Money Market Segmentation and the Transmission of Post-crisis Monetary Policy

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Abstract

Using a novel dataset of tri-party repo market transactions collected from money market fund filings, we show that market segmentation and leverage ratio constraints have a significant influence on the transmission of post-crisis interest rate policy. We develop a model where financially constrained intermediaries have differentiated access to the Fed's interest rate policy instruments. Market frictions and an abundance of reserves jointly create limited participation in the money market, which generates two regimes of interest rates. Even though local movements in debt supply do not affect interest rates within a single regime, large shocks to the level of debt supply or central bank reserves can trigger regime shifts with a magnitude close to the IOR-RRP spread, which constitutes a source of interest rate risk. Consistent with our theory, we find that the FICC's sponsored repo market reform, which allowed hedge funds and their sponsoring banks to get access to the FICC's repo netting service, triggered an upward regime shift of repo rates by about 20 basis points in January 2018. The reform, together with the Fed's balance sheet normalization, created an environment with scarce liquidity and an estimated supply elasticity of repo rates around one bps/billion. In comparison, the pre-reform supply elasticity is almost zero. Our results suggest that keeping an abundance of reserves in the key segments of money markets, such as repo markets, is essential for the Fed to control interest rates using post-crisis policy tools.

JEL Classification: E52, E43, G21, G23, G12
Keywords: unconventional monetary policy, regime shifts in interest rates, banks, limits to arbitrage, repo markets

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1 Introduction

During the past decade, macroeconomic researchers have paid tremendous effort in understanding the mechanics of post-crisis monetary policy. Yet, the environment within which these unconventional policy operations are transmitted is changing as well. In this paper, we will investigate how this changing environment poses challenges in understanding monetary transmission using traditional theories and what institutional features should be included in a general theory of monetary policy with a large central bank balance sheet.

Under the post-crisis setting of monetary policy, the Federal Reserve implements its target interest rate with two interest rate policy tools, including the overnight remuneration rate of reserve balances held by depository institutions (IOR hereafter) and the repo rate at which the Fed absorbs cash from the participants of the Fed's reverse repo facility (RRP hereafter). Given that reserve balances constitute a significant portion of depository institutions' total assets, the risk-free component of overnight short-term interest rates, such as the federal funds rate and Treasury repo rates, should be equal to IOR in a complete market.[1] Deviations from the complete-market benchmark would imply the existence of profitable arbitrage opportunities for banks and the arbitrage activities would close the interest rate spread.

However, we document that the risk-free component of a wide range of short-term interest rates deviated from their complete-market benchmark in the post-crisis sample. Such deviations, called the IOR spreads, are economically large with a sample mean of 20 basis points. Furthermore, there is significant time variation in the IOR spreads that is Markov-switching in both mean and dispersion (see Figure 1).

Traditional theories would attribute such variation to risk premia, liquidity premia, or the special demand for monetary services. However, assets in our sample are largely safe and liquid, so unless there is a demand shock for money-like assets, neither of them should generate a positive spread like what we observe. Alternatively, a friction-based theory would claim that such deviations from the law of one price reflect market frictions that limit the arbitrage activities.[2] Under this hypothesis, regime shifts in interest spreads can be explained by structural changes to the underlying market frictions.

In this paper, we propose a novel channel that builds on the segmentation of U.S. money markets in the post-crisis environment, the origination of which could be policy-related or purely institutional. For instance, the two deposit facilities set up by the Federal Reserve are only open to selected groups of market participants: depository institutions are the only group of financial intermediaries who have access to IOR; for the RRP facility, only selected money market funds,

[1] Based on Federal Reserve Board's H.8 table that records weekly balance sheet information on commercial bank operated in the United States, the average cash-to-asset ratio is 0.1 for the largest 25 U.S. domestic banks and 0.4 for foreign banking organizations in the post-crisis sample (2010-2019). In comparison, the same statistics is 0.06 for both groups in the sample before 2008.

[2] See Shleifer and Vishny (1997), Gromb and Vayanos (2002), and Gromb and Vayanos (2018) for theoretical foundations. Many works have found evidence that post-crisis financial regulations are responsible for positive arbitrage spreads in the currency market and the federal funds market. See Du, Tepper, and Verdelhan (2018), Rime, Schrimpf, and Syrstad (2017), and Cenedese et al. (2019) for evidence on the cause of CIP deviations. See Bech and Klee (2011) and Keating and Macchiavelli (2017) on how financial regulations and market segmentation affect the function of post-crisis federal funds market.

