Closing Pressure, Predatory Trading, and the Negative Price of Oil*

Abstract

This paper examines the contribution of closing pressure and predatory trading to the formation of the negative settlement price of NYMEX West Texas Intermediate (WTI) Crude Oil futures on April 20, 2020. The most common informal argument in social media argues that storage shortage and excessive long traders eager to close positions, namely, the closing pressure, pushes down the WTI price. Empirical tests confirm this negative price effect of closing pressure, but it is estimated to bring the price down to only \$7/barrel. We then incorporate two missing elements-intraday dynamics and TAS arbitrage-into the theoretical model and quantitively simulates the price to be around –\$40/barrel. Overall, closing pressure under physical settlement rules and TAS predatory trading with commodity financialization together contribute to the negative price of oil.

Key Words: Closing pressure, TAS market, predatory trading, negative oil price

JEL Classification: G18, G23, G29.

I. Introduction

Investors witnessed a historical event in the commodity futures market when the settlement price of NYMEX WTI Crude Oil futures' first-nearby contract (the May 2020 contract) collapsed to –$37.63/barrel on April 20, 2020, the first time in history that a negative oil price was recorded. The negative price means that, according to the May contract, an oil seller must *pay* the buyer 37,630 dollars per contract for taking the crude oil off her hands. This mind-bending price distortion has provoked widespread discussions on why it happened.

Generally, NYMEX WTI futures and ICE Brent Crude Futures, the two major oil pricing benchmarks in the world, comove under similar fundamental factors of demand and supply. To compare the price behavior of Brent futures when WTI futures prices suddenly went negative on April 20, we plot both the prices of WTI and Brent futures from January 2020 to May 2020. As Figure 1 shows, the WTI price is somewhat lower than the Brent price during this period, but April 20 recorded a huge and abnormal price divergence. To be more specific, Table 1 presents the settlement prices of three main comparable contracts to the May 2020 WTI contract, including the Brent first-nearby contract, Brent second-nearby contract, and WTI second-nearby contract, on four consecutive trading days around April 20. The May 2020 WTI contract was approximately $20/barrel before April 20 and $10/barrel on April 21, the last trading day. It is noteworthy that the price on April 20, the penultimate trading day, fell into the extremely negative zone unexpectedly and then rebounded quickly within a day. Moreover, if we compare the WTI price to the Brent price, the price spread fluctuated around –$9/barrel before and after April 20, but on April 20, the spread reached an astonishing –$63.2/barrel. Similarly, the spread between WTI first-nearby and second-nearby contracts was initially –$6/barrel but reached –$58.06/barrel on April 20. The unique and extreme price divergence of the May WTI contract indicates that the negative oil price is unlikely to be solely a fundamental-driven issue since these fundamentals also function for Brent futures and the second-nearby WTI contract, and they cannot change substantially in only one day.

The most common informal argument in the social media argues that storage shortage and excessive long traders are causing the negative WTI price. CNBC reports that there is limited tanker storage as a result of the collapse in oil demand, and WTI price is under pressure.[1] REUTERS states that the frenzied selling was driven by a lack of storage space to hold a glut of crude, meaning traders were willing to pay buyers to take oil off their hands. These arguments are talking about the issue of closing pressure that is specific to WTI first-nearby contracts and originates from its physical settlement rules. WTI market participants who do not close their positions before contract expiration are required to take physical deliveries of the real crude oil. Long-position traders must book storage in advance at the designated physical delivery point, Cushing, Oklahoma, to take in the oil; short-position traders must transport the physical oil to Cushing. The eagerness to close positions before contract expiration to avoid physical deliveries leads to closing pressure for WTI first-nearby contracts. Brent Futures, which admits cash settlement, does not encounter the problem of closing pressure. In this paper, we focus on closing pressure for long-position traders under the conditions that storage space is limited and long-position traders are more likely to be in trouble of having nowhere to store oil and, thus, to be more eager to close their contracts. The penultimate trading day experiences most of the pressure since the last trading day is usually illiquid with low trading volume and, thus, the penultimate trading day is the de facto last trading day to close the contracts.

Our paper first empirically examines the argument above by constructing measurements of closing pressure. Closing pressure for long-position traders is determined by two factors. One is how many positions must be closed, i.e., the

[1] https://www.cnbc.com/2020/04/20/coronavirus-us-oil-prices-collapse-as-storage-runs-out.html.

trading needs. This can be inferred from the starting open interest on the penultimate trading day since a very small number of contracts go to physical deliveries. The more contracts need to be closed, the higher closing pressure is. However, open interest does not tell whether the long or short side is more eager to close, and the oil inventory level can further indicate this. When the inventory level is high with limited spare space to store oil, booking storage will be difficult and, thus, long traders are more eager to close their contracts. We, therefore, measure closing pressure with the product of open interest and inventory level.

To verify the relationship between closing pressure and WTI first-nearby contract prices, we conduct an empirical analysis with the WTI-Brent price spread (the spread between WTI first-nearby contracts and Brent first-nearby contracts) and closing pressure. We use the WTI-Brent price spread to measure the price divergence of the WTI first-nearby contract resulting from the nonfundamental factor of physical settlement rules. We apply the product of open interest and inventory level as the proxy of closing pressure. April 20, 2020, experienced a historical peak of closing pressure, four deviations higher than the sample mean. An Interim Staff Report published by CFTC reveals that the starting open interest of the May 2020 WTI contract on April 20, 2020 was 108,593 contracts, approximately 69% higher than the trailing 12-month average of 64,101 contracts, and most of these positions were closed on April 20.[2] In addition to the extremely high open interest, the oversupply and stagnant demand of oil during the epidemic led to a high oil inventory level. Commercial crude oil inventory in U.S. almost reached its historical peak at nearly 520 million barrels. 76% of Cushing's storage capacities were occupied[3] and most of others had been leased out[4]. Together, the high open interest and inventory level

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[2] The open interest change is 95 thousand contracts on April 20 and 10 thousand contracts on April 21, confirming that the penultimate day receives most of the closing pressure.

[3] To be more specific, the total inventory at Cushing on April 17 was 60 million barrels, with 58 million barrels held in tank farms at Cushing and 2 million barrels in transit by pipeline, water, or trail, according to information from the EIA.

[4] A report from the EIA indicated that most of the unfilled storage had already been leased or committed.

brought substantially high closing pressure on April 20, 2020.

Regression results empirically show that closing pressure indeed pushes down WTI price on the penultimate trading day. This negative effect is further strengthened by the drying-up of market liquidity, according to our tests on the interactive effect of closing pressure and market illiquidity. The baseline regression predicts the WTI price on April 20, 2020 to be approximately $7/barrel, significantly lower than the Brent price of $25.57, confirming that closing pressure drags down WTI price on April 20. However, closing pressure is only a partial explanation of the negative oil price because there is still a large deviation—from the predicted seven dollars to the real settlement price of –37.63 dollars—left to be explained.

We further incorporate two missing elements-intraday dynamics and TAS arbitrage-to enrich our analysis. Firstly, we pay attention to the intraday price dynamics of the May 2020 WTI contract. The trading session for April 20 started the preceding evening at 18:00 EST with a price of $17.73/barrel, and then it dropped slowly to approximately $10/barrel at 12:00 and reached zero at 14:00, as Figure 2 shows. However, the price then plunged sharply 20 minutes immediately before the settlement period[5], and this dramatic collapse pushed the price far below zero. The settlement price, which is defined as the volume-weighted average price (VWAP) between 14:28 and 14:30, went to a record-breaking value of –$37.63/barrel.

Note that the negative price suddenly occurred immediately before the daily settlement period, we then explore the related special execution type of Trading at Settlement (TAS) and interpret the price reduction to –37 dollars with TAS predatory trading. With the process of commodity financialization (Tang and Xiong, 2012), more index traders regard oil futures as an asset class. They normally gain exposure to oil futures by trading with financial swap dealers, who then hedge their risks with positions in the oil futures market.

See Low liquidity and limited available storage pushed WTI crude oil futures prices below zero (2020).

[5] The daily settlement period for WTI contracts is 14:28–14:30 EST.

Index traders usually target settlement prices, and as a result, their trading needs are very likely to be met in the TAS market by swap dealers. Furthermore, index traders normally take long positions (Cheng and Xiong, 2014)[6]; therefore, there will be great selling demand in the TAS market before contract expiration, which makes TAS predatory trading possible.

Predatory trading (Brunnermeier and Pedersen, 2005) refers to trading that exploits the need of other investors to reduce their positions. If a strategic trader knows the asset liquidation need of another distressed trader in advance, she can conduct predatory trading by selling ahead or simultaneously with the distressed trader and subsequently buying back the asset after the liquidation is finished at a much lower price to make a considerable profit. It can be viewed as an aggressive short-term short-selling trading strategy. TAS predatory trading in the crude oil futures market is slightly more sophisticated than the original trading. It is conducted across two markets—the outright market and the TAS market. A TAS predatory trader (arbitrager) captures great selling demand in the TAS market and opens long positions via TAS orders; then she sells in the outright market around the settlement period to push down the daily settlement price that acts as the benchmark price for her TAS orders. Our theoretical model with TAS arbitrager suggests that TAS predatory trading will greatly drag down the daily settlement price and bring considerable profits to the arbitrager, especially when the outright market is highly illiquid. We calibrate the theoretical model and simulates the settlement price on April 20, 2020, to be around –\$40/barrel. The comparative static analysis further indicates that the physical settlement rules and commodity financialization open the window for the possibility of TAS predatory trading, and a greater extent of financialization brings a more negative oil price.

Overall, we explore the comprehensive causes of the negative oil price from perspectives of closing pressure (physical settlement rules, storage shortage and

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[6] The long-position in May 2020 WTI contracts of swap dealers are about three times higher than the short-position contracts in March and April 2020, according to the CFTC Interim Report.

excessive long traders) and TAS predatory trading (cross-market arbitrage and commodity financialization). Empirical tests confirm the negative price effect of closing pressure, as the most common argument suggests, but it is estimated to bring the price down to $7/barrel on April 20, 2020. The argument is good direction wise, but difficult to quantitatively generate a negative price. When we add the intraday dynamics and TAS arbitrage into our analysis, we quantitively simulate the settlement price to be around -$40/ barrel, very close to the real value of –$37.63/barrel. To conclude, the negative oil price is an accumulated result of closing pressure and TAS predatory trading, and predatory trading is the main driver of the extremely negative settlement price.

Our study contributes to several strands of literature in the following ways. Firstly, we provide a multidimensional explanation for the causes of the negative oil price; as far as we know, this is the first paper to fully explain the intraday price dynamics on April 20, 2020. There are some studies on the effects of negative oil price on financial markets and the real economy. Corbet et al. (2021) point out that the negative price event has volatility spillover effects on stock markets, currency markets and other futures markets, endangering the traditional role of WTI futures as a safe haven. Gilje et al. (2021) find that the negative price has a widespread effect on the real decisions of firms, and firms with physical purchase contracts indexed to WTI shut in production at greater rates after this event than those who did not. These studies highlight the importance of the negative oil price event, but there is still a lack of a comprehensive study on causes of it, and our research fills this gap. Several papers have analyzed this event (Burns and Kane, 2020; Le et al., 2021) but have not fully explored intraday price performances and specific mechanisms.

Secondly, we incorporate the storage market into the analysis of oil futures prices and determine the price distortion caused by the commonly neglected frictions. The futures market and spot market are the focus for analyzing commodities, while frictions in the storage market have never been a major issue.

This paper points out that a market that is generally perceived as frictionless can cause disasters for asset price volatility. This issue has been studied in the stock market (Blocher, Reed and Wesep, 2013; Banerjee and Graveline, 2014; Atmaz, Basak and Ruan, 2022) to explore stock price distortions when equity loans and short-selling are costly. We supplement this strand of studies on commodity futures prices by determining price distortions when storage space is costly. Besides, we study an inverse case of financial squeeze resulting from physical settlement rules and lend support to settlement rule reforms for WTI futures. Squeeze (or corner) is the most important type of manipulation in the commodity futures market.[7] Kyle (2008) states that it is difficult to implement the inverse squeeze since storage is widely available. Our research provides a special case of inverse squeeze in the trading of physically delivered and expensive-to-store crude oil. Physical settlement and cash settlement have always been compared (Lien and Tse, 2006). Our research finds that physical settlement is responsible for the negative price, and we call for reforms on WTI settlement rules.

