Risk Arbitrage Opportunities in Petroleum Futures Spreads

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This article investigates the long-term pricing relationship among crude oil, unleaded gasoline, and heating oil futures prices, and finds that these commodities futures prices are cointegrated. The study finds that the spreads between crude oil and its end products are stationary. Furthermore, this article investigates the risk arbitrage opportunities in three types of popularly traded petroleum futures spreads and finds that historically profitable risk arbitrage opportunities existed and were statistically significant. However, one cannot be certain that these opportunities still exist. The research also finds that moving averages are valid test variables for measuring spreads. Statistical and tabular constructions are used to illustrate findings. © 1999 John Wiley & Sons, Inc., Jrl Fut Mark 19: 931–955, 1999

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INTRODUCTION

Girma and Paulson (1998) show that certain petroleum futures spreads exhibit a strong seasonality. This was especially true for 3:2:1 crack spread (3 contracts crude, 2 contracts of unleaded gasoline, and 1 contract of heating oil), 1:1:0 gasoline crack spread (1 contract of crude oil and 1 contract of unleaded gasoline) and 1:0:1 heating oil crack spread (1 contract of crude oil and 1 contract of heating oil). Buying (selling) the spread at a seasonal low and holding for a specified time period was profitable, although the number of potential trades is limited. Oil producers and refiners can and do trade petroleum futures spreads to hedge their respective anticipated cash positions or to enhance operating profitability well beyond seasonal consideration. Similarly, speculators can trade petroleum futures spreads to profit from temporary relative mispricing between crude oil and its major refined products. These risk arbitrage opportunities, if and when they occur, are not likely to be available for extended periods of time because arbitrageurs will buy the cheaper commodity and sell the expensive commodities until the spreads are within "normal" range.

Economic theory suggests that relative mispricing between input prices and output revenue could exist for short period of time, but prolonged mispricing will force the producers (refiners) to cut production, and therefore supply of end products, until output revenue and input prices are in long-term equilibrium. Therefore, economic theory leads us to believe that there is a long-term pricing relationship between input prices and output revenue where the spread will tend to converge to the long-term average. Cointegration theory is extremely useful in estimating and testing long-term equilibrium relationships among nonstationary asset prices and allows one to make a valid statistical inference. Several studies have used theory of cointegration to test for long-run economic relationships between two or more asset price series in different financial markets. For example, in petroleum futures market Moosa and Al-Loughani (1995) and Crowder and Hamel (1993) investigated the relationship between crude oil futures and spot prices, using monthly observation, and find that crude oil spot and futures prices are cointegrated. Similarly, Schwarz and Szakmary (1994), using daily crude oil, heating oil, and unleaded gasoline futures and spot prices, find that the petroleum spot prices are cointegrated with their respective futures prices. Other studies in unrelated financial markets include, to list few, nonferrous metal, Chowdhury (1991); foreign currency, Lai and Lai (1991); treasury futures spreads, Park and Switzer (1996); and gold-silver spot and futures spread, Wahab, Cohn and Lashgari (1994).

This article investigates several underlying long-term economic and statistical relationships among petroleum futures spreads. Petroleum futures spreads may have provided, at least in the past, significant risk arbitrage opportunities for traders. Profitable spread trades or risk arbitrage situations, if any existed, will be found at the extremes. This study extends the existing research in petroleum futures in several important ways. First, cointegration theory is used to investigate several underlying long-term economic and statistical relationships among petroleum futures prices—specifically crude oil, unleaded gasoline and heating oil futures prices. Second, this research develops a methodology based on moving averages to identify extremes in petroleum futures spreads and develop trading strategies based on these extremes. Third, the methodology uses extremes as a basis to explore forms of risk arbitrage in relation to crack spread, in particular 3:2:1 crack spread, 1:1:0 gasoline crack spread, and 1:0:1 heating oil crack spread. Finally, the article assesses the profitability and risk-return relationship of the trading profits.

Our results are all positive. There are strong long-term relationships among the three spreads, these relationships justify the use of moving averages to measure the character of the spreads and to identify extremes in the spreads, and these extremes lead to profitable risk arbitrage opportunities in the spreads. The findings of this article are considerable interest and importance to refiners and retailers who routinely want to hedge both the input price and output revenue to lock in their profit margin. It is also important for refiners and retailers who only want to hedge their positions selectively when they believe the crack spreads represent an attractive opportunity to lock in a higher profit margin. Finally, risk arbitrageurs or speculator who are trading the spread to exploit relative mispricing. Traders can generate profits, and refiners and retailers can hedge their positions more effectively. Therefore, the findings of this paper are important to practitioners and researcher.

Spread trading provides risk arbitrage opportunities when relative mispricing occurs among related commodity futures prices. Spread trading can also be used as a risk management tool. Refiners and retailers can hedge their positions effectively through the use of spreads. Schrock (1971) was among the first to theoretically justify, using the mean-variance approach, that spread trading and straddles are risk management tools. He showed that it was rational to hold futures contracts that may have negative return in a portfolio as long as it reduced the overall risk of the portfolio sufficiently. Poitras (1989) derived an optimal condition for spread traders by assuming a trader maximizes his expected utility function that is defined over the mean and variance of the spread. In addition, he demonstrated that the optimal hedge ratio is independent of a trader's attitude towards risk; although, the optimal cash and futures positions are dependent on traders' risk preferences.

The literature on intercommodity spread trading is not large because intercommodity spread relationships are complex. There is consequently a lack of firm theoretical foundations to explain the behavior of these spreads. For this and other reasons,a number of researchers have conducted empirical studies to determine if there are profitable trading opportunities in intercommodity spread trading. Some of these studies included: treasury bills and treasury bonds (Jones, 1981; Easterwood and Senchack, 1986), gold (Rolfo, 1981), gold and Eurodollar turtles (Poitras, 1987), gold and T-bill spreads (Monroe & Cohn, 1986), municipal bond and treasury bond (Arak, Fischer, Goodman, & Daryanani, 1987), index futures (Billingsley & Chance, 1988), soybean complex spread (Johnson, Zulauf, Irwin, & Gerlow, 1991), gold-silver spread (Wahab, Cohn, & Lashgari, 1994), spreads in agricultural futures (Barrett & Kolb, 1995) and treasury futures spreads (Park & Switzer, 1996).

