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The Effect of the Term Auction Facility on the London Interbank Offered Rate

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Abstract

The Term Auction Facility (TAF), the first auction-based liquidity initiative by the Federal Reserve during the global financial crisis, was aimed at improving conditions in the dollar money market and bringing down the significantly elevated London interbank offered rate (Libor). The effectiveness of this innovative policy tool is crucial for understanding the role of the central bank in financial stability, but academic studies disagree on the empirical evidence of the TAF effect on Libor. We show that the disagreement arises from misspecifications of econometric models. Regressions using the daily level of the Libor-OIS spread as the dependent variable miss either the permanent or temporary TAF effect, depending on whether the dummy variable indicates the events of the TAF or the regimes before and after a TAF event. Those regressions also suffer from the unit-root problem and produce unreliable test statistics. By contrast, regressions using the daily change in the Libor-OIS spread are robust to the persistence of the TAF effect and the unit-root problem, consistently producing reliable evidence that the downward shifts of the Libor-OIS spread were associated with the TAF. The evidence indicates the efficacy of the TAF in helping the interbank market to relieve liquidity strains.

Key words: Libor, liquidity, money markets, Term Auction Facility

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Contents

1 Introduction

The U.S. dollar money markets ran into serious trouble in August 2007. The interest rates on interbank short-term and medium-term loans rose to levels that are unusually high. The spread between the three-month London interbank offered rate (Libor) and the federal funds rate rose from its typical level of a few basis points to about 50 basis points and ascended further to 90 basis points in September 2007. The widened spread was largely believed to be the result of a sharp increase in the liquidity risk as well as the credit risk perceived by the market players. Transactions in the interbank market declined, and borrowers often could not obtain funds at the posted rates. Since Libor affects interest rates on a wide variety of loans and securities (e.g. home mortgages and commercial loans), unusually high term rates had disruptive effects on the economy.

Responding to the disruption in the money markets, the Federal Reserve (the Fed) used open market operations to maintain the effective federal funds rate (i.e., the interest rate on overnight loans of reserves between U.S. domiciled depository institutions) close to its target rate. Although the Fed succeeded in stabilizing the overnight rate, the rates on term loans among banks continued to move up, reflecting a sustained reluctance of banks to lend to each other at longer terms.

When the conventional Federal Reserve open market operations brought down only the expectation of the federal funds rate but not Libor, the Libor-OIS spread widened in late 2007. The Libor-OIS spread, a widely watched index in the financial markets, is the difference between Libor and the overnight index swaps (OIS) rate of the same maturity term. The elevated Libor-OIS rate kept the interest rates high on many term loans in the markets because of the close ties of Libor to the fixed-income securities. To bring down the term rates in the economy, the Fed faced at least the following three challenges: (1) How to lower the term rates in the interbank market, (2) How to make banks in sound condition more willing to lend, and (3) How to overcome discount window stigma, which refers to banks' reluctance to borrow from the discount window.

On December 12, 2007, the Fed responded to the continuing difficulty that banks faced in obtaining term funds by introducing the Term Auction Facility (TAF). This was the first auction-based facility initiated by the Fed during the 2007–2009 financial crisis. The TAF provided term funding to eligible depository institutions in sound financial condition through periodic auctions, in which those depositories with the highest bid rates received the funds at the stop-out rate. The total amount of the funds available at each TAF auction was announced in advance by the Fed. The interest rate for the funds was set in a competitive auction process among the participating depository institutions.

Through TAF auctions, the Fed provided term funding to depositories that needed it most, with the purpose to relieve the strains arising from the unwillingness of sound institutions to lend to each other. Besides providing the needed term funding, an additional objective was to reduce the uncertainty of banks' access to future term funding. Since the TAF offered a new source for banks to obtain term funding, it makes banks more willing to supply loans if they had surplus funds. The increased availability of lending by some banks could also reduce the uncertainty of other banks' sources for short-term funds. It could also prevent inordinate reliance by some banks on overnight funding that might have caused excess volatility in the overnight market. The two intended effects of the TAF—meeting banks' immediate funding demands and reassuring potential lenders of their future access to funds—should both work to reduce bank liquidity risks, increase transaction volumes, and reduce market interest rates.

Theoretical and empirical studies prior to the initiation of the TAF suggest that direct funding provided by central banks may reduce liquidity risk premiums in private markets, especially when the markets face widespread uncertainty in liquidity. Holmstrom and Tirole (1998) theorize that government provision of funding lessens the premium of market-wide liquidity risk. Sundaresan and Wang (2009) show that the funds auctioned by the Fed right before the Millennium date change (Y2K) were associated with the drops in the liquidity risk premium in the Treasury bond markets when primary dealers feared that the Y2K might cause a market-wide liquidity shortage. The auctions that the Fed conducted for the Y2K have provided a valuable lesson for the Fed in mitigating market-wide uncertainty of liquidity shocks.

Studies since the initiation of the TAF also suggest that direct government funding should reduce the liquidity premium in the interbank market. Armantier et al. (2008) show that the $360 billion term funding offered through the first ten TAF auctions was highly demanded by the banks. Acharya and Skeie (2011) theoretically reason that the increase of loan supply by the TAF should lessen the liquidity risk in the interbank market. Armantier et al. (2015) empirically demonstrate that the TAF overcame the discount window stigma during the global financial crisis.

Since the TAF was the first auction-based facility during the 2007-2009 financial crisis, it is critical to know whether the facility helped in reducing the liquidity risk premium in the strained money markets. In addition, the study of the effectiveness of the TAF is part of a broader research geared to a better understanding of liquidity risk premia and the role of central banks. In theory (Tirole, 2006), when all banks face uncertainty of funding risk simultaneously, the liquidity risk premium is high. In this situation, the interbank term-loan markets come under stress, and the term interest rates may be disconnected from the overnight interest rate. The disconnection between the term and overnight rates was a key challenge faced by financial markets and the economy during the recent financial turmoil. The TAF was a new approach taken by central banks to address the problem of a high liquidity risk premium and the resulting misallocation of funds. Measuring the effects of the new liquidity facility is a crucial first step to understanding whether the central bank can reduce the liquidity risk premium effectively as well as gaining insight into the liquidity risk premium and its cause.

Academic studies so far disagree on the empirical evidence of the TAF effect on the London interbank offered rate. McAndrews, Sarkar and Wang (2008) present empirical results to show that the TAF helped in lowering the Libor-OIS spread. By contrast, Taylor and Williams (2009) do not find evidence that the TAF had a significant effect on the spread after controlling for the credit risk premium. Based on several alternative regressions, they argue that the evidence of the TAF effect is not robust. Wu (2011) joins the debate by comparing the averages of the Libor-OIS spread before and after the TAF was introduced and concludes that the spread was lower in the later period, after controlling for other factors such as the credit risk premium. However, the magnitude of the TAF effect estimated in Wu (2011) is unstable in his regressions, as pointed out by Taylor and Williams (2009).

In this paper, we investigate the controversy of the TAF effect. We show that these disagreements arise from mis-specifications of the econometric models. We show that the regressions using the daily level of the Libor-OIS spread as the dependent variable, as in Taylor and Williams (2009) and Wu (2011), miss either the permanent or the temporary TAF effect, depending on whether the dummy variable in the regression indicates the events of the TAF or the regimes before and after the TAF. Furthermore, we demonstrate that those regressions suffer from the unit-root problem, producing unreliable and confusing test statistics. By contrast, we prove that the regressions using the daily change in the Libor-OIS spread, as in McAndrews et al. (2008), are robust to the persistence of the TAF effect and the unit-root problem, consistently producing evidence that the TAF was associated with downward shifts of the Libor-OIS spread.

We develop a general econometric specification for the TAF effect. The general specification detects both persistent and temporary effects and is robust in the presence of the unit-root component in the Libor-OIS spread. This econometric specification is an extension to those used by McAndrews et al. (2008). The specification empirically tests the association of the TAF with the negatives shifts (or jumps) of Libor after controlling for the term premium and the credit risk premium. Such association provides a supporting evidence of the efficacy of the TAF in helping to relieve the strains in the interbank term loan markets. Our empirical results clearly indicate that the TAF helped in easing the strained conditions in money markets.

The rest of the paper is organized as follows. Section 2 provides the necessary information of the Term Auction Facility and Libor and discusses the data of the Libor-OIS spread. Section 3 develops and analyzes various alternative econometric specifications. Section 4 presents the empirical evidence of the TAF effect, examines its robustness, and looks at the symptoms of the unit-root problem. Section 5 offers some concluding remarks.

2 TAF and Libor-OIS spread

2.1 Term auction facility

The term auction facility (TAF) was designed to promote the distribution of liquidity when unsecured term funding markets were under stress. The Fed announced the creation of the liquidity program on December 12, 2007, in response to the continuing difficulty that banks faced in obtaining term funds. Under this facility, the Fed initially auctioned 28-day loans to eligible depository institutions and, since August 2008, also auctioned 84-day loans. All loans extended under the facility were fully collateralized. These term loans were secured by the same collateral that is accepted at the discount window, which accepts a broader range of collateral than the markets do.[1] Therefore, banks could post a broader range of collateral in the TAF, making easier to obtain liquidity when borrowing in markets was difficult.

[1] Complete information about the collateral is provided at http://www.frbdiscountwindow.org/.

The TAF was not designed to help bank solvency directly so that it focused on the liquidity problem. The participants of the TAF were banks in sound financial condition. The banks that were eligible to participate in the TAF were the depositary institutions eligible to borrow under the Federal Reserve's primary credit program, which is one of the discount window lending programs. These banks were a subset of those depository institutions that have access to the discount window of the Fed. By contrast, the overnight loans the Fed lends through the discount window are available to a larger class of banks that include all U.S. deposit-taking banks or U.S. branches of foreign institutions that maintain deposits and are subject to reserve requirements. Because the TAF was available only to financially-sound institutions, the Fed used it to address the liquidity problem in the interbank loan market, not to bail out financially stressed banks.

The TAF was designed to channel funds to banks that needed the funds the most, to be effective in addressing the liquidity problem. For this purpose, the funds were allocated competitively in uniform-price auctions. The total amount of funds available at each TAF auction was announced in advance by the Fed. Participating banks submitted bids by telephone through local Reserve Banks, specifying an amount of funds and an interest rate. A rate known as the "stop-out rate" was determined in each auction based on the demand function revealed in the bids. There was a floor rate for the bids allowed in each auction. The Fed set the minimum rate of bids based on the one-month OIS rate, which represents the market expectation of the average federal funds rate over that month. The depository institutions with the highest bidding rates received the funds at the stop-out rate. Through these auctions, the Fed provided term funds to depositories that most demanded the liquidity, with the intention of relieving the strains arising from the unwillingness of healthy institutions to lend to each other.

The first six TAF auctions conducted from December 17, 2007, to March 6, 2008, are the most distinctive in the test of the TAF's effectiveness. These were conducted when the TAF was the only extraordinary liquidity facility and before the implementation of additional Fed emergency actions, such as the introduction of the Term Securities Lending Facility (TSLF) and the Primary Dealer Credit Facility (PDCF), and the $30 billion loan to facilitate the purchase of Bear Stearns. The last auction was conducted on March 8, 2010. The Fed discontinued the TAF in 2010 when market conditions clearly convinced it that the auctions were no longer necessary.

To make the TAF effective, the Fed needed to auction significant amount of term loans relative to the liquidity demand of the banks. The term loans auctioned was $20 billion in each of the first two auctions and $30 billion in each of the next four auctions. The Fed then injected an additional $200 billion into the banking system through another four auctions from March 10 to April 21 in 2008. There was strong demand for the funds at the first ten TAF auctions. A summary of the first ten auctions can be found in Armantier et al. (2008). The number of banks bidding for the term loans in the TAF varied between 52 and 93, and the bid-to-cover ratio (i.e., the total amount bid as a ratio of funds auctioned) ranged between 1.25 and 3.08.

All events that brought new information about the supply of term funding in the TAF potentially affect the expectation and prices of term loans. In Table 1, we summarize all the TAF events during the first ten auctions. The events include all operations and announcements that indicate increases or decreases in the funds for future auctions. We further separate TAF announcements and operations in the table. TAF announcements consist of three sources of TAF news that could potentially change the market's anticipation of the market-wide liquidity risk:

(1) the initial introduction of the TAF program,
(2) the total loans to be auctioned in the TAF,
(3) and the promises of future TAF auctions.

By contrast, the TAF operations consist of three parts:

(1) setting the auction conditions,
(2) conducting the auctions,
(3) notifying banks of the auction results.

A major part of the auction condition is the minimum bidding rate. A bank learned about the TAF funds it received in each auction only from the Fed's notification of the auction results.

In conjunction with the TAF, some foreign central banks made dollar-denominated loans available to private banks in their own countries via bilateral currency swap lines with the U.S. Federal Reserve. These swap arrangements, called reciprocal currency arrangements, are described in detail by Fleming and Klagge (2010). The announcements that informed the markets of participation by other central banks in the swap lines affected the expectation of dollar supply available to private banks in the markets. For example, the European Central

Bank (ECB) notified the markets on February 1, 2008 that it would not join the February TAF auctions. Later on March 11, 2008, both the European Central Bank and Swiss National Bank (SNB) announced their participation in the TAF.

2.2 Libor-OIS spread

The spread between the interbank borrowing rate and the OIS rate is constructed as follows. Consider an interbank loan that matures in three months for instance. Let R^{LIB}_{t+1} denote the three-month Libor reported around 6:00 a.m. U.S. eastern time on date $t+1$, and R^{OIS}_{t} the three-month OIS rate reported at the close (4:00 p.m. U.S. eastern time) of date t.[2] The three-month Libor-OIS spread is defined by $Y^{\text{LOS}}_t = R^{\text{LIB}}_{t+1} - R^{\text{OIS}}_t$. We align date-$(t+1)$ Libor with date-t OIS rate to ensure that the two rates in the spread reflect the information about the same TAF event if the event happens on date t in the U.S. One should not use date-t Libor because it does not reflect such information when it was released at 6:00 a.m. on date t, well before the TAF event on day-t in the U.S.