Thirdly, we propose a new form of predatory trading in the commodity futures market and explore its resulting market distortion. Our work extends the traditional form of predatory trading (Brunnermeier and Pedersen, 2005) by analyzing TAS predatory trading conducted with public information across two different markets. Index rebalancing, contract roll trades and the resulting predictable order flows in commodity futures markets have been regarded as potential opportunities for predatory trading, but existing studies (Bessembinder et al., 2014; Yan et al., 2021) do not find evidence for it. Our paper determines the potential predatory trading originating from the TAS market before contract expiration and supplements studies on predatory trading in the commodity futures market. In addition, TAS manipulation has not been

[7] Squeeze (corner) refers to the trading strategy that a large buyer accumulates a dominant position to make it costly for short traders to take physical deliveries and, thus, pushes up futures prices. See Jarrow (1992), Pirrong(1995), Cooper and Donaldson (1998) and Pirrong (2010) for detailed discussions on squeeze.

widely explored in the literature other than Pirrong (2019).

Finally, this research also contributes to the literature on commodity financialization. The growing index investment since the early 2000s has substantially changed the participants and price behavior of the commodity futures market. The role of financialization on price booms (Irwin, Sanders and Merrin, 2009; Singleton, 2014; Kilian and Murphy, 2014), risk sharing and information discovery (Cheng and Xiong, 2014; Basak and Pavlova, 2016; Da et al., 2020; Goldstein and Yang, 2022) has been widely discussed. Our study concludes that financialization can also lead to extreme prices by facilitating new forms of market manipulation.

The rest of our paper is structured as follows. Section II introduces the rules of NYMEX WTI contracts and some anecdotal evidence of manipulation in the negative price of oil. Section III presents our hypotheses on closing pressure and WTI prices. Section IV describes data and empirical tests, as well as the closing-pressure-predicted WTI price on April 20, 2020. Section V shows the theoretical model with intraday dynamics and TAS predatory trading, together with the quantitative analysis. We conclude in Section VI.

II. NYMEX WTI Contracts and the Anecdotal Evidence of the Negative Oil Price

NYMEX WTI Crude Oil futures is one of the most actively traded contracts in the world. The currently listed contract series extends beyond ten years with monthly futures contracts, allowing participants to hedge and invest. It is underpinned by WTI crude oil that meets specific standards. As prescribed in the rulebook, trading of the first-nearby contract terminates three business days before the 25th calendar day of the month prior to the contract month. For example, the May 2020 WTI contract was the first-nearby contract in April 2020, and it expired on April 21. Each contract is daily settled to the volume-weighted average price (VWAP) during the settlement period from

14:28 to 14:30 EST, and the first-nearby contract is finally settled after the last trading day.

Physical settlement and cash settlement are two common modes to finally settle contracts in the commodity futures market. WTI contracts take physical settlement rules that traders, who still have their positions open after expiration, must take deliveries of real crude oil. Long traders must book storage in advance at the delivery point, Cushing, Oklahoma, to take in the physical oil, while short traders should transport oil to Cushing through designated pipelines. This is quite different from another oil futures pricing benchmark, the ICE Brent Crude futures, which admits cash settlement rules that traders in a contract can choose to transfer the net cash positions after expiration. Physical settlement rules induce a much higher cost to make a final settlement than cash settlement rules.

There are two major execution types in the trading of WTI contracts. One is to trade directly with real-time futures prices. The other instrument is Trading at Settlement (TAS), which is an order type that allows participants to trade at a defined number of tick increments (+/–0.01 dollars per tick with a maximum of ten ticks) to the base of the daily settlement price at any time during the trading session. The TAS clearing price equals the daily settlement price plus or minus the ticks, and it provides a mechanism for traders to capture daily settlement prices without trading in the real-time futures market. TAS has been used for crude oil contracts since 2001 and accounted for over 20% of the total trading volume on April 20, 2020, more than twice of the TAS trading volume in normal times. Although TAS does not often trade at tick limits, the number of contracts traded at the maximum negative limit (–0.1 dollar) on April 20 was approximately 70 times higher than all of 2019, according to the CFTC Interim Staff Report. This confirms that there was a substantially high selling demand in the TAS market on April 20, 2020.

WTI crude oil futures serve as a vital reference price in international derivative markets, and the negative price has had worldwide impacts. Since the

2000s, commodity futures have been viewed as a new asset class, and speculative index investment by financial institutions has greatly increased. The growing index funds, exchange-traded funds and exchange-traded notes are mainly transacted with swap dealers, and swap dealers further manage their price risks by establishing opposite positions in the commodity futures market. In other words, index traders' long positions in swaps will be reflected as swap dealers' long positions in the oil futures market. In this way, small individual investors are also able to gain exposure to commodity futures by buying over-the-counter derivative products from various financial institutions. The WTI crude oil futures price declined greatly from \$60/barrel to \$20/barrel in the first quarter of 2020 due to the epidemic, and more financial capital crowded into the oil futures market, betting on a rebound in the oil price. In general, open interest for the first-nearby contract starts to decline four weeks before expiration when most participants roll over to other more actively traded contracts. However, the great oversupply of oil at the beginning of 2020 resulted in an extreme contango structure in the WTI futures market, and the average spread between the May and the June 2020 contract from April 1 to April 17 was –\$5.1/barrel, meaning that rolling one contract from the May to the June before April 20 cost approximately 5,110 dollars. Faced with such a high rolling cost, a portion of investors continued to hold their contracts until the penultimate trading day and finally took the unexpected negative price. The negative price was a catastrophe for international financial investors, with Interactive Brokers, Bank of China, and Multi Commodity Exchange in India all suffering huge losses with products benchmarked against the daily settlement price of WTI crude oil futures.

When the negative oil price first occurred, it was generally believed that the sharply reduced oil demand and the resulting shortage of storage space were mainly to blame. Faced with the potential danger of having nowhere to store oil, futures traders would pay someone else to get rid of the oil in hand. However, other voices also questioned the potential price manipulation.[8] Dan M. Berkovitz, Commissioner of CFTC, has called for an investigation into the potential manipulation of TAS trading. In fact, TAS manipulation has been applied in the oil futures market to make speculative profits. The Dutch trading firm Optiver reaped great profits with the manipulative use of TAS in 2007 when the oil market was very hot and was finally charged by the CFTC for "banging the close".[9] This time, the extremely negative price occurred under conditions of the pandemic and economic stagnation, and the manipulative strategy may have worked in the opposite direction. In the following parts of the paper, we first empirically test the relationship between closing pressure and WTI prices, and then incorporate intraday dynamics and TAS predatory trading into the analysis.

III. Closing Pressure and WTI Price: Hypothesis Development

The most common explanation for the negative oil price in the social media focuses on the inventory surplus and excessive long trades under physical settlement rules. REUTERS argues that the frenzied selling was driven by a lack of storage space to hold a glut of crude, meaning traders were willing to pay buyers to take oil off their hands. Given that the prices of WTI and Brent oil futures diverged greatly (–37.63 vs. 25.57) on April 20, 2020, and the first-nearby and second-nearby WTI prices also deviated significantly (–37.63 vs. 20.43), it is possible that the negative price specific to the first-nearby WTI contract is associated with the closing pressure originating from the physical settlement rules. Participants on the long side are required to book storage at

[8] Chairman of oil producer Continental Resources Inc. argues for an investigation on the possible failed market system. An article in Bloomberg noticed the torrent of selling starting two hours before the settlement period and questioned whether the price was deliberately pushed down by someone. The article also mentioned that nine traders in Vega Capital London Ltd. may have had the largest impact on prices, making 660 million dollars in just a few hours with the negative price.
Source:
https://www.bloomberg.com/news/features/2020-12-10/stock-market-when-oil-when-negative-these-essex-traders-pounced.

[9] https://www.cftc.gov/PressRoom/PressReleases/5521-08.

Cushing, and investors on the short side ought to transport oil to Cushing. Therefore, in the condition of inventory surplus, the noncommercial buy-side is difficult to take delivery as capacity is limited; thus, the buy-side is eager to initiate the selling trades on the penultimate day, but the sell-side can easily find oil to deliver and, thus, is not eager to buy futures. The closing pressure for long-position traders is determined by two factors, one is how many contracts must be closed via the futures market, the other is the inventory level. A higher open interest and a higher inventory level result in higher closing pressure, and the closing pressure tends to reduce the WTI price on the penultimate trading day. We construct a simple model to clarify our hypotheses.

Denote A as the total starting open interest on the penultimate trading day. Before this day, traders make decisions on whether to take physical deliveries, and those who decide to take deliveries should book storage at Cushing ahead of time. Others must close their positions before contract expiration via the futures market, and we call this group financial settlers. Suppose there is a large long-position financial settler and a large short-position financial settler with initial positions of $a_L A$ and $a_S A$, respectively. These two financial settlers are liquidity demanders in the market. The last trading day is highly illiquid with a rather small trading volume; thus, we assume that financial settlers close all positions before the end of the settlement period on the penultimate trading day. Physical deliverers are regarded as the liquidity provider, consistent with the conclusions of Kang, Rouwenhorst and Tang (2020). Suppose the liquidity provider follows a linear pricing rule:

$$F - F_0 = -\lambda \times D \tag{1}$$

F_0 is the opening price, F is the daily settlement price, D is the net selling demand and λ measures market illiquidity. The market clearing condition is:

$$D = a_L A - a_S A \tag{2}$$

Combining (1) and (2), the settlement price is:

$$F = F_0 - \lambda \times (a_L - a_S) A \tag{3}$$

The net selling demand ratio[10] in the futures market, $a_L - a_S$, is a result of delivery decisions before the penultimate trading day, and is correlated with the cost of physical deliveries. If the delivery cost for the buy-side is high, the portion of physical delivery in long positions will be smaller, and this leads to a higher portion of financially-settled contracts in the long side, namely, a higher $a_L - a_S$. Therefore, the net selling demand ratio is a function of inventory level, and for simplicity, we set it as a linear function shown in Equation 4.

$$a_L - a_S = \gamma * I \tag{4}$$

γ is positive since a higher inventory level leads to a higher delivery cost for long-position traders and, thus, more imbalanced trading needs between the long and the short traders. As discussed above, we measure closing pressure by the product of open interest and inventory level, and we define it CLP:

$$CLP = A \times I \tag{5}$$

The consequent settlement price is:

$$F = F_0 - \lambda\gamma \times CLP \tag{6}$$

We come to hypotheses on how WTI price is influenced by closing pressure.

Hypothesis I: Higher closing pressure leads to lower WTI futures price.

Proof:

$$\frac{\partial F}{\partial CLP} =- \lambda\gamma < 0$$

Hypothesis II: The negative price effect of closing pressure is strengthened by the drying-up of market liquidity.

Proof:

$$\frac{\partial}{\partial \lambda}\left|\frac{\partial F}{\partial CLP}\right| = \gamma > 0$$

Overall, the simple model suggests that closing pressure, measured by the product of open interest and inventory level, will drag down WTI settlement price on the penultimate trading day (the de facto last trading day). This negative price effect is strengthened by the drying-up of market liquidity. In the

[10] Net selling demand ratio refers to the net selling demand as a proportion to the total open interest.

next section, we empirically test these hypotheses and estimate the contribution of closing pressure in causing the extremely negative oil price on April 20, 2020.

IV. Closing Pressure and WTI Price: Empirical Tests

A. The Data

We use publicly available data to study the WTI settlement price on the penultimate trading day. The WTI crude oil futures data, including settlement prices, trading volume and open interest, are collected from the Commodity Research Bureau (CRB), and Brent crude futures data are retrieved from Bloomberg. The U.S. ending stocks, excluding the special petroleum reservation (SPR) of crude oil, are obtained from the Energy Information Administration (EIA). We take the latest observable data before contract expiration as the close-to-maturity inventory level. Our sample starts from January 2003 to April 2020 with a monthly frequency[11], and the full sample includes 208 pairs of WTI and Brent contracts.