Monroe and Cohn (1986), for example, investigated the relative efficiency of gold futures to T-bill futures. They used a 60 trading day moving average of the difference between the implied gold rate and T-bill rate and the corresponding standard deviation. Appropriate positions will be taken when the difference moves outside of the average plus or minus one standard deviation with the expectation that it will return to the average. Their investigation revealed that between 1976 and 1982 there was a significant mispricing of gold futures relative to T-bill futures. They consistently generated positive profits net of transaction costs sufficient for a public trader to achieve positive returns. Poitras (1987) also investigated the spread between the implied gold rate and the Eurodollar rate using different trading strategies. He concluded that there were many profitable opportunities, especially for large traders with the means to monitor relevant market behavior for profitable trades.

More recently, Johnson, Zulauf, Irwin, and Gerlow (1991) studied the soybean complex spread, in particular the "crush" spread ("crush" spread is the spread between soybeans and soybean products, soybean meal, and soybean oil), covering the periods 1966–1988. Their trading strategy was to go long on the "crush" spread if the implied profit margin is positive and take a reverse "crush" spread if the implied profit margin is less than zero. Their trading length was 1.5 months to 9.5 months from maturity. They found that a trading strategy based on a trading length of 5.5 months or greater leads to significant profits exceeding transaction costs, and that trades based on trading length of less than 5.5 months were unprofitable. Finally, they concluded that traditional or routine hedges of the soybean complex will be unprofitable, and that selective spread trading strategies can increase the average return or reduce the variability of returns, or both, compared to a routine hedging strategy or an unhedged cash position. Here, selective hedging of the soybean complex might be more accurately described as risk arbitrage between input cost and revenue generated from the output.

DATA

The data used in modeling and testing the crack spread relationships consist of daily futures prices of crude oil and heating oil contracts from April 1983 to December 1994, and the unleaded gasoline contracts are from December 1984 to December 1994. Unleaded gasoline futures contracts began trading at the NYMEX in December 1984. "3:2:1 Crack Spread" relationships and trading results are based on data from December 1984 through December 1994. Similarly, "1:1:0 Gasoline Crack Spread" relationships and trading results are based on data from December 1984 through December 1994. Finally, the "1:0:1 Heating Oil Crack Spread" relationships and trading results are based on data from April 1983 through December 1994. Our data source is Dow Jones Information Services.

First, a single time series used to analyze the unit root and cointegration properties of crude oil, unleaded gasoline, and heating oil is created by taking daily closing prices for one month from each contract that is deliverable in two months. Specifically, for each trading month the daily closing prices are collected from a contract that is deliverable in two months; and on the first day of the next trading month it will be rolled over to the next contract that is deliverable in two months. For example, if the trading month is February, the daily closing prices would be collected from the contract that is deliverable in April, and on the first day of March it will be rolled over to the contract that is deliverable in May. The choice of two-month contracts provides a high degree of liquidity and at the same time avoids the volatility known to exist when futures contracts reach their delivery month. On the other hand, all traded crack spreads contract month data are used to develop the moving average methodology to identify extreme spreads and trading strategy. Using all traded crack spread contract months would provide more information and reduce the length of the moving average window. This would also be consistent with how traders or speculators and hedgers will do in reality—that is, observe all traded contract month spreads to get as much information as possible to identify relative mispricing. Throughout this article the contract month refers to the delivery month of the contract; for example, the April 1992 crude oil contract refers to the crude oil contract that is deliverable in April 1992.

Because crude oil prices are quoted in terms of dollars per barrel, whereas unleaded gasoline and heating oil prices are quoted in terms of dollars per gallon, it is necessary to convert all three quotations into the same unit of measure. Therefore, all prices are measured in dollars per barrel, and there are 42 gallons per barrel. The computations of the various crack spreads are as follows:

$$\text{3:2:1 Crack Spread (CS)}_t = \frac{2}{3} HU_t + \frac{1}{3} HO_t - CL_t \tag{1}$$

$$\text{1:1:0 Gasoline Crack Spread (GCS)}_t = HU_t - CL_t \tag{1a}$$

$$\text{1:0:1 Heating Oil Crack Spread (HOCS)}_t = HO_t - CL_t \tag{1b}$$

Where the symbols HU_t, HO_t and CL_t refer to unleaded gasoline, heating oil, and crude oil contracts, respectively. The subscript t refers to the time position in the time series; for example, CL_t is the closing price of crude oil contract at time t.

METHODOLOGY

Cointegration is used to analyze the long-term equilibrium relationship between crude oil, unleaded gasoline, and heating oil futures prices. If crude oil, unleaded gasoline, and heating oil futures prices are cointegrated and have stationary cointegrating regression residuals, then forms of the spreads are also stationary. Furthermore, this suggests that the crack spreads will not deviate without bounds and will revert to the "normal" levels. On the other hand, if the futures prices of crude oil, unleaded gasoline, and heating oil are not cointegrated, then the crack spreads can deviate without bounds and using these spreads as risk management tool or as speculative vehicle will be questionable. Therefore, cointegration among these petroleum futures prices will make it possible to use statistical tools such as the moving average and the corresponding standard deviation for determining extremes. The extremes in turn can then be used as a basis for trading strategies and to explore risk arbitrage opportunities in crack spreads. Therefore, a moving average and its standard deviation will be used to identify relative mispricings that could be exploited.

Test for Unit Root and Cointegration

For crude oil, unleaded gasoline and heating oil futures prices to be cointegrated, the futures price series of each of these commodities must: (i) be nonstationary at price level, (ii) have the same order of integration, and (iii) have stationary cointegrating regression residuals. Therefore, the test for cointegration of crude oil, unleaded gasoline, and heating oil requires first testing for unit roots in each series and then determining if crude oil is cointegrated with unleaded gasoline and heating oil. If these series are cointegrated, it implies that there are long-run equilibrium relationships among these petroleum futures markets, then the spreads should converge to the long-term average.