The Libor-OIS spread is mainly a measure of credit and liquidity premiums. An interest rate on a term loan consists of four main components: 1) the expected geometric average of overnight risk-free interest rates, 2) a premium for the interest rate risk, 3) a premium for credit risk, and 4) a premium for liquidity risk. Our focus in this paper is on the credit risk premium and the liquidity risk premium for the interbank loans. The empirical analyses by Michaud and Upper (2008) and Gefang, Koop, and Potter (2011) show that both the credit risk premium and the liquidity risk premium were important driving forces of the interbank borrowing rates during 2007–2008.

Subtracting the OIS rate from the Libor-OIS spread eliminates the components of the expectation and term premium of the overnight risk-free rates. An OIS rate is a fixed rate to swap with the geometric average of a floating overnight interest rate. Sundaresan, Wang and Yang (2016) show that an OIS rate reflects the expectation, plus a risk premium for the uncertainty of future rate, of the average overnight federal funds rates during the term of the OIS contract. They demonstrate that an OIS rate is mainly the expectation of the overnight rate plus

[2] Libor is an average interbank borrowing rate gathered and published daily by the British Bankers' Association (BBA). The BBA assembled the interbank dollar borrowing rates from 16 contributor panel banks at 11:00 a.m. (London time), kept the middle eight of these rates (discarding the top and bottom four) and used these to calculate an average, which then became that day's BBA Libor rate.

a small interest rate risk premium. They also show that the OIS rates contain almost no credit premium or liquidity risk premium. Their results corroborate prior studies of term structure of interest rates on short-term loans and swaps. Longstaff (1989, 1990, 2000) and Corte at al. (2008) show that interest rates on term repos are mostly expectation of overnight rate. Duffie and Huang (1996) show that netting reduces the effect of credit risk on swap rates by about 99 percent. Many major exchanges, including the Chicago Mercantile Exchange, have adopted OIS rates as benchmark risk-free rates for valuation and collateral settlement. For more details of the OIS, we refer readers to Sundaresan et al. (2016).

Figure 1 displays the daily observations of the three-month Libor-OIS spread from January 3, 2007, to April 24, 2008, and panel B displays the one-month Libor-OIS spread for the same period. We limit our sample to this period because the additional programs operated by the Federal Reserve and other government agencies proliferated after April 24, 2008. It is difficult to tease out the TAF effect after April 24, 2008, given all central bank and government actions. The figure shows that the three-month Libor-OIS spread was typically less than 10 basis points before it went up substantially during early August of 2007. Since then, it remained volatile with periods of ups and downs. The spread first peaked on September 7, 2007, and then moved downward until the end of October 2007. After this, the spread experienced another steep increase to reach its all-time high of 106 basis points on December 4, 2007. Then, the spread kept dropping until it reached 29 basis points on January 16, 2008, before entering a four-month period of upward trend and high volatility.

Table 2 presents the summary statistics of the Libor-OIS spread in our sample period. In the period from January 3, 2007 to April 24, 2008, there are 333 observations on the daily change in the Libor-OIS spread. As reported in panel A, both the mean and median of the three-month spread are about 39 basis points, and the standard deviation is about 31 basis points. However, it is clear from Figure 1 that the three-month Libor-OIS behaved very differently before and after August 2007. The behavior of the one-month Libor-OIS spread in Figure 2 is similar to its three-month counterpart.

A property of Libor-OIS spreads is high serial correlation, which is 0.99 for the three-month spread and 0.98 for the one-month spread. Such high serial correlation suggests the possibility of a random walk component, which can cause the unit-root problem and invalidate the standard interpretation of statistics from a regression. Panel A of Table 2 shows that both the three-month and one-month Libor-OIS spreads fail in Dickey-Fuller tests, suggesting the problem of unit roots. The statistics reported in Taylor and Williams (2009) also suggest unit-root problems—the serial correlation of the Libor-OIS spread is 1 (in their Table 6). The results reported by Wu (2011) also indicate unit-root problems—the estimated serial correlation (in his Table 4) is close to 1 with extremely large t-statistics. Nonetheless, neither of these papers addresses the issue of unit-root problems.

2.3 CDS spreads of Libor banks

Since the Libor-OIS spread contains a credit risk premium, a component that the TAF was not designed to affect directly, a statistical test that measures the TAF effects on Libor must control for the variation of credit risk premiums. A natural proxy for the credit risk premium for interbank loans is the credit default swap (CDS) spread on the banks. The credit risk premium can be inferred from the CDS spreads on the banks in the Libor panel. A CDS contract on the debt of a company provides insurance against the possibility that the company defaults on the debt. Should it default, the CDS seller covers the loss by paying out the par value though the debt is worth less than the par in the market. Companies with high default risk are generally associated with high CDS spreads for insuring their debt.

Because the CDS spread reflects the risk of default, we can calibrate the risk-neutral default probability of the debt or loan over time. The calibrated default probability can be used to calibrate the credit risk premium on a term loan. The details of the calibration of the default probabilities and the credit risk premiums on term loans are provided in the Appendix. Let C_t be the credit risk premium on a term loan implied by the CDS.

If the interbank borrowing rate consists of only the expectation of the short rate, the interest-rate risk premium, and the default premium, Libor-OIS spread should be the credit premium. However, Libor-spreads may have other components including a liquidity premium. Therefore, we decompose a Libor-OIS spread on each date t into two parts: $Y_t^{\text{LOS}} = C_t + L_t$, where L_t includes everything in Libor not explained by the OIS rate and the credit premium. Although there may be many other factors,[3] besides liquidity premiums, for L_t to be nonzero, we call L_t the "liquidity component" to keep the terminology simple. A similar approach in sep-

[3]Although it is hard to know all factors, an example of the other factors that affect the term loan rate is quarter-end. Financial institutions borrow money to improve the appearance of balance sheets at quarter-end. We later control for the quarter-end effects to check the robustness of our results.

arating the non-credit component out of the three-month term rate is employed by the Bank of England (2008) to study the behavior of Libor in 2007.

Most empirical studies of the Libor-OIS spread use CDS spreads as control variable in regressions, instead of extracting the credit risk premium in Libor implied by the CDS spreads. The extraction depends on the choice of the pricing model and other assumptions. One naturally worries about potential bias caused by pricing models. Using CDS spreads in regressions avoids relying on pricing models. Following the practice of using CDS spread as a control variable in regressions, we calculate the average CDS spread of banks in Libor panel and assume that the credit risk premium is a linear function of the CDS spread: $C_t = a + bX_t^{\text{CDS}}$, where X_t^{CDS} denotes the average CDS spread.

Figure 3 displays the daily time series of the average Libor bank CDS spread. This is the average of one-year CDS spreads of the banks in Libor panel. The CDS contracts used in the average are all on the senior unsecured debt. The banks include Bank of America, Bank of Tokyo-Mitsubishi UFJ Ltd, Barclays Bank plc, Citibank NA, Credit Suisse, Deutsche Bank AG, HBOS, HSBC, JP Morgan Chase, Lloyds TSBBank plc, Rabobank, Royal Bank of Canada, the Norinchukin Bank, the Royal Bank of Scotland Group, UBS AG, and West LB AG. The figure shows that the Libor banks' average CDS spread remained low until the summer of 2007. The sharp increase in the average CDS spread in late July pushed it to a peak on August 6, 2007. Since then, the average CDS spread fluctuated in a downward trend to reach a low point on October 12, 2007. Starting from that point, the banks' average CDS spread climbed for nearly five months, until it reached its highest point on March 17, 2008.

The summary statistics of the average CDS spread are reported in Table 2. Like the Libor-OIS spreads, this CDS spread also has a very high serial correlation. Dickey-Fuller test suggests that the time series of the CDS spread has a unit root. Hence, the change in the CDS spread is likely to be serially uncorrelated, as shown by the serial correlation and its p-value in panel B.

Comparing Figure 1 with Figure 3, we clearly see that the three-month Libor-OIS spread and the Libor banks' average CDS spread are related, but their moves during the sample period often have different directions. The correlation coefficient of the two variables in this sample period is 0.72. Both variables started to increase during the summer of 2007; the rise of the three-month Libor-OIS spread often followed an increase in the average CDS spread. However, the correlation of the daily changes of the two variables is only 0.22, which means that the two variables do not often move in the same direction. They often move in opposite directions in late 2007 and during the first four months of 2008. For instance, the three-month Libor-OIS spread declined during the last ten trading days of October 2007 while the average CDS spread was flat. The Libor-OIS spread dropped sharply during the first half of January 2008 whereas the average CDS spread was rising. We observe a similar relation of the one-month Libor-OIS spread to the average CDS spread if we compare Figure 1 with Figure 3.

A potential reason for the different movements of the Libor-OIS spread and the average CDS spread is the heavy intervention by the Fed, which initiated, adjusted, and operated the TAF during the period. The intensive TAF announcements and operations were intended to affect the Libor-OIS spread, but not to affect bank solvency. The short-term loans directly injected into banks were designed to ease the liquidity demand, but they were not designed to reduce the credit risk. The limitation of TAF's influence on credit risk was well recognized at the time by the Fed (see Armentier et al., 2008). Empirical tests of the TAF effect must separate the liquidity effects of the TAF on the Libor-OIS spread from its time-variation resulting from changes in credit risks.

3 Econometric specification

3.1 Regression models

The existing literature is confusing when it comes to regression specifications for testing the TAF effects on Libor. For example, Taylor and Williams (2009) regress the level of the Libor-OIS spread on an event indicator of TAF auctions. However, Wu (2011) regresses the spread on a regime indicator that equals 0 before the first TAF announcement and then switches to 1 thereafter. By contrast, McAndrews et al. (2008) use the daily change in the Libor-OIS spread as the dependent variable and regress it on event indicators of TAF announcements and auctions. In this section, we show that when using event indicators to detect the TAF effect, the dependent variable in a regression should be the daily change in the Libor-OIS spread, not the level of the spread. Regressions using the level of the Libor-OIS spread as the dependent variable produce biased statistics for the TAF effect irrespective of whether the event indicator or the regime indicator is used.

To demonstrate how an incorrect econometric specification affects empirical results, let us suppose the Libor-OIS spread consists of three components: a credit risk premium, a liquidity risk premium, and an error term, as hypothesized by Taylor and Williams (2009), Wu (2011), and McAndrews et al. (2008). Recall that we denote the liquidity risk premium on date t by L_t. Suppose the credit risk premium in the Libor-OIS spread is a linear function of the average CDS spread: $a + b \cdot X_t^{\text{CDS}}$. Also assume that the error term is an autoregressive process: $u_t = \rho \cdot u_{t-1} + \varepsilon_t$, where the innovation ε_t follows a normal distribution with zero mean and variance σ^2, conditional on the information of date $t-1$. Putting these three components together, we have the following data generating process of the Libor-OIS spread:

$$Y_t^{\text{LOS}} = a + b \cdot X_t^{\text{CDS}} + L_t + u_t\,. \tag{1}$$

The autoregressive coefficient in the error term is ρ, which ranges from -1 to 1. We allow $|\rho| = 1$ so that Y_t^{LOS} can have a unit root.

Suppose TAF announcements and operations are effective in reducing the liquidity premium, and the L_t drops on the days when TAF events happen. To keep the discussion simple, let us focus on one TAF event, but the analysis applies to the general case of multiple TAF events. Denote the TAF event date by t^*. The TAF regime indicator is I_t^{TAF} is a step function that equals 0 before t^* and 1 since t^*, indicating the regimes before and after the event. Panel A of Figure 4 illustrates the regime indicator. The step function has multiple steps if there are multiple TAF event dates. The TAF event indicator is $\Delta I_t^{\text{TAF}} = 1$ when $t = t^*$, and $\Delta I_t^{\text{TAF}} = 0$ for all t that are different from t^*. Panel B of Figure 4 illustrates the event indicator ΔI_t^{TAF}. Notice that $\Delta I_t^{\text{TAF}} = I_t^{\text{TAF}} - I_{t-1}^{\text{TAF}}$ by definition.

Suppose the liquidity premium L_t is constant c before the TAF event date t^*, drops by d on the event date, and then stays at the lower level after the event. That is, the liquidity premium is:

$$L_t = c - d \cdot I_t^{\text{TAF}}, \tag{2}$$

Equation (2) describes a permanent effect of the TAF on L_t. Panel C of Figure 4 illustrates liquidity premium L_t as a step function. Substituting equation (2) into equation (1), we obtain

$$Y_t^{\text{LOS}} = (a + c) + b \cdot X^{\text{CDS}} - d \cdot I_t^{\text{TAF}} + u_t\,. \tag{3}$$

This equation involves the TAF regime indicator I_t^{TAF}, not the TAF event indicator ΔI_t^{TAF}. To relate the generating process (3) to the TAF indicator ΔI_t^{TAF}, we rewrite it as

$$Y_t^{\text{LOS}} = (a + c) + b \cdot X_t^{\text{CDS}} - d \cdot \Delta I_t^{\text{TAF}} - d \cdot I_{t-1}^{\text{TAF}} + u_t. \tag{4}$$

Taylor and William (2009) regress the level of the Libor-OIS spread on the TAF event indicator ΔI_t^{TAF} and the level of the average CDS spread, X_t^{CDS}, of three large banks. Their econometric specification is:

$$Y_t^{\text{LOS}} = \alpha_{\text{INT}} + \gamma_{\text{CDS}} X_t^{\text{CDS}} + \alpha_{\text{TAF}} \Delta I_t^{\text{TAF}} + \epsilon_t. \tag{5}$$

A comparison of equations (5) and (4) reveals that regression (5) omits the lagged TAF regime indicator, I_{t-1}^{TAF}. Consequently, the estimates of parameters obtained from regression (5) are generally biased, even if all the variables in the regression have a finite stationary joint distribution. A comparison of panels B and C in Figure 4 also suggests that there is little chance for ΔI_t^{TAF} to capture the TAF effect if one regresses L_t on ΔI_t^{TAF}.