The penultimate trading day of each contract is the de facto last trading day for closing positions and it experiences most of the closing pressure, we therefore set it as day T. We construct the dollar spread between WTI and Brent futures on day T of each calendar month M, $WBdollarspread_{M,T}$:

$$WBdollarspread_{M,T} = P_{WTI,M,T,1} - P_{Brent,M,T,1} \tag{7}$$

$P_{WTI,M,T,1}$ and $P_{Brent,M,T,1}$ represent the settlement prices of WTI and Brent first-nearby contracts on Day T, month M, respectively. The WTI-Brent percentage spread, named $WBpercspread_{M,T}$, is calculated as:

$$WBpercspread_{M,T} = \frac{(P_{WTI,M,T,1} - P_{Brent,M,T,1})}{P_{Brent,M,T,1}} * 100 \tag{8}$$

Following the simple model in Section III, we empirically measure closing pressure for long-position traders on day T with the product of open interest and

[11] Note that commodity futures have emerged as a new asset class since the early 2000s, which is called a financialization process in Tang and Xiong (2012). The determinants of oil prices have changed since then. We set year 2003 as the starting point to avoid regime switching in our sample.

inventory level, as Equation 9 shows.

$$Closing\ pressure_{M,\ T-1} = Open\ Interest_{M,\ T-1} * Inventory^{*}_{M,T-1} \tag{9}$$

$Open\ Interest_{M,\ T-1}$ refers to total open interest after the trading of day T-1, i.e., the starting open interest on day T. As Figure 3 shows, $Open\ Interest_{M,\ T-1}$ normally fluctuate between 50 and 70 thousand contracts, but April 20, 2020 saw an extraordinary peak of more than 108 thousand contracts. We use the latest available weekly U.S. crude oil ending stock as the close-to-maturity inventory level before day T, $Inventory_{M,T-1}$. To obtain a unit-free measure of inventory with no trend, we follow Gorton, Hayashi and Rouwenhorst (2012) to define the normalized inventory level:

$$Inventory^{*}_{M,T-1} = \frac{Inventory_{M,T-1}}{(\sum_{m=M-12}^{M-1} Inventory_{m,\ T_m-1})/12}\ ^{12} \tag{10}$$

Figure 4 provides both the unadjusted and normalized inventory levels. As Figure 4 suggests, the inventory level around April 20, 2020 was very high at 519 million barrels, much higher than the sample average of 359 million. Figure 5 plots the time series of closing pressure from January 2003 to April 2020, with April 20, 2020 being the highest.

We also construct another form of closing pressure for robustness check. In the previous discussion, we use $Open\ Interest_{M,\ T-1}$ to represent the contract closing demand on day T. In the robustness check, we measure this closing demand as the difference between $Open\ Interest_{M,\ T-1}$ and $Open\ Interest_{M,T}$. However, as $Open\ Interest_{M,\ T}$ can only be determined after the trading session of Day T, we apply the previous-month open interest $Open\ Interest_{M-1,\ T}$ as an approximate substitute for predictive regressions because this time series is quite persistent.[13]

Marshall, Nguyen and Visaltanachoti (2012) show that the Amihud illiquidity measure is the best illiquidity measure for the commodity futures market; hence, we take the average of the daily Amihud ratio from Day T-5 to

[12] T_m refers to the last trading day in month m.
[13] The AR1 coefficient this time series data is 0.38 with a t-stat of 5.93.

Day T-1 (in log form) as a proxy for the overall market illiquidity before contract expiration:

$$Amihud_{M,T-1} = \log(\sum_{t=T-5}^{T-1} amihud_{M,t}/5) \tag{11}$$

During the early period of the sample, there is a declining trend in market illiquidity as the commodity futures markets become increasingly liquid; hence, we detrend the illiquidity measure by subtracting its past 12-month average:

$$Amihud^{*}_{M,T-1} = Amihud_{M,T-1} - \frac{(\sum_{\mathrm{m=M-12}}^{\mathrm{M-1}} \mathrm{Amihud}_{\mathrm{m},T_m-1})}{12} \tag{12}$$

Figure 6 plots the unadjusted and adjusted Amihud illiquidity, showing that April 20, 2020, had almost the lowest market liquidity of the last twenty years.

Table 2 presents summary statistics of the variables in our research. The WTI futures price is normally lower than the Brent futures with an average of –4.07 dollars or –4.15% spread. The price spread between WTI first-nearby and second nearby contract is –0.35 dollars or –0.60%. The value of open interest ($Open\,Interest_{M,\,T-1}$), inventory ($Inventory^{*}_{M,T-1}$), $Closing\,pressure_{M,\,T-1}$ and Amihud illiquidity ($Amihud^{*}_{M,T-1}$) for April 20, 2020 are 10.86, 1.16, 12.57 and 2.14, respectively, much higher than the sample averages of 6.06, 1.02, 6.14 and –0.08, respectively, showing that April 20, 2020, is an unusual day with extremely high closing pressure and low market liquidity.

B. The Baseline Regression

We start our analyses by looking at the relationship between closing pressure and WTI futures prices. According to our hypotheses in Section III, high closing pressure will push down WTI prices and result in a lower WTI-Brent price spread on Day T.

Since Brent oil can be settled by cash, it does not have the physical delivery issues mentioned above; therefore, we use the Brent contract as a benchmark and explore the dollar spread between the WTI and Brent prices of nearby contracts. In the regression, we also pay attention to the interactive effects of closing pressure and market illiquidity on price spread. Particularly, it is more difficult to find the counterparty for transactions in an illiquid market; hence, the price impact of trades tends to be magnified. Considering the seasonal difference between the UK and the U.S., we add monthly dummies in the regression to control for seasonality. In addition, the classical theory of storage (Kaldor,1939; Working, 1949; Brennan, 1958) shows that inventory itself can influence commodity prices; hence, we add the normalized inventory as a control variable in the regression. In addition, return on Day T-1 is also added as a control variable, as the momentum effect also commonly exists in commodity markets (Miffre and Georgios, 2007; Bakshi, Gao and Rossi, 2019). The baseline regression is shown in Equation 13. Hypotheses in Section III predict that $\beta_1 < 0$ and $\beta_2 < 0$.

$$\begin{aligned} &WBdollarspread_{M,T} \\ &= \alpha + \beta_1 * Closing\ Pressure_{M,T-1} + \beta_2 * \ Closing\ Pressure_{M,T-1} * Amihud^*_{M,T-1} \\ &\quad + \textstyle\sum_{k=2}^{12} \beta_{3,k} * D_k(Month_M) + \beta_4 * Inventory^*_{M,T-1} + \ \beta_5 * Return_{M,T-1} + \varepsilon_M \qquad (13) \end{aligned}$$

The sample period for the baseline regression is from January 2003 to April 2020. We first exclude the data point of April 2020 to explore the historical relationship between closing pressure and the WTI-Brent dollar spread, and the results are shown in Panel A of Table 3. We also provide results with the full sample, including the data point of April 2020, in Panel B.

Column (1) in Panel A shows that a higher closing pressure significantly predicts a lower WTI-Brent dollar spread on the penultimate trading day, consistent with hypotheses in Section III. Column (2) of Panel A reports that market illiquidity and closing pressure have interactive effects on the WTI-Brent spread with an estimated coefficient of -0.255 and a t-value of -2.33; the price impact of closing pressure tends to be larger in illiquid market periods. Turning to the control variables, the monthly dummies in Column (3) do not attenuate the impact of key variables and slightly improve the R-square to 5.7%.

Inventory and returns on Day T-1 do not show great significance. According to Column (4) A one standard deviation increase in the closing pressure tends to reduce the spread by 1.3 dollars.

Consistent with the implications of Panel A, the results in Panel B with the full sample, including the data point of April 2020, show greater impacts with higher t values. The coefficient of closing pressure on WTI-Brent dollar spread after adding the control variables is −1.90 with a t value of −4.65. A one standard increase in closing pressure will result in a lower spread of 2.3 dollars. Again, market illiquidity significantly enhances the negative price effect of closing pressure

Overall, closing pressure under WTI physical settlement rules indeed affects WTI futures prices; a higher closing pressure significantly reduces the WTI price (WTI-Brent dollar spread) on the penultimate trading day of each contract, and this negative effect is strengthened by market illiquidity. The empirical results fully support our hypotheses in Section III. It is worth noting that this relationship was not driven by the extreme case on April 20, 2020, but already existed before that.

C. Robustness Checks

In this subsection, we first utilize an alternative way to construct WTI-Brent price spread and then use a different method for measuring closing pressure.

1. Alternative Price Spread

In this subsection, we use the WTI-Brent percentage spread as the dependent variable and explore whether the results in Table 3 are robust, and the results are reported in Tables 4. Panels A and B are the results of the samples excluding and including the data point of April 2020, respectively.

Table 4 shows that the estimated coefficient of closing pressure in Column (1) is −2.294 with a t value of −5.14, meaning that a one standard deviation increase in closing pressure drags down the WTI-Brent percentage spread by 2.8%. Market illiquidity also plays an important role in amplifying the effect, and these two factors account for more than one-fifth of the total variation in the WTI-Brent percentage spread. The key results do not change when we control for other factors in Column (3) and Column (4) or when we add the data point of April 2020 into the sample in Panel B.

Therefore, our main findings are robust when we replace the spread from dollar form with the percentage form. Closing pressure predicts a lower WTI futures price compared to the concurrent Brent price, and the negative effect of closing pressure is reinforced by market illiquidity.

2. Alternative Closing Pressure

Note that our major measure of closing pressure shown in Equation 9 is the product of open interest and inventory level. As a robustness check, we apply the product of open interest change on day T and inventory level. The open interest change, $Open\,Interest_{M,\,T-1} - Open\,Interest_{M,\,T}$ can only be determined after the trading session of day T. To conduct a predictive regression, we replace $Open\,Interest_{M,\,T}$ with $Open\,Interest_{M-1,\,T}$. Panel A of Table 5 shows that the closing pressure has an estimated coefficient of –1.386 with a t-value of –4.27. Market illiquidity magnifies the impact of the closing pressure on price movements with marginal significance. The important role of closing pressure still holds when control variables are incorporated. When adding the data point of April 2020, Panel B shows that the effect of closing pressure is larger and the interactive item with illiquidity is statistically significant.

To conclude, closing pressure significantly pushes down the close-to-maturity WTI price and drives it away from its benchmark value (the Brent price), and this effect is strengthened by market illiquidity. The findings are robust to different forms of closing pressures and price spreads.

D. Closing-Pressure-Predicted WTI Price on April 20, 2020

Considering that April 20, 2020 saw the highest closing pressure and almost the lowest market liquidity over the sample period, we wonder whether the closing pressure can adequately explain the occurrence of the extremely negative WTI price of –$37.63/barrel. We, therefore, compute the predicted value of the WTI-Brent dollar spread and, thus, the WTI price on April 20, 2020, using the estimated coefficients with historical data in Panel A of Table 3.

Table 6 provides all the closing-pressure-predicted WTI-Brent dollar spread and the corresponding WTI prices. When applying closing pressure alone in Model (1), we obtain an estimated WTI price of 15.9 dollars. The predicted WTI price decreases to 8.4 dollars when the interactive item with market illiquidity is added in Model (2), and the predicted price further declines to around $7/barrel when month dummies and other control variables are used. This is close to the actual price performance before 14:00 on April 20, 2020, when the price started from $17.73/barrel and gradually declined to close to zero.

The predicted results, therefore, validate the importance of closing pressure, together with market illiquidity, in dragging down the WTI price on April 20, 2020, as most of the social media argues. Our empirical tests confirm that the argument is good direction wise, but difficult to quantitatively generate a negative price. There is still a large portion of the price drop, from $7 to –$37.63, left to be explained. The analysis above misses two important points-the intraday dynamics and the TAS arbitrage. In the next section, we incorporate these two missing points into our model to analyze the role of TAS predatory trading and quantitively generate the extremely negative price.

V. TAS Predatory Trading and WTI Price

A. Intraday Dynamics of Price and Market Liquidity

Analysis in Section III and IV focuses on WTI settlement price on the penultimate trading day, but neglects the intraday price performances. As Figure 2 shows, the intraday price dynamics on April 20, 2020, can be divided roughly into three phases. Trading started the preceding evening at 18:00 EST with an opening price of $17.73/barrel, and the price dropped slowly to $10 at 12:00. It declined more quickly after 12:00 and reached zero at 14:00. The price then collapsed 30 minutes right before the daily settlement period (14:28 to 14:30) and went to a shocking settlement price of -$37.63.