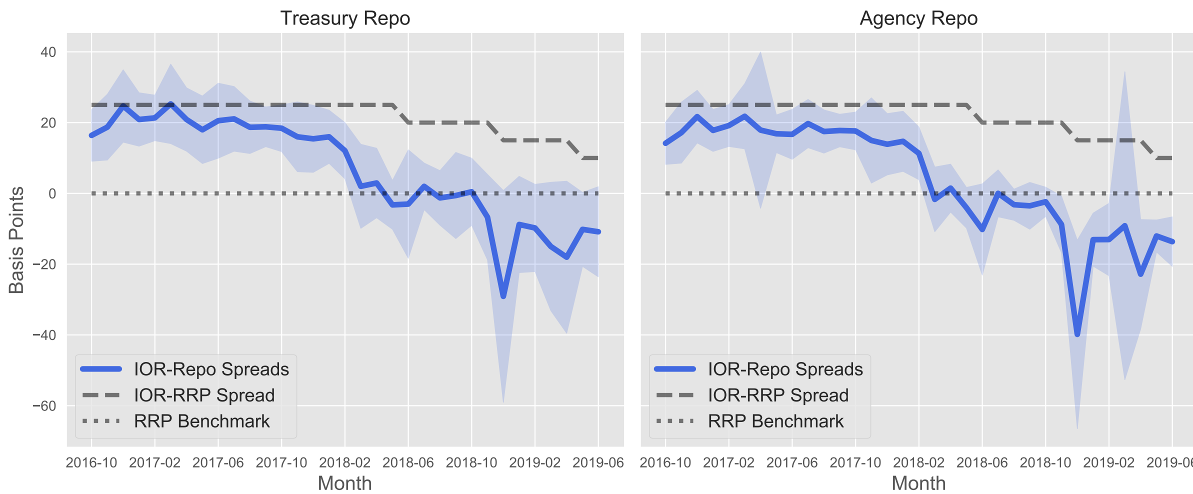


Figure 1. Time-series plots of IOR-repo spreads from Oct 2016 to June 2019. The left panel shows the spreads constructed using tri-party Treasury repos and the right panel is constructed with tri-party agency repos. The solid lines represent cross-sectional average of IOR-repo spreads and the error bands are calculated using cross-sectional standard deviations. Source: N-MFP2 filings and the author's calculation.

GSEs, and banks are eligible to be counterparties with the Fed. As an example of institutional segmentation, hedge funds were restricted by SEC from issuing repos via the FICC's repo netting platform before January 2018.[3]

To understand the economic forces behind these observations, we develop a general-equilibrium model with two central bank deposit facilities and heterogeneous access to these facilities among cash investors. Investors maximize their lifetime utility by trading risk-less government bonds with different maturities. We impose short-sale constraints for bonds and policy facilities to represent the fact that banks face Basel III leverage constraints and investors cannot take short positions in the Fed's policy facility, which also allows us to investigate different hypotheses in a unified framework. The key friction in my model is market segmentation that prevents a group of investors from making risk-free Fed deposits using the policy rate accessible only to another group. To map to the real world, I set up two policy facilities, denoted by H and L, and there are three groups of investors with different access to these policy facilities. We assume that the policy interest rate for facility H is always higher than that for facility L, just like IOR is higher than RRP.

In a two-period version of the model, we derive the closed-form solution of the equilibrium bond yield and show that the equilibrium bond yield has two regimes, which originates from the threshold strategy of bond holdings: when the expected returns on the government bond is not higher than a policy rate, the investor can optimally stay out of the bond market and hold reserves instead. Therefore, when the bond supply is relatively small compared to cash held by money market funds, the bond market is cleared at the RRP rate, in which case banks only hold reserve balances. But when the amount of cash holdings of money market funds is not enough to clear the bond market, banks will find it optimal to step into the bond market and purchase

[3] See Section 2.2 for details on the payment and clearing system of the United States and Section 2.3 for details of U.S. repo markets.

bonds at a yield equal to IOR. The model also shows that the equilibrium bond yield is not sensitive to the variation in bond supply as long as the marginal bond investors are abundant in cash. With realistic parameter values, the supply-sensitive region only constitutes a small fraction of all possible realization of states, which suggests that regime-switching of interest rates is a low-frequency phenomenon.

When we extend the model to infinite horizon, the role of short-sale constraints become more apparent. The model solution boils down to the following set of first-order conditions:

$$y_t^{(\tau)} = -\frac{1}{\tau} \log \mathbb{E}_t \left[\exp\left(-\sum_{k=0}^{\tau-1} (y_{t+k}^i + \psi_{t+k}^i) \right) + \sum_{k=0}^{\tau-1} \beta^k \tilde{\mu}_{H,t+k}^{b,\tau-k} \right] \quad i = H, L$$

where $y_t^{(\tau)}$ denotes the equilibrium yield of a τ-day government bond; y_t^i is the policy rate eligible to type-i investors; ψ_t^i and μ_i^b represent the Lagrangian multipliers of the short-sale constraints on policy facilities and bonds, respectively. For type-i investors, the equilibrium yield is equal to the expected average of future policy rates and Lagrangian multipliers. So a binding short-sale constraint will make the equilibrium bond yield deviate away from the expectation hypothesis. More importantly, since $\partial y_t^{(\tau)}/\partial \psi_{t+k}^i < 0$ and $\partial y_t^{(\tau)}/\partial \mu_{i,t+k}^{i,\tau-k} > 0$, the sign of IOR spread is sufficient to identify which constraint is binding for type-i investors.[4] This property, plus the fact that each bond market has to be cleared by a single yield, implies that:

(a) Conditional on both types of investors taking positive positions in policy facilities, banks must face a binding short-sale constraint and the positive spreads between the IOR and equilibrium yields are caused by the funding constraint that prevents banks from closing the arbitrage spread.

(b) Conditional on banks taking long positions in both bonds and reserves ($\mu_H^b = 0$ and $\psi^H = 0$), L-type investors, such as money market funds, will exit their policy facility ($\psi^L > 0$) and the equilibrium yield will be equal to the expected average value of y_t^H.

Therefore, the regime shift of interest rate can be treated as a transition from the steady state of equilibrium (a) to equilibrium (b). Consistent with this interpretation, the volume of the Fed's RRP suddenly became almost zero since January 2018, see Figure 13.

Since both a relaxation of funding constraints and a shock that makes reserves more scarce can trigger regime switching in our model, what causes the observed transition is an empirical question.[5] We choose the tri-party repurchase agreement market as the main subject of our empirical analysis. The tri-party repo market is the most important short-term secured funding market for financial institutions and cash lenders in this market are also the major participants

[4]More concretely, the identification requires that bond yield is not affected by expectations of future monetary policy. Assets with a maturity of around several days, such as repos, satisfy this requirement for most of the time.

[5]The importance of this identification exercise lies in the fact that friction-based and equilibrium-based theories deliver *qualitatively* different views on the long-term trend of interest rate spreads. Under the limits-to-arbitrage hypothesis, regime shifts in IOR spreads reflect structural changes to the underlying regulatory frictions. Such changes are permanent until the regulator applies new rules. But, if the observed regime shift is driven by the scarcity of reserves, then the regime-switching of interest rates will be recurring in the future unless the Fed eliminates the spread between policy rates.

of the RRP facility. Despite this importance, detailed data on repo markets are notoriously rare. So we collect a unique data set that contains all repo contracts held by U.S. money market funds from SEC filings.

