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Crude Oil Price Differentials and Differences in Oil Qualities: A Statistical Analysis

October 2005

JOINT UNDP / WORLD BANK

ENERGY SECTOR MANAGEMENT ASSISTANCE PROGRAMME (ESMAP)

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Executive Summary

1. Many developing countries depend heavily on oil revenues to contribute to the government budget and to exports. Forecasting such revenues requires an assessment of the likely price of oil produced and exported. Forecasts for certain “marker” crude oils, such as North Sea Brent, West Texas Intermediate (WTI), and Dubai, are widely available, but for the more than 150 varieties of crude oils produced worldwide individual forecasts are not available. The differential between a particular crude oil and its marker can be large (more than 25 percent) and widens as the general level of oil prices rises. Several methods have been utilized to relate these differentials to the characteristics or properties of the crudes in question.

2. This report updates and extends previous work in this area by a statistical analysis of the relationship between crude price differentials and three quality differentials, as well as transport costs and seasonal effects. In addition to the API (American Petroleum Institute) gravity number and the sulfur content of the crudes, which are the qualities generally included in existing analysis, the report presents the impact of acidity (measured by the Total Acid Number – “TAN”) on the price differential. This is because acidity has become increasingly important as the volume of high acid crudes, particularly from West Africa, has steadily increased in recent years.

3. The model used is based on data for 56 crudes for the months from January 2004 to April 2005. The pooled cross-section time series estimation indicates that each extra degree of API gravity (relative to another crude) raises the relative crude price by US$0.007 per dollar of the Brent price, each 1 percent of sulfur lowers the price by US$0.056 per dollar of Brent, and each degree of TAN lowers the price by US$0.051 per dollar of Brent. The model, which has a high explanatory power overall and with respect to each of the key explanatory variables, confirms that the differential between crudes at current Brent prices will be large for low quality crudes, and that the differentials will widen as the Brent price increases.

4. Further tests of the model by estimating differentials for crudes not included in the original estimation (for example, the Chadian Doba blend, a high acid heavy crude) generate accurate results.

5. The model presents a valuable tool to understanding the differentials between crude oil prices, and producers of new oil streams can use it to provide first estimates of their likely oil prices relative to the well-known marker crudes.

1

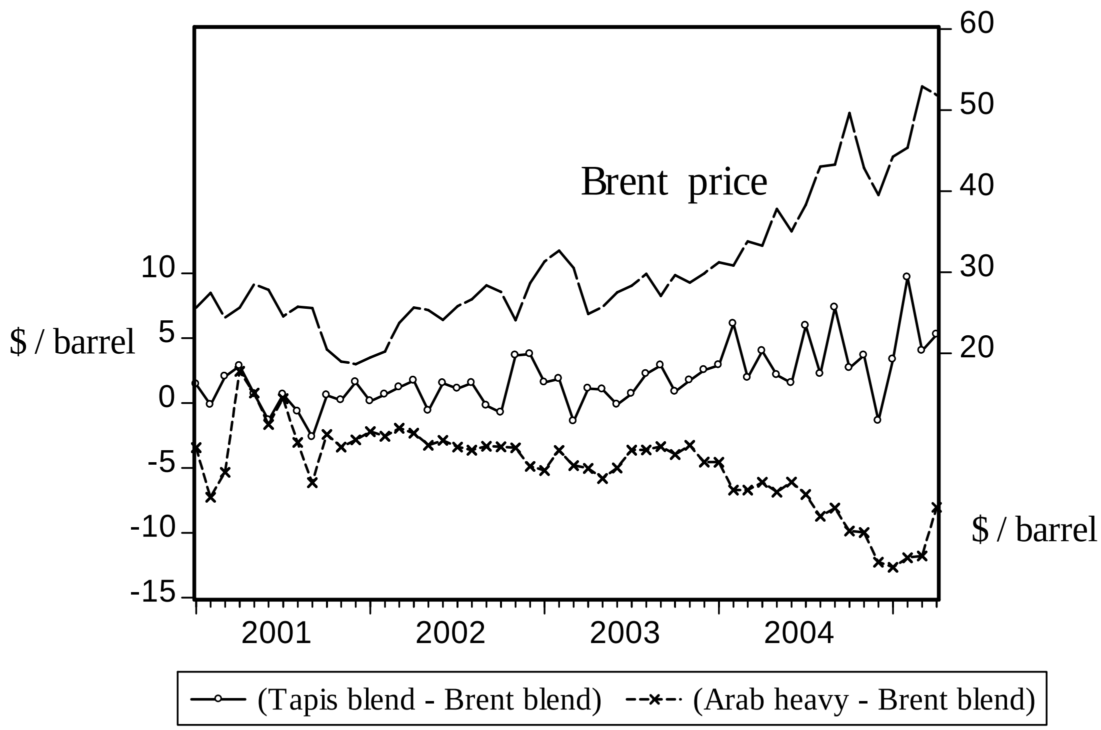
Crude Oil Prices and Differentials

1.1 The number and variety of crude oils that are traded on the international market has steadily increased over the past years, partly as a response to the desire to diversify sources of supply, and partly because increasing global demand has encouraged production in less well-known oil-producing areas. Currently more than 150 crude grades are described in *The International Crude Oil Market Handbook* (2004).[1]

1.2 Although the prices of these different crude oils move broadly together, two features are very important. First, the differentials (or discounts) between certain crude oils are very large; and second, the size of the differentials between given pairs of crude oils appears to change as the general oil price increases. Figure 1.1 illustrates the magnitude of the differentials between Arab heavy (from Saudi Arabia) and Brent blend (from the U.K. North Sea), and between Tapis blend (from Malaysia) and Brent blend, and also how these changed during the period January 2001 to April 2005. The differentials can also be compared to the price of Brent which is shown on the same figure. The graph indicates that in February 2005, when differentials were at their most extreme, the average price of Tapis blend was US$55.10, and the average price for Arab heavy was US$33.50, while the price of Brent was US$45.42. Earlier in the period of observation, at lower Brent prices, the differentials were very much smaller.

[1] Crude oils are complex mixtures of a large number of organic compounds that vary in appearance and composition from one oilfield to another. Carbon and hydrogen make up around 98 percent of the content of a typical crude oil type. The rest is made up of sulfur (1-3 percent), nitrogen, oxygen, metal and salts (less than 1 percent each). Crude oils are classified as paraffinic, naphtenic, aromatic, or asphaltic based on the predominant proportion of hydrocarbon series molecules, which dictates their physical and chemical properties.