In addition to the price dynamics, market liquidity also varies greatly in these three phases. Following Kyle (1985), we apply tick data of the May 2020 WTI Contract on April 20 to estimate the market liquidity of the three phases. For each trade, we classify it as buyer-initiated (seller-initiated) based on whether the trading price is higher (lower) than the prevailing average of bid and ask prices. If these two prices are equal, then we continue to compare the trading price of this transaction with that of the last transaction. If transaction j is buyer-initiated, define $Ticker_j = 1$; if it is seller-initiated, define $Ticker_j = -1$. Denote market liquidity of the three phases as λ_1, λ_2 and λ_3, respectively. Our estimates of λ_i follow the estimating method of Kyle's lambda, as shown in Equation 14.

$$P_j - P_{j-1} = \theta_i + \lambda_i * OrderImbalance_j + \varepsilon_j \qquad i=1, 2, 3 \qquad (14)$$

$$OrderImbalance_j = Ticker_j * TradingVolume_j$$

$OrderImbalance_j$ is the product of $Ticker_j$ and the trading volume of transaction j. We run this regression with transactions before 12:00, from 12:00 to 14:00, and from 14:00 to 14:30 on April 20 respectively, and the estimated results are shown in Table 7. λ_1 is estimated to be 0.0303 with a t-value of 25.13, λ_2 is estimated to be 0.2738 with a t-value of 26.74, and λ_3 is estimated to be 0.6211 with a t-value of 7.92. λ_3 is 20 times as large as λ_1 and more than twice of λ_2, indicating that market liquidity dries up quickly as it approaches the settlement period.

Intraday dynamics of price and market liquidity indicate that the event of negative oil price consists three different phases. The unprecedented price drop right before the daily settlement period suggests the potential existence of TAS predatory trading across the outright futures market and TAS market.

B. TAS Predatory Trading

TAS is an order type that allows participants to establish positions with yet-to-be-determined daily settlement price at any time during the trading session. The daily settlement price is calculated as the volume-weighted average price from 14:28 to 14:30. It is designed to facilitate traders who target settlement price, and is widely used with the process of commodity financialization. Financial index traders usually gain long positions in oil futures by trading with swap dealers, and swap dealers then hedge their risks in the futures market via TAS orders that match the target price in swap contracts. These positions need to be closed before contract expiration since financial index traders will not take physical deliveries. We propose a TAS predatory trading strategy[14] that captures the great selling demand from financial swap dealers. Specifically, the strategy includes two legs: 1) buy as many futures as possible (from swap dealers) in the TAS market, and 2) sell the same number of futures in the outright market. The number of trades of the two legs cancel each other out, but the average selling price in the outright market could be higher than the purchase price (settlement price) in the TAS market. Hence, this strategy, overall, yields a great profit for the predators.

TAS predatory trading strategy captures the intrinsic defect of TAS orders that transaction time misaligns with the price formation time. Two conditions are necessary for the success of this TAS predatory trading strategy: one is the

[14] Predatory trading is a strategy that exploits the bulk selling demand of others, sells ahead or simultaneously with them to generate a price overshooting, and buys back the asset with a lower price.

existence of a great selling demand in the TAS market so that one can capture it by buying many TAS contracts and "banging the close" in the outright market afterward; the other is that the settlement price can be easily pushed down.

For the first condition, the net selling demand in the TAS market can be inferred from the starting open interest on April 20, 2020. As discussed in Section III, trading volume on the last trading day is rather small, and only 1% of futures traded go to physical deliveries. Therefore, a high starting open interest on the penultimate day suggests high closing needs on that day, and TAS trades account for a large amount with the process of financialization. Observing the high open interest, an experienced trader will quickly realize that there is going to be great selling demand in the TAS market and it is possible to conduct predatory trading.

For the second condition, it is easier to influence the settlement price when there is high closing pressure in an illiquid outright market. A fair amount of selling trades from predators can make prices follow down, and no trader is willing to act as the counterparty. In other words, high closing pressure and market illiquidity not only directly influence the WTI price, but also provide necessary conditions for TAS predatory trading.

In summary, extremely large long positions from swap dealers, high closing pressure and low market liquidity are necessary for conducting profitable TAS predatory trading; all these conditions were met on April 20, 2020.

We add TAS predatory trading into our three-period model to analyze intraday dynamics of the negative oil price. Suppose there is a large long-position financial settler, $Financial\,Settler_L$, with initial positions of $a_L A$, and a large short-position financial settler, $Financial\,Settler_S$, with initial positions of $a_S A$. $Financial\,Settler_L$ must sell all $a_L A$ in the three periods and the decision is how many contracts to sell in each period. Similarly, $Financial\,Settler_S$ must sell all $a_S A$ and the decision is how many contracts to buy in each period. There is an TAS arbitrageur with no initial position and conducts predatory trading across the TAS market and the outright futures market.

Three specific steps of the TAS arbitrageur are illustrated in Figure 7: 1) purchase a large number of contracts that swap dealers sell in the TAS market during period 1; 2) sell part of the established positions in the outright market during period 2; and 3) sell the remaining positions during period 3 (the settlement period). As long as the selling price in period 1 and period 2 is higher than the daily settlement price in period 3, this predatory trading strategy is profitable. The key variables used in our theoretical model are explained in Table A1 of Appendix A.

C. The Model Specification

1. $\boldsymbol{Financial\,Settler_L}$

$Financial\,Settler_L$ decides to sell x_{L1} in period 1 with the price of $F(t_1)$, sell x_{L2} in period 2 with the price of $F(t_2)$, and close x_{L3} during period 3 with the daily settlement price, $F(t_3)$. $Financial\,Settler_L$ chooses the optimal x_{L1}, x_{L2} and x_{L3} to maximize the total profit:

$$F(t_1) * x_{L1} + F(t_2) * x_{L2} + F(t_3) * x_{L3} \tag{15}$$

$$\text{s.t. } x_{L1} + x_{L2} + x_{L3} = a_L A$$

2. $\boldsymbol{Financial\,Settler_S}$

$Financial\,Settler_S$ decides to buy x_{S1} in period 1 with the price of $F(t_1)$, buy x_{S2} in period 2 with the price of $F(t_2)$, and close x_{S3} during period 3 with the daily settlement price, $F(t_3)$. $Financial\,Settler_S$ chooses the optimal x_{S1}, x_{S2} and x_{S3} to minimize the total cost:

$$F(t_1) * x_{S1} + F(t_2) * x_{S2} + F(t_3) * x_{S3} \tag{16}$$

$$\text{s.t. } x_{S1} + x_{S2} + x_{S3} = a_S A$$

3. TAS Arbitrageur

The TAS arbitrageur captures the large selling demand in the TAS market and establishes long positions of Δ via TAS orders with yet-to-be-determined settlement price, $F(t_3)$. The arbitrageur simultaneously sells Δ_1 in the outright market during period 1 with the price of $F(t_1)$, sells Δ_2 during period 2 with the price of $F(t_2)$, and closes Δ_3 during period 3 with the price of $F(t_3)$. The TAS arbitrageur chooses the optimal Δ_1, Δ_2 and Δ_3 to maximize the total profit:

$$F(t_1) * \Delta_1 + F(t_2) * \Delta_2 + F(t_3) * \Delta_3 - F(t_3) \times \Delta \tag{17}$$

$$\text{s.t. } \Delta_1 + \Delta_2 + \Delta_3 = \Delta$$

According to the TAS trading rules, the actual trading price of a TAS contract is the daily settlement price plus or minus the quoted ticks (up to 0.1 dollars). The ticks are omitted from our model for simplicity since they are very small. The maximum number of TAS contracts that the TAS arbitrageur can purchase, Δ, is the net selling demand in the TAS market exogenously given.

4. Market-clearing Conditions

Pricing rules in three periods are:

$$F(t_1) - F(t_0) = -\lambda_1 \times D_1 \tag{18}$$

$$F(t_2) - F(t_1) = -\lambda_2 \times D_2 \tag{19}$$

$$F(t_3) - F(t_2) = -\lambda_3 \times D_3 \tag{20}$$

Market-clearing conditions for three periods are:

$$D_1 = x_{L1} + \Delta_1 - x_{S1} \tag{21}$$

$$D_2 = x_{L2} + \Delta_2 - x_{S2} \tag{22}$$

$$D_3 = x_{L3} + \Delta_3 - x_{S3} \tag{23}$$

D. Solutions

Combining Equation 15 to Equation 23, the optimal decisions of financial settlers and the TAS arbitrageur can be solved. The optimal decisions of TAS arbitrageur and the corresponding three-period prices are:

$$\Delta_1 = \frac{3\lambda_3\Delta + (\frac{4\lambda_1\lambda_3}{\lambda_2} - \lambda_1)(a_L - a_S)A}{16\lambda_3 - 3\lambda_2} \tag{24}$$

$$\Delta_2 = \frac{\lambda_3\Delta + (6\lambda_1 - \frac{\lambda_1\lambda_2}{\lambda_3} - \frac{4\lambda_1\lambda_3}{\lambda_2})(a_L - a_S)A}{16\lambda_3 - 3\lambda_2} \tag{25}$$

$$F(t_1) = F(t_0) - \lambda_1 \frac{16\lambda_3 - 3\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} * (a_L - a_S)A - \frac{9\lambda_1\lambda_3}{16\lambda_3 - 3\lambda_2} * \Delta \tag{26}$$

$$F(t_2) = F(t_0) - \lambda_1 \frac{20\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} * (a_L - a_S)A - \frac{\lambda_3(9\lambda_1 + 3\lambda_2)}{16\lambda_3 - 3\lambda_2} * \Delta \tag{27}$$

$$F(t_3) = F(t_0) - \lambda_1 \frac{21\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} * (a_L - a_S)A - \frac{\lambda_3(9\lambda_1 + 4\lambda_3)}{16\lambda_3 - 3\lambda_2} * \Delta \tag{28}$$

The net selling demand ratio of financial settlers, $a_L - a_S$, is positively related to the physical delivery cost indicated by the inventory level, as discussed in Section III. Following Section III, we assume that $a_L - a_S$ is a linear function of the oil inventory level with $\gamma > 0$. We also define the product of open interest and inventory level as the closing pressure, CLP.

$$a_L - a_S = \gamma * I \tag{29}$$

We can rewrite three-period prices as follows:

$$F(t_1) = F(t_0) - \gamma\lambda_1 \frac{16\lambda_3 - 3\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} * CLP - \frac{9\lambda_1\lambda_3}{16\lambda_3 - 3\lambda_2} * \Delta \tag{30}$$

$$F(t_2) = F(t_0) - \gamma\lambda_1 \frac{20\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} * CLP - \frac{\lambda_3(9\lambda_1 + 3\lambda_2)}{16\lambda_3 - 3\lambda_2} * \Delta \tag{31}$$

$$F(t_3) = F(t_0) - \gamma\lambda_1 \frac{21\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} * CLP - \frac{\lambda_3(9\lambda_1 + 4\lambda_3)}{16\lambda_3 - 3\lambda_2} * \Delta \tag{32}$$

Given that market liquidity dries up as the contract gets closer to settlement, we have $\lambda_1 < \lambda_2 < \lambda_3$. We come to some propositions on how prices are influenced by closing pressure and TAS predatory trading in our extended model.

Proposition I: Higher closing pressure leads to lower WTI futures prices, and the negative price effect of closing pressure is strengthened by the decline of market liquidity. This is consistent with the hypothesis in Section III. The proof is shown in Appendix B.

Proposition II: A higher selling demand in the TAS market (a larger TAS predatory space) brings lower WTI futures prices. With more available TAS contracts to buy, the arbitrageur can push prices to much lower values. The proof is shown in Appendix B.

E. Price Simulation

To intuitively explain the role of TAS predatory trading in driving the negative oil price, we apply a reasonable set of values for all the parameters in the theoretical models to simulate price performances of the three trading periods.

Market liquidity is estimated in Section V.A with λ_1 =0.0303, λ_2 =0.2738, and λ_3 =0.6211. We further estimate other parameters in the theoretical model and simulate the WTI futures prices of the three periods. CFTC reports the starting open interest on April 20 for the May 2020 WTI contract by the Disaggregated Commitment of Traders (DCOT) trader type, as shown in Figure 8. We aggregate managed money, nonreportable and other reportable traders as financial settlers and regard swap dealers as TAS traders in our model. The normalized inventory level is 1.16 for April 20, and Figure 8 shows that $a_L - a_S$ is approximately 16%. Combining these numerical values, we estimate that $\gamma = 0.14$. Figure 8 also shows that the ratio of long-position swap dealers is approximately 25% higher than that of the short group; thus, we set $\Delta = 25\% * A$. The starting open interest A is 108,593 contracts, and the opening price, $F(t_0)$, is $17.73/barrel on April 20, 2020.