The granularity of our data allows us to identify exogenous variation in funding constraints via two institutional events. First, the regional implementation of Basel III leverage ratio rule generates seasonal movements in tri-party repo issuance that is exogenous to many other confounding factors. While U.S. bank holding companies have to report daily average statistics of their balance sheets, foreign bank holding companies only report the snapshot of their balance sheets on the reporting day. As a result, foreign bank dealers have a strong incentive to engage in window-dressing activities: they take excess leverage during non quarter-end months and gradually deleverage to the required level by the end of each quarter (see Munyan (2015)). Second, on Jan 31st 2018, DTCC opened the FICC's sponsored repo market to hedge funds in order to alleviate the balance sheet constraint faced by bilateral repo market makers.[6] Since the FICC's sponsored repo can be netted on an intraday basis, the reform can be treated as relaxing the funding constraints for sponsoring banks, which are mainly U.S. large banks. As can be seen from Figure 12, the volume FICC's sponsored repo greatly increased after Jan 2018.

Using contract-level repo rates, we estimate the size of IOR spreads driven by the variation in funding constraints as the fixed effects of these two identifying events. On the extensive margin, foreign banks issue more repos than U.S. banks in months that are not quarter-end in our full sample, confirming the existence of window-dressing. On the intensive margin, IOR spreads are the same across issuers from different regions and are stable across different months in the same quarter before the FICC's reform. This result is consistent with the view that the Fed's RRP facility helps absorb excess supply and let the repo market clear on the extensive margin with little impact on repo rates (see Anbil and Senyuz (2018)).

However, we find that window-dressing does affect the GCF repo rate, a bilateral repo rate. The GCF repo market is a platform wihin the tri-party repo market infrastructure but operated by FICC using its netting technology. Large bank dealers channel funds from the tri-party repo market to the GCF repo market and earn the GCF-repo spreads. Since the GCF repo market is blind-brokered, the spread largely reflects the degree of imbalances between aggregate supply and demand in the GCF repo market. According to our results, GCF-repo spreads widen at the end of each quarter by 11 basis points for almost all bank dealers in the first sub-sample, which is possibly due to the quarter-end declines of cash supply to this market.

The FICC's market reform makes several changes to the previous results. On the one hand, the FICC reform significantly reduces the IOR-repo spreads by 23 basis points, indicating that bank dealers seem to have more balance sheet capacity to do arbitrage and close the IOR-repo spread. On the other hand, IOR-repo spreads also drop by an additional 11 basis points in quarter-end months after the FICC reform. Since the IOR-repo spreads are effectively negative after the quarter-end drops, it is more likely that such large spikes of tri-party repo rates are

[6] The sponsored repo market is a tri-party Treasury repo market in which a sponsoring bank who has access to the FICC clearing platform acts as the intermediary between cash lenders and borrowers eligible to the sponsored repo program. Before Jan 2018, sponsored members are restricted to registered investment companies, including mutual funds and investment trusts, and sponsoring banks are limited to several large U.S. commercial banks that are FICC/GSD members.

driven by cash demand originated from the bilateral repo market. This hypothesis is supported by the observation that the quarter-end GCF-repo spreads become more wide after January 2018, despite the fact that repo rates already spike at quarter ends.

We then estimate the response of repo rates to repo supply shocks, or the supply elasticity of repo rates, in a panel regression model with window-dressing dummy variables as instruments (see Table B.11). Consistent with the interpretation that RRP facility, the supply elasticity of repo rates are almost zero before January 2018. We attribute this insensitivity to the role of RRP in absorbing excess cash supply at quarter ends. For RRP-eligible funds, around 90% of the movements in bank-issued repos are absorbed by the RRP facility, as shown in Table B.12. However, after January 2018, the estimated supply elasticity turns positive around quarter ends. The entry of hedge funds into the FICC's sponsored repo market generated a large cash demand that absorbed all residual cash supply that used to stay in the RRP facility and forced the tri-party repo market to be cleared on the intensive margin. Therefore, bank dealers face more severe competition for cash supply at quarter ends, which drives up tri-party repo rates. For each billion dollars of decline in repo issuance at the end of each quarter, the repo rates increase by about 1 basis point for bank dealers. For FICC's sponsored repos, the supply elasticity is more than twice as large as that for Treasury repos issued by non-FICC entities, consistent with our theory that it is the cash demand shocks from the FICC-cleared bilateral repo market that drives the quarter-end rate spikes.

Our paper contributes to the large literature that studies the role of financial intermediation in the transmission of post-crisis monetary policy. On the modeling part, we are among a large macro literature that studies the mechanics of unconventional monetary policy. Earlier works in this field mainly focus on how central bank credit provision helps accommodate a financial crisis (see Gertler and Kiyotaki (2010), Gertler and Karadi (2011), and Negro et al. (2017), etc.), or how large-scale asset purchases lower the long-term yields (e.g. Jing and Wu (2011), Greenwood and Vayanos (2014), Greenwood et al. (2015), Huther et al. (2017), Bauer and Rudebusch (2014), Bhattarai et al. (2015), and Gorodnichenko and Ray (2018)). The level of reserve balances and IOR do not play an explicit role in this papers. Rather, monetary policy works by changing the maturity distribution of government bonds, the local supply of Treasury securities (under the risk-habitat hypothesis), or direct signaling of future path of interest rates.