Figure 1.1: Crude Price Differentials and the Brent Price between January 2001 and April 2005 (US$ per barrel)



1.3 The existence of these differentials and their potential variation over time poses a number of important issues for governments of oil-exporting countries, for which oil revenues can be a very important source of government revenue and of exports. For example, in 2004 earnings from oil revenues accounted for more than 50 percent of total government revenues in Kazakhstan, while in Azerbaijan in 2001 oil revenues accounted for 30 percent of government revenues and 90 percent of exports. The picture is very similar in many West African oil-exporting countries. For such countries, the formulation of expenditure plans will crucially depend on government revenue forecasts, and these in turn will depend heavily on the accuracy of the forecasts of oil production and oil prices.

1.4 Locally generated forecasts of oil production for a few years ahead are usually reasonably accurate, but forecasting oil prices is a highly specialized skill. There are many consultancies and international agencies which produce alternative price scenarios, but these virtually always produce forecasts for either Brent blend or for West Texas Intermediate (WTI) a leading United States crude oil. The large number of crude oils produced precludes the simultaneous forecasting of the prices of all oil varieties.

1.5 The data presented above shows that a country cannot simply use a forecast of these so called “marker” crude prices, unless it has established that the behavior and level of the country’s own crude price does indeed approximate the marker crude price closely. For example, if a country selling a crude similar to Arab heavy used the Brent price forecast, this could have overestimated the oil price to be received by a factor of 20 percent in early 2004, and by a factor of 35 percent in early 2005. The magnitude and variability of the differential indicates the need for a systematic way to allow for differences between crudes in their price behavior.

1.6 An even more extreme version of the same issue arises for new oil-producing countries, or countries with major new sources of oil coming on stream. The evaluation of the oil project and the likely revenues to be earned will depend on how closely the price received for this particular oil will follow the international marker prices, for which forecasts will be available. In these cases there is not even past experience on the price of the oil in question, so that the magnitude of even the average differential to the “markers” will be unknown.

1.7 Faced with these problems, industry analysts have for a long time looked for some way of understanding the relationship between the prices of different crudes. The analysis of these price differentials has focused on the differences between the crude oils under discussion. Crude oils differ in two important respects:

1. ***The quality of the crudes.*** Crude oils are mixtures of a large number of complex hydrocarbons and small amounts of other chemicals. The exact composition of the mixture will determine the mix of products that can be obtained from the crude oil by refining and the ease of refining the crude. Different products are more or less valuable at any one time, depending on the overall supply and demand for them. Refineries will try to produce the most valuable products if they are able to do so, but the overall supply of refineries of different complexities will limit the overall capacity to supply certain products. Hence, those crude oils which yield a large proportion of more valuable products and which can be treated by a large number of the world’s refineries, will command a premium over crude oils which produce a larger proportion of lower value products or which can be processed by only a limited number of refineries.
2. ***Location of production.*** Oils produced close to major markets for refining will require less transportation and therefore will be more attractive and command a premium over oil produced further from the market which has to incur larger transportation costs to get to the market.

1.8 Although crude oils can vary in a very large number of quality characteristics, which have to be taken into account in running them in a refinery, price analysts have focused on two principal quality (namely API gravity and sulfur content) differentials between crudes to explain intercrude price differentials. Indeed, oil traders, buyers and sellers of crude oil use price adjustments based on quality differentials when the quality of oil received differs from that assumed on the basis of the name on the cargo. For new crudes, where there is no historic price data on their specific crude, guidance for expected sale prices is sought by looking at the situations of similar crudes, as defined by quality and yield.

2

Oil Price Differentials and Quality Differentials

2.1 To estimate relative crude values several methods have been developed. The methods most commonly used by industry operators can be grouped under two categories: (a) assay [2]-based valuation; and (b) gravity and sulfur-based valuation.

2.2 The first method, normally used by refiners,[3] estimates the crude value based on its properties and their relation to product specifications. Premiums and discounts are applied to each distillation fraction to reflect the difference between the quality of the fraction and the specifications of the final product. Two main approaches are used: (1) valuation by simulation and (2) valuation by linear programming (LP). Both forms of valuation provide the refiner with an instrument to ensure the optimum use of its plant while considering the market conditions. The valuation by simulation has the advantage of explicating the cause/effect relationships, thus allowing the refiner to simulate the effect of all possible processing and routing options. The configuration of the refinery, the refinery operation, and the markets determine the relative value of a crude. As refining is a continuing operation, the value of a crude, or better its opportunity cost, is also influenced by the type and quantity of the crudes that are already being processed.

2.3 The second method relates price differentials to differences in API (American Petroleum Institute) gravity number [4] and sulfur content[5] of the two crudes in question, as illustrated in ExxonMobil (2001) and discussed by Hartman. This comparison is made in two different ways.

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[2] An assay describes a crude in terms of its properties, and gives volumetric and weight yields of standard distillation fractions. Properties relate to the specifications of final products and to the suitability of the fractions for further processing. A simplified flowchart of a typical refining process is described in Ruschau and Al-Anezi (2001).

[3] A refiner's valuation of crude quality depends on its refining technology. The selection of the optimum "crude mix" is therefore of critical importance to a refiner.

[4] Degrees API is the most commonly used density scale. The higher the API gravity number the lighter the crude. Crude oils with low carbon, high hydrogen, and high API gravity are usually rich in paraffins and tend to yield greater proportions of gasoline and light petroleum products.

[5] Sulfur is an undesirable impurity in fossil fuels for reasons ranging from pollution to corrosion of production and refinery equipment. Crude oils that contain appreciable quantities of hydrogen sulfide (H_2S) or other reactive sulfur compounds are called sour. Those with less sulfur are called sweet.

1. ***The method of pairwise comparisons.*** If two crude oils differ substantially in only one quality dimension (for example, API) while the other (sulfur) is almost identical then a pairwise comparison between the two prices yields a differential which can be related to the extent of the difference in quality. If the API differs by 10 degrees and the price differential is one dollar per barrel then it can be inferred that each degree of API is "worth" ten cents. Although this may give a reasonable first approximation, it is very dependent on any individualities of the crudes in question. Further pairwise comparisons between other crudes which are identical in the second quality might yield different results. Averages over a time period could be used to remove impacts of any date specific factors. This method can also be extended to evaluating the impact of the second quality, by finding two crudes nearly identical in the first quality and different in the second quality. An extension to deal with more than two quality factors would be extremely difficult because it would rely on finding pairwise comparisons between crudes identical in two of three qualities, for each two of the qualities.

