregate for all non-OECD countries and for China. For India, we only have data for 2018 from International Energy Agency (2019b). While it would be preferable to have more disaggregate data, the data that is available is sufficient to make important inferences because the OECD countries and China make up a significant portion of both gasoline and diesel consumption worldwide.

F.3 Coverage

Generally speaking, our research finds that sulfur content regulations were minimal to non-existent before the early 1990s. Most OECD countries started implementing regulations on both gasoline and diesel during the 1990s. By 2009, most OECD countries had transitioned to LSD or ULSD for on-highway use and LSG. By 2018, ULSD was required in most OECD countries for most purposes, and most had transitioned to ULSG. A handful of developing countries began imposing restrictions in the first decade of the 2000s. The number has increased significantly over the last 10 years, particularly in regards to diesel regulations. Residual fuel oil regulations came into effect in the mid-2000s. The most stringent regulations for residual fuel oil use will come into effect in 2020.

The gasoline consumption shares are calculated as follows. By 2007, the OECD countries, excluding Mexico and Turkey, had transitioned to LSG. In 2007, global consumption of gasoline was 21.84 million barrels per day (mb/d). Consumption among the OECD countries, excluding Mexico and Turkey, was 14.17 mb/d. The share is therefore roughly 65 percent (64.9 percent). By 2018, all OECD countries had transitioned to ULSG, except Mexico which still used LSG. China had transitioned to ULSG while India transitioned to LSG. In 2018, global gasoline consumption was 26.18 mb/d. Gasoline consumption for the OECD countries, China and India equaled 18.25 mb/d. The share is about 70 percent (69.7 percent). This number represents a lower bound as a handful of other countries have been identified as having transitioned to either LSG or ULSG. This includes Argentina, Brazil, Peru, Russia, Thailand and several countries in Africa.

The diesel consumption shares are calculated as follows. By 2007, China and all of the OECD countries, except Turkey, had passed regulations for use of LSD for on-highway use. In 2007, global consumption of diesel was 24.51 mb/d. Consumption in China and the OECD countries, excluding Turkey, amounted to 15.71 mb/d. This gives a share of 64 percent. As stated in the paper, this is likely over-estimating the actual amount of diesel impacted by the regulations in 2007. For example, these regulations did not affect heating oil use in the United States at the time.

By 2018, ULSD was being used in China and all of the OECD, except for Mexico. LSD was in use in Mexico and in India. In 2018, global consumption of diesel was 28.45 mb/d. Consumption for the OECD countries, China and India was 18.73 mb/d. This gives a share of about 66 percent (65.8 percent). This is likely a lower bound on the amount of diesel impacted by sulfur content regulations. Information from the United Nations map and other sources show that in 2018 LSD or ULSD was used in Brazil, Pakistan, the Philippines Russia, Thailand, more than a dozen countries in Africa and a handful of other countries in Latin America.

In regards to residual fuel oil use, International Energy Agency (2019b) reports 2018 total consumption at 6.67 mb/d. Of this, about half seems to be used in shipping. The 2020 regulations will cover all use of residual fuel oil for shipping.

Table 16: Heavy crude production

	2000	2005	2010	2015	2016	2017	2018	Change (2018-2010)
Heavy sour (by region)								
Europe	0.41	0.48	0.33	0.24	0.29	0.33	0.31	-0.02
Middle East	0.46	0.60	0.61	1.25	1.35	1.42	1.47	0.86
Iraq	0.00	0.00	0.00	1.05	1.21	1.28	1.33	1.33
Africa	0.06	0.22	0.45	0.31	0.20	0.28	0.28	-0.18
Americas	6.09	7.11	6.69	7.57	7.18	7.06	7.05	0.36
Canada	0.85	0.97	1.10	1.84	1.89	2.05	2.32	1.22
Mexico	1.78	2.39	1.42	1.15	1.10	1.05	1.07	-0.35
Venezuela	1.06	1.07	1.10	1.22	1.17	1.10	0.86	-0.24
Other	2.40	2.68	3.06	3.37	3.01	2.86	2.80	-0.28
Heavy sour (all regions)	7.02	8.40	8.08	9.37	9.01	9.09	9.10	1.02
Heavy sweet (all regions)	1.40	1.61	2.25	2.19	2.10	1.89	1.90	-0.34
Total heavy production	8.41	10.01	10.32	11.56	11.11	10.98	11.00	0.68

Notes: Units are millions of barrels per day. Source: Eni World Oil Review 2019; Authors' calculations.

G. ADDITIONAL CRUDE PRODUCTION DATA

Table 16 provides a more detailed breakout of heavy crude production by geographic area and, in some cases, by country. All data is sourced from Eni's World Oil Review 2019. Please note that Syncrude production in Canada is included in the medium crude category by Eni as it is marketed as a medium sweet crude with an API gravity of about 32 and a sulfur content well below 0.50 percent. Details on the API gravity of various upgraded crude oils in Canada can be found from the Canadian Crude Quick Reference Guide (http://www.crudemonitor.ca).

H. ADDITIONAL REFINERY DATA

H.1 U.S. Gulf Coast refinery data

The U.S. Gulf Coast refinery data comes from the Energy Information Administration. We use the "Downstream processing of fresh feed input" series and the "Downstream charge capacity" series to construct utilization rates. The fresh feed input series is available at https://www.eia.gov/dnav/pet/pet_pnp_dwns_dc_nus_mbblpd_m.htm. The charge capacity data is available at https://www.eia.gov/dnav/pet/pet_pnp_capchg_dcu_nus_a.htm. There is a single series available for the input and capacity for cokers. The units for the capacity data is barrels per calendar day, which means the capacity series is adjusted to take into account normal downtime at those units. As a result, utilization rates at or above 100 percent are theoretically possible. Capacity data is unavailable in 1996 and 1998. For those two years, we average the capacity data from the preceding and following year to construct an estimate. Table 17 shows the full time series for the U.S. Gulf Coast coking capacity.