With the recognition of the institutional difference between pre- and post-crisis monetary settings, more papers incorporate reserves and IOR into their models. The key research question addressed by this strand of papers is how effective are these policy tools in achieving the dual mandate of monetary policy and whether they require coordination with each other. Many papers argue that the Fed can use IOR to uniquely pin down inflation and nominal rates (examples include Curdia and Woodford (2011), Kashyap and Stein (2012), Reis (2016), Hall and Reis (2016), and Ennis (2018), among others). However, whether the level of reserves affects the effectiveness is under debate. Consistent with the cash-less limit tradition in most macro models, the majority of these works negate the role of the level of reserve balances in the determination of interest rates and other real variables, including Curdia and Woodford (2011), Reis (2016), and Hall and Reis (2016). As one of the few exceptions, Kashyap and Stein (2012) argues that the Fed can control short-term rates by making reserves more scarce, as long as such an action do not cause an excessive issuance of private short-term debt. Ennis (2018) introduces banks' capital constraints into a standard model and shows that reserve balances are not effective only when banks do not face binding capital constraints. Our results complement the latter strand of papers by showing that the implementation of interest rate policy is not independent from balance sheet policy. In order to use IOR to anchor other market interest rates, the Fed has to make sure that major participants of policy facilities have abundant cash holdings.

Though kept at a minimal scale, our theoretical model is flexible enough to capture many important aspects of the post-crisis monetary setting, especially after the initialization of the reverse repo facility. By incorporating both long and short positions on bonds with short-sale constraints, we are able to account for both the reserve supply channel in Curdia and Woodford (2011) and Kashyap and Stein (2012), as well as the funding friction channel in Gromb and Vayanos (2002) and Gromb and Vayanos (2018). Our model is also able to identify the channel at work with the sign of the IOR spread.[7] More importantly, with the reverse repo facility, which channel is in effect not only depends on the relative scarcity of reserve balances, as in previous works, but also on how these reserve balances are distributed across different types of financial institutions. To the best of our knowledge, we are the first to propose such a channel of balance sheet policy.

On the empirical side, we provide novel evidence on how market frictions and financial regulations affect the transmission of monetary policy. For the federal funds market, Keating and Macchiavelli (2017) provides direct evidence that banks that face lower FDIC insurance cost, such as foreign banks, actively borrow from GSEs to do basis arbitrage. The IOR-EFFR spread mainly reflects the degree of funding constraints and the insurance cost associated with arbitrage activities. Bech and Klee (2011) relates the positive spread between IOR and the effective fed funds rate to market segmentation. Since GSEs are not eligible to earn IOR, borrowers in the fed funds market can earn a positive arbitrage spread if they have large bargaining power. The higher the market share of GSEs, the larger bargaining power for borrowers, and the larger the IOR-EFFR spread. On the other hand, if the Fed supplies more bank reserves, the spread will also increase because this decreases GSEs bargaining power. Duffie and Krishnamurthy (2016) and Boyarchenko et al. (2018) investigate the issue in a broader range of markets and rates and claim that SLR significantly hampers the transmission efficiency in wholesale funding markets.

We extend such type of analysis to repo markets, the most important market of secured funding. The first contribution is to collect and construct a novel transaction-level repo market data, the granularity of which allows us to identify repo supply shocks via a quasi-experiment and control for idiosyncratic effects. We shares the same result with Anbil and Senyuz (2018) and Munyan (2015) that quarter-end repo rates are not affected by window-dressing because of the Fed's RRP role in absorbing excess cash supply.[8] On top of that, this paper is the first

[7] Note that allowing for the constrained arbitrage is necessary to generate positive IOR spreads in models without a special demand for certain assets, which is absent in Curdia and Woodford (2011). By modeling the special demand for bank deposits, Piazzesi et al. (2019) and Piazzesi and Schneider (2018) can explain the positive IOR spread on deposit rates, which can also be driven by banks' market power in the deposit market Drechsler et al. (2017b).

[8] Anbil and Senyuz (2018) shows that the implementation of Basel III intensified European dealers' window-dressing by 80%. Money market funds ineligible to RRP cut their lending to European dealers by 15%. The Fed

one to quantify the impact of window-dressing on repo rates in an environment without active participation in the RRP facility. By identifying FICC's repo netting reform as the triggering event of regime shift, we also confirm the prediction in Duffie and Krishnamurthy (2016) that central-clearing platforms (CCPs), such as FICC, can improve the pass-through efficiency of monetary policy in repo markets. However, our results indicate that policy makers also have to ensure that CCP does not lead to excessive issuance of short-term debt.

In this sense, our paper also speaks to the role of the Fed's balance sheet policy in improving financial stability. One the one hand, some theoretical papers argue that expanding the Fed's balance sheet can crowd out private short-term debt and eliminate excessive maturity transformation that poses a threat to financial stability (see Stein (2012), Greenwood et al. (2016), Krishnamurthy and Vissing-Jorgensen (2015), and Woodford (2016)). However, there is also evidence that asset purchases may induce more risk-taking through a portfolio rebalancing channel, either at the bank level (Kandrac and Schlusche, 2018; Dell'Ariccia et al., 2017), or at the fund level (Koijen et al., 2019; Goldstein et al., 2018). We showed that expanding the level of reserves helps the Fed to peg nominal rates and reduce interest rate sensitivity to demand shocks, which improves financial stability. But it does not necessarily crowd out private debt unless financial intermediaries are constrained. With unconstrained financial intermediation, more reserve balances encourage risk-taking via more issuance of private debt and lower interest rates.

This result has very informative implications for the repo market turmoil in September 2019. Given the decreasing size of the Fed's balance sheet and an increasing supply of FICC's sponsored repos, the September 2019 repo market crisis might be caused by an unprecedented excess cash demand in the bilateral repo market. Therefore, we help answer an important question for balance sheet policy: what level of reserves is sufficient for implementing the floor system? This paper implies that the level of reserves that is sufficient to implement the floor system must keep the supply elasticity of repo rates close to zero. In other words, the supply elasticity of repo rates is a direct measure of reserve scarcity.