Test for Unit Roots

The Augmented Dickey-Fuller (ADF) and Phillips-Perron Z_t test (Phillips, 1987; Phillips & Perron, 1988) are used to check for unit roots in crude oil, unleaded gasoline and heating oil futures prices. The ADF(p) statistics uses the Ordinary Least Squares (OLS) regressions, eq. (2), to test for unit roots for each of these petroleum futures prices.

$$\Delta X_{kt} = \alpha_{k1} + \beta_{k1} X_{kt-1} + \sum_{i=1}^{p} \delta_{ki} \Delta X_{kt-i} + e_{kt} \tag{2}$$

The Phillips-Perron statistics uses the residuals of the Ordinary Least Squares (OLS) regressions, eq. (2a), to test for unit root in these commodities.

$$X_{kt} = \alpha_{k2} + \beta_{k2} X_{kt-1} + e_{k2i} \tag{2a}$$

where X and ΔX are the futures price series and first difference of the series respectively; and the subscript k refers to the series under investigation. The lag length P for individual futures price series is selected based on the Schwarz's (1978) information criterion and the optimal lag length for crude oil, unleaded gasoline and heating oil are lags 8, 1 and 1 respectively. The null hypothesis in eq. (2) is that the series has a unit root and the alternative is that it is stationary. The null hypothesis will be rejected in favor of the alternative if the t-statistic on the coefficient β_{k1} exceeds the critical values in Fuller (1976). Similarly, Phillips-Perron test uses the residual from eq. (2a) to test if the series has unit root. The null hypothesis of a unit root will be rejected in favor of the alternative if the Z_t statistics exceeds the critical values in Fuller (1976). Phillips-Perron

TABLE I

Unit Root Test for Petroleum Futures

	Lag (p)	*Panel A: ADF Test*	*Panel B: Phillips-Perron Test*
Crude Oil	4	−2.387	−2.397
	6	−2.645	−2.338
	8	−2.154	−2.296
Unleaded Gasoline	1	−2.977[b]	−2.895[b]
	4	−2.811[a]	−2.933[b]
Heating Oil	1	−2.400	−2.320
	4	−2.419	−2.324

Critical Values are from Fuller (1976). [a]Significant at 10% level. [b]Significant at the 5% level.
Lag *P* for individual series are selected based on the Schwarz's (1978) information criterion and the optimal lag length for crude oil, unleaded gasoline and heating oil are lags 8, 1 and 1 respectively.
The data cover the periods from April 1983 to November 1994 for crude oil and heating oil, and from December 1984 to November 1994 for unleaded gasoline and includes all contracts that were deliverable through December 1994.

test is more robust because it accounts for the departure of the errors from iid normal distribution. The results of the unit root test are also robust to lag length specification.

Table 1 shows the results of Augmented Dickey-Fuller (ADF) and Phillips-Perron (Z_t) test for crude oil, unleaded gasoline and heating oil futures prices. Results of unit root test in both Panel A and Panel B shows that the null hypothesis of a unit root can not be rejected for crude oil and heating oil futures prices at any conventional level of significance. However, the null hypothesis of unit root can be rejected at the 5% level for gasoline futures prices but will not be rejected at 1% level of significance. Schwarz and Szakmary (1994), using futures prices adjusted for interest carrying costs, found that all three petroleum futures prices had a unit root. This difference could be due to the adjustment in their futures price series. Similar results are also reported by Fhjihara and Mougoue (1997) over the 1984–1993 sample period using the same three petroleum futures contracts as Schwarz and Szakmary. Test for two unit roots (not shown here) was done and the null hypothesis is rejected in favor of single unit root for the three petroleum futures prices. Therefore, all three commodities have the same order of integration of one—that is, I(1).

Cointegration Modeling and Testing

In the last section it was shown that the three petroleum futures exhibit random walk behavior at the price level and are integrated of order one [I(1)]. Both ADF and Phillips-Ouliaris (1990) Cointegration test are done to determine if there are long-term equilibrium relationships between

TABLE II

Test for Cointegration in Models 1, 2, and 3

Cointegrating Regressions	*Panel A: ADF Test* (t_α)	*Panel B: Phillips-Ouliaris Test* ($\hat{Z}_\alpha$)
$CL_t = \alpha_0 + \alpha_1 (HU)_t + \alpha_2(HO)_t + e_{1t}$	−6.564	−100.975
$\Delta e_{1t} = \rho e_{1t-1} + \sum_{i=1}^{p} \phi_i \Delta e_{1t-i}$		
$CL_t = \beta_0 + \beta_1(HU)_t + e_{2t}$	−4.682	−43.158
$\Delta e_{2t} = \rho e_{2t-1} + \sum_{t=1}^{p} \phi_i \Delta e_{21t-1}$		
$CL_t = \gamma_0 + \gamma_1(HO)_t + + e_{3t}$	−5.049	−69.721
$\Delta e_{3t} = \rho\ e_{31t-1} + \sum_{t=1}^{p} \phi_i \Delta e_{3t-1}$		

Critical values for t_α statistics are from Engle and Yoo (1987) and critical values for $\hat{Z}_\alpha$ are from Phillips-Ouliaris (1990). The data cover the periods from April 1983 to November 1994 for crude oil and heating oil, and from December 1984 to November 1994 for unleaded gasoline and includes all contracts that were deliverable through December 1994.

crude oil, unleaded gasoline, and heating oil. If these futures prices are not cointegrated, then the spread can deviate without bounds and use of the crack spread as a risk management tool or attempt to conduct profitable speculative trade will be questionable. To investigate the three crack spreads in eq. 1, 1a and, 1b, the following cointegrating regression models are used to investigate these relationships:

$$\text{Model 1: } CL_t = \alpha_0 + \alpha_1\ (HU)_t + \alpha_2\ (HO)_t + e_{1t} \tag{3}$$

$$\Delta e_{1t} = \rho e_{1t-1} + \sum_{i=1}^{p} \phi_i \Delta e_{1t-i} \tag{3a}$$

$$\text{Model 2: } CL_t = \beta_0 + \beta_1(HU)_t + e_{2t} \tag{4}$$

$$\Delta e_{2t} = \rho e_{2t-1} + \sum_{t=1}^{p} \phi_i \Delta e_{21t-i} \tag{4a}$$

$$\text{Model 3: } CL_t = \gamma_0 + \gamma_1\ (HO)_t + + e_{3t} \tag{5}$$

$$\Delta e_{3t} = \rho e_{31t-1} + \sum_{i=1}^{p} \phi_i \Delta e_{3t-i} \tag{5a}$$

Table II shows the result of the cointegration test for Model's 1–3. Results for model 1 show that crude oil, unleaded gasoline and heating oil futures prices are cointegrated. In addition, when model 1 is normalizing on heating oil or unleaded gasoline (not shown in the table), the three futures

TABLE III

Results of Unit Root Test for Crack Spreads

	Panel A: ADF Test	*Panel B: Phillips-Perron Test*
3:2:1 Crack Spread	−5.515	−5.700
1:1:0 GCS	−4.705	−4.638
1:0:1 HCS	−5.376	−5.818

Critical Values are from Engle and Yoo (1987)
The data cover the periods from April 1983 to November 1994 for 1 0:1 HCS, and from December 1984 to November 1994 for 3:2.1 crack spread and 1:1:0 GCS and includes all contracts that were deliverable through December 1994.

prices are still cointegrated. Similarly results for model 2 and model 3 show that crude oil and unleaded gasoline are cointegrated and crude oil and heating oil are also cointegrated. Engle and Granger (1987), and Bierens (1994, p. 207) indicated that there might be more than one cointegrating vector when the number of variables is greater than 2. In the case of petroleum futures contracts, there is not a unique input output relationship between crude oil and it refined products. The input-output relationship depends on the quality of crude oil, the refining technology used and the seasonal demand for the refined products. In addition, the NYMEX (1989) requires that on crack spread trades the total number of crude oil futures contract(s) bought (sold) should equal the total number of the refined products futures contracts sold (bought). In spite of this, there is no reason to believe that the 3:2:1 crack spread, the 1:1:0 gasoline crack spread and the 1:0:1 heating oil crack spread would not be stationary.