Although regression (5) is generally biased for a permanent TAF effect, it can potentially work for a temporary TAF effect that lasts for a very short time, if all variables in the regression have finite stationary distributions. For example, if the TAF effect lasts for exactly one day and reverses the next day, the liquidity risk premium is

$$L_t = c - d \cdot \Delta I_t^{\text{TAF}}, \tag{6}$$

which decreases by d on the TAF event day and reverses to the original level the next day. Panel D of Figure 4 illustrates this temporary effect. Substituting this function into equation (1), we obtain

$$Y_t^{\text{LOS}} = (a + c) + b \cdot X_t^{\text{CDS}} - d \cdot \Delta I_t^{\text{TAF}} + \epsilon_t, \tag{7}$$

which is consistent with regression (5), implying $\alpha_{\text{INT}} = a + c$, $\gamma_{\text{CDS}} = b$ and $\alpha_{\text{TAF}} = -d$. Thus, regression (5) is correctly specified for detecting a single-day TAF effect but is mis-specified if the effect is persistent. Obviously, a long-lasting TAF effect is economically more important than a temporary effect. If the TAF effect is temporary, the statistics obtained from regression (5) are still difficult to interpret correctly because the Libor-OIS spread is not stationary.

If the TAF effect is permanent, the data generating process in equation (3) appears consistent with the regression specified by Wu (2011):

$$Y_t^{\text{LOS}} = \alpha_{\text{INT}} + \gamma_{\text{CDS}} X_t^{\text{CDS}} + \gamma_{\text{TAF}} I_t^{\text{TAF}} + \epsilon_t\,. \tag{8}$$

A comparison of panels A and C in Figure 4 suggests that the regime indicator I_t^{TAF} can identify the permanent effect on L_t. However, for this to work, we need $\epsilon_t = u_t$ to be stationary. That is, were the error term u_t stationary, the above regression would produce unbiased estimates. If u_t is a random walk ($\rho = 1$) instead, the standard statistics obtained from regression (8) cannot be interpreted in the normal way. In addition, if the TAF effect is temporary, the above regression will produce biased estimates even when u_t is stationary. To see this, we rewrite the data generating process in equation (7) as

$$Y_t^{\text{LOS}} = (a+c) + b \cdot X_t^{\text{CDS}} - d \cdot I_t^{\text{TAF}} + d \cdot I_{t-1}^{\text{TAF}} + \epsilon_t, \tag{9}$$

and then compare it with regression (8). Clearly, the lagged TAF regime indicator I_{t-1}^{TAF} is missing in equation (8).

The regression specification by McAndrews et al. (2008) uses the change in the Libor-OIS spread as the dependent variable. Let $\Delta Y_t^{\text{LOS}} = Y_t^{\text{LOS}} - Y_{t-1}^{\text{LOS}}$ be the daily change in the Libor-OIS spread and $\Delta X_t^{\text{CDS}} = X_t^{\text{CDS}} - X_{t-1}^{\text{CDS}}$ the daily change in the average CDS spread. It follows from equations (1) and (2) that the changes satisfy

$$\Delta Y_t^{\text{LOS}} = b \cdot \Delta X_t^{\text{CDS}} - d \cdot \Delta X_t^{\text{TAF}} - (1-\rho) \cdot u_{t-1} + \varepsilon_t. \tag{10}$$

Therefore, we should specify the regression as

$$\Delta Y_t^{\text{LOS}} = \alpha_{\text{INT}} + \alpha_{\text{CDS}} \Delta X_t^{\text{CDS}} + \alpha_{\text{TAF}} \Delta I_t^{\text{TAF}} + \epsilon_t, \tag{11}$$

which is exactly the regression equation used by McAndrews et al. Panel E of Figure 4 illustrates how the permanent TAF effect shows up in the change in the liquidity component: $\Delta L_t = L_t - L_{t-1}$. A comparison of panels B and E suggests that the TAF event indicator can identify the effect from the change ΔL_t.

If the error term u_t is a random walk ($\rho = 1$), then $\epsilon_t = \varepsilon_t$, which implies that the error term ϵ_t is independent and stationary. In this case, the estimates obtained from regression (11) are unbiased. It follows that $\alpha_{\text{INT}} = 0$, $\alpha_{\text{CDS}} = b$, and $\alpha_{\text{TAF}} = -d$. The parameters b and d can be identified from the regression without bias. Generally, the error term u_t of the regression can be an autoregressive process. The standard approach in accommodating the possibility of a stationary time-series of u_t is to include the lagged level of the Libor-OIS spread Y_{t-1}^{LOS} as an independent variable in regression (11).

We can adjust regression (11) so that it captures a temporary TAF effect. If we take the difference between equation (9) at t and the same equation at $t-1$, we obtain

$$\Delta Y_t^{\text{LOS}} = b \cdot \Delta X_t^{\text{CDS}} - d \cdot \Delta I_t^{\text{TAF}} + d \cdot \Delta I_{t-1}^{\text{TAF}} + \epsilon_t. \tag{12}$$

The above equation suggests that the lagged TAF event indicator, $\Delta I_{t-1}^{\text{TAF}}$, can be included in the regression to capture the temporary TAF effect, as we do in the following:

$$\Delta Y_t^{\mathrm{LOS}} = \alpha_{\mathrm{INT}} + \alpha_{\mathrm{CDS}} \Delta X_t^{\mathrm{CDS}} + \alpha_{\mathrm{TAF}} \Delta I_t^{\mathrm{TAF}} + \beta_{\mathrm{TAF}} \Delta I_{t-1}^{\mathrm{TAF}} + \epsilon_t. \tag{13}$$

A comparison of panels B and F suggests that the lagged event indicator identifies the reversal of a temporary effect in the change ΔL_{t-1}. By contrast, a comparison of panels D with A of Figure 4 suggests that, Wu's (2011) specification misses temporary effects when the level of Libor-OIS spread is regressed on the TAF regime indicator.

Specification (13) is powerful because it identifies both permanent and temporary TAF effects. If the TAF effect is permanent as assumed in (2), equation (10) implies $\alpha_{\mathrm{CDS}} = b$, $\alpha_{\mathrm{TAF}} = -d$, and $\beta_{\mathrm{TAF}} = 0$. If the TAF effect is temporary as assumed in (6), equation (12) implies $\alpha_{\mathrm{CDS}} = b$, $\alpha_{\mathrm{TAF}} = -d$, and $\beta_{\mathrm{TAF}} = d$. Therefore, if the TAF has an effect, either permanent or temporary, on the liquidity premium of the Libor-OIS spread, the coefficient α_{TAF} is negative. If one wants to explore the persistence of the TAF effect in more detail, one can include more lags of the TAF event indicator in regression (13).

An additional advantage in using the changes of the Libor-OIS spread is its robustness to the unit-root problem. The statistics generated by regressions (11) and (13) are not distorted by nonstationarity of the data. If the Libor-OIS spread is nonstationary, the coefficient of the lagged level of the Libor-OIS spread should be zero. if the Libor-OIS spread is a stationary autoregressive process, the statistics are still unbiased because the lag of the spread is included. Stationarity implies that the coefficient of the lagged level of the Libor-OIS spread is between -1 and 1. In summary, controlling for the lagged Libor-OIS spread, specification (11) delivers an unbiased estimate of the permanent TAF effect, whether the Libor-OIS spread is stationary or non-stationary, and specification (13) captures the temporary TAF effect.

3.2 Monte Carlo simulations

To evaluate the performance of alternative specifications, we perform 100,000 Monte Carlo simulations on each of regressions (5), (8), (11), and (13). These regressions can be viewed as special cases of the following general expression:

$$\begin{aligned} Y_t^{\mathrm{LOS}} \text{ or } \Delta Y_t^{\mathrm{LOS}} = {} & \alpha_{\mathrm{INT}} + \beta_{\mathrm{LOS}} Y_{t-1}^{\mathrm{LOS}} + \alpha_{\mathrm{CDS}} \Delta X_t^{\mathrm{CDS}} + \gamma_{\mathrm{CDS}} X_t^{\mathrm{CDS}} \\ & + \alpha_{\mathrm{TAF}} \Delta I_t^{\mathrm{TAF}} + \beta_{\mathrm{TAF}} \Delta I_{t-1}^{\mathrm{TAF}} + \gamma_{\mathrm{TAF}} I_t^{\mathrm{TAF}} + \epsilon_t. \end{aligned} \tag{14}$$

Regressions (5) and (8) use the daily level of the Libor-OIS spread, Y_t, as the dependent variable, whereas regressions (11) and (13) use the daily change in the Libor-OIS spread, $\Delta Y_t^{\mathrm{LOS}}$.

The four regression specifications use four different subsets of the independent variables listed in (14).

We simulate Y_t^{LOS} from the data generating process (1) with the following assumption of parameter values: $a = 0$, $b = 0.5$, $c = 40$, $d = 2$, $\sigma^2 = 9$, and $\rho = 1$. The autoregressive coefficient is set to 1 because the observed Libor-OIS data show evidence of a component with the unit root. We focus on a single TAF event date: December 12, 2007, the day the Federal Reserve made its first public announcement about TAF. By setting $d = 2$, we assume that the TAF event reduces the liquidity component by 2 basis points in the data generating process. The TAF effect is either permanent or temporary in the data generating process for simulation. If the effect is permanent, L_t is a step function defined in equation (2). If the effect is temporary, L_t is constant except for a drop on the event day, as defined in equation (6).

Table 3 reports the results of simulations on the econometric specifications used by Taylor and Williams (2009) and Wu (2011). These regressions use the daily level of Y_t^{LOS} as the dependent variable. Panel A is for regression (5), in which the TAF event indicator, ΔI_t^{TAF}, is the independent variable for testing the TAF effect. The first part of the panel shows that this regression (5) misses the TAF effect when the effect is permanent. The average estimate of the coefficient of ΔI_t^{TAF} is -1.34, a much smaller magnitude than -2, which is the true value. The average t-statistic is -0.09, too small to be significant. The regression has little chance to discover the TAF effect because the rejection rate for the hypothesis of zero coefficient is only 5 percent. If the TAF effect is temporary, the regression produces ambiguous results, shown in the second part of the panel. The average estimate of the coefficient is -1.97, very close to the true value, but the chance to reject the hypothesis of zero coefficient is only 6 percent while the average t-statistic is only -0.14.

The ambiguity in the simulation results is a consequence of a unit root in the dependent variable Y_t, for which we set $\rho = 1$ in the simulations. If we include the lagged spread Y_{t-1}^{LOS} as an independent variable in the regression, the R-squared jumps from 40% to 97%. The average estimate of the coefficient of Y_{t-1} is 0.97 with extremely large t-statistics, which causes the rejection rate to be 100 percent. These simulation results are clearly the symptoms of the unit-root problem. With a unit root, the statistics in panel A cannot be interpreted as in the standard OLS regressions. Another indication of the unit-root problem is that the average estimate of the coefficient of ΔI_t^{TAF} is unstable. When the TAF effect is permanent, the inclusion of Y_{t-1}^{LOS}

changes the average estimate of coefficient of ΔI_t^{TAF} from -1.34 to -2.89.

Panel B of Table 3 presents the simulation results for regression (8), where the TAF regime indicator, I_t^{TAF}, is the independent variable for testing the TAF effect. The first part of the panel shows that this regression can detect the TAF effect if the effect is permanent. The average estimate of the coefficient of I_t^{TAF} is -2.05, which is almost the same as its true value. The average t-statistic is -0.67, and the rejection rate is 71 percent. However, the regression produces confusing results if the TAF effect is temporary. The average estimate of the coefficient is -0.12, very close to zero, and the t-statistic is -0.04 on average. But, the rejection rate is as high as 71 percent, which means the t-statistic in this regression is incorrect for inferring the significance of the TAF effect.

The confusing results in the first part of panel B of Table 3 are again consequences of the unit root in the data generating process of Y_t^{LOS}. When we include the lagged Libor-OIS spread Y_{t-1}^{LOS} in the regression, the R-squared jumps from about 45% to 97%, and the coefficient of Y_{t-1}^{LOS} is 0.97, accompanied by extremely large t-statistics. The TAF effect, as measured by the coefficient of I_t^{TAF}, is unstable. If the TAF effect is permanent, the inclusion of Y_{t-1}^{LOS} changes the average estimate of the coefficient of I_t^{TAF} from -2.05 to -0.28. For the temporary effect, the rejection rate changes from 71 percent to 11 percent. Therefore, anyone relying on the statistics of regression (8) may incorrectly conclude that the evidence of the TAF effect is unclear, although there is a solid effect in the true data generating process.

Will regressions (5) and (8) always work well if the Libor-OIS spread has no unit-root problem? The answer is no. If Y_t^{LOS} is stationary, although the statistics obtained from these regressions are valid for standard interpretations, the regressions miss either permanent or temporary TAF effects. Our simulations with $|\rho| < 1$, not reported to save space, show that regression (5) produces correct statistics if Y_t^{LOS} is stationary and contains a temporary TAF effect. If the effect is permanent instead, regression (5) underestimates the effect and most likely reports insignificant t-statistics. By contrast, regression (8) produces the correct statistics for the permanent effect if Y_t^{LOS} is stationary, but generates insignificant statistics for the temporary effect. Therefore, even if the Libor-OIS spread is stationary, it makes little sense to compare the empirical results produced by regressions (5) and (8) because the regressions catch different types of TAF effects. The bottom line is that regressions (5) and (8) are not reliable for empirical tests of the TAF effects.

Table 4 reports the simulation results for regressions (11) and (13). These regressions use the daily change in the simulated Libor-OIS spread as the dependent variable. The coefficient of ΔI_t^{TAF} measures the TAF effect in those regressions, where ΔI_t^{TAF} is the TAF event indicator. Our most important observation from this table is the robust estimation of the TAF effect: the average estimate is very close to -2, the true value, in both regressions (11) and (13) and for both permanent and temporary effects. The average t-statistic of the coefficient is around -0.67, producing a 10 percent rejection rate. These statistics stay the same when the regression does or does not include the lagged variables, Y_{t-1}^{LOS} and $\Delta I_{t-1}^{\text{TAF}}$.