Our work is also related to the literature on the demand of money-like claims, which builds around the debate about what drives the liquidity premium of money-like assets (e.g., Krishnamurthy and Vissing-Jorgensen (2012), Nagel (2016), and Sunderam (2015)). We show that in an environment with various market frictions and policy intervention, interest rates on short-term safe assets can also be driven by funding constraints and the scarcity of reserve balances. In particular, when cash investors actively participate in the RRP facility, changes in the supply of Treasuries do not necessarily affect short-term interest rates, complicating the results in Krishnamurthy and Vissing-Jorgensen (2012).

The remainder of the paper is organized as follows. Section 2 introduces the institutional backgrounds of our study. Section 3 provides details of our data. Section 4 presents some motivating facts on the transmission of post-crisis interest rate policy. Section 5 builds a general-equilibrium model and generates some theoretical predictions for empirical tests. Section 6 provides empirical evidence from repo markets. Section 7 concludes.

RRP leads to adjustment in repo quantities instead of repo rates.

2 Institutional Backgrounds

In the modern macroeconomics literature, the transmission of monetary policy is typically decomposed into the following components:

$$\frac{\partial C_t}{\partial r_t^*} = \frac{\partial r_t}{\partial r_t^*}\left[\underbrace{\int_i \frac{\partial C_t^i}{\partial r_t} m_i \, di}_{\text{Substitution Effect}} + \underbrace{\int_i \frac{\partial C_t^i}{\partial W_t^i}\frac{\partial W_t^i}{\partial r_t} m_i \, di}_{\text{Income Effect}}\right] + \underbrace{\frac{\partial C_t}{\partial r_t^*}}_{\text{Information Channel}} \tag{2.1}$$

where C_t is the real aggregate consumption, r_t^* is the policy interest rate directly controlled by the central bank, r_t is the short-term interest rate faced by economic agents, and $\{C_t^i, W_t^i, m_i\}$ represents real consumption, real wealth and the measure of type-i agents, respectively. Many famous models of monetary policy can be represented as a special case of this formulation. For example, New-Keynesian models assume that the substitution and income effects are homogeneous across agents and there is no role for the information channel. In the class of borrow-saver models, the substitution effect almost shut down for constrained households because they cannot borrow more. More recently, researchers started to incorporate forward guidance into standard DSGE models of monetary policy analysis (Nakamura and Steinsson, 2018).

Nonetheless, this formulation builds on an important hypothesis: the central bank indeed has perfect control over the short-term risk-free rate r_t using its policy tools: $\partial r / \partial r^* = 1$. This paper examines the validity of this assumption. Namely, given the changing environment for market infrastructure, financial regulation, technology, macroeconomic conditions, and most importantly, the implementation scheme of monetary policy, does the Fed manage to tightly control market interest rates using its policy tools?

We will start with the historical development of post-2008 monetary policy and new issues faced by the Fed in designing these tools. Then, we move to some important institutional details, which mainly includes the structure of financial market that are relevant for monetary transmission. Finally, we will evaluate the effectiveness of money policy tools based on a simple empirical framework of money markets. Based on this framework, we show some interesting yet puzzling facts about the transmission of post-crisis monetary policy in Section 4.

2.1 The New Setting for Implementing Monetary Policy

The way that central bank implements its target interest rate has dramatically changed since the 2008 financial crisis. Before the financial crisis, bank reserves are relatively scarce, and banks actively borrow reserves in the federal funds market on an intraday basis to fulfill payment and clearing requests from their clients. The non-pecuniary demand for reserves and the FDIC's reserve requirement generates a downward-sloping demand curve in the federal funds market and the Federal Reserve can control the policy interest rate – the federal funds rate – by changing the supply of aggregate bank reserves through temporary open market operations.

However, quantitative easing programs totally changed the landscape of money markets. From 2009 to 2014, LASPs injected over three trillion U.S. dollars of reserves into the banking