2. ***Multiple regression analysis.*** The use of multiple regression analysis is based on a natural generalization of the pairwise comparison approach. This allows for a single model to incorporate simultaneous differences in qualities by taking information for a large number of crudes and estimating the impact of each quality differential on the price differential. A key assumption is that quality differences are additive, so that the model in its simplest form can be written:

   $$\mathbf{\Delta\ price_j = a + \Sigma_i\ b_i\,(\Delta\ quality_{ij})} \qquad \mathbf{(1)}$$

   Where:

   Δ price$_j$ is the difference between the price of a given crude (j) and that of some marker crude;

   Δ quality$_{ij}$ is the difference in between the quality "i" of the crude (j) and that of the marker crude;

   Σ represents the sum over the various qualities;

   a and **bi** are parameters to be established by regression analysis.

2.4 In this model the coefficients "b" measure the impact on the price differential of a one unit increase in the difference of each of the qualities between the crude in question and the marker crude. The model can be generalized to combine data from different time periods for the prices, by making the assumption that the quality effects do not change over time.

2.5 A number of studies have analyzed the relations between prices of different crude oils and have effectively relied on one or other of these latter approaches.

An early study, which recognized that crude quality differences must be taken into account when analyzing oil markets, is that of Kohli and Morey (1990). The report looked at the problem of explaining imports of crude into the United States. Recognizing that oil imports from different countries are not identical in quality, it was suggested that instead of attempting to estimate a separate demand function for each crude imported, a model could be devised in which a single equation for shares of the different crudes in total crude imports is determined by an aggregative quality index. This characteristics-based model reduced data from eight countries to five characteristics, namely API, the percentage of sulfur, the shipping distance to the United States, availability as measured by production of the region, and a political reputation variable. This model could be extended to a larger number of crudes without increasing the number of quality characteristics. The characteristic levels were combined together through an exponential weighting function. In this model the estimated chacteristic elasticities of import shares were highest and positive for API, were negative for sulfur content, negative for distance from the United States, positive for availability, and positive for reputation, all of which are intuitively sensible.

2.6 The importance of crude qualities has been emphasized in a number of papers, including Weiner (1991), Gülen (1997, 1999), Kleit (2001) and Lanza, Manera, and Giovannini (2003), which have investigated the so called “regionalization hypothesis” in which the sale prices of similar crudes in different markets for the same time period were investigated. If the prices of nearly identical crudes moved closely together in different regions with a nearly constant differential being attributable to transportation costs, the market was said to be “globalized,” with opportunities for arbitrage having been utilized; while if prices exhibited some significant independent movements the markets were identified as “regionalized.” These studies, based on time series data, attempted to remove the impacts of quality differentials on prices by choosing a relatively small set of crudes that had very similar API and sulfur content. The overall conclusion from more recent studies favored the “globalization” hypothesis, but these studies did not focus on the magnitude of any systematic and constant differences between the various crude prices, such as could be caused by the small quality differentials between them.

2.7 The use of the regression method with respect to differences in API and sulfur is illustrated in ExxonMobil (2001), Hartman (2003), and Wang (2003). Wang, using 1992 average prices, for a set of 55 crudes, estimated that each percentage point of sulfur content lowered the price by US$1.46 a barrel, and each degree increase in API raised the price by 13.2 cents per barrel. Hartmann, writing in 2003 about recent experience, suggested that each additional percentage point of sulfur lowered the price by about US$1 a barrel, while each degree increase in API raised the price by one percent, which is equivalent to 3 cents per barrel for a degree of API at a price of US$30, and 4 cents at US$40 a barrel, suggesting that differentials between two crudes of a given difference in API will increase very slightly at higher crude prices.[6]

2.8 Crude oils have a large number of other chemical and physical differences in addition to API and sulfur content, and Wang tested for the additional impact of viscosity, pour point, and Reid vapor pressure on the prices of crudes. He concluded that simple gravity and sulfur-based valuation methods could be improved by adding more quality variables, and that the price differentials among crude streams in the world market are primarily linked to their quality differentials.

2.9 An important recent development in the international crude market is the arrival of substantial amounts of high acid crudes. Crudes with a Total Acid Number (TAN)[7] of 1.0 mg KOH/g or more are conventionally labeled as High TAN, and such crudes are projected to take an increasing share of the rising volume of global oil production. Already some 5 million barrels a day of Atlantic basin crudes are high TAN, and these are sold at a discount to marker crudes that can be substantial. A country such as Chad, which exports only Doba blend crude with a TAN value of about 4.80 mg KOH/g, is substantially affected by this market development. Processing acidic crudes creates corrosion issues to refinery equipment and requires special and expensive technical solutions. Mitigation of process corrosion includes blending, inhibition, material upgrading, and process control. Very few refineries are presently able to refine high TAN crudes, so that most refiners need to blend them with other crudes before refining. Given that crude is purchased in large parcel sizes, the need to blend one such parcel with multiple parcels of low TAN crudes is costly and worthwhile only if there is a substantial discount available for the high TAN crude. Those few refineries which can process high TAN crudes are then able to benefit from the existence of the price discount.

2.10 All the above formal analyses of the impacts of quality differentials on price differentials are based on the implicit hypothesis that the presence of a given set of differences between the qualities of two crudes will result in a fixed price differential between them. However, analysts of the oil industry, such as Cook (1998) and BMO (2004) have also noted that for pairs of crudes there is a tendency for the differential to widen as the general price level of crude increases. The sharp increase in the general level of crude prices dating from late 2003 has seen the differential between light (high API) and heavy (low API) crudes, and between sweet (low sulfur) and sour (high sulfur)

[6] Analysts of crude markets always focus on the absolute differences in crude prices, since this is measured in $ per barrel and gives an indication of economic opportunities.