However, because the aim of this paper is to investigate risk arbitrage opportunities in these most popularly traded crack spreads it would be prudent to validate that these spreads are indeed stationary. Table III, Panel A and Panel B, show the result of the unit root test of the 3:2:1 crack spread, 1:1:0 gasoline crack spread, and 1:0:1 heating oil crack spread. The null hypothesis that these crack spreads have a unit root is rejected at 1.0% level of significance and therefore the spreads are integrated of order zero, I(0), and therefore are stationary as expected.

Since it was shown in Table III that the 3:2:1 crack spread, 1:0:1 gasoline crack spread and 1:1:0 heating oil crack spreads are stationary, it would be reasonable to use a moving average and moving standard deviations for determining extremes as a basis for developing trading strategies. Moving averages were used by researchers to develop trading strategies and for testing arbitrage opportunities and market efficiency in other commodities market. Monroe and Cohn (1986) used a 60-day moving average to examine the relative efficiency of gold future to T-bill futures. Wahab, Cohn, and Lashgari (1994) used various lengths of moving averages and error correction model to study the gold–silver spread arbitrage opportunities. Finally, Park and Switzer (1996) used 150-day moving average to develop trading strategy for treasury futures spreads.

Moving Averages

The moving average and its standard deviation are used to examine if these crack spreads show an extreme departure from "normal." The question is what should be the moving average window and how many standard deviations from the moving average constitute an extreme? Because there are infinite combinations of moving average windows and units of standard deviation, the n day moving averages and their respective standard deviations have to be determined empirically. Much preliminary work was conducted to find reasonable window sizes. Since relative mispricing should not persist for long period of time, we settled on 5-day and 10-day windows. Previous researchers used the single continuous time series that were created to study the time series properties to also develop their trading strategy. In this study, all traded crack spread contract month data are used to develop the moving average methodology for determining extremes in crack spreads and for developing trading strategy. Using all traded crack spread contract month data would provide more information and will reduce the length of the moving average window. This would also be consistent with how traders or speculators and hedgers will do in reality—that is, observe all traded contract month spreads to get as much information as possible to identify relative mispricing.

The moving average was designed to measure the overall level of crack spreads for a given window of time by taking into account all available information from all spreads that were observed during a given window. It is expected to be a representative of the long-term average spread. The crack spread data is arranged in form of array, where the rows are time and the columns are the contract months, as follows:

$$\begin{array}{cccccc} x_{11} & x_{12} & \cdot & \cdot & \cdot & x_{1k} \\ x_{21} & x_{22} & \cdot & \cdot & \cdot & x_{2k} \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ x_{t1} & x_{t2} & \cdot & \cdot & \cdot & x_{tk} \end{array}$$

where x_{ik} is the spread on day t and k is the contract month (such as

January) of the spread. The moving average and the standard deviation of the crack spread are computed as follows:

$$\bar{X}_n = \frac{\sum_{i=0}^{i=n-1} \sum_{k=1}^{k=n_i} x_{i-i,k}}{\sum_{i=0}^{i=n-1} n_i} \tag{6}$$

$$S_n = \sqrt{\frac{\sum_{i=0}^{i=n-1} \sum_{k=1}^{k=n_i} (x_{t-i,k} - \bar{X}_n)^2}{\sum_{t=0}^{t=n-1} n_t}} \tag{6a}$$

where n_t the number of contract months traded on day t, $\bar{X}_n$ is the n-day cross-sectional average and S_n is the cross-sectional and longitudinal standard deviation (STD).

To use these averages and standard deviations to identify what would be considered extremely large or small crack spreads, assumptions or tests about the distribution of the crack spreads have to be made. It will be assumed that the n-day average $\bar{X}_n$ is a random variable with expectation $E(\bar{X}_n) = \mu$ and variance $V(\bar{X}_n) = \sigma^2/N$. Then one can say that, by the central limit theorem, $(\bar{X}_n - \mu)\sqrt{N}/\sigma$ is approximately normally distributed.

The assumption that the crack spread has approximately normal distribution makes it possible to define what an extreme spread is. A spread will be considered extremely low if:

$$x_{\min,t} \leq \bar{X}_n - c^* S_n \tag{7}$$

and extremely high if:

$$x_{\max,t} \geq \bar{X}_n + c^* S_n \tag{7a}$$

The parameters n, number of days, and c, the number of standard deviation units, can be chosen by experimentation or arbitrarily; but once selected are constant.

It is possible that on a given day, there may be more than one contract spread that may meet the definition of extreme spread given in eq. (7) and (7a). If a trader wishes to maintain only one open position at a time or wants to open only one new position on a given day but will hold open multiple contracts simultaneously, then the trader will need additional criteria to make the appropriate choice.

If two or more spreads meet the criterion of extreme in a given day, then a trader will select the spread that has the greatest absolute difference from the average. For example, suppose the following situation is observed on a given day:

$$x_{\min,t} \leq \bar{X}_n - c^*S_n \text{ (Say, January contract) and}$$

$$x_{\max,t} \geq \bar{X}_n + c^*S_n \text{ (Say, April contract)}$$

Since both of these spreads meet the criterion of extreme spread only one of the spreads will be selected for trading. As such, the trader will select the contract month that meets the following additional criterion:

$$Max\{|\bar{X}_n - x_{\min,t}|,|\bar{X}_n - x_{\max,t}|\} \tag{8}$$

Therefore, for any contract month spread to be considered extremely high or low, and for a trader to initiate a long (short) position in the spread, it must satisfy eqs. (7) or (7a) and equation (8).