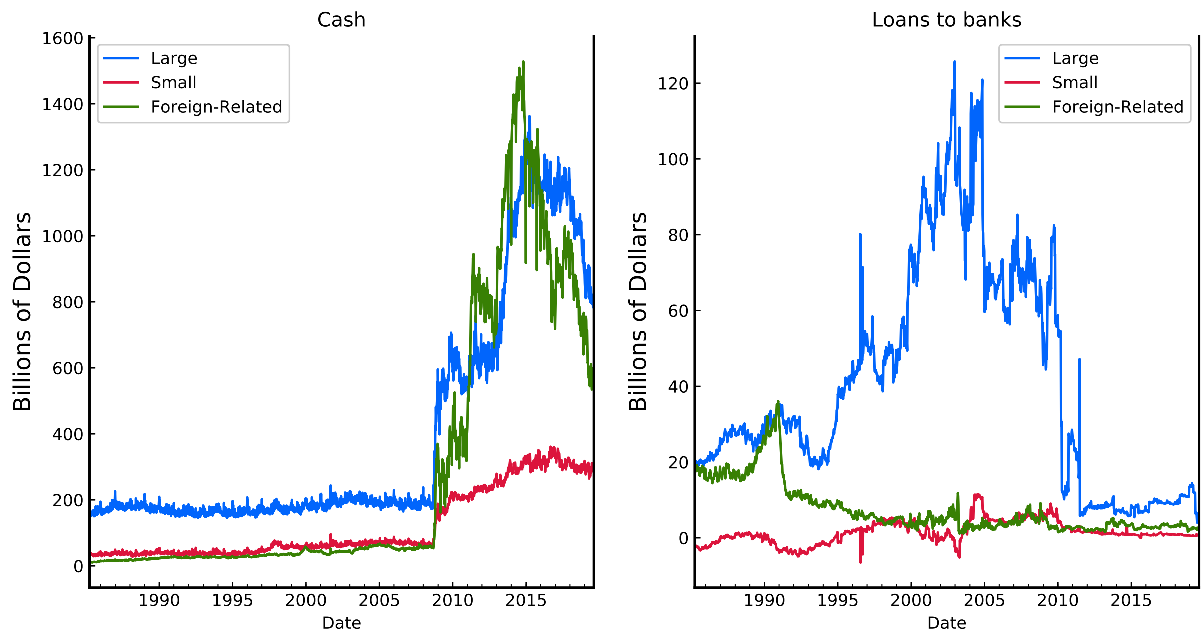


Figure 2. Cash holdings (including bank reserves) and loans to depository institutions (an approximated measure of fed funds lending) by groups of banks. Large refers to the largest 25 domestically chartered commercial banks by assets in domestic offices. Source: Federal Reserve Board H.8 Table. Weekly by each Wednesday. Sample: 1984-2019.

system.[9] By paying interests on reserve balances, the Federal Reserve eliminates the opportunity cost of holding money for depository institutions, thereby allowing banks to accumulate precautionary reserve balances so that the liquidity constraint never binds. However, such operations also deprive the Federal Reserve's ability to control the fed funds rate through the traditional supply-demand channel since the marginal demand for reserve balances is perfectly elastic at the current federal funds rate. Figure 2 shows that this prediction is borne out in the data. Before the crisis, the largest 25 domestic commercial banks actively extended loans to other banks, with a peak value of around 120 billion U.S. dollars. After the first round of Q.E., the volume of inter-bank loans extended by large banks dropped to around 10 billion dollars, and aggregate cash holdings on banks' balance sheet increased to over 1000 billion dollars, compared to around 200 billion dollars before the crisis.

To reestablish its control over short-term interest rates, the Fed initiated the interest on reserves program in October 2008 and started to pay interest on reserve balances held by depository institutions at an overnight remuneration rate of 25 basis points. The reason behind this new policy setting has several folds. First, paying interest on reserve balances helps alleviate the balance sheet cost borne by depository institutions who have to pay FDIC insurance fees on every dollar of asset on their balance sheet. In this way, the Fed uses the interest payment on reserves to compensate for the cost associated with quantitative easing operations when banks act as intermediary agents for the Fed in the process of asset purchases. Second, the Fed also

[9] QE1, Mar 2009 - Dec 2009, $1.75 trillion; QE2, Nov 2010 - June 2011, $600 billion; MEP, Sep 2011 - Dec 2012, $667 billion; QE3, Sep 2012 - Oct 2014, $1.5 trillion.

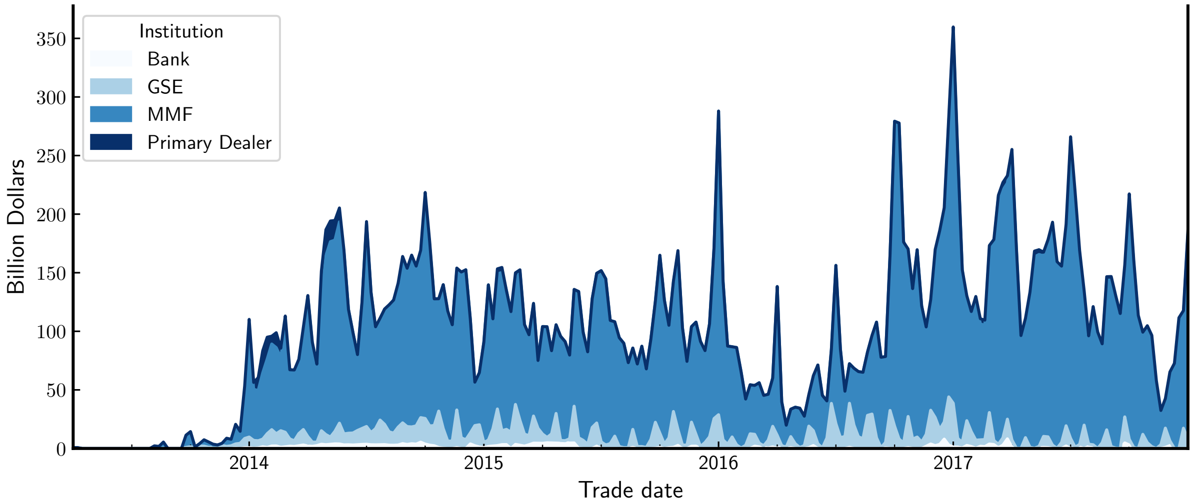


Figure 3. Participation in the Fed RRP facility by group.

restored its ability to anchor market interest rates to the interest rate on reserve balances (IOR hereafter) by the law of one price. In a complete market setting, the risk-free component of any overnight interest rate should be equal to IOR. Any non-zero spread between the IOR rate and a market interest rate should indicate a profitable arbitrage opportunity for depository institutions and the arbitrage activities would close up the interest rate spread.

With the recognition that not every part of the money market is covered by the anchoring effect of interest on reserves (some investors just do not have access to this type of asset, see Section 2.4), the Fed initialized another program called the reverse repo facility (RRP) to eligible participants. The RRP facility is a passive open market operation in which the Fed borrows any feasible amount of bank reserves by posting Treasury securities as collateral to the participants.[10] In other words, the Fed provides a constant-rate deposit account for selected participants so that these investors can use this benchmark risk-free rate to determine the interest rate that they would otherwise accept when trading in the financial market. Again, in a complete market, RRP participants would find it optimal to take arbitrage activities if some risk-free rates are not the same as the RRP rate.