[7] The TAN of crude oils is an accepted measure of potential corrosivity: it quantifies the number of milligrams of potassium hydroxide (KOH) needed to neutralize one gram of sample crude oil. The acidity of a crude oil has important economic and technical impacts on refining operations. A TAN exceeding 1 mg KOH/g is commonly considered corrosive; however corrosion problems can occur in crudes with TAN as low as 0.3 for several reasons including velocities and the nature of acidic species present.

crudes widen.[8] Such differentials depend on a number of factors, including the demand for various petroleum products, the costs and availability of refineries able to run various crudes to produce the products most in demand, refinery capacity utilization, transportation costs, and the relative supply of the different crudes. If the demands for all petroleum products increased proportionately, and all product prices and the general crude price also increased proportionately, then those crudes producing the largest proportion of high value products would increase in price relative to those crudes with a lower proportion of high value products. This effect would be magnified if the demand for the higher value products increased relatively more, so that the price of high value products rose faster than that of low value products.

2.11 At the same time, the costs of refining and the availability of refineries able to produce high value products can be important. Crudes with high sulfur content are more corrosive and require more expensive process mitigation measures. Sulfur and sulfur compounds are undesirable impurities for the environment and may pose health and safety hazards. For these reason, limits on the sulfur content of hydrocarbon products are set by national and international standard specifications. These are often backed by legislation, as is the case in many industrialized nations, including the EU member states, the United States and Japan. Shortage of refining capacity able to produce these low sulfur products gives an extra premium to those crudes which do not need the most expensive treatment.

2.12 Although over long periods the average API number of all crudes produced has not noticeably changed, recently the response of OPEC, especially Saudi Arabia, to increase production has been possible only through increasing production of heavier, sour crudes. Changes in the supply mix influence differentials, and their effect is amplified when they do not match changes in the demand mix.[9] Given that the increase in demand has been mainly driven by transportation fuel, the higher proportion of heavier, sour, crudes on the market has increased the differential between the light and heavy crudes, and that between sweet and sour crudes. The limited availability of refinery spare capacity has also recently been highlighted as a factor in determining overall crude price levels. In general terms if capacity is extremely tight then a disruption of refining availability or further increase in demand will lead to a bottleneck situation in which the most valuable crudes will be run first, and the least valuable would be marginalized, leading to a yet further widening of differentials. Once capacity becomes sufficiently tight then the fear of such a situation will already make itself known through crude pricing as the markets build in a risk premium.

[8] Light, sweet crude oils contain a higher percentage of low boiling point materials than heavy crude oils and therefore more gasoline and distillate (high value products) can be produced from these crude oils without needing expensive upgrading equipment. In addition, the low sulfur content diminishes the need for expensive sulfur removing processes. As a result, light, sweet crude oils are considered high quality crude oils, and they command a price premium over the heavier, sour crude oils.

[9] Horsnell (1990).

2.13 Based on these arguments it appears that any statistical modeling of crude price differentials based on quality differentials should incorporate an effect to allow the quality differentials to widen as the market becomes tighter, which can be modeled by creating interaction variables between the Brent price (standing for the general level of crude prices) and quality differentials.

3

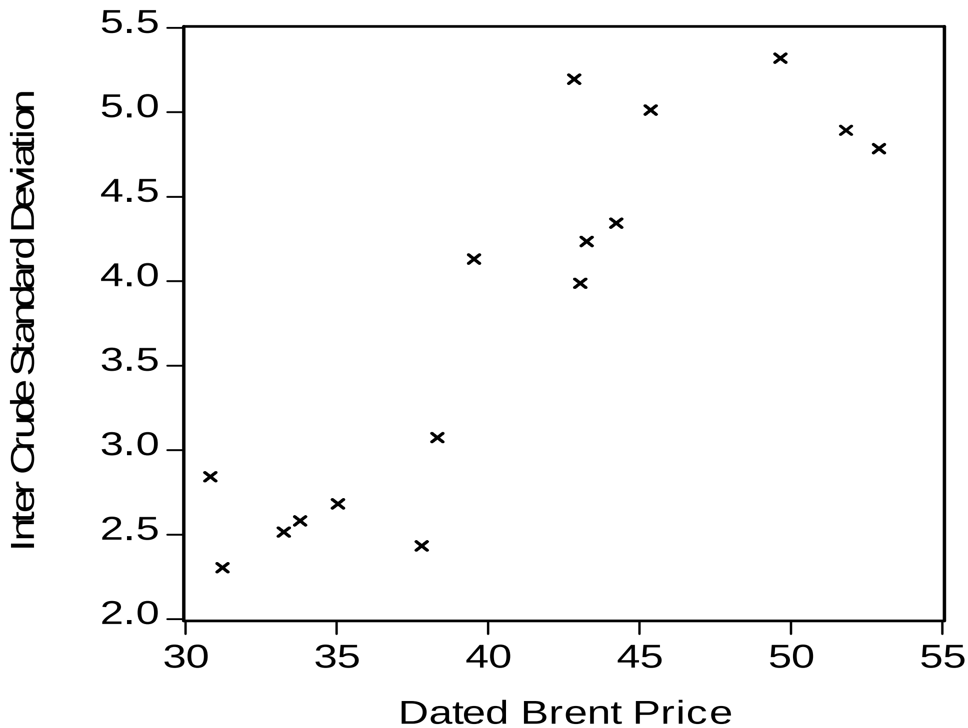
The Statistical Analysis of Crude Price Differentials

3.1 The present study is based on a set of monthly average prices for 56 different crudes for the period January 2004 to April 2005[10] (see Annex for the list of crudes). This period represents recent experience in the global market for crudes, but is not extended back beyond the beginning of 2004 because of the fundamental change in the market situation that has occurred with a very rapid increase demand for certain products and hence for certain high quality crudes. As a preliminary to the main regression, estimates of the inter-crude standard deviation of these prices was calculated for each month for the set of crudes used in the study, to give a measure of the extent to which differentials have widened over the period. The standard deviation ranged between US$2.31 in January 2004 and US$5.32 in October 2004, and the plot of the standard deviation each month against the dated Brent price for that month is shown in figure 3.1.[11] The squared correlation between the two series is 78 percent, and the regression indicates that every dollar increase in the Brent price is associated with a 14 cents increase in the inter-crude standard deviation, giving strong support to the observation that differentials systematically and substantially widen as the general crude price level increases.

[10] With the exception of the Gulf war period, the oil price has been relatively stable around US$18/bbl to US$30/bbl since the mid 1980s. From the start of 2004 the price moved out of this range, reaching US$52/bbl in April 2005. Although oil price volatility is a normal feature of this commodity, the new range marked a paradigm shift in the market, i.e. a permanent rather than transient change. For a detailed analysis of the reasons behind the new oil price level see IMF (2005).