In addition, the n-day moving average of the individual month crack spread ($\bar{X}_{kn}$) and standard deviation (S_{kn}) are computed and maintained. The average and standard deviation of the individual contracts will be used to determine exit criteria for long (short) trades. The moving average and standard deviations for a given contract month k are computed as follows:

$$\bar{X}_{kn} = \frac{\sum_{l=0}^{l=n-1} x_{t-l,k}}{n} \tag{9}$$

$$S_{kn} = \sqrt{\frac{\sum_{l=0}^{l=n-1} (x_{t-l,k} - \bar{X}_{kn})^2}{n - 1}} \tag{9a}$$

TRADING STRATEGIES

The NYMEX has institutionalized oil spreads, since 1984, by permitting crack spread trading as a single transaction. The only requirement NYMEX imposes on spread trades is that the total number of crude oil futures contract(s) bought (sold) should equal the total number of the refined products futures contracts sold (bought).

This section employs a moving average trading strategy to exploit any extreme departure of the spread from "norm", as defined in the previous section. These strategies have two parameters that must be determined either experimentally or arbitrarily by the decision maker, and these parameters are the length of moving window, n days, and the number of standard deviation units, c. There are an unlimited number of variations of trades that could be developed and tested by changing these two parameters simultaneously or one at a time. The authors have experimented with a number of variations of these parameters and selected the five and ten days moving window and have chosen five values for the parameters, $c = \pm 1.5, \pm 1.75, \pm 2.0, \pm 2.25, \textit{ and } \pm 2.50$ to enter both long and short trades. In addition the authors selected one exit criterion for these entry conditions, and the specifics are given below and described in the exit criterion. When the spreads are $\bar{X}_n - cS_n \leq x_{kt} \leq \bar{X}_n + cS_n$ it is considered to be within the normal trading range and no new positions will be taken. However, if there were an open position that was taken when the spreads were outside these bounds, it would remain open until the exit criterion is met.

The following guidelines are part of the trading strategy and must be observed in addition to trade entry and exit criteria. First, take only one new long (short) position on any given day but can hold open multiple contracts simultaneously. Second, maintain only one open position in a given contract at any given time. This means that trader will not take additional positions on a contract in which he has an open position, either long or short, until the open position is closed. Third, all trades are opened and closed at the closing spread of the day the trading criterion is met. Finally, no new position will be taken on a contract within 20 days of its expiration. However, if there is an open position on a contract, it will be maintained until the exit criterion is met or the position will be liquidated on the last trading day's closing spread.

1. Criteria to take a long position on a crack spread:

$$x_{\min,t} \leq \bar{X}_n - cS_n \quad \text{Where: } c = -1.5, -1.75, -2.0, -2.25,$$

$$\textit{and } -2.50 \text{ and } |\bar{X}_n - x_{\min,t}| \geq |\bar{X}_n - x_{\max,t}|$$

Taking a long position on a crack spread, for example 3:2:1 crack spread, means: (a) buy two contracts of unleaded gasoline futures, (b) buy one contract of heating oil futures; and (c) sell three contracts of crude oil futures.

Criterion for Closing a long position:

$$x_{tk} \geq \bar{X}_{kn}$$

Exiting from a long or short position is based strictly on the relative position of the individual contract daily spread to its n-day moving average. Closing a long position is the reverse of taking a long position on a spread. That is also true for short positions in a crack spread.

Exiting from a long (short) position is based strictly on the relative position of the individual contract daily spread to its n-day moving average—that is, it depends on whether the spread for that day is greater than or equal (less than or equal) to the contract's moving average. The rationale for using the individual contract moving average for exit criteria is that:

1. The individual contract could remain at above (below) the n-day overall average for the entire contract life, and thus if not monitored could lead to a significant loss. For example, suppose a trader entered a long (short) trade for a January 1986 contract spread in July 1985. It is possible that this contract spread could remain below $\bar{X}_n$ for the remainder of the contract life, but may go higher (lower) than the trade entry spread. This necessitates the use of an individual n-day moving average for exit criteria.
2. The overall average and standard deviation mask the variability of the individual contracts. Therefore, once a new trade is entered, it is important to know the individual contract's behavior to ensure that losses are minimized and potential profits are maximized. It is possible that the individual contract behavior relative to its n-day average and standard deviation may not be attractive—that is, the position may be losing. Thus, monitoring the behavior of the individual contract spread is very important to allow an early exit from an undesirable position.
3. Criteria to take a short position on a crack spread:

$$x_{\max,t} \geq \bar{X}_n + cS_n \quad \text{Where: } c = +1.5,\ +1.75,\ +2.0,\ +2.25,$$

$$\textit{and } +2.50 \text{ and } |\bar{X}_n - x_{\min,t}| \leq |\bar{X}_n - x_{\max,t}|$$

Criterion for closing a short position:

$$x_{tk} \leq \bar{X}_{kn}$$

The results of these trading strategies will be provided in the next section.

RESULTS OF TRADING STRATEGIES

Profitability in the spreads trading is computed in the following way. Suppose a trader is interested trading the spread between any three petroleum futures, say crude oil, unleaded gasoline, and heating oil, with their respective prices of HU_t, HO_t and CL_t at time t. Suppose further that a trader is interested in taking a spread position and goes short 3 contracts of crude oil and goes long 2 contracts of unleaded gasoline and 1 contract of heating oil. The authors define this as taking a long position in a 3:2:1 crack spread (The NYMEX specification for one contract of crude oil is 1,000 barrels, and one contract of heating oil and one contract of unleaded gasoline is 42,000 gallons each). If a long position in the spread is taken at time t and closed k days later, the profit for this long position (π_l) would be expressed as:

$$\pi_l = \alpha_1(HO_{t+k} - HO_t) + \alpha_2(HU_{t+k} - HU_t) - \alpha_3(CL_{t+k} - CL_t) \tag{10}$$

where α_1, α_2, and α_3 could be the number of contracts long and short. The computation for profit on the short spread trade is simply the negative of equation (10).

Eq. (10) is used to compute the profitability of 3:2:1 crack spread, and with minor modification it can be used to compute the profitability of the 1:1:0 gasoline crack spread and 1:0:1 heating oil crack spread. For example, say $\alpha_2 = 0$, then eq. (10) can be used to determine profitability of 1:0:1 heating oil crack spreads.