Combining the numerical values estimated above, we have the simulated prices that $F(t_1) = \$7.5$, $F(t_2) =- \$9.0$, and $F(t_3) =- \$40.1$. Overall, this strategy brings the TAS arbitrageur a profit of $338 million, consistent with the with the report of Bloomberg Business Week ($660 millions). Figure 9 provides our estimated price dynamics, very close to the actual price performances shown in Figure 2. The price gradually decreases to around $10 during period 1 until 12:00, and then it drops more quickly below zero around 14:00. After 14:00, there is an unexpected price collapse to an extremely negative price of approximately –40 dollars in only half an hour around the settlement period.

In the next section, we have some further analysis on the roles of physical settlement rules and commodity financialization in facilitating TAS predatory trading and its resulting WTI prices.

F. Further Analysis

1. Settlement Rules

We first explore the effect of physical settlement rules on TAS predatory trading and WTI prices. The great net selling demand in the outright futures market on April 20, 2020, comes from the imbalanced physical delivery cost that long traders lack storage space while short traders can easily buy crude oil with sufficient supply. Therefore, long traders are faced with closing pressure and the settlement price can be easily pressed down. If WTI contracts are cash settled like Brent futures, there will be almost no delivery cost for long-position traders, and it will be difficult for the TAS arbitrageur to drag down the settlement price. In addition, those who close contracts via TAS orders are not forced to close before contract expiration since they can net their positions by cash after that. As a result, there will be no space for the TAS arbitrageur to establish large long positions via TAS orders. With the cash settlement rules, all traders are not eager to close the contracts, and the net selling demand in both the TAS market and the outright market goes closer to zero. Consequently, there would be no TAS predatory trading and the extremely negative WTI price would not exist. WTI settlement price on April 20, 2020 would be around the opening price, and the dollar spread between WTI and Brent futures is reasonable at $-8.

Overall, the physical settlement rules are to blame for the negative oil price since it not only leads to closing pressure before contract expiration, but also makes it possible to conduct TAS predatory trading in the oil futures market.

2. Commodity Financialization

We further study how commodity financialization drives the negative price. As more capital crowds into the oil futures market, open interest (A) on the penultimate day is more likely to be greater since many financial traders unfamiliar with futures trading rules, like investors of YuanyouBao launched by Bank of China, will not roll the contracts in advance. In addition, $\frac{\Delta}{A}$ will also be larger since swap dealers usually take long positions and settle via TAS orders. As a result, commodity financialization makes it more likely for the TAS arbitrageur to establish a higher position (a greater Δ) via the TAS market. Figure 10 presents how WTI prices and predatory profit varies with the value of $\frac{\Delta}{A}$. If there is more imbalanced selling demand in the TAS market, the price will continue to go down, and the predatory profit grows with a faster rate. Figure 10 indicates that even a more negative price could occur with the process of financialization if no measures are taken to improve the current trading rules.

Our analysis confirms that physical settlement rules and commodity financialization are important factors contributing to TAS predatory trading and the resulting negative price in the May 2020 WTI contract. To date, the material impact of TAS predatory trading on the occurrence of negative prices on April 20, 2020, is left unaddressed. However, our theoretical model provides in-depth analysis for understanding the potential role of TAS predatory trading. Furthermore, our model successfully simulates the actual price performances during the trading session and obtains a final estimated settlement price around –40 dollars, which is very close to the real conditions on April 20, 2020.

VI. Conclusion

This paper argues that the historical event of the negative WTI crude oil futures price on April 20, 2020, is a comprehensive result of closing pressure (physical settlement rules) and TAS predatory trading (commodity financialization).

The most common argument in the social media argues that the limited storage space and excessive long traders contribute to the negative oil price. Our paper first empirically tests the relationship between WTI prices and closing pressure for long-position traders measured by the product of open interest and inventory level. Empirical tests confirm that closing pressure significantly predicts a lower WTI futures price on the penultimate trading day, and this negative effect is strengthened by the drying-up of market liquidity. Furthermore, the empirical analysis predicts WTI price to be approximately \$7/barrel.

Although the argument is good direction wise in dragging down the WTI price, it fails to explain the unprecedented price collapse from 0 to approximately –40 dollars right before the daily settlement period. We further add two missing points-intraday dynamics and TAS arbitrage-into our analysis, and determine the important role of TAS predatory trading in driving the negative oil price with a three-period model. TAS predatory trading is based on the commodity financialization practice of many index traders to establish long positions in oil futures via TAS orders conducted by financial swap dealers, which results in a great selling demand in the TAS market before contract expiration. The TAS arbitrageur absorbs this great selling demand in the TAS market and then sells in the outright market to push down the daily settlement price that acts as the base of the TAS purchase price. April 20, 2020 provides a good opportunity for TAS predatory trading with high closing pressure and low market liquidity, and we quantitively produce a WTI settlement price of –\$40 with our model, very close to the actual price performance.

Our research fully explains the causes of the extremely negative oil price from perspectives of closing pressure resulted from physical settlement rules and TAS predatory trading facilitated by commodity financialization. Based on our findings, we propose adding the cash settlement option to WTI settlement rules and implementing more restrictions on the use of TAS orders, especially for the first-nearby contract near expiration. Our research also highlights the importance of frictions in the oil storage market that have been neglected in previous studies and determine the shocking consequences that inconspicuous friction could have on asset price volatility.

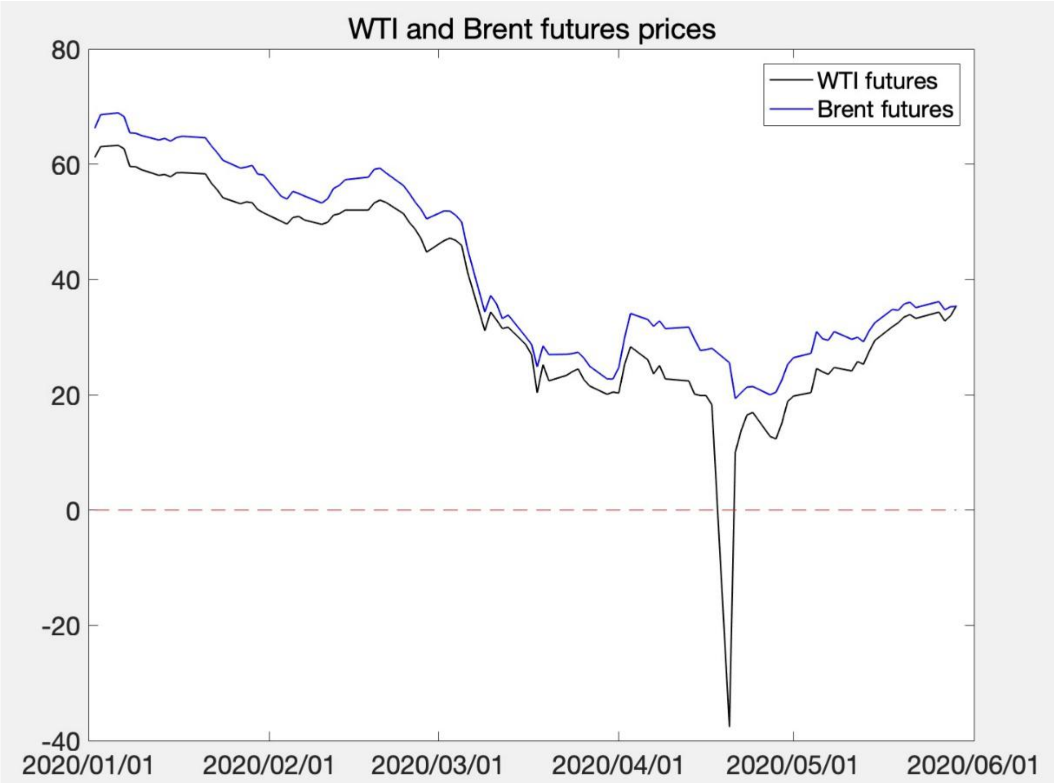


Figure 1: WTI and Brent crude oil futures prices

This figure shows prices of WTI and Brent crude oil futures from January 2, 2020 to May 29, 2020, with a significant and shocking price divergence on April 20, 2020.

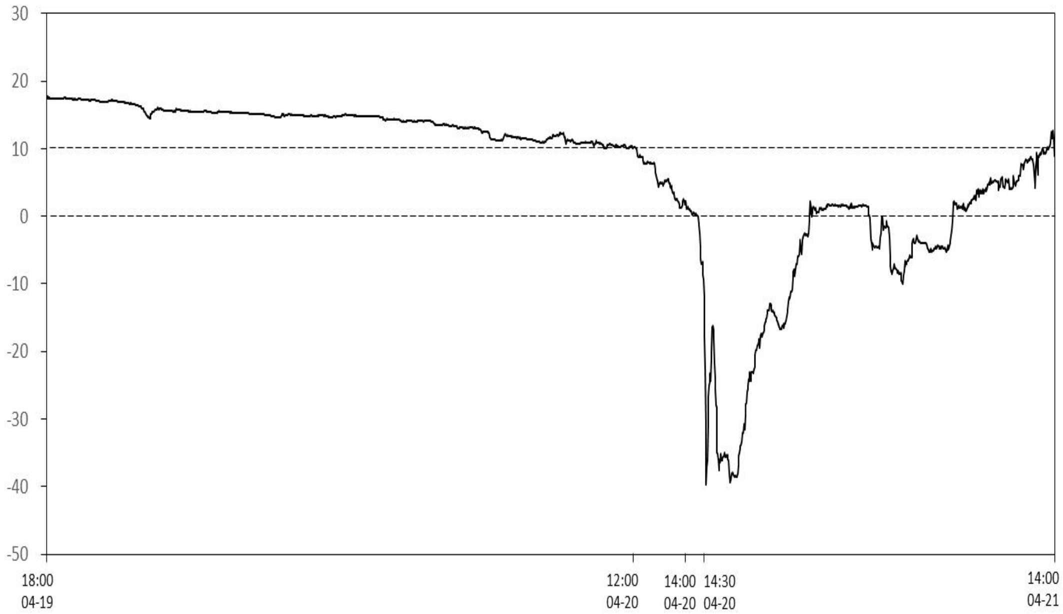


Figure 2: Intraday price of the May-2020 WTI Contract around April 20, 2020

This figure shows the intraday price dynamics of the May 2020 WTI contract around April 20, 2020 when the negative oil price occurred. The trading for April 20 started at 6 p.m. on April 19.

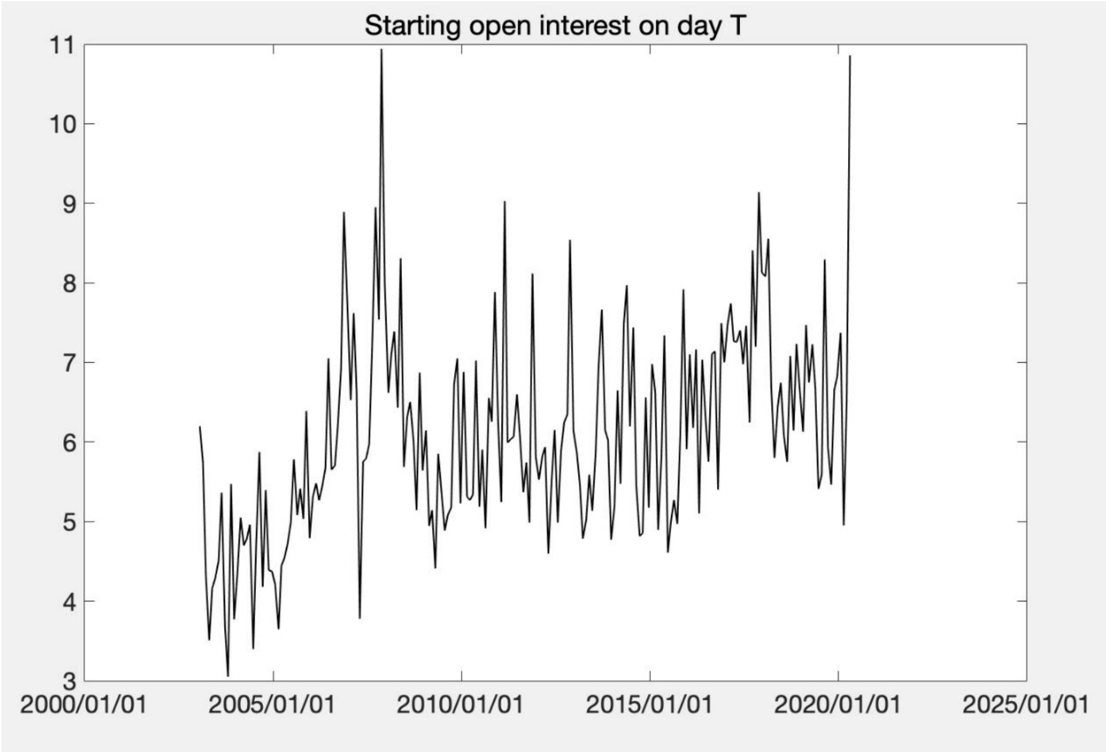


Figure 3: Starting open interest on the penultimate trading day

This figure plots the starting open interest (in ten thousand) on the penultimate trading day throughout the full sample from January 2003 to April 2020.