[11] A similar calculation based on a set of 46 crudes for which data was available back to January 2000, showed a similar picture, and there were many months where the inter crude standard deviation of prices was about one dollar, corresponding to periods when the Brent price was around US$20, indicating that even a few years ago the inter crude spread tended to be small and crude prices were generally close to each other.

Figure 3.1: Monthly Inter Crude Price Standard Deviation and the Dated Brent Price January 2004–April 2005 (US$ per barrel)



3.2 The model as estimated in this report uses Brent blend as the crude against which other crude prices are compared for the impact of quality differentials between themselves and Brent. It is also assumed that over the time period used, the quality coefficients do not change. By confining the analysis solely to a period of rapidly rising demand for lighter products the coefficients are expected to be fairly stable, despite an almost doubling of the Brent price.

3.3 In this report the price differentials between the 56 crudes and Brent crude are related to quality differences in API, sulfur and TAN of the individual crudes and Brent.[12] Because it is generally accepted in the industry that low levels of TAN (below around 0.5)[13] do not generally present refiners with corrosion problems, a nonlinear formulation is used for the TAN differential from Brent (which itself has an extremely low TAN at 0.07). This is done by creating a variable for "excess" TAN, which takes the value of 0 if the difference in TAN between the crude in question and Brent is less than

[12] Brent is a fairly high quality crude, with high API, and low sulfur and TAN. Accordingly, many crudes, being lower quality on one or more of these measures would be expected to sell at a discount to Brent. However, there are crudes with higher API than Brent, and with rather similar sulfur and TAN, and these would be expected to sell at a premium to Brent.

[13] The report recognizes that more accurate correlation exists between the naphthenic acid number (NAN) and corrosivity. However, NAN was not available for a significant number of crudes in the sample.

0.5, and otherwise takes the actual difference in TAN (eleven crudes were in this category).

3.4 The evidence presented above confirms that the general inter-crude price spread has systematically widened over this period as the general crude price has risen. The matches the previous argument that the effect of given quality differentials will become more important as the general oil price rises, and this effect is tested by including regression variables that are the product of the Brent price and the quality differentials.[14] The model becomes of the form:

$$\mathbf{\Delta\ price_{jt} = a + \Sigma_i\ bi\ (p_{Bt}{*}\Delta\ quality_{ij})} \qquad \mathbf{(2)}$$

Where $\mathbf{p_{Bt}}$ is the price of Brent blend in period t.

3.5 The basic quality differential model (2) is augmented by a number of additional variables, which include:

1. ***Transport costs and regional effects.*** Since every crude is being compared to Brent blend, an allowance for the transport cost between the region of the crude and NW Europe is included. If these crudes have to compete with Brent in its own market then the full effect of these transport costs would be expected to impact the price differential.[15] Hence, depending on the region of production of the crude in question (Africa, Asia, the Middle East, the Americas, or Europe) the relevant monthly transport cost per barrel to Europe is introduced, thus normalizing all price differentials to Brent, and allowing for changes in the costs of transportation over time and between regions. Also, to allow for an additional specific regional differential, which observers have claimed to notice for Asian crudes (Ogawa 2002), regional dummy variables are introduced for each of the above regions, which would allow the prices of all crudes common to a region to have an extra discount (or premium) to Brent, once their quality characteristics have been allowed for.

2. ***Refinery capacity utilization.*** As argued above, when refinery capacity utilization becomes tight, especially with respect to the ability to process low quality crudes, these crudes would be expected to face a deeper discount to a high quality crude such as Brent. Without data on the specific refineries to which each crude is sent, it is not possible to make a direct test of the impact of available capacity on specific differentials, but two proxy variables are introduced to test for impacts of refinery capacity utilization on prices. The first is an index of global capacity utilization

[14] Although qualities of some crudes, notably blends, may have changed even over the 16 month period analyzed, there is no data available on this feature, so that the estimated model assumes quality differentials are unchanged over the period.

[15] This approach implicitly endorses the hypothesis that world oil markets are "globalilized" and that opportunities for arbitrage between crudes, allowing for quality differentials, have been utilized, so that the only ex quality differentials between them should relate to the transport costs.

which would impact all differentials equally at one point in time, while the second formulation is the product of the refinery capacity index and the difference in API, which would allow the capacity utilization effect to vary with the API of the specific crude considered (relative to Brent). The measure of refining capacity, on which the utilization figures are based, is the OECD total and so does not represent exactly the total world picture, and it also does not distinguish between different types of refining capacities.[16]

3. ***Dynamic adjustment.*** In order to allow for partial adjustment to changing prices, the lagged price differential is included. The variables in the model which change over time, and hence would be able to explain that price differentials can change over time, are the price of Brent multiplied by the quality differential, the transport cost and the refinery capacity utilization. The lagged differential will capture the extent to which a change in one of these dynamic variables is not fully and immediately reflected by the crude in question, but rather only after a delay. The model assumes that the speed of adjustment is the same for all crudes.

4. ***Monthly seasonal effects.*** Oil prices and differentials may show some seasonal variation, and this was tested for by including monthly dummy variables common to all crudes. Effectively this will pick up any extra differential to Brent in a given month common to all crudes.

3.6 The model is estimated[17] as a pooled time series cross section, with 894 observations, in which the parameters are assumed to be constant over time and between crudes.[18]

3.7 The data for the monthly average crude prices were taken from Platts Price Average Supplement and from Bloomberg Daily Wire. In every case data were taken to be as near to spot prices as possible (for example, dated Brent, and first month for other crudes where forward prices are also quoted). Quality characteristics were taken from a variety of internet sources and from the International Crude Oil Market Handbook. Some of the values for the quality variables are taken from assays that were undertaken several years ago, and it is possible that the quality of certain crudes has altered since the assay was published. This is particularly an issue for blends, where variations in the streams from different sources can result in changes in the composition of the blend.

[16] The type and complexity of available refining capacity greatly affects price differentials among crudes and products. Each refinery has a unique set of characteristics (configuration, scale, efficiency, nature of crude processed, location) that allow the refinery to produce a particular slate of products from a particular crude oil input at a particular cost. Refining capacity is not easily substituted. For example, the war in Kuwait not only produced a shock to supply, it also deprived the market from the use of complex and sophisticated hydrocracking facilities able to produce a slate of lighter products.