All profits in Tables IV, IVA, and IVB are measured in terms of dollars rather than rates of return. These profits are based on the sale (purchase) of three crude oil contracts and the purchase (sale) of an appropriate number of heating oil and unleaded gasoline contracts, thus allowing a direct comparison of the profitability of the three spreads. There are reasons for choosing this approach. First, there is no agreement in the literature about what should be considered the appropriate investment—that is, is it the required margin or is it the required capital that should be the basis for measuring returns? Another is that the above trading strategy does not require maintaining an open position continuously—that is, trade is initiated only when there is an attractive opportunity for profitable trading, according to entry and exit criteria established earlier. Otherwise no position is taken in the market. Measuring profits in terms of rates of return requires making many assumptions which in the end may produce a non-satisfactory measure. However, if required, one can give a rough approximation of the rate of return for these strategies if the maximum capital needed to trade for the entire period is known in advance. The maximum capital necessary to engage in crack spread trades could be determined by examining the daily cash flows of each trade, and

TABLE IV

Results of Moving Average Trading Strategies[a]
(Total Profitability of combined Long and Short Trades)

C[b]	*Total Profits*	*Avg. Profit ($)*	*Std. Dev. ($)*	*No. of Trades*	*Avg. day in Trade*	*% of winning Trades*	*Std. error of Mean*	*t-value*	*CV*[c]
Panel A: Profitability of Five Day Moving Average Trading Strategy									
3:2:1 Crack Spread									
±1.50	$155,212	$281	$920	552	4.2	77.7	39.157	7.176	3.274
±1.75	$144,663	453	827	319	4.1	84.3	46.303	9.783	1.826
±2.00	$97,142	552	870	176	4.2	85.2	65.579	8.417	1.576
±2.25	$51,257	589	929	87	4.3	87.4	99.600	5.914	1.577
±2.50	$20,048	557	946	36	4.3	88.9	157.667	3.533	1.698
1:1:0 Gasoline Crack Spread									
±1.50	$138,959	$307	$ 1,204	453	4.3	74.4	56.569	5.427	3.922
±1.75	$117,479	546	1,156	215	4.2	82.8	78.839	6.926	2.117
±2.00	$68,199	662	987	103	4.0	84.5	97.252	6.807	1.491
±2.25	$24,983	757	737	33	4.3	81.8	128.295	5.900	0.974
±2.50	$12,967	997	621	13	3.9	100.0	172.234	5.789	0.623
1:0:1 Heating Oil Crack Spread									
±1.50	$226,972	$305	$1,154	743	4.2	75.1	42.336	7.204	3.784
±1.75	$124,195	409	1,467	304	4.5	81.3	84.138	4.861	3.587
±2.00	$74,563	802	1,841	93	4.4	86.0	190.903	4.201	2.296
±2.25	$27,098	934	1,604	29	4.4	82.8	297.855	3.136	1.717
±2.50	$4,603	767	1,139	6	4.0	83.3	464.995	1.649	1.485
Panel B: Profitability of Ten Day Moving Average Trading Strategy									
3:2:1 Crack Spread									
±1.50	$185,211	$372	$1,044	498	5.2	82.1	46.783	7.952	2.806
±1.75	$143,598	475	1,183	302	5.4	85.1	68.074	6.978	2.491
±2.00	$103,741	644	1,349	161	5.8	86.3	106.316	6.057	2.095
±2.25	$57,706	641	1,320	90	6.0	84.4	139.140	4.607	2.059
±2.50	$25,136	474	1,359	53	6.0	81.1	186.673	2.539	2.867
1:1:0 Gasoline Crack Spread									
±1.50	$163,778	$402	$1,213	407	5.2	79.6	60.126	6.686	3.017
±1.75	$118,250	550	1,433	215	5.5	84.2	97.730	5.628	2.605
±2.00	$84,280	826	1,378	102	5.7	83.3	136.442	6.054	1.668
±2.25	$33,755	703	1,157	48	6.4	81.3	166.999	4.210	1.646
±2.50	$20,230	1,012	1,272	20	6.4	80.0	284.428	3.558	1.257
1:0:1 Heating Oil Crack Spread									
±1.50	$271,281	$429	$1,100	633	5.0	80.1	43.721	9.812	2.564
±1.75	$157,654	569	1,436	277	6.0	83.0	86.281	6.595	2.524
±2.00	$97,897	906	1,513	108	6.0	86.1	145.588	6.223	1.670
±2.25	$59,383	1,485	2,398	40	6.0	82.5	379.157	3.917	1.615
±2.50	$21,712	1,447	2,385	15	5.3	86.7	615.804	2.350	1.648

[a]The trading results cover the periods from April 1983 to November 1994 for 1.01 heating oil crack spread (from December 1984 to November 1994 for other spreads) and includes all contracts that were deliverable through December 1994. [b]Entry parameter C is the number of standard deviations away from corresponding n-day moving average. [c]CV is coefficient of Variation

TABLE IVA

Results of Moving Average Trading Strategies[a]
(Profitability of Long Trades)

C^b	Total Profits	Avg. Profit ($)	Std. Dev. ($)	No. of Trades	Avg. day in Trade	% of winning Trades	Std. error of Mean	t-value	CV^c
Panel A: Profitability of Five Day Moving Average Trading Strategy									
3:2:1 Crack Spread									
−1.50	$79,802	$376	$632	212	4.1	78.3	43.406	8.662	1.681
−1.75	67,571	568	742	119	3.9	82.4	68.019	8.351	1.306
−2.00	54,466	756	849	72	3.9	86.1	100.056	7.556	1.123
−2.25	31,233	822	861	38	4.0	86.8	139.673	5.885	1.047
−2.50	11,252	703	675	16	4.5	81.3	168.750	4.166	0.960
1:1:0 Gasoline Crack Spread									
−1.50	$101,944	$502	$927	203	4.0	76.9	65.063	7.716	1.847
−1.75	79,600	780	1041	102	3.9	85.3	103.074	7.567	1.335
−2.00	41,092	790	886	52	3.5	86.5	122.866	6.430	1.122
−2.25	9,705	647	704	15	4.3	80.0	181.772	3.559	1.088
−2.50	6,223	1037	627	6	4.0	100	255.972	4.051	0.605
1:0:1 Heating Oil Crack Spread									
−1.50	$152,254	$498	$759	306	3.9	84.3	43.389	11.478	1.524
−1.75	77,320	729	809	106	3.8	88.7	78.577	9.278	1.110
−2.00	25,486	910	1451	28	4.1	82.1	274.213	3.319	1.595
−2.25	6,278	785	879	8	4.8	87.5	310.773	2.526	1.120
−2.50	1,161	581	669	2	4.0	100.0	473.054	1.228	1.152
Panel B: Profitability of Ten Day Moving Average Trading Strategy									
3:2:1 Crack Spread									
−1.50	$100,231	$484	$747	207	4.9	84.5	51.920	9.322	1.543
−1.75	75,054	620	846	121	5.0	87.6	76.909	8.062	1.365
−2.00	44,602	697	945	64	5.3	85.9	118.125	5.901	1.356
−2.25	31,777	883	954	36	5.7	86.1	159.000	5.554	1.080
−2.50	18,821	991	1066	19	5.5	84.2	244.557	4.052	1.076
1:1:0 Gasoline Crack Spread									
−1.50	$105,274	$585	$948	180	5.0	85.0	70.660	8.279	1.621
−1.75	75,786	758	1133	100	4.9	91.0	113.300	6.690	1.495
−2.00	42,623	969	1134	44	5.2	88.6	170.957	5.668	1.170
−2.25	19,450	973	1142	20	5.8	90.0	255.359	3.810	1.174
−2.50	10,440	1,160	1613	9	5.8	77.8	537.667	2.158	1.391
1:0:1 Heating Oil Crack Spread									
−1.50	$171,745	$629	$874	273	4.7	89.0	52.897	11.891	1.390
−1.75	96,313	909	1106	106	5.2	88.7	107.424	8.462	1.217
−2.00	42,749	1,125	1404	38	5.4	89.5	227.759	4.939	1.248
−2.25	13,318	1,024	1274	13	6.2	84.6	353.344	2.898	1.244
−2.50	4,664	777	833	6	5.5	83.3	340.071	2.285	1.072