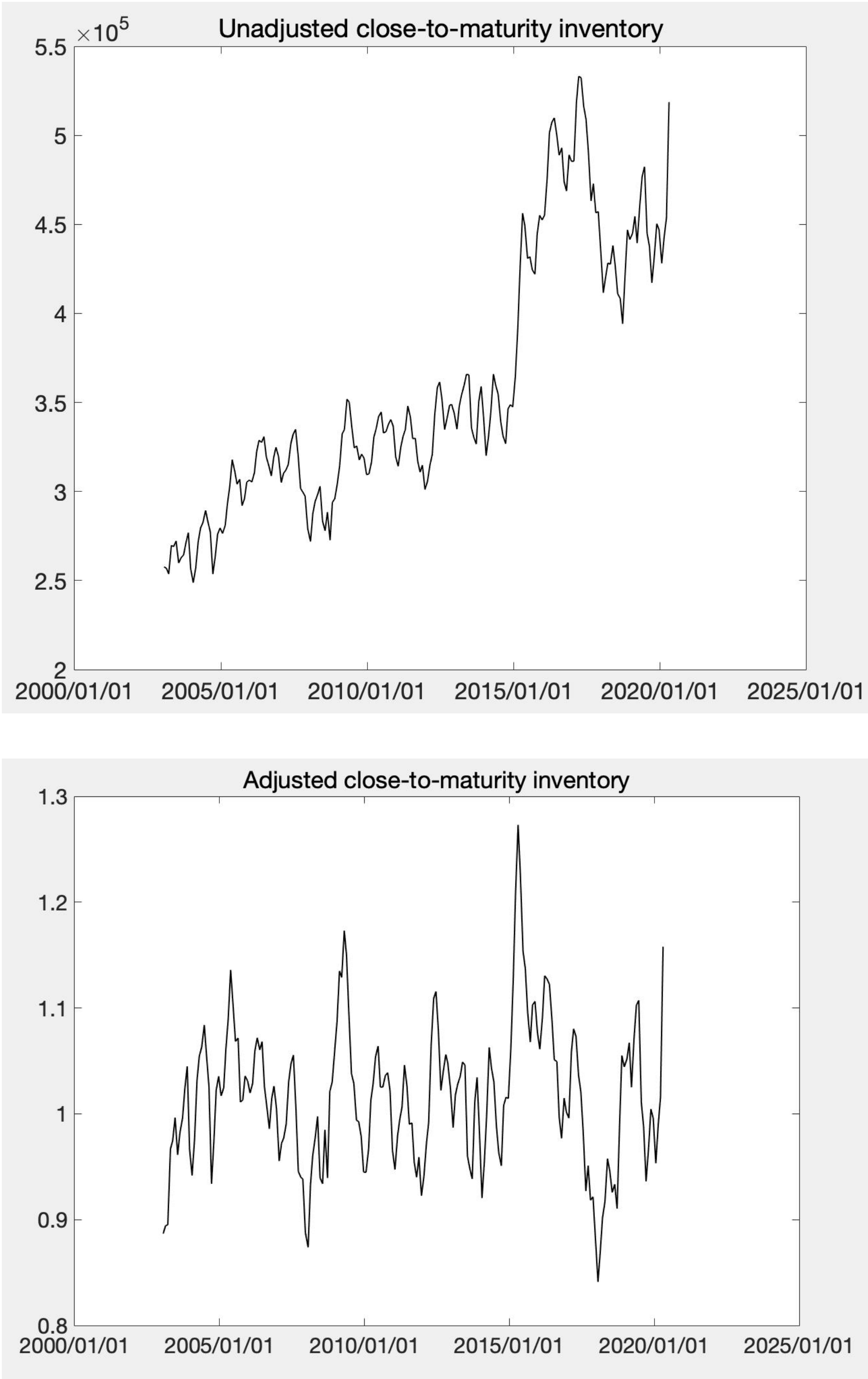


Figure 4: U.S. crude oil inventory level before contract expiration

This figure shows the closest publicly available inventory level before contract expiration each month, both unadjusted (in thousand barrels) and normalized, from January 2003 to April 2020.

The normalized inventory level is: $Inventory^{*}_{M,T-1} = \frac{Inventory_{M,T-1}}{(\sum_{m=M-12}^{M-1} Inventory_{m,T_m-1})/12}$.

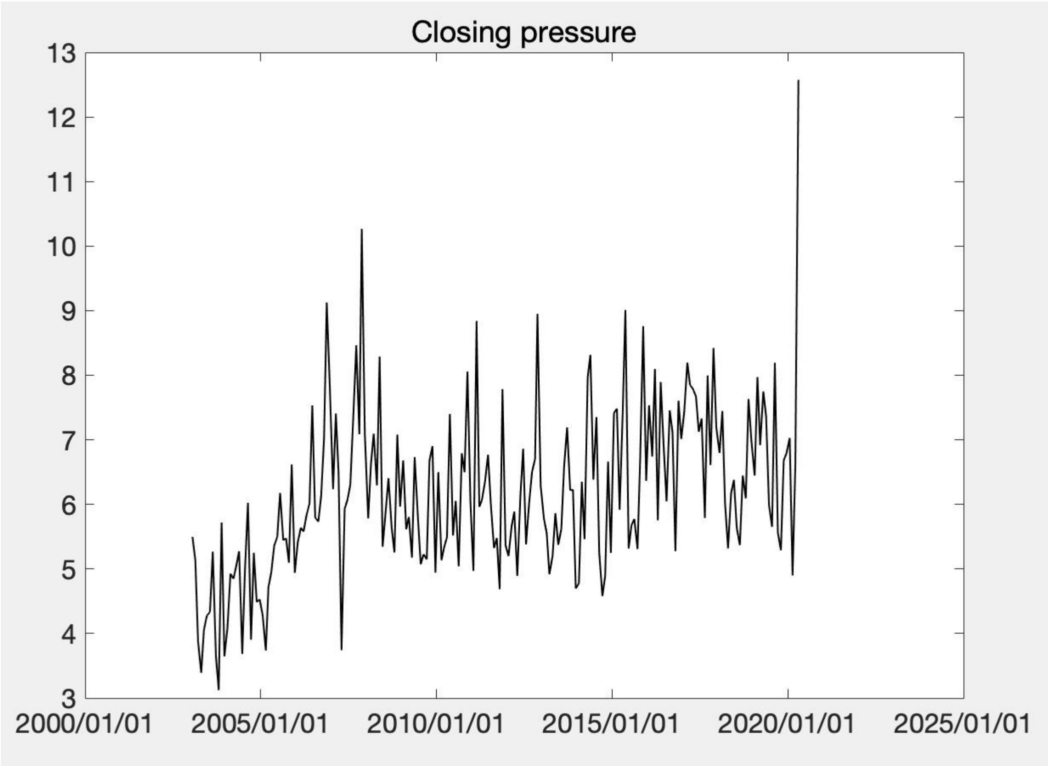
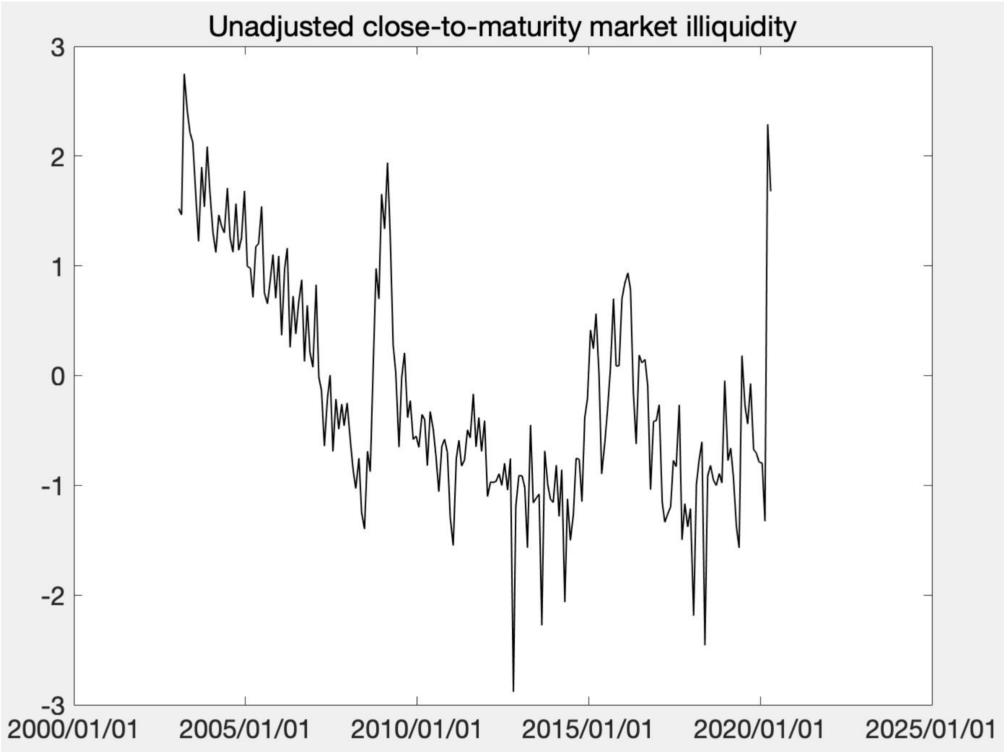


Figure 5: Closing pressure on the penultimate trading day of each contract

This figure plots the closing pressure on the penultimate trading day, defined as $Closing\ pressure_{M,\ T-1} = Open\ Interest_{M,\ T-1} * Inventory^{*}_{M,T-1}$, from January 2003 to April 2020.



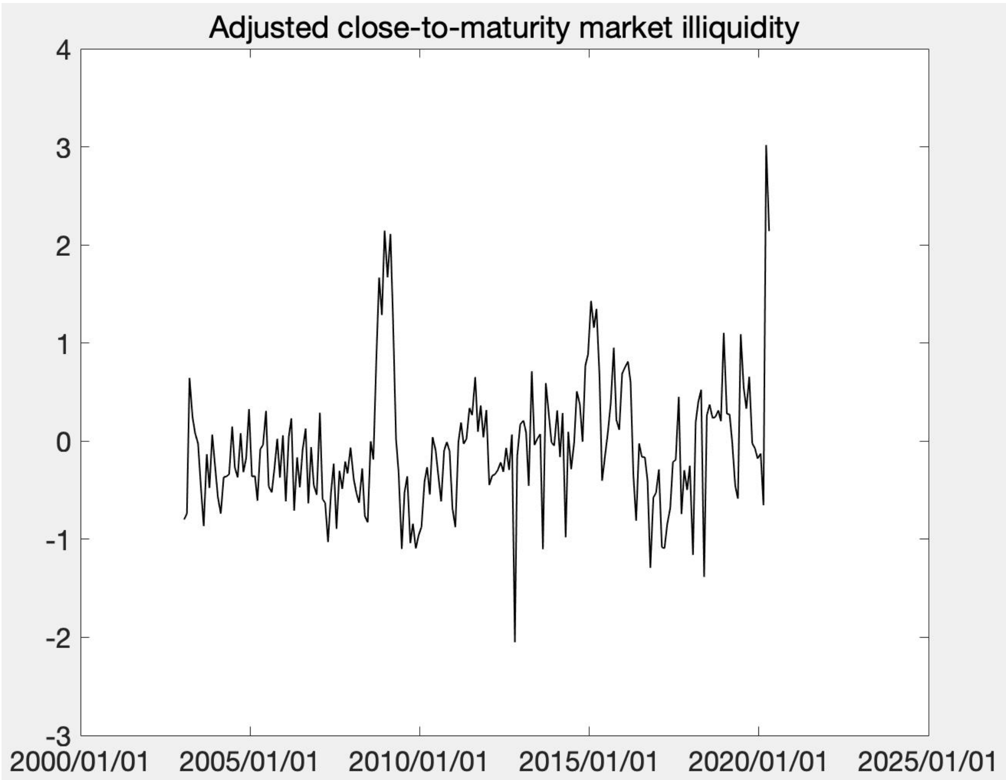


Figure 6: Unadjusted and adjusted market illiquidity before contract expiration

This figure depicts the market illiquidity each month before contract expiration, both unadjusted and adjusted, throughout the full sample period from January 2003 to April 2020.