2.2 Payment, Clearing, and Settlement Systems in the U.S.

The conduct of monetary policy relies on a financial system that allows the Federal Reserve to distribute and collects currency, also known as central bank reserves. In the United States, the Federal Reserve designates depository institutions, including commercial banks and thrift institutions, to control the supply of reserves. Using reserves, loans, and financial securities as collateral, commercial banks issue bank deposits to households, firms, and other non-bank financial institutions as a storage of value (time deposits) or a means of payment (demand deposits). When a depositor of Bank A purchases one dollar of goods from a depositor of Bank B, Bank A has to transfer one dollar of reserve balances to Bank B and debit one dollar from

[10]The theoretical cap of the RRP facility is the reserves total reserves outstanding.

its depositor's checking account, while Bank B will increase its reserve balances by one dollar and credit one dollar to its depositor's checking account.

To facilitate the interbank payment process, the Federal Reserve sets up the Fedwire Funds Service system in which banks can make real-time electronic transfers of reserves with each other. Since almost all payments of goods and services are made using checkable deposits, the Fedwire Funds serves as the basis of all other payment services in the United States. The Federal Reserve also provides settlement and depository services for interbank securities transactions through the Fedwire Securities Service. Government securities and agency securities can only be deposited in the Fedwire Securities. Both the Fedwire Funds and Fedwire Securities are Delivery-versus-Payment (DVP) systems, meaning that the transfer of securities or goods happen at the same time as the transfer of payment means. By design, a DVP system has to process all transactions originated by its end users, which inevitably processes many unnecessary transactions that can be netted out otherwise. To tackle this problem, modern payment and settlement systems tend to adopt a netting procedure that cancels out transactions with reverse directions. The Clearing House Interbank Payments System (CHIPS) is such a payment system that nets out intraday payment requests from all participating depository institutions. After establishing an opening position at the CHIPS prefunded balance account using Fedwire Funds transfers before 9:00 ET, participating banks can make payment requests throughout the day without making further Fedwire transfers. After 17:00 ET, participating banks pay down their remaining balances or receive reserves through the Fedwire Funds. The CHIPS system is mainly used to clear idiosyncratic transfer requests for goods and services. In 2010, CHIPS processed approximately 360,000 payments with a total value of 1 trillion USD per day. There is another important payment system called National Settlement Service (NSS) that deals with transfer requests related to securities trades. The number of payments settled in NSS is much less than that of CHIPS, partially reflecting the fact that payment requests are netted by clearing houses before they are sent to NSS at the end of each trading day, around 4:30 ET.

The majority of securities transactions are cleared and settled through book-entry clearing platforms operated by The Depository Trust & Clearing Corporation (DTCC). In particular, payments related to securities transactions are usually netted throughout a given trading day so that investors only have to pay the remaining balance (through NSS). Settlement and delivery of securities are processed by the Depository Trust Company, also a subsidiary operated by DTCC. Except for securities that are eligible to be delivered through the Fedwire Securities Service, all other securities have to be delivered through the DTC, which include equities, corporate debt, municipal bonds, and money market instruments such as commercial papers. Securities are settled on DTC in a DVP2 manner, meaning that securities are delivered in gross intraday but payments are netted and paid down at the end of the trading day. The DTC also provide securities depository services. We summarize the features of DTCC's clearing houses in Table. B.2.

2.3 Repurchase Agreement Markets in the U.S.

A crucial segment of the current U.S. financial system is the repurchase agreement markets. A repurchase agreement is a secured financing contract in which a borrower posts securities as collateral to get funds, with a promise to repurchase the collateral securities at the end of the contract term at a pre-specified price. The difference between the funds borrowed and the repurchase proceeds reflects the rate of return for cash lenders, or the "repo rate" for short. Cash lenders have the right to keep the collateral if cash borrowers fail to repurchase the collateral. To buffer the potential volatility in collateral price, cash lenders typically charge a discount on the value of collateral securities, called the "haircut".[11]

Depending on the number of counterparties involved, a repo transaction can be categorized as "bilateral" or "tri-party". In a bilateral repo transaction, two counterparties directly negotiate the contract terms and instruct their custodian banks to settle the transaction in a DVP manner. The settlement of such transactions is the same as outright purchases and sales of collateral assets, which may make use of Fedwire Funds and Securities for settlement. An obstacle for financing through bilateral repo transactions is that it requires expertise in collateral valuation, collateral management, and has substantial balance sheet cost for settlement banks. Gradually, a new repo market emerges in which a third-party clearing bank acts as both the settlement agency and the collateral manager for two repo counterparties. In the tri-party repo market, borrowers are allowed to use a class of securities as collateral, rather than specific securities. So the tri-party repo market is also called a general collateral (GC) repo market. Cash investors such as money market funds (MMFs), securities lenders are the dominant investors in the GC tri-party market, which serves as the largest source of secured funding for U.S. broker-dealers.

In the United States, JPMorgan Chase and the Bank of New York Mellon are two designated clearing banks for GC tri-party repo transactions. GC tri-party repos are settled in a DVP manner on the books of these clearing banks. When the repo expires, clearing banks return cash and collateral securities back to participants.[12] In contrast, centrally-cleared repos with multilateral netting allows both sides of a repo transaction to save balance sheet capacity. Built upon the settlement infrastructure of the tri-party repo market and FICC's clearing technology, DTCC provides central clearing and netting to repo transactions through its General Collateral Repo Service (GCF Repo®, or GCF for short) and DVP repo service. In the GCF repo market, lenders and borrowers submit their trade requests to FICC and the platform settles matched trades without letting participants know the identity of their counterparties (blind-brokered). At the end of the trading day, FICC calculates the participants' net delivery and receive obligations of each security and participants clear their net positions directly with FICC. In the FICC's DVP repo market, cash lenders can obtain specific securities in the opening leg. Such collateral

[11] For example, if the borrower posts a share of Amazon common stock at price \$2000 to borrow \$1500 cash, the haircut is $1 - 1500/2000 = 0.25$. If the borrower repurchases collateral at price \$2000.2 after one day, the annualized repo rate is $(2000.2/2000 - 1) * 365 = 3.65\%$.