[a]The trading results cover the periods from April 1983 to November 1994 for 1.0.1 heating oil crack spread (from December 1984 to November 1994 for other spreads) and includes all contracts that were deliverable through December 1994. [b]Entry parameter C is the number of standard deviations away from corresponding n-day moving average. [c]CV is coefficient of Variation

TABLE IVB

Results of Moving Average Trading Strategies[a]
(Profitability of Short Trades)

C^b	Total Profits	Avg. Profit ($)	Std. Dev. ($)	No. of Trades	Avg. day in Trade	% of winning Trades	Std. error of Mean	t-value	CV[c]
Panel A: Profitability of Five Day Moving Average Trading Strategy									
3:2:1 Crack Spread									
1.50	$75,409	$222	$1058	340	4.3	77.4	57.378	8.662	4.766
1.75	77,092	385	868	200	4.1	85.5	61.377	6.273	2.255
2.00	42,676	410	860	104	4.4	84.6	84.323	4.862	2.098
2.25	20,024	409	948	49	4.6	87.8	135.429	3.020	2.318
2.50	8,796	440	1121	20	4.2	95.0	250.663	1.755	2.548
1:1:0 Gasoline Crack Spread									
1.50	$37,016	$148	$1370	250	4.5	72.4	86.646	1.708	9.257
1.75	37,879	335	1216	113	4.5	80.5	114.392	2.929	3.630
2.00	27,107	532	1074	51	4.5	82.4	150.390	3.537	2.019
2.25	15,278	849	771	18	4.3	83.3	181.726	4.672	0.908
2.50	6,745	964	663	7	3.9	100.0	250.590	3.847	0.688
1:0:1 Heating Oil Crack Spread									
1.50	$74,717	$171	$1348	437	4.4	68.7	64.484	2.652	7.883
1.75	46,875	237	1695	198	4.9	77.3	120.458	1.967	7.152
2.00	49,076	755	1994	65	4.5	87.7	247.325	3.053	2.641
2.25	20,820	991	1822	21	4.2	81.0	397.593	2.492	1.839
2.50	3,442	860	1406	4	4.0	75.0	703.000	1.223	1.635
Panel B: Profitability of Ten Day Moving Average Trading Strategy									
3:2:1 Crack Spread									
1.50	$84,980	$292	$1207	291	5.4	80.4	70.756	4.127	4.134
1.75	68,544	379	1357	181	5.6	83.4	100.865	3.758	3.581
2.00	59,139	610	1563	97	6.1	86.6	158.699	3.844	2.562
2.25	25,928	480	1503	54	6.2	83.3	204.532	2.347	3.131
2.50	6,315	186	1432	34	6.2	79.4	245.586	0.757	7.912
1:1:0 Gasoline Crack Spread									
1.50	$58,504	$258	$1372	227	5.4	75.3	91.063	2.833	5.318
1.75	42,464	369	1634	115	6.1	78.3	152.371	2.422	4.428
2.00	41,657	718	1538	58	6.2	79.3	201.949	3.555	2.142
2.25	14,305	511	1149	28	6.9	75.0	217.141	2.353	2.249
2.50	9,790	890	977	11	6.9	81.8	294.577	3.021	1.098
1:0:1 Heating Oil Crack Spread									
1.50	$99,536	$276	$1224	360	5.2	73.3	64.511	4.278	4.435
1.75	61,342	359	1574	171	6.5	79.5	120.367	2.983	4.384
2.00	55,148	788	1565	70	6.4	84.3	187.053	4.213	1.986
2.25	46,066	1,706	2778	27	5.8	81.5	534.626	3.191	1.628
2.50	17,047	1,894	2994	9	5.1	88.9	998.000	1.898	1.581

[a]The trading results cover the periods from April 1983 to November 1994 for 1:0:1 heating oil crack spread (from December 1984 to November 1994 for other spreads) and includes all contracts that were deliverable through December 1994. [b]Entry parameter C is the number of standard deviations away from corresponding n-day moving average. [c]CV is coefficient of Variation

by using the worst draw down of all the strategies plus the required initial margin. Based on this analysis it was concluded that initial investment of \$75,000, for each type of crack spread trade, will meet the capital requirements and will provide a safety margin. A concise summary of the total trading results, combined long and short trades, is given in Table IV.

Given the initial commitment of funds and the average profits per trade, the average number of days in trade, and assuming a 252 trading days, an estimated rate of return can be computed for each trading strategy. For example, the lowest average profit per trade for the 3:2:1 crack spread is \$281, the 5-day moving average strategy when trades are entered at ± 1.50 standard deviation. The approximate annual rate of return for this profit is determined by first computing the daily return and then converting it to annual return. The assumption is that the daily returns will be compounded to arrive at annual rate of return—that is, compound annual rate of return is $\{(1 + \text{Average profit}/(\text{Avg. No. of days in Trade}^*\text{Initial Investment}))^{252} - 1\}$. Thus, the return of the lowest average profit for 3:2:1 crack spread is 25.19% $\{(1 + (281/(4.2^*75{,}000)))^{252} - 1\}$. Similarly, the lowest gasoline crack spread compound annual rate of return was 27.10%, and the lowest heating oil crack spread compound annual rate of return was 27.61%. These estimated rates of return are before transaction costs. After transaction cost of \$100 per round trade, the above returns will decline to 15.58%, 17.55%, and 17.82%, respectively. These returns are still very attractive and they are a very conservative lower bound; because no consideration was given to the return that idle funds could have earned, say, in a money market account. Overall dollar profits of these trading strategies are also reasonably attractive. Given an efficient market, any trading strategy should not generate profits that are significantly greater than zero.