In the second part of panel B, which is for regression (13) and the temporary TAF effect, the average estimate of the coefficient of $\Delta I_{t-1}^{\text{TAF}}$ is about 1.99 without Y_{t-1}^{LOS} and 1.95 with Y_{t-1}^{LOS}, indicating a quick reversal of the TAF effect. Interestingly, omitting $\Delta I_{t-1}^{\text{TAF}}$ in regression (11) does not bias the estimation of the TAF effect captured by ΔI_t^{TAF}, as shown in the second part of panel A. The estimate, t-statistic, and rejection rate are similar whether the regression omits the lagged TAF event indicator or not. Therefore, regression (11) does not miss the temporary TAF effect. To summarize, the regression models that use the change of the Libor-OIS spread as dependent variable are robust for estimating the TAF effects, whether the effect is permanent or temporary. However, inclusion of the lagged TAF event indicator has the advantage of identifying the reversal of a TAF effect when it is temporary.

While Tables 3 and 4 focus on the two polar cases of the TAF effect, permanent or temporary, the effect of a TAF event may be neither permanent nor temporary, but decay gradually. If the TAF effect decays gradually, we will need more lags of the TAF event indicator to identify it. Also, some of the TAF events may have permanent effects, some temporary, while others decay at various speeds. The simulations show that regression (11) specified by McAndrews et al. (2008) is robust for testing the TAF effect. If one wants to identify the speed of decay of the TAF effect, one can add more lagged TAF event indicators in regression (13).

4 Empirical results

4.1 Estimating the TAF effect

As discussed earlier, we use the TAF event indicator to flag the days when the central banks made TAF announcements or conducted TAF operations. As an indicator of the TAF program, a variable ΔI_t^{TAF} equals 1 on the days when any of the TAF announcements and operations happen and 0 on other days. An exception is February 1, 2008, for which $\Delta I_t^{\text{TAF}} = -1$ because the ECB announced that it would not participate in the February TAF auctions. The ECB's withdrawal from the February auctions reduced the anticipated funds supplied in the TAF. Table 1 lists the dates when ΔI_t^{TAF} is nonzero and gives a brief description of each event. The table also indicates whether an event is an announcement or an operation and defines two additional event indicators to distinguish between announcements and operations. The TAF event indicator denoted by ΔI_t^{ANN} equals 1 on a day with any TAF announcement and zero on other days (except on February 1, 2008 when $\Delta I_t^{\text{ANN}} = -1$). The dates when TAF operations were conducted are indicated by $\Delta I_t^{\text{OPS}} = 1$. Some of the TAF announcements informed the markets of participation by other central banks, whereas others dealt only with operations inside the U.S. Accordingly, we split the TAF announcements into two types: those about international participation and those about the supply of funds by the Fed. The variables ΔI_t^{ANI} and ΔI_t^{AND} are used to indicate the announcement dates of international and domestic dollar supplies via swap lines and TAF. We further distinguish the three parts of operations (conditions, auctions, and notifications) by ΔI_t^{CON}, ΔI_t^{AUC} and ΔI_t^{NOT}.

Based on the simulation analysis, we choose equation (11) as our basic econometric specification in the empirical investigation. Table 5 presents the results of the regression. In panel A, we test the TAF effect on the three-month Libor-OIS spread. The coefficient of the TAF event indicator is about −2 and significant, showing that the TAF were associated with a significant reduction in the Libor-OIS spread. These results stay the same when the change in the CDS spread or the lagged level of the Libor-OIS spread, or both, is added as control variable in the regression.

In panel A of Table 5, the coefficients of the control variables turn out to be as expected. First, the change in the CDS spread has a positive and significant coefficient, consistent with the hypothesis that credit risk is part of the elevated Libor-OIS spread during the financial crisis. Thus, the inclusion of the CDS spread substantially improves the R-squared of the regression. Second, the lagged level of the Libor-OIS spread has an insignificant coefficient, suggesting its non-stationarity. This further confirms that the level of the Libor-OIS spread should not be used as the dependent variable in the regression for detecting the TAF effect.

In panel B of Table 5, we repeat the test on the one-month Libor-OIS spread and obtain similar results. The coefficient of the TAF event indicator is again about -2 and significant. The coefficient of the lagged level of the Libor-OIS spread is insignificant. The only difference is that the CDS spread is less significant for the one-month Libor-OIS spread than it is for the three-month Libor-OIS spread. This difference is reasonable because credit risk should be less consequential in one-month loans than in three-month loans.

To identify the potential temporary TAF effect on Libor, we estimate regression (13) and report the results in Table 6. If we include one-day lag of the TAF event indicator in the regression, the estimated coefficient of the TAF event indicator is approximately -1.89 for the three-month Libor-OIS spread and -1.86 for the one-month Libor-OIS spread. These estimates are not very different from the estimates in Table 5. They are also very significant. The estimated coefficient of the lagged TAF event indicator is insignificant, suggesting that the TAF effect was not quickly reversed. These results are robust to the inclusion of the CDS spread and the lagged level of the Libor-OIS spread as control variables. In the last column of the table, we present the regression with two lagged TAF event indicators. The estimate of the coefficient of the second lagged TAF event indicator is much closer to zero with very small t-statistics. Apparently, the TAF effect detected from regression (11) is not temporary. The permanent nature of the TAF effect explains why Taylor and Williams (2009) do not find it, given that their regression specification works only for a temporary effect.

The TAF announcements and operations may have different effects on the Libor-OIS spread. The reduction of interest rates in the interbank market might be directly associated with the change in expectations, instead of the actual lending, of the funds provided by the Fed. Credible announcements of the TAF program may be enough to reassure fearful lenders of the availability of future funding and to mitigate liquidity hoarding. In efficient markets, news releases often cause prices to change immediately when the prices incorporate new information. Since TAF announcements occurred in the morning, and since we use daily data, there is enough time for TAF news to be partially or fully reflected in the prices on the same day.

Apart from announcements, TAF operations may help resolve the uncertainty faced by market participants. As describe in Section 2.1, TAF operations included: the setting of the auction condition (i.e., the minimum bid rate), the auction (in which banks submitted bids), and the notification of the auction results (such as the success of bids, the stop-out rate, the aggregate amount bid, and other statistics). The auction process and its results might have affected both the actual demand and the expected demand for liquidity and resolved the uncertainty regarding the distribution of funds allocated in the auction, thereby affecting perceived liquidity risk. For example, on an auction day, some banks might have felt assured about the prospect of funding from the auction if they chose to bid high to increase the chance of winning funds. Similarly, the public release of the auction result might have settled the uncertainty regarding the result of an auction.

To identify the announcement and operations effects separately, we modify specification (11) by splitting the TAF event indicator into two indicators: one for the events of announcements, ΔI_t^{ANN}, and the other for the events of operations, ΔI_t^{OPS}, both of which are defined in Table 1. The regression becomes

$$\Delta Y_t^{\text{LOS}} = \alpha_{\text{INT}} + \beta_{\text{LOS}} Y_{t-1}^{\text{LOS}} + \alpha_{\text{CDS}} \Delta X_t^{\text{CDS}} + \alpha_{\text{ANN}} \Delta I_t^{\text{ANN}} + \alpha_{\text{OPS}} \Delta I_t^{\text{OPS}} + \epsilon_t. \tag{15}$$

If the TAF announcements or operations were helpful in reducing the term borrowing rates, the estimated α_{ANN} and α_{OPS} in regression (15) should be negative.

The statistics of regression (15) are reported in the first two columns of numbers in Table 7. Panel A shows that the effect of each TAF announcement on the three-month Libor-OIS spread is much stronger than that of each TAF operation event. The coefficient of the TAF announcement indicator is −5.90 and significant with 99 percent confidence. The coefficient of the TAF operation indicator is −1.32, and it is statistically significant with 90 percent confidence. For the one-month Libor-OIS spread, panel B shows that the TAF effect estimated from regression (15) is similar. Again, the estimated coefficient of the TAF announcement indicator is far bigger than that of the TAF operation indicator. The smaller estimate of coefficient of the TAF operation indicator does not necessarily mean that TAF operations are less important. Since there are far more operation events than announcements, the cumulative effect of operations can be as large as the effect of announcements, although the estimated α_{OPS} is smaller.

To distinguish the two types of announcement effects (international vs. domestic), we replace ΔI_t^{ANN} by the two indicators, ΔI_t^{ANI} and ΔI_t^{AND}:

$$\Delta Y_t^{\text{LOS}} = \alpha_{\text{INT}} + \beta_{\text{LOS}} Y_{t-1}^{\text{LOS}} + \alpha_{\text{CDS}} \Delta X_t^{\text{CDS}} + \alpha_{\text{ANI}} \Delta I_t^{\text{ANI}} + \alpha_{\text{AND}} \Delta I_t^{\text{AND}} + \alpha_{\text{OPS}} \Delta I_t^{\text{OPS}} + \epsilon_t. \tag{16}$$

The statistics of regression (16) are reported in the third and fourth columns in Table 7. Both international and domestic announcements had significant effects. For the three-month Libor-OIS spread, panel A shows that the estimated coefficient of international announcements is

-7.40 and significant with 99 percent confidence. The estimated coefficient of domestic announcements is -4.39 and statistically significant with 99 percent confidence. Panel B shows similar results for the one-month Libor-OIS spread. In addition, splitting the announcements into international and domestic does not alter the estimated effects of operations. These empirical results suggest that both the international central bank coordination and the domestic auction program are important to banks. The importance of the international announcements might reflect the international banks' dependence on U.S. dollar wholesale funding markets. Those banks did not have extensive branch operations in the U.S. but needed to fund their U.S. dollar-denominated assets.[4]

Since the operation of each TAF auction consists of three parts, as described earlier, we are interested in the separate effects. We replace ΔI_t^{OPS} by three indicators, ΔI_t^{CON}, ΔI_t^{AUC}, and ΔI_t^{NOT}, for the three types of operations, for which the exact definitions are provided in Table 1, and obtain the following regression specification:

$$\begin{aligned}\Delta Y_t^{\text{LOS}} = \alpha_{\text{INT}} + \beta_{\text{LOS}} Y_{t-1}^{\text{LOS}} + \alpha_{\text{CDS}} \Delta X_t^{\text{CDS}} + \alpha_{\text{ANN}} \Delta I_t^{\text{ANN}} \\ + \alpha_{\text{CON}} \Delta I_t^{\text{CON}} + \alpha_{\text{AUC}} \Delta I_t^{\text{AUC}} + \alpha_{\text{NOT}} \Delta I_t^{\text{NOT}} + \epsilon_t.\end{aligned} \tag{17}$$

The results of regression (17) are reported in the last two columns of Table 7. In panel A, which is for the three-month Libor-OIS spread, the estimated coefficients are -1.59 for setting conditions, -0.23 for conducting auctions, and -0.82 for notifying auction results, but only the coefficient for setting conditions is statistically significant with 90 percent confidence. In panel B, which is for the one-month Libor-OIS spread, the estimated coefficients of the operation indicators are even less significant. Maybe because many operations are expected, identification of the operation effects is difficult. But, the negative coefficients support the view that each part of the TAF operation helped in reducing the Libor-OIS spread.

4.2 Robustness of the TAF effect

When estimating the TAF effects, it is necessary to control for other factors that drive the daily change in the Libor-OIS spread. As we have discussed in sections 2.2 and 3.1, a major factor we need to control for is credit risk. However, one may be concerned that the liquidity component

[4] It is true that international banks in the Libor panel had access to the discount window and TAF auctions via their U.S. branches. However, since the supply of funds through TAF was limited, it is likely that the funding needs of foreign banks were not fully satisfied by the domestic TAF auctions. Also, Armantier et al. (2015) shows that the use of the discount window facility by banks (whether domestic or foreign) was severely limited during our sample period.

correlates systematically with the term premium, the market risk, or the special features of bank loan markets such as window-dressing at quarter-ends. In this section, we control for these additional factors to check the robustness of the TAF effects.

If the liquidity component of the Libor-OIS spread covaries with the term premium of interest rate, in the regressions we control for the change in the spread between the OIS rate and the effective overnight federal funds rate, denoted by ΔX_t^{TRM}. The variation of the risk environment in the money markets may drive Libor to change. To account for this variation, the change in interest rate volatility, denoted by ΔX_t^{RSK}, is added as an independent variable. We measure interest rate volatility by the implied volatility of the three-month Eurodollar interest rate options and obtain the implied volatility from Datastream.

Short-term interest rates are well known to spike on quarter-ends, when institutions report information on their balance sheets. We construct an indicator, denoted by ΔI_t^{QRT}, to capture the potential quarter-end effect. This indicator equals $+1$ for the last three days at the end of a quarter to capture the potential positive changes. The indicator equals -1 for the first three days at the beginning of a quarter to capture the potential negative changes. The indicator equals zero on other days. We choose a three-day window before and after a quarter-end to account for the fact that the settlement of Eurodollar deposits occurs two days after the quote of the rate and the fact that the date t Libor-OIS spread uses the Libor published at 6:00 a.m. on date $t+1$.