[17] Estimation is by Generalized Least Squares using cross section weights, so that error variances for different crudes are not assumed to be equal.

[18] A simpler version of this model was given in Bacon and Tordo (2004).

Unfortunately there is no published information relating to systematic changes in assays, so that the published data have to act as a proxy for current qualities.

3.8 The crudes included in the study cover a wide range of qualities and can be taken as representative of all but the most extreme cases. For API the lightest crude is Griffin (55.1) while the heaviest is Marlim (20.1); for sulfur the sweetest crude is Belida (0.02) while the sourest is Lloyd blend (3.5); and Duri (1.27) is the most acid crude as measured by its TAN, while many crudes are below the 0.5 excess TAN threshold.

3.9 Transport costs per barrel between the producing regions and North West Europe are taken from The Oil and Gas Journal, and refinery capacity utilization data are taken from the IEA's Monthly Oil Market Trends.

4

Estimates of the Magnitude of Quality Differentials

4.1 The model is run in two forms. Model 1 includes all variables, including the price multiplied by quality differentials and the quality differentials separately, the transport costs, the regional dummy variables, all seasonal dummy variables, the refinery capacity utilization multiplied by the difference in API for each crude, and the lagged discount term. The results are shown in table 1 (excluding the seasonal dummy variables and the insignificant regional dummy variables). The results indicate that the variables built from quality differences multiplied by the Brent price, are of the correct sign and are statistically significant for API and sulfur, while the separate variables measuring just the quality differentials are insignificant for all three qualities. The refinery capacity utilization variable is also insignificant, as are the regional dummies, except for the one relating to the crudes produced in Asia. The seasonal dummy variables are insignificant for March, May, August, and October, while that for November has a large and significantly positive value. The equation is re-estimated (model 2) dropping the three quality variables in their basic form, the refinery capacity utilization, the insignificant regional dummy variables, and the insignificant seasonal variables. In this form all three price adjusted quality variables are of the expected sign and significance, as are the transport costs, the remaining seasonal dummies, and the regional dummy for Asia. In both models the lagged discount variable is highly significant indicating that, following a change in an independent variable, primarily the Brent price level, discounts do not immediately settle to a new equilibrium value, but rather adjust over time as the market becomes fully aware of the new situation. The overall goodness of fit is very high which supports the hypothesis that different crude prices are indeed linked by quality differentials, and that omitted factors are not dominant.

4.2 An alternative formulation introduced the forward price of Brent multiplied by the quality differentials to test whether expectations of future market developments were more important than current prices in determining current inter-crude price differentials. The results from this version of the model gave similar, but slightly less significant, results to the model using the current price of Brent, and so are not reported separately.

Table 4.1: Regression of Price Discounts to Brent on Quality Differentials*

Variable	*Model 1*	*Model 2*
Intercept	0.741 (1.89)	0.716 (2.98)
Price × API difference	0.00267 (2.23)	0.00166 (6.39)
Price × sulfur difference	-0.0321 (2.68)	-0.0133 (5.70)
Price × excess TAN	0.0080 (0.36)	-0.0122 (2.91)
Africa freight rate	-0.619 (4.09)	-0.591 (4.64)
America freight rate	-0.386 (4.50)	-0.361 (5.50)
Asia freight rate	-0.889 (9.15)	-0.849 (11.02)
Middle East freight rate	-0.473 (5.11)	-0.444 (6.07)
Europe freight rate	-0.469 (5.18)	0.0446 (6.39)
Asia dummy variable	1.003 (3.65)	0.957 (3.62)
Lagged price discount	0.753 (33.26)	0.761 (34.37)
API difference	-0.133 (0.31)	
Sulfur difference	0.778 (1.58)	
Excess TAN	-0.849 (0.92)	
Refinery utilization × API difference	0.00105 (0.22)	
R squared	0.884	0.885

* Numbers in brackets are "t" statistics, which measure the degree of statistical significance of the coefficients.

4.3 The size of the quality coefficients are measured in quality units per dollar of Brent: taking the long run equilibrium values,[19] model 2 estimates that each degree of API raises the price US$0.007 per dollar of Brent; each additional one percentage point of sulfur lowers the price US$0.056 per dollar of Brent, and each additional unit of TAN lowers the price by US$0.051 per dollar of Brent. Hence, for example, at a Brent price of US$40 a barrel, a crude with 10 degrees API lower than Brent, all other factors being identical, would sell for US$2.80 less than Brent; a crude with one percentage point more sulfur than Brent, all other factors being identical, would sell for US$2.24 less than Brent, and a crude with excess TAN of one unit would sell for US$2.04 units less than Brent. Since these factors are all proportionate to the Brent price, the effects would be halved at a Brent price of US$20 a barrel, and would be 50 percent greater at US$60 a barrel. All three quality variable are not only statistically significant but are also qualitatively important at the ranges of qualities experienced and Brent prices prevailing in the recent past. The estimates are broadly similar to those obtained by Wang if evaluated at a price of around US$20 a barrel, which was the level prevailing at the time of his analysis in 1992. The model is then consistent with observations that the light/heavy spread, the

[19] These are calculated by taking the regression coefficient of the quality variables and dividing them by a value of one minus the lagged discount coefficient.

sweet/sour spread, and the high TAN/low TAN spread all widen as the general crude price level rises.

4.4 The transport cost effects are all small but strongly significant. A striking finding was that all crudes originating from Asia sold at a premium of around one dollar, once all other factors had been taken into account, which is consistent with the observation that consumers in the Asian market tend to pay more than consumers elsewhere for identical crudes.

5

Making Estimates with the Model

5.1 A further test of the model 2 was undertaken by performing an out of sample set of backcasts for a set of five crudes for which assay data was not originally identified, so that they were not included in the original estimation data set. Using the estimated model and actual Brent prices, the estimated values of the discounts were calculated for each month from January 2004 to April 2005. Table 5.1 shows the average monthly actual and estimated discounts to Brent. The average estimation errors are all small, with the exception of Oriente, where the model did not estimate a deep enough discount to Brent. The average estimation error for Soudieh, which is sold at a very large discount to Brent, is extremely small. The large differential reflects the fact that it is a heavy crude (API 24) and is sour (sulfur 3.9), both of which are expected to become increasing disadvantages as the general crude price level rises. The accurate estimation of the differential for an extremely low quality crude, such as Soudieh, from a set of data which did not include it, gives strong support to the approach used.