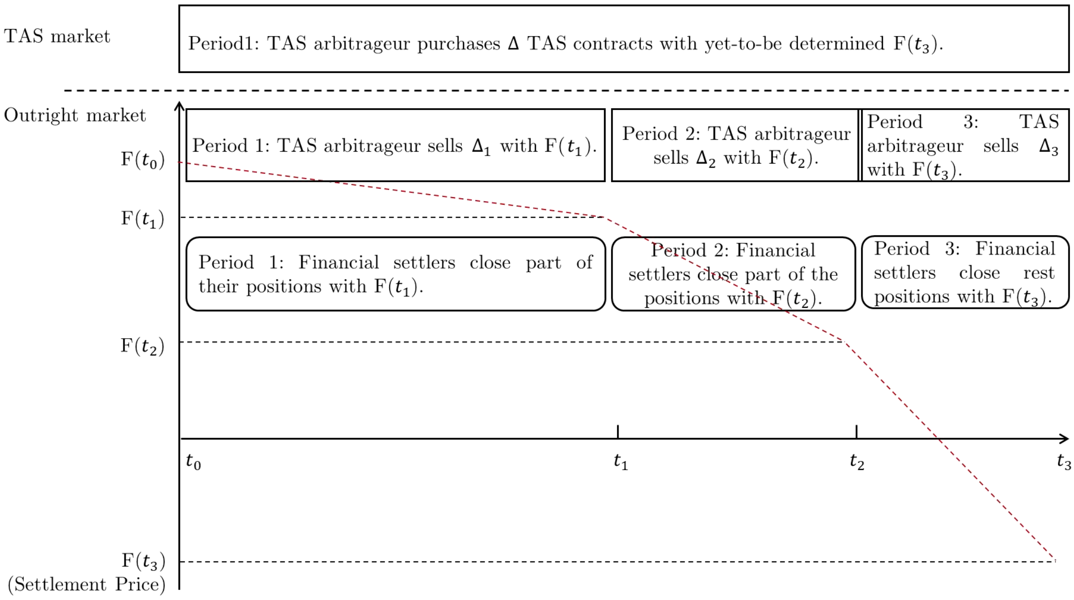


Figure 7: Trading decisions of different participants on April 20, 2020

This figure shows the three trading periods and corresponding trading decisions of financial settlers and TAS arbitrageur.

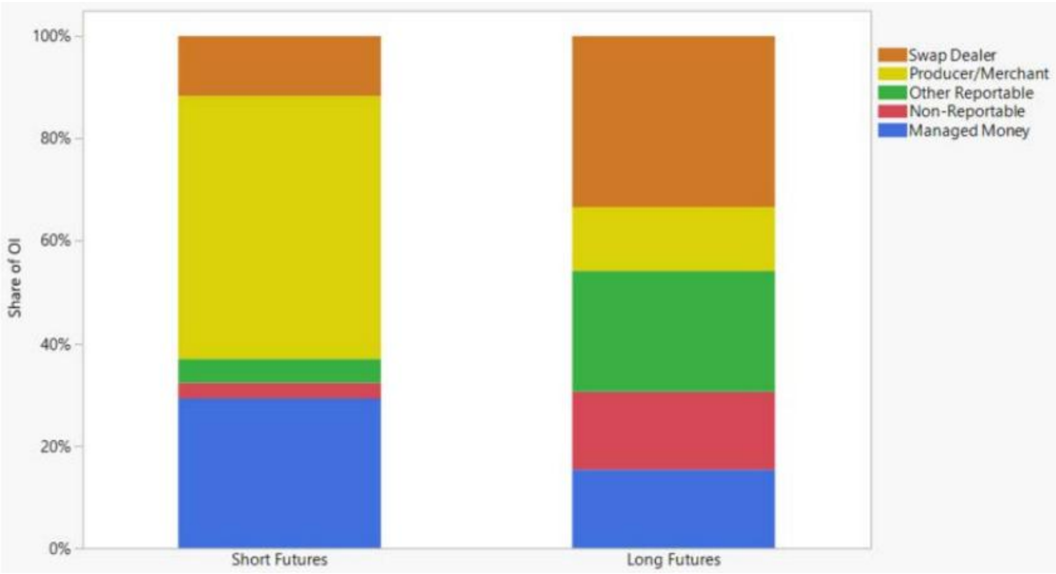


Figure 8: Starting open interest on April 20, 2020 for May Contract, by DCOT Trader Type. Source: CFTC

This figure provides position structures of the long traders and short traders on April 20, 2020 by DCOT trader types including swap dealer, producer, managed money, other reportable and non-reportable.

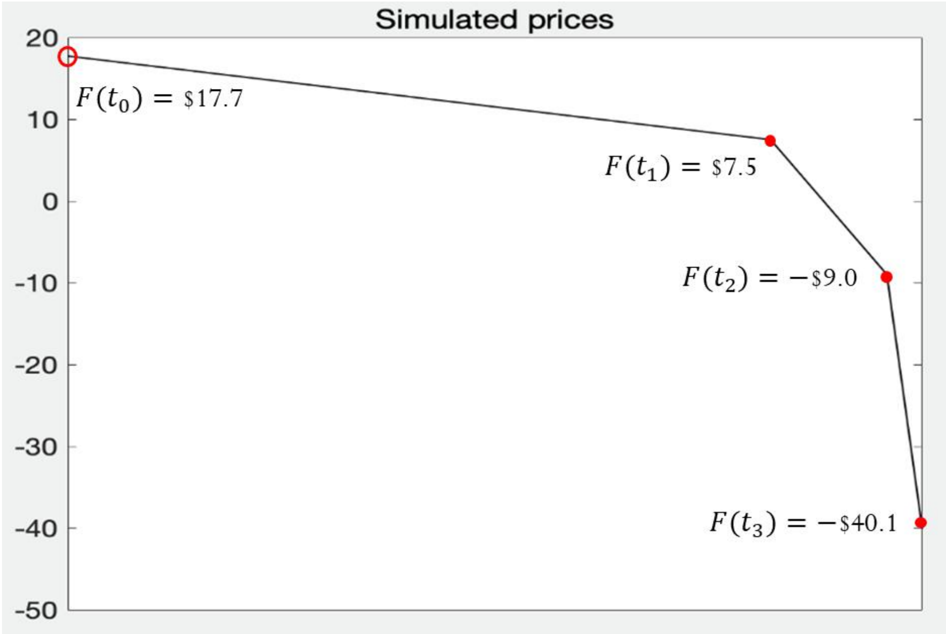


Figure 9: Price simulations on April 20, 2020

This figure provides the simulated prices with the three-period theoretical model. The simulation results are highly consistent with what happened as shown in Figure 2.

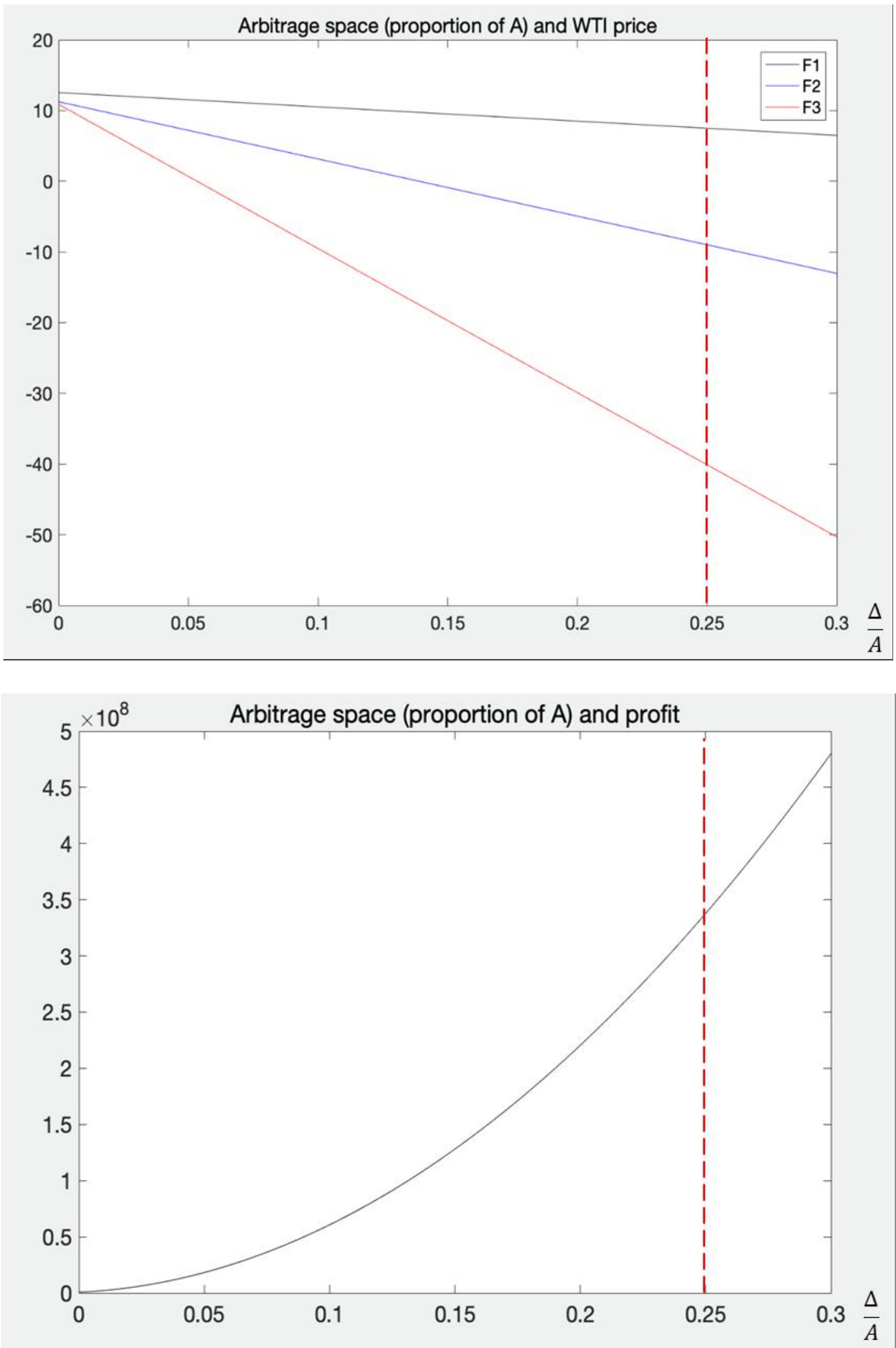


Figure 10: Commodity financialization and WTI future prices

This figure presents how WTI futures prices and predatory profit varies with the net selling demand ratio ($\frac{\Delta}{A}$) in the TAS market. All the other parameters are the same as those in Figure 9.

Table 1: WTI and Brent crude oil futures prices around April 20, 2020

This table presents prices of first-nearby and second-nearby contracts for WTI and Brent crude oil futures around the day that negative price occurred. Dollar spread between WTI and Brent futures, as well as dollar spread between first-nearby and second-nearby contracts are calculated. Data suggest that prices of all the three comparable contracts kept steady around April 20, 2020 while the May WTI contract (first-nearby) was unexpectedly traded at an extremely negative price on the penultimate trading day.

		First-nearby	Second-nearby	**First-second spread (dollars)**
April 16	WTI	19.87	25.53	**-5.66**
	Brent	27.82	31.55	**-3.73**
	WTI-Brent spread (dollars)	**-7.95**	**-6.02**	
April 17	WTI	18.27	25.03	**-6.76**
	Brent	28.08	31.58	**-3.50**
	WTI-Brent spread (dollars)	**-9.81**	**-6.55**	
April 20	WTI	-37.63	20.43	**-58.06**
	Brent	25.57	29.21	**-3.64**
	WTI-Brent spread (dollars)	**-63.20**	**-8.78**	
April 21	WTI	10.01	11.57	**-1.56**
	Brent	19.33	23.12	**-3.79**
	WTI-Brent spread (dollars)	**-9.32**	**-11.55**	

Table 2: Descriptive statistics

This table provides summary statistics based on WTI and Brent crude oil futures data between January 2003 and March 2020 (We exclude April 2020 to compare it with the past sample mean). Main variables are constructed with daily settlement price, trading volume and open interest. The primary dependent variable is dollar spread between WTI and Brent futures: $WBdollarspread_{M,T} = P_{WTI,M,T,1} - P_{Brent,M,T,1}$, where $P_{WTI,M,T,1}$ and $P_{Brent,M,T,1}$ are settlement prices of WTI and Brent first-nearby contracts on day T, month M. We also construct percentage spread between WTI and Brent futures, $WBpercspread_{M,T} = \frac{(P_{WTI,M,T,1} - P_{Brent,M,T,1})}{P_{Brent,M,T,1}} * 100$.