Incorporation of these additional control variables leads to the following expanded regression:

$$\begin{aligned}\Delta Y_t^{\text{LOS}} = \alpha_{\text{INT}} + \alpha_{\text{LAG}} Y_{t-1}^{\text{LOS}} + \alpha_{\text{CDS}} \Delta X_t^{\text{CDS}} + \alpha_{\text{TRM}} \Delta X_t^{\text{TRM}} \\ + \alpha_{\text{RSK}} \Delta X_t^{\text{RSK}} + \alpha_{\text{QRT}} \Delta X_t^{\text{QRT}} + \alpha_{\text{TAF}} \Delta I_t^{\text{TAF}} + \varepsilon_t.\end{aligned} \tag{18}$$

We also separate out the effects of announcements and operations:

$$\begin{aligned}\Delta Y_t^{\text{LOS}} = \alpha_{\text{INT}} + \alpha_{\text{LAG}} Y_{t-1}^{\text{LOS}} + \alpha_{\text{CDS}} \Delta X_t^{\text{CDS}} + \alpha_{\text{TRM}} \Delta X_t^{\text{TRM}} \\ + \alpha_{\text{RSK}} \Delta X_t^{\text{RSK}} + \alpha_{\text{QRT}} \Delta I_t^{\text{QRT}} + \alpha_{\text{TAF}} \Delta I_t^{\text{ANN}} + \alpha_{\text{TAF}} \Delta I_t^{\text{OPS}} + \varepsilon_t.\end{aligned} \tag{19}$$

The results of the above two regressions are reported in Table 8. For the regression using the three-month Libor-OIS spread, the change in the term premium has a negative coefficient, which is significant with 95 percent confidence. The change in risk has a positive coefficient, which is significant with 99 percent confidence, which shows the influence of risk and risk aversion. The quarter-end indicator has an insignificant coefficient, possibly because there are quarter-end effects in both Libor and the OIS rate and they cancel each other in the spread.

As an important benefit, the additional control variables boost the R-squared from 3.37% for regression (11) to 15.98% for regression (18). The large increase in the R-squared reflects the enhanced power of the specification against potentially spurious attribution of some fluctuations of the Libor-OIS spread to the TAF.

Most importantly, the estimated coefficient of the TAF event indicator is about −2 and significant with 95 percent confidence in regression (18), as reported in the third and fourth columns of numbers in panel A of Table 8. The magnitude of the TAF effect estimated from this regression is almost the same as that estimated from regression (11) reported in panel A of Table 5. If we split the TAF events into announcements and operations as in regression (19), we find a large TAF effect associated with the announcements, as reported in the last two columns in panel A of Table 8. These empirical results do not change qualitatively when we obtain them from the one-month Libor-OIS spread, as we show in panel B of Table 8.

To distinguish the effects of the TAF from other Fed's liquidity programs during the global financial crisis, we have been focusing on the announcements and operations for the first ten auctions in TAF. To isolate the TAF effects further, we repeat regressions (18) and (19) with a subsample of our data covering the period up to March 10, 2008. This subperiod was before the Fed introduced a series of new liquidity facilities (i.e., the Term Securities Lending Facility (TSLF) and the Primary Dealer Credit Facility (PDCF)) and lent to JP Morgan Chase for its acquisition of Bear Stearns. The regressions using only the data (306 observations) up to the introduction of other facilities at least exclude the effects of the Fed's actions after March 10, 2008. Table 9 presents the empirical results obtained from the subsample. The coefficients of the event indicators of the TAF announcements and operations are negative and significant, just as we have seen earlier. Therefore, the TAF effect on the Libor-OIS spread remains notable after excluding the effect of later facilities.

To check the robustness of the TAF effect further, we use the average expected default frequency (EDF) of Libor banks as control variable in regressions.[5] We obtain the EDF data of Libor banks from Moody's KMV. Table 10 presents the empirical results. The table shows that the coefficient of the change in the EDF is insignificant in all the regressions. A possible reason for its insignificance may be because the EDFs are estimates, which are not very sensitive to markets. By contrast, the CDS spreads are quoted prices, which are very sensitive to changes

[5]We thank the anonymous referee for the suggestion of checking this robustness.

in market conditions. Most importantly, the estimate of the TAF effect in Table 10 is similar to the estimates in previous tables.

Aside from serving as a control variable in the regression, the CDS prices allow us to separate out the liquidity component from the Libor-OIS spread as described in Section 2.2. For this purpose, we estimate the credit risk premium from the CDS prices on the debts of the banks and subtract it from the Libor-OIS spread. We provide the technical details in the Appendix. The daily time series of the average estimated credit premiums of banks is denoted by C_t^{CDS}. The credit premium C_t^{CDS} is different from X_t^{CDS} for the following reasons. First, the term of the default risk in Libor is one or three months, whereas the term of the CDS in our data is one year. Second, the recovery rate of dollar deposits is substantially higher than the recovery rate of corporate debts, as explained in the Appendix. Therefore, the changes of C_t^{CDS} and X_t^{CDS} should not be expected to have similar magnitudes, although they are anticipated to be correlated.

We define the liquidity component of the Libor-OIS spread as the difference between the Libor-OIS spread and the credit risk premium estimated from the CDS prices and denote it by $Y_t^{\text{LQD}} = Y_t^{\text{LOS}} - C_t^{\text{CDS}}$. Then, we test for the TAF effect on the liquidity component using the following regressions:

$$\Delta Y_t^{\text{LQD}} = \alpha_{\text{INT}} + \alpha_{\text{LAG}} Y_{t-1}^{\text{LQD}} + \alpha_{\text{CDS}} \Delta X_t^{\text{CDS}} + \alpha_{\text{TAF}} \Delta I_t^{\text{TAF}} + \varepsilon_t \,, \tag{20}$$

where $\Delta Y_t^{\text{LQD}} = Y_t^{\text{LQD}} - Y_{t-1}^{\text{LQD}}$ is the change in the liquidity component in the Libor-OIS spread. The results for regression (20) are reported in Table 11. Again, all the TAF-related coefficients have magnitudes and significance similar to those reported in Table 8, underscoring the robustness of our empirical results. A major difference is that the estimated coefficient of the CDS spread change is no longer significant. This is reasonable because the credit premium is excluded from the liquidity component.

Throughout this paper, we use the one-year CDS spread so that the term of the CDS is not too much longer than the terms of Libor and the OIS rate. We do not use the six-month CDS because it is much less liquid, and the Markit database often does not have six-month CDS spreads for some Libor banks. The five-year CDS contracts are regarded as the most liquid, but the term is much longer. To check the robustness of our empirical results to the choice of CDS terms, we repeated our analysis with the five-year CDS spread and found the same empirical results, as the statistics related to the CDS spread differ only quantitatively but not qualitatively. To save space, we do not report the empirical results obtained from using the five-year CDS spread.

A potential problem of focusing on Libor is that the banks were suspected of under-reporting the borrowing costs during the recent financial crisis. The issue of systematic under-reporting of Libor was first raised by the Wall Street Journal on April 16, 2008, and was subsequently investigated in numerous academic studies. For example, Abrantes-Metz et al. (2012) find no consistent evidence of material manipulation of the U.S. dollar one-month Libor. By contrast, Youle (2015) finds that the three-month Libor was systematically distorted downward by eight basis points during the 2007–2009 financial crisis. A systematic under-reporting may affect the level of Libor but should have little effect on its daily changes. This is another advantage of using the change, instead of the level, of the Libor-OIS spread in the tests for the TAF effect.

Manipulation of Libor is actually more complicated than simple under-reporting. There were sharp increases in Libor on April 17, and 18, 2008, immediately after the BBA announced its intent to investigate banks' submissions of borrowing rates. The sharp increases on those dates can cause underestimation, not overestimation, of the TAF effect in our study if those dates coincide with some TAF events. However, there were no TAF events on or around those dates. Moreover, litigation against the banks, such as Barclays, UBS, and Citigroup, involve not only downward but also upward manipulation of Libor by the banks to increase the profitability of their business. If the dates and direction of manipulation were related to the TAF events, our empirical evidence of the TAF would potentially be contaminated by the manipulation. However, there is no clear reason to believe a priori that such relation should exist. Neither are there data on possible manipulation for us to examine such a potential relation.

4.3 Symptoms of the unit-root problem

As we discussed in Section 2.3, the Libor-OIS spread, as well as the CDS spread, is likely to have unit roots. If so, the statistics produced from econometric specifications (5) and (8), as set out in Taylor and Williams (2009) and Wu (2011), cannot be interpreted in the normal way, as we have shown in Section 3.1 and confirmed by Monte Carlo simulations in Section 3.2. In this section, we use these specifications to test the TAF effect and discuss the problems of these regressions.

In Table 12 we report the statistical results of regression (5). The dependent variable in this regression is the level, not the change, of the Libor-OIS spread, and the variable used to capture the TAF effect is the TAF event indicator ΔI_t^{TAF} defined in Table 1. If we do not control for the credit spread, as in the first two columns of numbers in each panel, the TAF event indicator has a positive and significant coefficient. The positive coefficient does not make economic sense because the TAF should not raise the Libor-OIS spread.

Once we add the level of the CDS spread in the regression, the coefficient of the TAF event indicator becomes insignificant, shown in the middle two columns of numbers in each panel of Table 12. In addition, the coefficient of the CDS level is positive and significant. These results are qualitatively the same as those reported by Taylor and Williams (2009). They are also qualitatively the same as the Monte Carlo simulation results presented in panel A of Table 3. Recall that we obtained the simulation results from a data generating process that contains the TAF effect. The simulation shows that even when the TAF effect exists, regression (5) leads to the conclusion that the TAF effects are not significant. We see exactly the same in the empirical results presented in Table 12.

To show the unit-root problem in regression (5), we add the lagged level of the Libor-OIS spread as an independent variable. The results are shown in the last two columns of numbers in each panel of Table 12. The lagged variable has three consequences. First, the estimated coefficient of the lagged variable is extremely significant, with a very large t-statistic. Second, the R-squared jumps to 98% for the three-month Libor-OIS spread and 96% for the one-month Libor-OIS spread. Third, the coefficient of the TAF event indicator is negative and significant. Notice that the same consequences happen in the simulation results shown in panel A of Table 3, where the data generating process contains a TAF effect. Also, notice that these three consequences occur in Table 6 of Taylor and Williams (2009), where the researchers add the lagged Libor-OIS spread in their regression. They conclude that the evidence of TAF effect is unstable when comparing to the results with and without the lagged variable, but the instability they reported is actually a manifestation of the unit-root problem.

The statistical test using specification (8) suffers from the unit-root problem too. The dependent variable in this regression is the level, not the change, of either the three-month or one-month Libor-OIS spread. The variable that captures the TAF effect is the regime indicator defined by Wu (2011), which equals one since December 12, 2007, (the day of the first TAF announcement) and zero before that date. The statistics of the regression are reported in Table 13.

If we simply regress the level of the Libor-OIS spread on the regime indicator, the coefficient of the indicator is positive and significant, shown in the first two columns of numbers in each panel of Table 13. After we control for the level of the CDS spread, the coefficient of the regime indicator becomes negative, as we show in the two middle columns of numbers. A problem with the result is that the absolute value of the coefficient is very large while the t-statistic is not significant. For the three-month Libor-OIS spread, the estimated coefficient of the TAF regime indicator is -10.37, but its t-statistic is only -0.51. For the one-month Libor-OIS spread, the estimated coefficient of the TAF regime indicator is -7.39, but its t-statistic is merely -0.38. This is exactly what we observe in the simulations of specification (8) as presented in panel B of Table 3. It simply indicates that the TAF effect based on this specification is not reliable.

The unit-root problem of specification (8) clearly shows up when we control for the lagged level of the Libor-OIS spread in the regression, as reported in the last two columns of numbers in Table 13. Now, the estimated coefficient of the TAF indicator becomes much smaller but far more significant. Inclusion of the lagged Libor-OIS spread reduces the absolute value of the TAF coefficient from 10.37 to 2.93 in panel A and from 7.39 to 4.09 in panel B. However, the absolute value of the t-statistic increases from 0.51 to 2.67 in panel A and from 0.38 to 2.52 in panel B. In addition, the t-statistic of the lagged variable is extremely large. Another symptom of the unit-root problem is that the R-squared jumps to 98% for the three-month Libor-OIS spread and 96% for the one-month Libor-OIS spread. We have already observed these symptoms in the simulation results reported in panel B of Table 3. These symptoms also appear in the empirical results reported by Wu (2011), as seen in his Table 6.

Overall, the TAF effects estimated by Taylor and Williams (2009) and Wu (2011) are unreliable because their econometric specifications suffer from the unit-root problem, besides missing either the permanent or temporary effect. The unit-root problem causes the TAF effect to be insignificant in some of their regressions. The problem causes the magnitude of the estimated TAF effects to swing by a very large scale when alternative control variables are used in their regressions.

5 Conclusion

In this paper, we resolve the controversy over the effect of the Term Auction Facility on the London interbank offered rate. We show that the disagreement in the literature arises from mis-specifications of econometric models. One cannot reliably identify the TAF effect by using the daily level of the Libor-OIS spread as dependent variable in regressions. Such a regression misses a permanent effect if the TAF event indicator is used as an independent variable. It misses a temporary effect if the TAF regime indicator is used instead. Those regressions also generate invalid test statistics because the probability distribution of the Libor-OIS spread is not stationary. The biased statistics produced from those regressions cannot be interpreted in the normal way. By contrast, regressions using the daily change in the Libor-OIS spread are robust to the type of the TAF effect and the stationarity problem of the Libor-OIS spread. These regressions are reliable for testing the TAF effect on Libor, consistently producing evidence that the TAF is associated with downward shifts of the Libor-OIS spread.

The evidence we present indicates the efficacy of the Term Auction Facility in helping the interbank market to relieve liquidity strains, but the TAF effect we examine is confined to the Libor-OIS spread. If the TAF helped relieve the strains in the interbank market, it might have effects on other interest rates, on the volume of loans, or on the conditions in various markets. The TAF effects beyond Libor are subjects that calls for further research. One example of such research is the analysis of the micro-level loan data by Benmelech (2012). Benmelech shows that the TAF helped the liquidity provision to be disseminated efficiently when the unsecured interbank market was under stress. He reports that a large part of the loans went to banks that lend actively in the economy. Were the TAF ineffective in relieving the strains in the interbank market, a broader effect would have been unlikely.

Although the downward shifts of the Libor-OIS spread reflect the efficacy of the TAF, the problems encountered in 2008 by banks in meeting their funding needs in the interbank market were not fully solved by the TAF alone. Subsequently, the Federal Reserve undertook additional actions to further improve market conditions. These actions include further increasing the TAF auction sizes, lengthening the term of loans in the primary credit programs, lowering the interest rate premium in the discount window, and introducing several other lending facilities. The effectiveness of the TAF during the early stage of the global financial crisis was important in the Fed's decision and design of additional lending facilities in 2008, as described by Geithner

(2014).