An alternative way to measure the attractiveness of the trading profits is to determine if these profits are significantly greater than zero. A t-test was used to determine if the average profits per trade are greater than zero, and a t-test provides information about the direction and magnitude of the profits.

Table IV provides a summary of, combined long and short trades, trading profits and a number of statistical measures. First, except for 1:0:1 heating oil crack spread with the 10-day moving average at 2.50 STD trading strategy, all of the trading strategies provided significantly positive profit, at 1% level of significance, before transaction costs. If a transaction cost of \$100 per round trade is subtracted from the average profit per trade, the 3:2:1 crack spread and the 1:0:1 heating oil crack spread with the 10-day moving averages at 2.50 STD are significant at the 5% level of significance. All the other spreads trading strategies provided profits, after \$100 transaction cost per round trade, that are still significant at the 1% level of significance. Second, as the number of standard deviation units increase from ± 1.50 to ± 2.50 the average profit per trade also increases, as does the standard deviation of the profits. The exception to this is the trading results of 1:1:0 gasoline crack spread 5-day moving average strategies. The 5-day moving average strategies, in this case, leads to an increasing average profit per trade and simultaneously decreasing standard deviation of profits. There is no apparent explanation for these results. Third, both the 5-day and 10-day moving average strategies provide the lowest average profit when trades are entered at ± 1.50 standard deviation away from the mean and these are statistically significant. Fourth, except for 3:2:1 crack spread, the moving average strategies lead to very few trades when trades are entered at ± 2.50 standard deviation away from the mean, and the results are not statistically reliable. Finally, for both 5-day and 10-day moving average strategies, the most desirable profit and risk combination seem to occur when trades are entered between ± 1.75 and 2.25 standard deviations from the average.

In addition to analyzing the profitability of trading strategies, consideration has to be given to the risk-reward characteristics of the spread trades to provide a more complete picture. Generally, because risk has many dimensions, one can assess the risk reward characteristics of an investment in many ways. One way is to measure risk of an investment using the standard deviation of returns or coefficient of variation. There are also other measures of risk that could be used to explain other dimensions of risk such as the number of days in trade, the magnitude of average loss per trade, margin requirements, and the proportion of winning trades. The authors believe that the coefficient of variation, in this case, is a reasonable measure of risk. Further examination of Table IV, last column, shows that the 5-day moving average trading strategy provided an excellent return with very low risk for 3:2:1 crack spread and 1:1:0 gasoline crack spreads when trades are entered at ± 1.75 through ± 2.50 standard deviations from the mean. Similar results were found for 1:0:1 heating oil crack spread when trades are entered at ± 2.00 through ± 2.50 standard deviation from the average. The 10-day moving average trading strategy provided equally good results for 1:1:0 gasoline crack spread and 1:0:1 heating oil crack spread when trades are entered at ± 2.00 through ± 2.50 standard deviation from the average. On the other hand, the 3:2:1 crack spread showed very good results when trades are entered at ± 2.00 and ± 2.50 standard deviation from the average. Given that the 5-day moving average and 10-day moving average trades are correlated, it is not surprising that the two strategies lead to similar results. Finally, Table IV also shows that the average number of days in a trade for any given strategy is less than 7 days and the proportion of winning trades is greater than 70%. The average number of days in losing trades is at least twice as long as the number of days for winning trades (not shown on the table).

Table IVA and Table IVB represent the long and short trade components of the results shown in Table IV and discussed above. Examination of these two tables provides additional insight into the profitability and the risk of trading the spreads.

Table IVA shows the profitability of long trades. It shows that the 5-day moving average profit per trade for 1:0:1 heating oil crack spread, when trades are entered at ± 2.50 standard deviation away from the mean, are not significant. But, when trades are entered at ± 2.25 standard deviation from the average, it is significant at 5% significance level. The 10-day moving average trading strategies for 1:1:0 gasoline crack spread and 1:0:1 heating oil crack spread, when trades are at ± 2.50 standard deviation away from the mean, are significant at the 10% significance level. For all other trades the average profits are significant at the 1% significance level. The long trades exhibit excellent risk-reward characteristics; all trades had a coefficient of variation less than 2.0, in most cases less than 1.5. In contrast, the result for the short trades, Table IVB, shows that short trades are also very profitable but are much riskier than long trades. The coefficient of variation for short trades is greater than 2.0 and less than a third have coefficient of variation less than 2.0. In addition, the average loss per trade for short trades is much greater than the average loss per trade for long trades (not shown in table).

CONCLUSIONS

This article investigates the long-term pricing relationship among crude oil and its end products (unleaded gasoline and heating oil) futures prices and finds that these commodities futures prices are cointegrated. The study finds that the spreads between crude oil and its end products are stationary. Furthermore, this article investigates the risk arbitrage opportunities in three types of popularly traded crack spreads: 3:2:1 crack spread, 1:1:0 gasoline crack spread, and 1:0:1 heating oil crack spread. A 5-day and a 10-day moving average and corresponding standard deviations were used to identify exploitable risk arbitrage opportunities. This research showed that historically profitable risk arbitrage opportunities existed and they were statistically significant. However, one cannot be certain that these opportunities still exist. The following are summaries of our findings and recommendations:

First, 3:2:1 crack spread, 1:1:0 gasoline crack spread, and 1:0:1 heating oil crack spreads provided average profits that are significantly different from zero at the $\alpha = 0.01$ level of significance. However, the 1:0:1 heating oil crack spread, when trades are entered at ± 2.50 standard deviation from the average, is not significant at $\alpha = 0.01$ level of significance. This research shows that taking a long position on crack spreads, when the spreads are at extreme lows, is highly profitability and has very low risk. The usual trade has a coefficient of variation less than 2. In contrast short positions have a coefficient of variation greater than 2 for most of the strategies.

Second, this research suggests that refiners can manage risk of gross profit margin effectively if they used 3:2:1 crack spread. The risk-reward characteristics of this spread are very attractive. The hedge could be even more effective if only long trades in 3:2:1 crack spread are taken when the spreads are at extreme lows.

Finally, retailers such as gas stations and heating oil distributors can hedge their position more effectively if they take long positions in 1:1:0 gasoline crack spread and 1:0:1 heating oil crack spread respectively. As indicated above, both 1:1:0 gasoline crack spread and 1:0:1 heating oil crack spreads are profitable and can be used effectively by refiners to manage their gross profit margin. However, refiners can benefit more if they used 3:2:1 crack spread. The 5-day and 10-day moving averages trading strategies, at least historically, were very effective in exploiting relative mispricing among petroleum futures contracts.

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