Table 17: U.S. Gulf Coast coking capacity data

	Coking		
Year	Capacity	Input	Utilization
1987	535	509	95.1
1988	556	552	99.3
1989	542	563	103.9
1990	566	552	97.6
1991	612	588	96.1
1992	612	623	101.8
1993	639	653	102.2
1994	698	680	97.4
1995	715	724	101.3
1996	756	778	102.9
1997	797	773	97.0
1998	840	817	97.2
1999	884	857	97.0
2000	923	843	91.3
2001	1009	999	99.0
2002	1086	1095	100.9
2003	1133	1086	95.8
2004	1206	1141	94.6
2005	1229	1132	92.1
2006	1255	1173	93.5
2007	1274	1152	90.4
2008	1282	1073	83.7
2009	1294	1041	80.5
2010	1322	1114	84.3
2011	1318	1183	89.7
2012	1373	1223	89.1
2013	1459	1299	89.0
2014	1479	1312	88.7
2015	1490	1347	90.4
2016	1458	1351	92.7
2017	1485	1338	90.1
2018	1500	1349	89.9

Notes: Units for capacity and inputs are in thousands of barrels per day. Utilization is inputs divided by capacity multiplied by 100.

Table 18: Refinery capacity additions based on International Energy Agency data

Year	Primary	Upgrading	Desulphurisation
2006	1.256	0.735	2.684
2007	0.786	0.573	0.838
2008	1.125	1.069	1.396
2009	2.236	1.643	2.755
2010	1.026	0.643	1.645
2011	0.652	1.078	1.096
2012	0.555	1.037	1.066
2013	0.547	0.918	1.433
2014	0.832	1.023	1.032
2015	1.44	1.473	1.419
2016	0.033	0.757	0.329
2017	0.75	0.326	0.466
2018	1.002	0.965	0.929

Notes: Units are growth rates in millions of barrels per day. The International Energy Agency tables list the data as Refining Capacity Additions and Expansions, Upgrading Capacity Additions, and Desulphurisation Capacity Additions. The sources are Medium-Term Oil Market Reports for 2006 - 2009, Medium-Term Oil & Gas Markets 2010 - 2011, Medium-Term Oil Market Reports for 2012 - 2016, and Oil Market Reports for 2017 - 2019.

H.2 Other refinery data

Table 18 shows the full time series available from the International Energy Agency for refinery capacity additions. Table 19 shows the full time series available from Eni reports along with the source year for each observation.

Table 19: Full time series from Eni publications

Year	Primary capacity	Conversion capacity	Conversion ratio	Nelson Complexity	Source
1995	76.3	27.5	0.36	7.9	Eni 2013
1996	77.8	28.0	0.36	N/A	Eni 2008
1997	80.0	29.6	0.37	N/A	Eni 2006
1999	82.1	31.2	0.38	N/A	Eni 2008
2000	83.2	31.6	0.38	7.9	Eni 2018
2001	84.7	33.9	0.40	N/A	Eni 2006
2003	85.5	36.7	0.43	N/A	Eni 2008
2005	87.3	37.5	0.43	8.2	Eni 2018
2007	89.2	40.1	0.45	N/A	Eni 2008
2010	92.4	43.4	0.47	8.7	Eni 2018
2011	93.4	46.7	0.50	7.8	Eni 2012
2012	94.0	47.9	0.51	8.0	Eni 2013
2013	95.1	49.4	0.52	8.0	Eni 2014
2014	96.3	48.1	0.50	9.0	Eni 2015
2015	96.5	50.2	0.52	9.1	Eni 2016
2016	98.1	52.0	0.53	9.3	Eni 2017
2017	98.7	53.3	0.54	9.3	Eni 2018

Notes: Units for capacity are millions of barrels per day. Conversion ratio is conversion capacity divided by primary capacity. Eni 2018 refers to the World Oil Review 2018 volume 1. The other reports are titled World Oil & Gas Review.

REFERENCES

Agerton, M. and G. B. Upton Jr. (2019). "Decomposing crude price differentials: Domestic shipping constraints or the crude oil export ban?" *The Energy Journal*, 40:155–172. https://doi.org/10.5547/01956574.38.1.mage.

Bacon, R. and S. Tordo (2005). "Crude oil price differentials and differences in oil qualities: A statistical analysis" *ESMAP Technical Paper*, October, 2005.

Fattouh, B. (2010). "The dynamics of crude oil price differentials" *Energy Economics*, 32:334–342. https://doi.org/10.1016/j.eneco.2009.06.007.

Giulietti M. and A. M. Iregui and J. Otero (2015). "A pair-wise analysis of the law of one price: Evidence from the crude oil market" *Economics Letters*, 129:39–41. https://doi.org/10.1016/j.econlet.2015.02.002.

International Council on Clean Transportation (2014). "China V gasoline and diesel fuel quality standards" *International Council on Clean Transportation*, 2014.

International Council on Clean Transportation (2016). "Technical background on India BS VI fuel specifications" *International Council on Clean Transportation*, 2016.

International Energy Agency (2019a). "Oil Market Report: Annual Statistical Supplement" *International Energy Agency*, 2019.

International Energy Agency (2019b). "Oil Market Report" *International Energy Agency*, November, 2019.

Perron P. (1989). "The great crash, the oil price shock, and the unit root hypothesis" *Econometrica*, November:1361–1401. https://doi.org/10.2307/1913712.

Worldwide Fuel Charter Committee (2013). "Worldwide Fuel Charter" *Worldwide Fuel Charter Committee*, 2013.