We measure closing pressure as the product of open interest and inventory level: $Closing\ pressure_{M,T-1} = Open\ Interest_{M,T-1} * Inventory^{*}_{M,T-1}$. $Amihud^{*}_{M,T-1}$ is calculated based on commonly-used Amihud illiquidity measure: first compute Amihud ratio for each trading day: $amihud_{M,t} = \frac{|Return_{M,t}|}{Trading\ Volume_{M,t}}$, then take the average of daily ratio from day T-5 to day T-1 as the close-to-maturity illiquidity (in log form): $Amihud_{M,T-1} = \log(\sum_{t=T-5}^{T-1} amihud_{M,t}/5)$, and finally we obtain the ratio that has no trend: $Amihud^{*}_{M,T-1} = Amihud_{M,T-1} - \frac{(\sum_{m=M-12}^{M-1} Amihud_{m,T_m-1})}{12}$.

	Mean	*Standard Deviation*	25%	50%	75%
$WBdollarspread_{M,T}(dollar)$	-4.07	6.54	-7.08	-2.72	0.94
$WBpercspread_{M,T}(\%)$	-4.15	8.33	-9.97	-4.58	1.26
$Open\ interest_{M,T-1}$ $(in\ ten\ thousand\ contracts)$	6.06	1.24	5.18	5.94	6.94
$Inventory^{*}_{M,T-1}$	1.02	0.07	0.97	1.02	1.06
$Closing\ pressure_{M,T-1}$	6.14	1.23	5.31	6.02	6.97
$Amihud^{*}_{M,T-1}$	-0.08	0.65	-0.47	-0.13	0.23

Table 3: Closing pressure, market illiquidity and WTI-Brent dollar spread

This table reports baseline regression results with closing pressure, market illiquidity and WTI-Brent dollar spread on the penultimate trading day. Month dummies, inventory level and return on day T-1 are added as control variables. Panel A and Panel B provide results of samples exclude and include the data point of April 2020. *, **, and *** represent significance at the 10%, 5% and 1% levels, respectively.

Panel A: Sample excludes the data point of April 2020

Estimated Coefficients	*(1)*	*(2)*	*(3)*	*(4)*
Closing Pressure	-0.869** (-2.36)	-0.951*** (-2.60)	-1.058*** (-2.61)	-1.045** (-2.53)
*Closing Pressure*Illiquidity*		-0.255** (-2.33)	-0.262** (-2.28)	-0.268** (-2.10)
Normalized Inventory				-1.574 (-0.19)
Return				-0.058 (-0.30)
Month Effect	No	No	Yes	Yes
R^2	2.6%	5.2%	5.7%	5.8%
No.	207	207	207	207

Panel B: Sample includes the data point of April 2020

Estimated Coefficients	*(1)*	*(2)*	*(3)*	*(4)*
Closing Pressure	-1.847*** (-4.71)	-1.731*** (-4.66)	-1.888*** (-4.69)	-1.902*** (-4.65)
*Closing Pressure*Illiquidity*		-0.539*** (-5.03)	-0.533*** (-4.80)	-0.542*** (-4.31)
Normalized Inventory				1.980 (0.23)
Return				-0.006 (-0.03)
Month Effect	No	No	Yes	Yes
R^2	9.7%	19.6%	21.9%	21.9%
No.	208	208	208	208

Table 4: Closing pressure, market illiquidity and WTI-Brent percentage spread

This table reports regression results when we apply WTI-Brent percentage spread as the dependent variable. Independent variables, control variables and sample period are the same as those in Table 3. *, **, and *** represent significance at the 10%, 5% and 1% levels.

Panel A: Sample excludes the data point of April 2020

Estimated Coefficients	*(1)*	*(2)*	*(3)*	*(4)*
Closing Pressure	-2.294***	-2.473***	-2.814***	-2.705***
	(-5.14)	(-5.73)	(-5.95)	(-5.64)
*Closing Pressure*Illiquidity*		-0.550***	-0.554***	-0.496***
		(-4.27)	(-4.13)	(-3.34)
Normalized Inventory				-12.87
				(-1.37)
Return				0.010
				(0.04)
Month Effect	No	No	Yes	Yes
R^2	11.4%	18.7%	20.5%	21.3%
No.	207	207	207	207

Panel B: Sample includes the data point of April 2020

Estimated Coefficients	*(1)*	*(2)*	*(3)*	*(4)*
Closing Pressure	-6.466***	-6.066***	-6.724***	-6.739***
	(-7.19)	(-7.75)	(-8.19)	(-8.08)
*Closing Pressure*Illiquidity*		-1.860***	-1.830***	-1.786***
		(-8.23)	(-8.07)	(-6.97)
Normalized Inventory				3.850
				(0.22)
Return				0.253
				(0.60)
Month Effect	No	No	Yes	Yes
R^2	20.1%	39.9%	45.3%	45.4%
No.	208	208	208	208

Table 5: Alternative measurement of closing pressure

This table produces replicating results of regressions in Table 3 with the alternative measurement of closing pressure. Instead of applying the product of open interest and inventory level, we use the product of open interest change and inventory, $Closing\,pressure^{*}_{M,\,T-1} = (Open\,Interest_{M,\,T-1} - Open\,Interest_{M-1,\,T}) * Inventory^{*}_{M,T-1}$ as the main independent variable. Control variables and sample period are the same as those in Table 3. *, **, and *** represent significance at the 10%, 5% and 1% levels.

Panel A: Sample excludes the data point of April 2020

Estimated Coefficients	*(1)*	*(2)*	*(3)*	*(4)*
Closing Pressure	-1.386*** (-4.27)	-1.416*** (-4.38)	-1.608*** (-4.52)	-1.611*** (-4.42)
*Closing Pressure*Illiquidity*		-0.288* (-1.76)	-0.279* (-1.65)	-0.292 (-1.55)
Normalized Inventory				0.254 (0.03)
Return				-0.031 (-0.17)
Month Effect	No	No	Yes	Yes
R^2	8.2%	9.6%	10.8%	10.8%
No.	207	207	207	207

Panel B: Sample includes the data point of April 2020

Estimated Coefficients	*(1)*	*(2)*	*(3)*	*(4)*
Closing Pressure	-2.190*** (-6.37)	-1.982*** (-6.03)	-2.185*** (-6.11)	-2.217*** (-6.09)
*Closing Pressure*Illiquidity*		-0.746*** (-4.91)	-0.711*** (-4.50)	-0.746*** (-4.17)
Normalized Inventory				4.378 (0.53)
Return				-0.034 (-0.17)
Month Effect	No	No	Yes	Yes
R^2	16.5%	25.2%	27.6%	27.8%
No.	208	208	208	208

Table 6 Closing-pressure-predicted WTI futures price on April 20, 2020

This table reports predicted WTI-Brent dollar spread and the corresponding WTI futures price on April 20, 2020 based on the baseline regression estimated coefficients in Panel A of Table 3.

	Dependent variable: WTI-Brent dollar spread			
	Model (1)	*Model (2)*	*Model (3)*	*Model (4)*
R^2	2.6%	5.2%	5.7%	5.8%
Fitted dollar spread (dollar)	-9.66	-17.18	-18.95	-18.71
Fitted WTI price (dollar)	15.91	8.39	6.62	6.86

Table 7 Estimated market illiquidity based on tick-by-tick trading data

This table reports the estimated market illiquidity of three periods with tick-by-tick trading data. *, **, and *** represent significance at the 10%, 5% and 1% levels.

	Before 12:00	12:00-14:00	14:00-14:30
Estimated λ_i	0.0303***	0.2738***	0.6211***
	(25.13)	(26.74)	(7.92)

Appendix A

Table A1: Key variables in the theoretical model

Variable	Explanation
A	Starting open interest on April 20, 2020 (in the unit of barrel)
a_L	Total selling demand of the long-position financial settler as a proportion to total open interest (the total outright selling demand is a_LA)
a_S	Total purchase demand of the short-position financial settler as a proportion to total open interest (the total outright purchase demand is a_SA)
$x_{L1}/x_{L2}/x_{L3}$	Optimal number for the long-position financial settler to sell in three periods
$x_{S1}/x_{S2}/x_{S3}$	Optimal number for the short-position financial settler to buy in three periods
Δ	Total number of TAS contracts that the TAS arbitrageur purchases
$\Delta_1/\Delta_2/\Delta_3$	Optimal number for the TAS arbitrageur to sell in the outright market in three periods
I	Normalized inventory level
γ	Coefficient in the linear function between $a_L - a_S$ and I
$F(t_0)$	Opening price on April 20, 2020
$F(t_i)$	Market clearing price of period i, i =1, 2, 3
λ_i	Market illiquidity of period i, i =1, 2, 3

Appendix B

Proof of Proposition I:

$$\frac{\partial F(t_1)}{\partial CLP} = -\gamma\lambda_1 \frac{16\lambda_3 - 3\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} < 0 \tag{A1}$$

Proof: $\gamma > 0$, $\lambda_1 > 0$, $16\lambda_3 - 3\lambda_2 > 13\lambda_2 > 0$, $16\lambda_3 - 3\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2} > 12\lambda_3 - 3\lambda_2 > 9\lambda_2 > 0$. Thus, $-\gamma\lambda_1 \frac{16\lambda_3 - 3\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} < 0$.

$$\frac{\partial F(t_2)}{\partial CLP} = -\gamma\lambda_1 \frac{20\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} < 0 \tag{A2}$$

Proof: $\gamma > 0$, $\lambda_1 > 0$, $16\lambda_3 - 3\lambda_2 > 13\lambda_2 > 0$, $20\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2} > 16\lambda_3 - 4\lambda_2 > 12\lambda_2 > 0$. Thus, $-\gamma\lambda_1 \frac{20\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} < 0$.

$$\frac{\partial F(t_3)}{\partial CLP} = -\gamma\lambda_1 \frac{21\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} \tag{A3}$$

Proof: $\gamma > 0$, $\lambda_1 > 0$, $16\lambda_3 - 3\lambda_2 > 13\lambda_2 > 0$, $21\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2} > 17\lambda_3 - 4\lambda_2 > 13\lambda_2 > 0$. Thus, $-\gamma\lambda_1 \frac{21\lambda_3 - 4\lambda_2 - \frac{4\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} < 0$.

Similarly, we can prove[15]:

$$\frac{\partial \frac{\partial F(t_1)}{\partial CLP}}{\partial \lambda_1} = -\gamma \frac{16\lambda_3 - 3\lambda_2 - \frac{8\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} < 0 \tag{A4}$$

$$\frac{\partial \frac{\partial F(t_2)}{\partial CLP}}{\partial \lambda_1} = -\gamma \frac{20\lambda_3 - 4\lambda_2 - \frac{8\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} < 0 \tag{A5}$$

$$\frac{\partial \frac{\partial F(t_3)}{\partial CLP}}{\partial \lambda_1} = -\gamma \frac{21\lambda_3 - 4\lambda_2 - \frac{8\lambda_1\lambda_3}{\lambda_2}}{16\lambda_3 - 3\lambda_2} < 0 \tag{A6}$$

Proof of Proposition II:

$$\frac{\partial F(t_1)}{\partial \Delta} = -\frac{9\lambda_1\lambda_3}{16\lambda_3 - 3\lambda_2} < 0 \tag{A7}$$

$$\frac{\partial F(t_2)}{\partial (c_L - c_S)A} = -\frac{\lambda_3(9\lambda_1 + 3\lambda_2)}{16\lambda_3 - 3\lambda_2} < 0 \tag{A8}$$

$$\frac{\partial F(t_3)}{\partial (c_L - c_S)A} = -\frac{\lambda_3(9\lambda_1 + 4\lambda_3)}{16\lambda_3 - 3\lambda_2} < 0 \tag{A9}$$

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[15] We regard λ_1 as the overall market liquidity during the day.

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