The Fed's additional lending facilities to assist the money market in 2008 included the following major programs: The Primary Dealer Credit Facility was established in March to improve the ability of primary dealers in providing financing to participants in securities markets. The Term Securities Lending Facility (TSLF) was also introduced in March as a way of addressing the pressure faced by primary dealers in their access to term funding and collateral. Meanwhile, the TSLF Options Program offered additional liquidity during periods of heightened collateral market pressure, such as quarter-end dates.[6] The Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility was introduced in September to help money-market mutual funds that held asset-backed commercial paper meet investors' demands for redemptions. To complement this program, the Fed introduced the Money Market Investor Funding Facility in October. The Commercial Paper Funding Facility also started in October to provide liquidity to U.S. issuers of commercial paper if credit was not available in the market. A much broader program, the Term Asset-Backed Securities Loan Facility, was announced in November, in which the Fed issued non-recourse loans with a term of up to five years to holders of eligible asset-backed securities. Finally, the Fed had reduced its target federal funds rate to a range of between 0 and 1/4 percent by December 2008 and introduced the Agency Mortgage-Backed Securities Purchase Program, which is commonly called the Fed's "quantitative easing."

Given the multiple actions by the Federal Reserve mentioned above, the Term Auction Facility is just one of many facilities designed to improve the liquidity conditions in the money markets during the 2007–2009 financial crisis. Identifying the impact of each individual liquidity facility, such as the impact of TAF analyzed in this paper, is crucial for future policy decisions of the central bank. The separate benefit of the TAF measured in this paper suggests that the TAF was useful as a complement to the other tools of the Federal Reserve in supporting liquid market conditions.

We only measure the TAF effects on the liquidity premium in this paper, but the TAF may affect bank credit risk. It is well known that credit risk and liquidity risk are often interrelated. A firm that has a credit problem is more likely to experience a liquidity problem. It is also well known that a liquidity problem can aggravate the credit problem in a firm. Although the Fed

[6] These options gave primary dealers the right, but not the obligation, to draw upon a TSLF loan, in exchange for eligible collateral, on a specified date in the future.

designed the TAF to address only the liquidity problem, disentangling the credit risk premium and the liquidity risk premium is an interesting and challenging research question as shown by Schwarz (2016). It is likely that the TAF also helped with banks in reducing both the credit risk premium and the liquidity risk premium. Therefore, after controlling the changes in credit risk premium, our analysis potentially underestimates the TAF effect in helping banks in the interbank market. If this is true, the total TAF effect is even larger.

Appendix

A CDS contract is characterized by the time to maturity (τ), the notional principal of the underlying corporate bond (B), the interval (δ) of periodic payments, and the annualized spread (s) that determines the amount of periodic payments. The buyer of the CDS pays $s\delta B$ at the end of each period until the bond defaults. If the bond does not default, the total number of payments is $n = \tau/\delta$, which is assumed to be an integer. If the bond defaults during the ith interval, we assume that the default happens at the midpoint of the interval for simplicity. Suppose the recovery rate of the bond is c. At default, the CDS buyer pays the accrued periodic payment and is paid $(1-c)B$ to the buyer.

Following the standard pricing model of CDS, we assume that the risk-neutral default probability increases along with the length of time horizon at a constant default intensity, denoted by λ. Under this assumption, the probability that the bond survives by time t is $\exp(-\lambda t)$. The probability that the bond defaults during $(t, t+\Delta t]$ is $[1-\exp(-\lambda\Delta t)]\exp(-\lambda t)$. Using the observed CDS spread s on a bank, we calibrate the default intensity λ of the bank using risk-neutral pricing, as described below.

In risk-neutral pricing, we need the risk-free discount rate. We treat OIS rates as the observed risk-free term rate. Using the observed OIS rates, we estimate the term structure of continuously compounding risk-free interest rates, which is a function $r(t)$ that maps the term t to a risk-free interest rate $r(t)$. The present value of one dollar to be paid at time t is $\exp(-t \cdot r(t))$ dollars.

Since no money changes hands at the initiation of a CDS contract, a CDS with a fair spread s should be worth zero to both the buyer and seller. Then, the sum of the expected present value of the periodic payments by the buyer should equal the expected present value of the insurance obligation of the seller. Thus, the pricing restriction of the CDS is

$$\textstyle\sum_{i=1}^{n} s\delta B\,\pi_i(\lambda)\,p_i + \sum_{i=1}^{n} s(\delta/2)B\pi_i'(\lambda)\,p_i' = \sum_{i=1}^{n}(1-c)B\pi_i'(\lambda)\,p_i', \tag{21}$$

where the risk-neutral probabilities and discount factors are defined by

$$\pi_i(\lambda) = \exp(-\lambda i\delta) \tag{22}$$
$$\pi_i'(\lambda) = [1-\exp(-\lambda\delta)]\exp(-\lambda(i-1)\delta) \tag{23}$$
$$p_i = \exp(-i\delta r(i\delta)) \tag{24}$$
$$p_i' = \exp(-(i-1/2)\delta r((i-1/2)\delta)). \tag{25}$$

This valuation follows Hull and White (2003). Canceling out B and solving s from the above equation, we obtain

$$\frac{s\delta}{1-c} = \frac{\sum_{i=1}^{n}\pi_i'(\lambda)\,p_i'}{\sum_{i=1}^{n}\pi_i(\lambda)\,p_i + (1/2)\sum_{i=1}^{n}\pi_i'(\lambda)\,p_i'}. \tag{26}$$

The above is a CDS pricing formula that incorporates the term structure of the OIS rates. Since the CDS spread s is observable, we can solve λ from the above pricing equation to obtain the default intensity implied by the market price of the default risk.

The default intensity allows us to calculate the default premium of term loans in the interbank market, if we know the recovery rate of the loan after default. Let $\tilde{r}$ be the continuously compounding risky rate for a term loan whose time to maturity is t and face value is L dollars. Suppose the recovery rate of the loan is $\tilde{c}$ and the risk-free rate of the same term is r. The pricing formula of the term loan is

$$L\exp(-\tilde{r}t) = L\exp(-\lambda t)\exp(-rt) + L\,\tilde{c}\,[1-\exp(-\lambda t)]\exp(-rt). \tag{27}$$

The interest rate $\tilde{r}$ carries a default premium and can be solved from the above pricing equation as:

$$\tilde{r} = r - \frac{1}{t}\log\Big(\exp(-\lambda t) + \tilde{c}\,[1-\exp(-\lambda t)]\Big), \tag{28}$$

which is the risky rate of the term loan implied by the CDS Let R_t^{CDS} be the equivalent simple compounding rate of $\tilde{r}$. The credit premium implied by the CDS spread is $C_t^{\text{CDS}} = R_t^{\text{CDS}} - R_t^{\text{OIS}}$.

In the calibration of default intensity, we use the CDS spreads and recovery rates provided by Markit. The risk-free rates for discounting are the OIS rates obtained from Bloomberg.

The calculation of the credit risk premium from default probability requires an assumption about the recovery rate $\tilde{c}$ of the interbank loans. Although the recovery rate of the unsecured corporate debt under each CDS contract is provided by Markit (usually around 40%), there is no available data on the recovery rate of the interbank loans. Since the interbank loans are claims senior to the unsecured corporate debt, the former should have a higher recovery rate than the latter. Based on Table 3 in Kuritzkes et al. (2005), the U.S. banks with at least $5 billion in assets have a recovery rate of around 91.25% for unsecured deposits. Therefore, the recovery rate of the interbank loans is set to 90% for the calculation in this study. In fact, the level of the recovery rate does not affect the empirical results because the statistical tests in this study are based on the changes (not the level) of the premiums.

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Table 1: Dates of the TAF announcements and operations

Date	Central bank action	ΔI_t^{ANN}		ΔI_t^{OPS}			ΔI_t^{TAF}
		ΔI_t^{ANI}	ΔI_t^{AND}	ΔI_t^{CON}	ΔI_t^{AUC}	ΔI_t^{NOT}	
12/12/07	Announcement of TAF initiation	1	0	0	0	0	1
12/14/07	Set conditions for the 1st auction	0	0	1	0	0	1
12/17/07	Conduct the 1st auction	0	0	0	1	0	1
12/19/07	Set conditions for the 2nd auction	0	0	1	0	0	1
12/20/07	Notify the result of the 1st auction Conduct the 2nd auction	0	0	0	1	1	1
12/21/07	Notify the result of the 2nd auction Announce continuation of TAF	0	1	0	0	1	1
01/04/08	Announce an increase of TAF quantity	0	1	0	0	0	1
01/11/08	Set conditions for the 3rd auction	0	0	1	0	0	1
01/14/08	Conduct the 3rd auction	0	0	0	1	0	1
01/15/08	Notify the result of the 3rd auction	0	0	0	0	1	1
01/25/08	Set conditions for the 4th auction	0	0	1	0	0	1
01/28/08	Conduct the 4th auction	0	0	0	1	0	1
01/29/08	Notify the result of the 4th auction	0	0	0	0	1	1
02/01/08	ECB won't join February auctions	-1	0	0	0	0	-1
02/08/08	Set conditions for the 5th auction	0	0	1	0	0	1
02/11/08	Conduct the 5th auction	0	0	0	1	0	1
02/12/08	Notify the result of the 5th auction	0	0	0	0	1	1
02/22/08	Set conditions for the 6th auction	0	0	1	0	0	1
02/25/08	Conduct the 6th auction	0	0	0	1	0	1
02/26/08	Notify the result of the 6th auction	0	0	0	0	1	1
03/07/08	Announce an increase of TAF quantity	0	1	0	0	0	1
03/10/08	Set conditions for the 7th auction Conduct the 7th auction	0	0	1	1	0	1
03/11/08	Notify the result of the 7th auction ECB & Swiss announce participation	1	0	0	0	1	1
03/24/08	Set conditions for the 8th auction Conduct the 8th auction	0	0	1	1	0	1
03/25/08	Notify the result of the 8th auction	0	0	0	0	1	1
04/07/08	Set conditions for the 9th auction Conduct the 9th auction	0	0	1	1	0	1
04/08/08	Notify the result of the 9th auction	0	0	0	0	1	1
04/21/08	Set conditions for the 10th auction Conduct the 10th auction	0	0	1	1	0	1
04/22/08	Notify result of the 10th auction	0	0	0	0	1	1

The table lists the dates of the TAF announcements and operations, for which $\Delta I_t^{\text{TAF}} = 1$. The column under ΔI_t^{ANI} uses 1 to indicate the dates of the announcements regarding international central bank participation. Similarly, the column under ΔI_t^{AND} indicates the dates of the announcements without international central bank participation. The column under ΔI_t^{CON} indicates the dates when the conditions of the auctions (such as the minimum bid rate) were set. The column under ΔI_t^{AUC} indicates the auction dates. The column under ΔI_t^{NOT} indicates the notification dates of auction results. The event indicator of announcements and the event indicator of operations are defined by $\Delta I_t^{\text{ANN}} = \Delta I_t^{\text{ANI}} + \Delta I_t^{\text{AND}}$ and $\Delta I_t^{\text{OPS}} = \Delta I_t^{\text{CON}} + \Delta I_t^{\text{AUC}} + \Delta I_t^{\text{NOT}}$, respectively.

Table 2: Summary statistics of data

Panel A: Daily level of the spreads and volatility

	3-month Libor-OIS spread	1-month Libor-OIS spread	3-month OIS term spread	1-month OIS term spread	Average CDS spread	Eurodollar implied volatility
Mean	39.02	29.17	-14.66	-8.16	18.68	18.98
Median	39.45	19.72	-4.85	-2.95	10.56	18.67
St.Dev	31.25	27.70	24.44	18.02	21.39	14.67
S.Corr	0.990	0.980	0.822	0.691	0.996	0.990
Test	Fail	Fail	Pass	Pass	Fail	Fail

Panel B: Daily change in the spreads and volatility

	3-month Libor-OIS spread	1-month Libor-OIS spread	3-month OIS term spread	1-month OIS term spread	Average CDS spread	Eurodollar implied volatility
Mean	0.23	0.22	-0.06	-0.05	0.11	0.10
Median	0.00	0.00	-0.25	-0.05	0.00	-0.03
St.Dev	4.44	5.50	14.60	14.17	2.02	2.12
S.Corr	-0.106	-0.027	-0.264	-0.262	0.105	0.074
p-value	0.051	0.618	0.000	0.000	0.053	0.177

The units are basis points for all spreads and percentage for volatility. The three-month Libor-OIS spread is the difference between the three-month Libor and the three-month OIS rate from January 3, 2007, to April 24, 2008. The three-month term spread is the difference between the three-month OIS rate and the overnight effective federal funds rate. The one-month Libor-OIS and term spreads are defined similarly. The average CDS spread is the mean of the one-year CDS spreads of the 16 banks in the U.S. dollar Libor panel. The volatility is implied by three-month Eurodollar options. Panel A reports the basic statistics (mean, median, standard deviation, and serial correlation) of the level of the spreads and volatility observed daily. The last row reports the results of the Dickey-Fuller test; failing the test means a failure to reject the null hypothesis of a unit root. Panel B reports the basic statistics of the daily changes in the spreads and volatility. A p-value is for an estimated serial correlation under the null hypothesis of zero serial correlation. (*Authors' calculations, based on data from Bloomberg L.P., Markit, and Thomson Reuters.*)