Table 5.1: Average Estimation Errors for Five Out of Sample Crudes (January 2004–April 2005) in US$ per barrel

	Brent blend	*Kumkol*	*Oriente*	*Sahara blend*	*Soudieh (Syrian Heavy)*	*Soyo*
API	38.3	42.5	24.0	45.7	24.1	33.7
Sulfur	0.37	0.07	1.50	0.10	3.90	0.23
TAN	0.07	0.05	0.25	0.05	0.17	0.07
Average actual differential	-	0.14	-8.67	0.11	-11.51	-0.28
Average estimated differential	-	0.51	-7.74	0.68	-11.23	-0.40

5.2 A more severe test of the model is given by the case of the Doba blend from Chad. In the fall of 2003, Chad started to produce oil from one field, the Miandoum. Miandoum is a viscous oil with API gravity of around 25 degrees, low sulfur (0.11

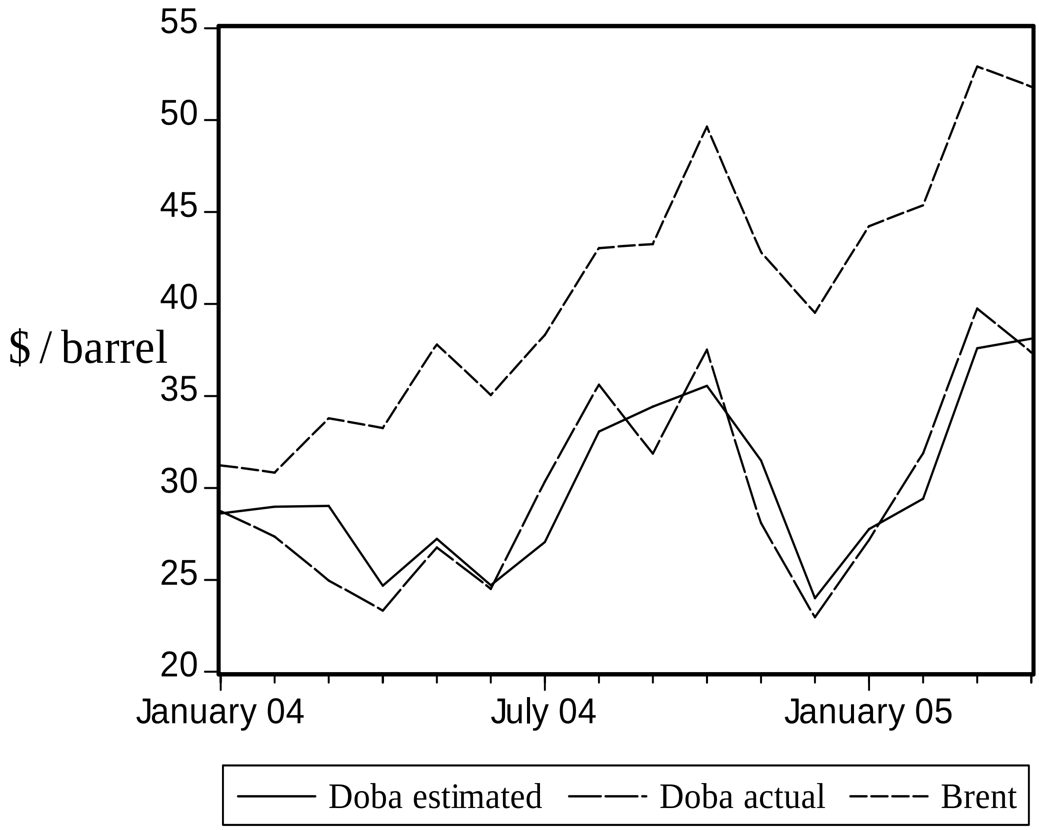
percent by weight), and a moderate acidity level (TAN around 0.28 KOH/mg). In the spring of 2004, a new field (Kome) came on stream, and the Doba blend began appearing on the market. Oil produced from the Kome field is substantially more viscous, with a higher calcium content, lower API gravity (approximately 19 degrees) and a substantially higher TAN. A third field came on stream in August 2004 and the characteristics of the blend improved slightly. Presently Doba is a heavy (API gravity around 20.6°), low sulfur, high acid (approximately 4.7 KOH/mg) blend. Compared to the other crudes in the data sample used in the modeling exercise, or indeed to virtually any other crude marketed in substantial quantities, this blend has an unusually high TAN. Refining such a blend poses considerable technical problems and only a few refineries are able to run it without substantial blending.

5.3 Initially, Doba sold at a discount of approximately US$2 a barrel to Brent, which was entirely expected due to its then quality differential. At the beginning of 2004, the oil market was starting to tighten up due to an increased demand for transportation fuel, which pushed the general price level up and increased the price differential between "light" and "heavy" products. The joint effect of a demand driven price increase and of the sharp change in the quality characteristic of the Doba blend, affected the magnitude of the discount to Brent, which averaged US$9 a barrel in 2004 and widened further in the first quarter of 2005 to stabilize at around US$13 a barrel below the Brent price (average US$52 a barrel) during the second quarter of 2005 as illustrated in Esso Exploration and Production Chad (2005). The price behavior of such a crude was difficult to estimate without reference to some model, and especially a model which could incorporate the effects of the substantial increase in acidity over the period.

5.4 Model 2 was used to make a backcast of the monthly Doba blend prices for the period January 2004 to April 2005. An important aspect of this set of estimates is that the three quality indicators, which changed over time, were available on a month-by-month basis, so that the estimated discount to Brent would widen as the qualities worsened.

5.5 Figure 5.1 plots the price of dated Brent, the actual average price of Doba and the estimated average price of Doba. The estimates on average follow the actual price of Doba Blend extremely closely, with the average monthly tracking error for the 16-month period being 20 cents a barrel too high. Two features of the estimates stand out. First, as the price of Brent rose during the period, the actual discount of Doba to Brent widened considerably, and the model was able to track this well. This indicates that the model variables formed from the interaction of the quality differences between crudes and the general price level were successful in accounting for the widening of differentials, even in this extreme case. Second, the one period when the model was not successful was February to March 2004. In February qualities had not yet deteriorated, but it was known that oil entering the pipeline for later delivery would be substantially lower in quality, and it is possible that the uncertainty surrounding the quality of the Doba blend and its implications for refinery operations made it difficult to find buyers, so that an unusually large discount emerged to cover the unknown risks. Once the blend stabilized and its quality became better known and understood, its pricing behaved very much as that of other crudes, in terms of the allowances for the low API and extra high TAN.