Table 3: Simulations on the specifications using the level of Libor-OIS spread

Panel A: Taylor and Williams' specification

	Est.	t-stat	Rej.	Est.	t-stat	Rej.
Permanent effect:						
Constant	39.87	38.12	0.98	1.13	1.58	0.48
Y_{t-1}^{LOS}				0.97	91.11	1.00
X_t^{CDS}	0.47	12.73	0.93	0.02	1.25	0.35
ΔI_t^{TAF}	-1.36	-0.09	0.05	-2.86	-0.91	0.14
R^2_{adj}		40.32%			97.09%	
Temporary effect:						
Constant	39.76	38.05	0.98	1.14	1.60	0.49
Y_{t-1}^{LOS}				0.97	91.03	1.00
X_t^{CDS}	0.50	13.58	0.93	0.02	1.29	0.36
ΔI_t^{TAF}	-1.98	-0.14	0.06	-2.89	-0.92	0.14
R^2_{adj}		41.34%			97.14%	

Panel B: Wu's specification

	Est.	t-stat	Rej.	Est.	t-stat	Rej.
Permanent effect:						
Constant	39.76	39.30	0.98	1.23	1.65	0.51
Y_{t-1}^{LOS}				0.97	87.64	1.00
X_t^{CDS}	0.50	7.79	0.87	0.02	1.31	0.31
I_t^{TAF}	-1.95	-0.64	0.71	-0.29	-0.39	0.13
R^2_{adj}		44.43%			97.09%	
Temporary effects						
Constant	39.75	39.29	0.98	1.24	1.66	0.51
Y_{t-1}^{LOS}				0.97	87.59	1.00
X_t^{CDS}	0.50	7.81	0.87	0.02	1.23	0.29
I_t^{TAF}	-0.02	-0.01	0.71	-0.16	-0.22	0.11
R^2_{adj}		45.14%			97.14%	

Monte Carlo simulations are conducted for regression (5) specified by Taylor and Williams (2009) and regression (8) specified by Wu (2011), in which the dependent variable is the Libor-OIS spread (Y_t^{LOS}) simulated under the assumption of a permanent or temporary TAF effect. The independent variables include the level of average CDS spread (X_t^{CDS}), the event indicator function of TAF (ΔI_t^{TAF}), and the regime indicator function of TAF (I_t^{TAF}). For each specification, the lagged spread (Y_{t-1}^{LOS}) is added to check for stationarity. The average and standard deviation of the simulated estimates, as well as the rejection rate, are reported for each coefficient. A rejection rate is the frequency that a simulated t-statistic rejects the hypothesis of zero coefficient at 95 percent confidence ($|t| > 1.96$). The average adjusted R-squared is reported for each regression specification.

Table 4: Simulations on the specifications using the change in the Libor-OIS spread

Panel A: Specification (11)

	Est.	t-stat	Rej.	Est.	t-stat	Rej.
Permanent effect:						
Constant	-0.00	-0.00	0.05	0.60	0.97	0.24
Y_{t-1}^{LOS}				-0.01	-1.40	0.26
ΔX_t^{CDS}	0.50	6.18	1.00	0.50	6.16	1.00
ΔI_t^{TAF}	-1.99	-0.66	0.10	-1.99	-0.66	0.10
R_{adj}^2		10.30%			10.76%	
Temporary effect:						
Constant	0.01	0.03	0.05	0.60	0.99	0.23
Y_{t-1}^{LOS}				-0.01	-1.39	0.26
ΔX_t^{CDS}	0.50	6.17	1.00	0.50	6.15	1.00
ΔI_t^{TAF}	-2.00	-0.67	0.10	-2.00	-0.67	0.10
R_{adj}^2		10.27%			10.72%	

Panel B: Specification (13)

	Est.	t-stat	Rej.	Est.	t-stat	Rej.
Permanent effect:						
Constant	-0.00	-0.00	0.05	0.60	0.97	0.24
Y_{t-1}^{LOS}				-0.01	-1.40	0.26
ΔX_t^{CDS}	0.50	6.18	1.00	0.50	6.16	1.00
ΔI_t^{TAF}	-1.99	-0.66	0.10	-1.99	-0.66	0.10
$\Delta I_{t-1}^{\text{TAF}}$	-0.01	-0.00	0.05	-0.04	-0.01	0.05
R_{adj}^2		-0.36%			-1.41%	
Temporary effect:						
Constant	-0.00	-0.00	0.05	0.60	0.97	0.23
Y_{t-1}^{LOS}				-0.01	-1.38	0.26
ΔX_t^{CDS}	0.50	6.18	1.00	0.50	6.16	1.00
ΔI_t^{TAF}	-1.99	-0.66	0.10	-1.99	-0.67	0.10
$\Delta I_{t-1}^{\text{TAF}}$	1.99	0.66	0.10	1.95	0.65	0.10
R_{adj}^2		66.36%			65.19%	

Monte Carlo simulations are conducted for econometric specifications (11) and (13), in which the dependent variable is the daily change ($\Delta Y_t^{\text{LOS}} = Y_t^{\text{LOS}} - Y_{t-1}^{\text{LOS}}$) in the Libor-OIS spread. The spread (Y_t^{LOS}) is simulated under the assumption of a permanent or temporary TAF effect. The independent variables include the daily change in the average CDS spread ($\Delta X_t^{\text{CDS}} = X_t^{\text{CDS}} - X_{t-1}^{\text{CDS}}$), the event indicator function of TAF (ΔI_t^{TAF}), and the lagged TAF event indicator ($\Delta I_{t-1}^{\text{TAF}}$). For each specification, the lagged Libor-OIS spread (Y_{t-1}^{LOS}) is added to check for stationarity. The average and standard deviation of the simulated estimates, as well as the rejection rate, are reported for each coefficient. A rejection rate is the frequency for a simulated t-statistic to reject the hypothesis of zero coefficient at 95 percent confidence ($|t| > 1.96$). The average adjusted R-squared is reported for each regression specification.

Table 5: The TAF effect in the basic specification

Panel A: Three-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	0.41	1.62	0.37	1.49	0.47	1.69*
Lagged Libor-OIS spread					-0.00	-0.27
Change in CDS spread			0.32	1.92*	0.32	1.92*
TAF event indicator	-2.24	-3.34***	-2.18	-2.76***	-2.11	-2.54**
Adjusted R-squared	1.73%		3.62%		3.37%	

Panel B: One-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	0.43	1.20	0.39	1.12	0.63	2.13**
Lagged Libor-OIS spread					-0.01	-0.55
Change in CDS spread			0.25	1.70*	0.25	1.65
TAF event indicator	-2.52	-2.95***	-2.47	-2.61***	-2.29	-2.32**
Adjusted R-squared	1.38%		1.97%		1.85%	

The estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regression (11). The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. Panel A reports the TAF effect on the three-month Libor-OIS spread, and panel B reports the TAF effect on the one-month Libor-OIS spread. (*Authors' calculations, based on data from Bloomberg L.P. and Markit.*)

Table 6: The lagged TAF effect

Panel A: Three-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	0.44	1.72*	0.40	1.60	0.47	1.70*	0.47	1.70*
Lagged Libor-OIS spread					-0.00	-0.21	-0.00	-0.19
Change in CDS spread			0.32	1.93*	0.32	1.93*	0.32	1.92*
TAF event indicator	-1.89	-3.58***	-1.84	-2.77***	-1.80	-2.59**	-1.81	-2.59***
1-day lagged TAF event	-0.67	-1.04	-0.66	-0.99	-0.63	-0.93	-0.56	-0.98
2-day lagged TAF event							-0.13	-0.16
Adjusted R-squared	1.57%		3.46%		3.19%		2.91%	

Panel B: One-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	0.46	1.29	0.43	1.20	0.64	2.16**	0.64	2.17**
Lagged Libor-OIS spread					-0.01	-0.50	-0.01	-0.48
Change in CDS spread			0.25	1.74*	0.25	1.68*	0.25	1.68*
TAF event indicator	-2.03	-2.28**	-1.99	-1.98**	-1.86	-1.87*	-1.87	-1.85*
1-day lagged TAF event	-0.95	-1.38	-0.94	-1.33	-0.85	-1.13	-0.83	-1.14
2-day lagged TAF event							-0.04	-0.06
Adjusted R-squared	1.26%		1.85%		1.70%		1.40%	

The estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regression (13). The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. Panel A reports the TAF effect on the three-month Libor-OIS spread, and panel B reports the TAF effect on the one-month Libor-OIS spread. (*Authors' calculations, based on data from Bloomberg L.P. and Markit.*)

Table 7: The TAF effect in the detailed specification

Panel A: Three-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Intercept	0.41	1.53	0.41	1.52	0.40	1.48
Lagged Libor-OIS spread	-0.00	-0.11	-0.00	-0.12	-0.00	-0.13
Change in CDS spread	0.32	1.95*	0.30	1.81*	0.33	1.91*
TAF announcement indicator	-5.90	-4.21***			-6.05	-3.94***
International			-7.40	-4.12***		
Domestic			-4.39	-2.92***		
TAF operation indicator	-1.32	-1.69*	-1.32	-1.75*		
Condition					-1.59	-1.89*
Auction					-0.23	-0.42
Notification					-0.82	-0.61
Adjusted R-squared	5.35%		5.27%		4.73%	

Panel B: One-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Intercept	0.52	1.93*	0.53	1.93*	0.51	1.89*
Lagged Libor-OIS spread	-0.01	-0.36	-0.01	-0.36	-0.01	-0.40
Change in CDS spread	0.25	1.76*	0.26	1.77*	0.24	1.68*
TAF announcement indicator	-8.99	-4.97***			-9.00	-4.59***
International			-7.90	-3.43***		
Domestic			-10.08	-4.36***		
TAF operation indicator	-0.82	-1.05	-0.82	-1.05		
Condition					-0.11	-0.16
Auction					-0.31	-0.48
Notification					-0.67	-0.55
Adjusted R-squared	5.24%		5.03%		4.57%	

The estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regressions (15), (16), and (17). The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. Panel A reports the TAF effect on the three-month Libor-OIS spread, and panel B reports the effect on the one-month Libor-OIS spread. (*Authors' calculations, based on data from Bloomberg L.P. and Markit.*)

Table 8: The TAF effect in the extended specification

Panel A: Three-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Intercept	0.37	1.47	0.36	1.46	0.30	1.27
Lagged Libor-OIS spread	-0.01	-0.59	-0.00	-0.11	0.00	0.03
Change in CDS spread	0.01	0.18	0.01	0.18	0.01	0.15
Change in term spread	-0.05	-2.15**	-0.05	-2.13**	-0.05	-2.05**
Change in volatility	0.68	4.26***	0.67	4.39***	0.68	4.35***
Quarter-end indicator	-0.14	-0.38	0.14	0.31	0.20	0.50
TAF event indicator			-2.02	-2.14**		
TAF announcement					-6.04	-3.84***
TAF operation					-0.98	-0.90
Adjusted R-squared	14.69%		15.98%		17.95%	

Panel B: One-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Intercept	0.53	1.87*	0.56	2.00**	0.45	1.78*
Lagged Libor-OIS spread	-0.01	-0.84	-0.01	-0.52	-0.00	-0.33
Change in CDS spread	-0.02	-0.19	-0.02	-0.15	-0.02	-0.18
Change in term spread	-0.03	-0.83	-0.03	-0.81	-0.02	-0.67
Change in volatility	0.63	4.05***	0.62	4.04***	0.64	4.24***
Quarter-end indicator	0.16	0.25	0.46	0.60	0.55	0.64
TAF event indicator			-2.24	-2.08**		
TAF announcement					-9.17	-5.70***
TAF operation					-0.56	-0.51
Adjusted R-squared	6.35%		7.31%		10.83%	

The estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regressions (18) and (19). The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. Panel A reports the TAF effect on the three-month Libor-OIS spread, and panel B reports the effect on the one-month Libor-OIS spread. The first two columns of each panel report the results for the regression excluding the TAF event indicator. (*Authors' calculations, based on data from Bloomberg L.P., Markit, and Thomson Reuters.*)

Table 9: The TAF effect before March 11, 2008

Panel A: Three-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Intercept	0.39	1.58	0.38	1.54	0.33	1.41
Lagged Libor-OIS spread	-0.01	-0.72	-0.00	-0.30	-0.00	-0.22
Change in CDS spread	-0.04	-0.36	0.00	0.05	0.01	0.05
Change in term spread	-0.05	-2.00**	-0.05	-1.97**	-0.05	-1.91*
Change in volatility	0.66	2.82***	0.70	3.24***	0.71	3.21***
Quarter end indicator	-0.44	-1.36	-0.22	-0.64	-0.07	-0.19
TAF event indicator			-2.62	-2.78***		
TAF announcement					-5.18	-2.95***
TAF operation					-1.70	-1.37
Adjusted R-squared	9.18%		11.20%		11.78%	

Panel B: One-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Intercept	0.53	1.99**	0.56	2.13**	0.43	1.83*
Lagged Libor-OIS spread	-0.02	-1.06	-0.01	-0.76	-0.01	-0.55
Change in CDS spread	0.08	0.58	0.15	1.25	0.16	1.38
Change in term spread	-0.03	-0.77	-0.03	-0.74	-0.03	-0.62
Change in volatility	0.65	2.88***	0.70	3.29***	0.74	3.61***
Quarter-end indicator	0.04	0.05	0.31	0.33	0.57	0.53
TAF event indicator			-3.30	-2.92***		
TAF announcement					-9.31	-4.35***
TAF operation					-1.71	-1.44
Adjusted R-squared	4.65%		6.57%		9.01%	

Using the sub-sample of data before March 11, 2008, the estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regressions (18) and (19). The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. Panel A reports the TAF effect on the three-month Libor-OIS spread, and panel B reports the effect on the one-month Libor-OIS spread. The first two columns of each panel report the results for the regression excluding the TAF event indicator. (*Authors' calculations, based on data from Bloomberg L.P., Markit, and Thomson Reuters.*)

Table 10: The TAF effect after controlling for default probability

Panel A: Three-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	0.22	0.84	0.40	1.58	0.37	1.47	0.47	1.71*
Lagged Libor-OIS spread							-0.00	-0.31
Change in CDS spread					0.31	1.90*	0.30	1.90*
Change in EDF spread	0.47	0.99	0.55	1.30	0.39	1.11	0.40	1.12
TAF event indicator			-2.33	-3.41***	-2.24	-2.87***	-2.17	-2.63***
Adjusted R-squared	0.12%		2.01%		3.62%		3.38%	

Panel B: One-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	0.22	0.63	0.42	1.20	0.39	1.12	0.63	2.13**
Lagged Libor-OIS spread							-0.01	-0.55
Change in CDS spread					0.26	1.76*	0.25	1.69*
Change in EDF spread	-0.01	-0.03	0.08	0.16	-0.06	-0.12	-0.03	-0.07
TAF event indicator			-2.53	-2.91***	-2.46	-2.57**	-2.28	-2.31**
Adjusted R-squared	-0.30%		1.10%		1.68%		1.56%	

The estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regressions as variations of (11). The variation is to replace the CDS spread by the expected default frequency (EDF) estimated by Moody's KMV. The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. Panel A reports the TAF effect on the three-month Libor-OIS spread, and panel B reports the TAF effect on the one-month Libor-OIS spread. (*Authors' calculations, based on data from Bloomberg L.P., Markit, and Moody's.*)

Table 11: The TAF effect on the liquidity component of Libor

Panel A: Three-month Libor-OIS spread

Constant	0.39	1.55	0.37	1.49	0.52	1.82*
Lagged liquidity component					-0.00	-0.42
Change in CDS spread			0.16	0.94	0.16	0.93
TAF event event indicator	-2.21	-3.01***	-2.18	-2.76***	-2.08	-2.50**
Adjusted R-squared	1.71%		1.95%		1.74%	

Panel B: One-month Libor-OIS spread

Constant	0.40	1.15	0.39	1.12	0.70	2.37**
Lagged Libor-OIS spread					-0.01	-0.72
Change of CDS spread			0.09	0.60	0.08	0.52
TAF event indicator	-2.49	-2.70***	-2.47	-2.60***	-2.26	-2.32**
Adjusted R-squared	1.35%		1.17%		1.20%	

The estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regression (20). The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. Panel A reports the TAF effect on the liquidity component of three-month Libor, and panel B reports the effect on the liquidity component of one-month Libor. (*Authors' calculations, based on data from Bloomberg L.P. and Markit.*)

Table 12: The TAF effect in Taylor and Williams' specification

Panel A: Three-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	37.09	6.75***	22.48	4.30***	0.44	1.68*
Lagged Libor-OIS spread					0.98	76.62***
CDS spread			0.88	4.99***	0.03	2.45**
TAF event indicator	24.19	3.17***	1.85	0.23	-2.68	-3.87***
Adjusted R-squared	4.49%		36.41%		98.04%	

Panel B: One-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	27.64	5.98***	17.62	3.93***	0.37	1.51
Lagged Libor-OIS spread					0.98	54.90***
CDS spread			0.60	4.05***	0.04	3.00***
TAF event indicator	19.14	2.28**	3.81	0.43	-3.07	-3.56***
Adjusted R-squared	3.52%		22.52%		96.18%	

The estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regression (5). The dependent variable is either the level of the three-month Libor-OIS spread (in panel A) or the level of the one-month Libor-OIS spread (in panel B). The independent variables are the lagged level of the Libor-OIS spread Y_{t-1}^{LOS}, the level of the average CDS spread X_t^{CDS}, and the TAF event indicator ΔI_t^{TAF} defined in Table 1. The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. (*Authors' calculations, based on data from Bloomberg L.P. and Markit.*)

Table 13: The TAF effect in Wu's specification

Panel A: Three-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	30.15	4.83***	21.94	4.10***	0.38	1.38
Lagged Libor-OIS spread					0.98	80.00***
CDS spread			1.07	2.47**	0.08	2.64***
TAF regime indicator	32.24	4.06***	-10.37	-0.51	-2.93	-2.67***
Adjusted R-squared	21.06%		37.06%		98.04%	

Panel B: One-month Libor-OIS spread

Independent variables	Est.	t-stat	Est.	t-stat	Est.	t-stat
Constant	22.98	4.37***	17.23	3.77***	0.24	0.85
Lagged Libor-OIS spread					0.97	58.41***
CDS spread			0.75	1.98**	0.10	2.75***
TAF regime indicator	22.49	2.79***	-7.39	-0.38	-4.09	-2.52**
Adjusted R-squared	12.93%		22.82%		96.22%	

The estimated coefficients and their t-statistics, as well as the adjusted R-squared, are reported for regression (8). The dependent variable is either the level of the three-month Libor-OIS spread (in panel A) or the level of the one-month Libor-OIS spread (in panel B). The independent variables are the lagged level of the Libor-OIS spread Y_{t-1}^{LOS}, the level of the average CDS spread X_t^{CDS}, and the TAF regime indicator X_t^{TAF}, which equals 1 since December 12, 2007, and 0 before this date. The t-statistics are adjusted for serial correlation and heteroscedasticity by the Newey-West method with 10 lags. Statistical significance at 90, 95, or 99 percent confidence is indicated by *, **, or ***, respectively. (*Authors' calculations, based on data from Bloomberg L.P. and Markit.*)

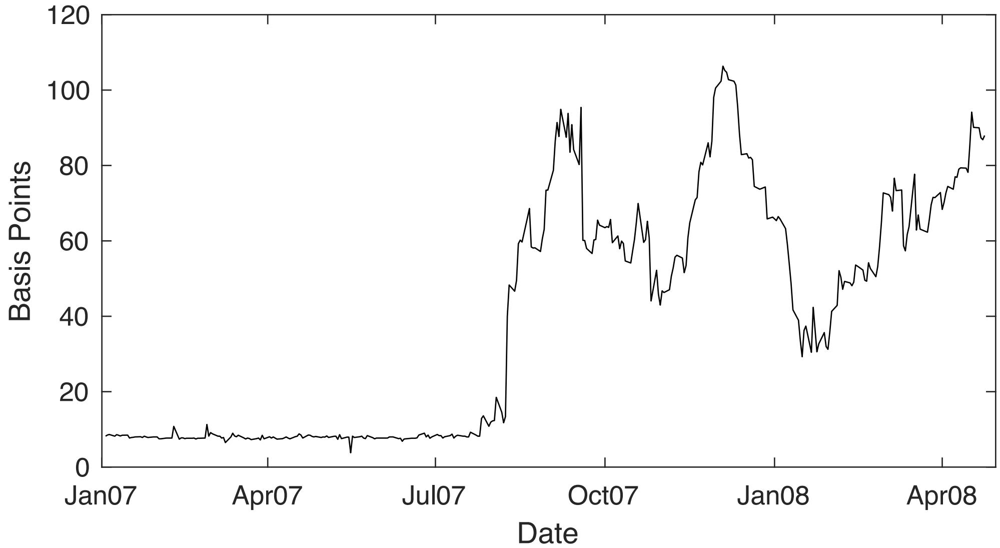

Figure 1: Three-month Libor-OIS spread (*Data source: Bloomberg*)

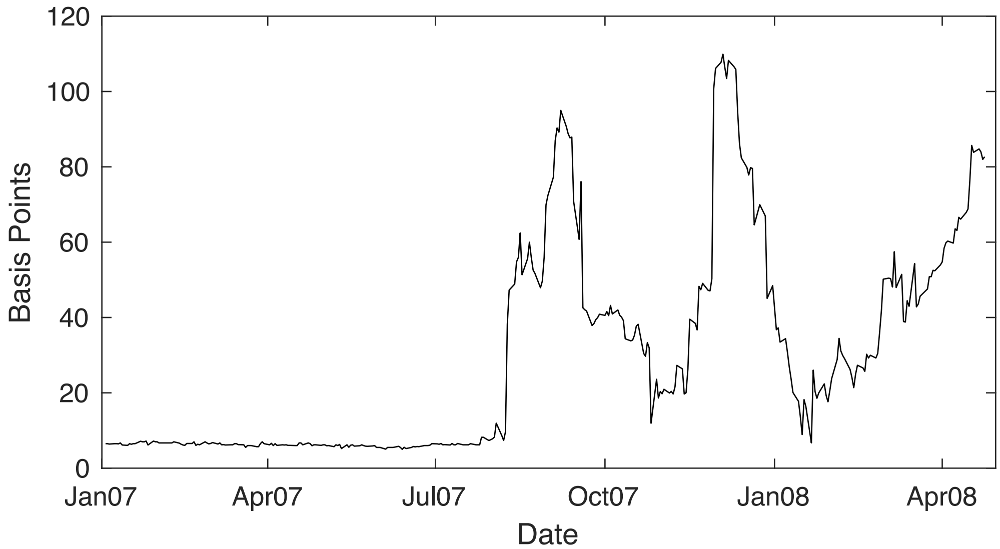

Figure 2: One-month Libor-OIS spread (*Data source: Bloomberg*)

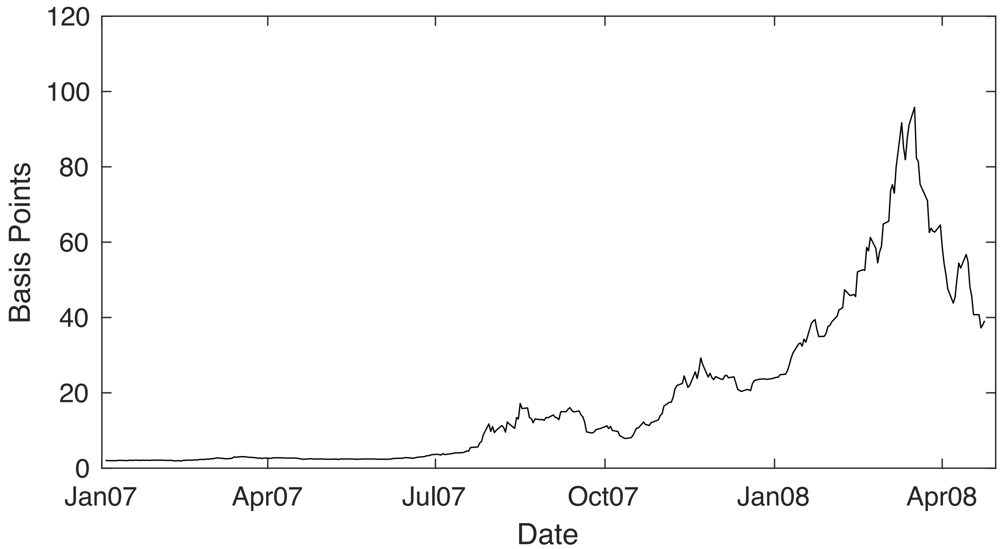

Figure 3: Average CDS spread of Libor banks (*Data source: Markit*)

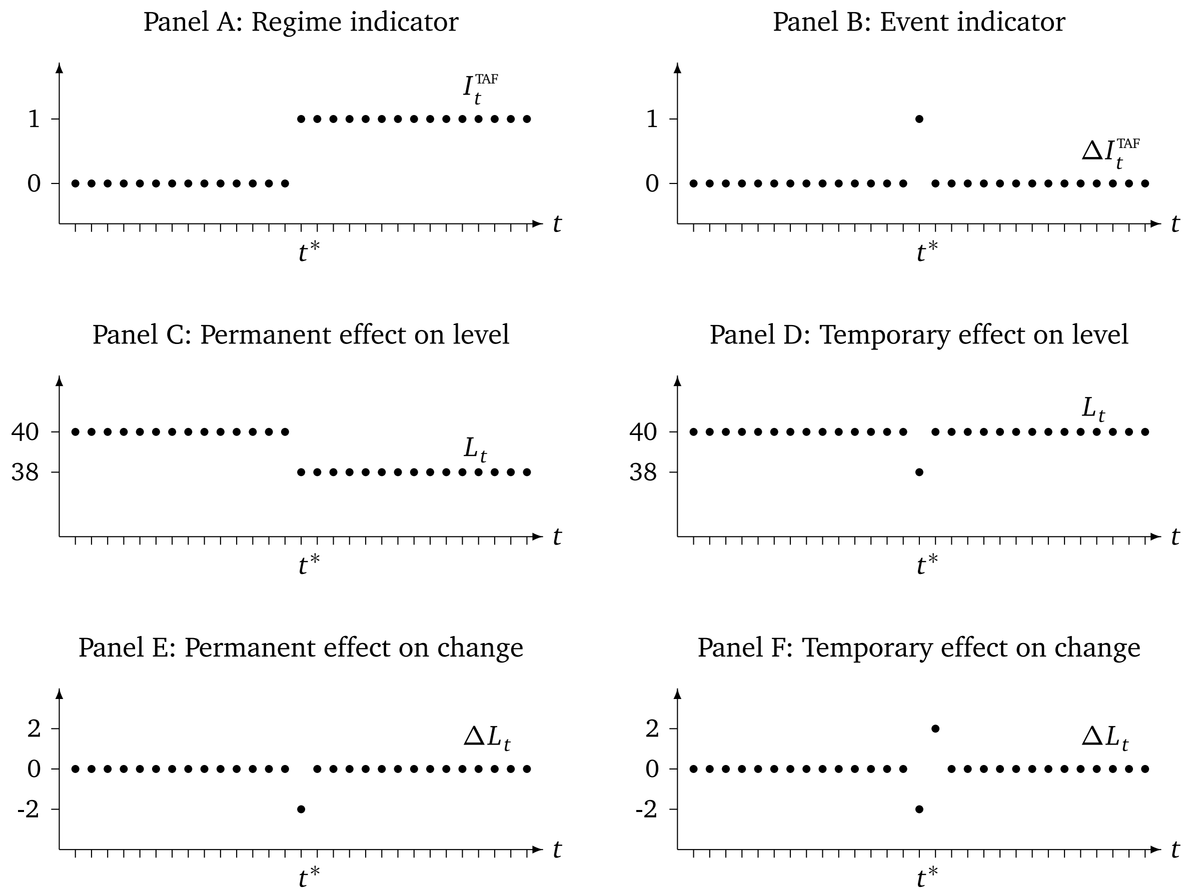

Figure 4: Illustrations of indicators and effects