Figure 5.1: The Price of Brent Blend and Doba Blend and the Model Estimation of the Price of Doba Blend



6

Conclusions

6.1 This report investigates the relationship between price differentials of a large number of different crudes and the Brent price. It finds that three quality variables—API, sulfur, and TAN—have important impacts of the size of the differential and that the magnitudes of these effects are proportionate to the general crude price level. This finding helps explain why the inter-crude variation of prices has increased with the general crude price level. Transport cost differentials between markets were also found to play a small but significant part in determining the differentials. There are also small seasonal differences common to all differentials on a month-by-month basis. An attempt to identify whether refining capacity utilization play a significant role in explaining differentials was unsuccessful, but this may be due to data and information limitations, since the only global index available was for the OECD and treated all refinery configurations equally. Finally there was a small premium for Asian crudes, which could not be explained by any of the other factors included in the analysis, but was consistent with the results of other researches in this area.

6.2 The model performs well statistically, with significant t statistics and a high multiple correlation coefficient. An out of sample backcasting test for an additional set of five crudes also produces small average errors in the estimation of the discounts. The model also estimates accurately the discount of a new crude, the Doba blend, suggesting that its large and widening discount to the Brent blend is entirely consistent with what happened to other crudes during the same period of time, once allowance is made for the significant acidity and low API of the blend.

References

Bacon R. and S. Tordo (2004). "Crude Oil Prices: Predicting Price Differentials Based on Quality." Viewpoint 275, Private Sector Development Vice Presidency, The World Bank.

BMO Commodity Derivatives Group (2004). "Managing Heavy Oil Price Risk." corporate.bmo.com/cm/market/cdcom/images/Managing_Heavy_Oil_Price_Risk.pdf.

Cook J. (1998). "California Crude Oil Prices". www.eia.doe.gov/pub/ .

Energy Intelligence Group (2004). *International Crude Oil Market Handbook.*

Esso Exploration and Production Chad (2005). "Chad Export Project: Project Update Number 18."

ExxonMobil (2001). "Quality bank policy applying on crude petroleum from points offshore Texas to points onshore Texas." *F.E.R.C.*, 102.

GE Water Technology (2004). *A complete approach to corrosion control with opportunity crudes.*

Gülen, G.S (1997). "Regionalization in the World Crude Oil Market." *The Energy Journal*, 18(2): 109–126.

Gülen, G.S. (1999). "Regionalization in the World Crude Oil Market: Further Evidence." *The Energy Journal*, 20(1): 125–139.

Hartman, J.C.M. (2003). "Crude valuation for crude selection." *Petroleum Technology Quarterly,* Winter 2002/03, 123–127.

Horsnell, P. (1990). "Oil price differentials: markets in disarray" *Oxford Institute for Energy Studies*.

International Monetary Fund (2005). *Oil Market Development and Issues*.

Kohli, U. and E. R. Morey (1990). "Oil characteristics and the U.S. Demand for Foreign Crude by Region of Origin." *Atlantic Economic Journal*, 18(3): 55–67.

Kleit, A. N. (2001). "Are Regional Oil Markets Growing Closer Together? An Arbitrage Cost Approach." *The Energy Journal*, 22(2): 1–15.

Lanza, Alessandro, Matte Manera and Massimo Giovannini (2003). *Oil and Product.*

Price Dynamics in International Petroleum Markets.. Nota Di Lavoro, 81. Fondazione Eni Enrico Mattei.

Ogawa, Yoshiki (2002). *Proposals on Measures for Reducing Asian Premium of Crude Oil.* Presented at Institute of Energy Economics of Japan, 375th regular research meeting.

Ruschau, G.R. and Al-Anezi, M.A. (2001). "Oil and Gas Exploration and Production: Corrosion and Prevention", in: *Corrosion Costs and Preventive Strategies in the United States, Appendix S*, U.S. Department of Transportation.

Ruschau, G.R. and Al-Anezi, M.A. (2001). "Petroleum Refining: Corrosion Control and Prevention", in: *Corrosion Costs and Preventive Strategies in the United States, Appendix U,* U.S. Department of Transportation.

U.K. Department of Trade and Industry (2005). *U.K. Process Plant Capability: Removal of Sulphur from Oil and Gas Fuels and Sulphur Recovery.*

Wang, Z. (2003). "Hedonic prices for crude oil." *Applied Economics Letters* (10): 857–861.

Weiner, Robert J. (1991). "Is the World Oil Market 'One Great Pool?" *The Energy Journal*, 12(3): 95–107.

Annex 1

Crudes Included in Estimation and Testing by Country of Origin

Abu Dhabi	Lower Zakum	***Indonesia (continued)***	Cinta
	Murban		Duri
Algeria	Sahara blend		Handlil
Angola	Cabinda		Minas
	Palanca	***Iran***	Forozan
	Soyo	***Kazakhstan***	Kumkol
Argentina	Canadon Seco	***Malaysia***	Tapis blend
	Escalante	***Mexico***	Isthmus
	Medanito		Maya
Australia	Cossack		Olmeca
	Gippsland	***Norway***	Ekofisk
	Griffin		Flotta
	Jabiru		Oseberg
	Thevenard		Statfjord
Azerbaijan	Azeri light		Troll
Brazil	Marlim	***Oman***	Oman
Cameroon	Kole	***Papua New Guinea***	Kutubu
Canada	Hibernia	***Qatar***	Qatar Marine
	Lloyd blend	***Russia***	Urals
	Terra Nova		Siberia light
Colombia	Cusiana	***Saudi Arabia***	Arab heavy
	Vasconia		Arab light
China	Nanhai	***Syria***	Syrian light
	Shengli		Soudieh
Congo (B)	Djeno	***United Kingdom***	Brent blend
Dubai	Fateh		Forties
Ecuador	Oriente	***United States***	Alaska north slope (ANS)
Gabon	Mandji		Mars blend
Indonesia	Attaka		West Texas Intermediate (WTI)
	Ardjuna	***Vietnam***	Bach Ho
	Belida		