[12] For reasons related to the limitation of clearing technology, before 2013 clearing banks adopted an approach that returns cash and securities for all repo transactions, including non-maturing term repos. This process is known as "unwind". Because of the risk posed by this approach, the Federal Reserve designated two clearing banks to design new clearing systems and by the end of 2013, such unwind approach is replaced by an approach that claims to reduce intraday clearing bank credit exposure by 90%.

securities are “special” and the repo rate is typically lower than GC repo rates. The FICC’s DVP repo market is very active, with an average daily volume of 409 billion USD from September 2014 to September 2016, compared to 406 billion USD in other segments, including GCF, non-GCF tri-party, and Fed ONRRP (Bowman et al., 2017). Typically, primary dealers and large banks who are also FICC/GSD members borrow money from the GC tri-party repo market and lend to participants in the FICC’s GCF and DVP repo market.

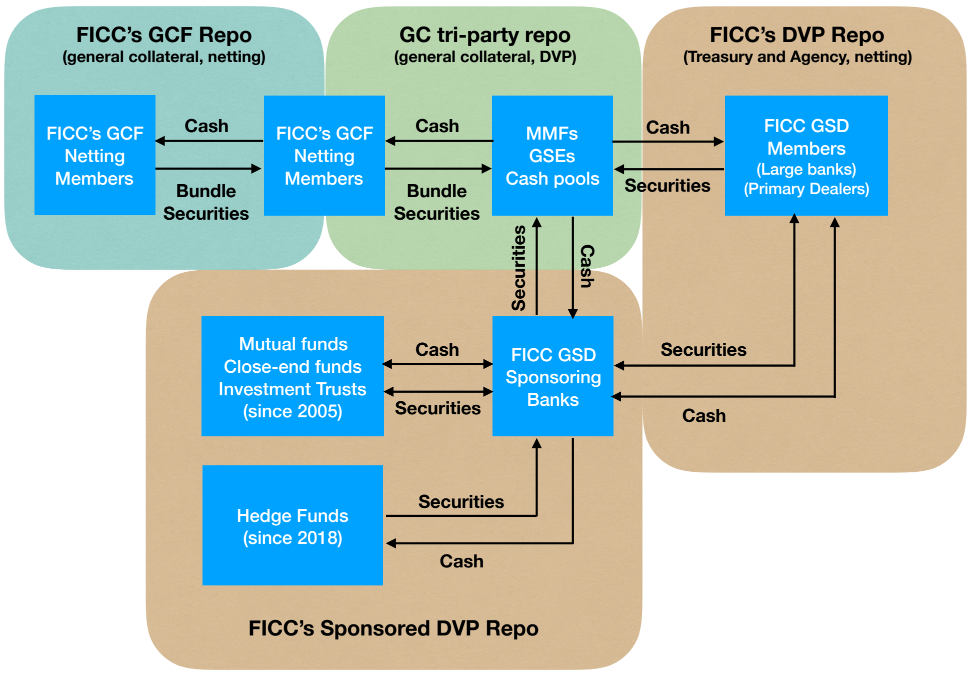


Figure 4. The structure of U.S. repo markets. “FICC”: Fixed Income Clearing Corporation, a subsidiary of DTCC engages in clearing of fixed-income securities transactions. Transactions cleared by FICC, including secured financing and outright transactions, are netted before settlement at the end of the day. There are three repo market segments operated by FICC: General Collateral Finance Repo Service (GCF), Delivery-versus-Payment Repo Service (DVP), and Sponsored DVP Repo Service.

The development of the U.S. repo market is closely related to financial regulations. Under the Basel III supplementary leverage ratio (SLR) rule, any transaction that expands the size of bank-affiliated dealers’ balance sheet will increase the leverage ratio defined under Basel III, regardless of the riskiness of such transactions. For this reason, researchers have argued that SLR hampers the market-making ability of bank-affiliated dealers and indirectly increase the funding cost of end borrowers (see Duffie (2018) and Boyarchenko et al. (2018)). In particular, since Euro-based bank dealers are regulated based on quarter-end snapshots of their balance sheet, Euro-based dealers engage in window-dressing activities in the tri-party repo market, which is direct evidence of the impact of Basel III regulations (Munyan, 2015). To meet the hiking demand of repo netting, DTCC made several reforms that expanded the pool of participants that enjoy its repo netting service. When the FICC-cleared repo market was first created, it was only available to sell-side FICC/GSD members, including large banks, broker-dealers, Fannie Mae, and Freddie Mac. Almost all members participate in the FICC's DVP repo and around half of them participate in the GCF repo market. In 2005, DTCC offered FICC/GSD member banks with at least $5 billion in equity capital the ability to sponsor Registered Investment Companies (RICs) into GSD membership.[13] Transactions eligible to sponsored members include FICC's DVP repo and reverse repo in U.S. Treasury and Agency securities, as well as outright purchases and sales of such securities with netting. When sponsored members want to submit a reverse repo transaction in the FICC's DVP repo market, the sponsoring bank needs to be the counterparty of the sponsored member and executes the designated transaction with other GSD netting members as cash lenders. Thus, sponsored repo transactions still consume sponsoring banks' balance sheet capacity. In addition, sponsoring banks need to post additional capital to FICC as liquidity buffer, which makes it more costly for GSD members to be a sponsor. In May 2017, the SEC approved DTCC's proposal to establish the Centrally Cleared Institutional Tri-party Service (CCIT) that enables non-RIC institutional counterparties to participate in the GCF Repo market as cash lenders.[14] In January 30 2018, DTCC announced that it will expand the group of collateral providers in its Sponsored DVP Repo Service to include hedge funds.[15] More recently, in March 2019, SEC approved DTCC's proposal to include a broader group of FICC netting members as sponsoring members and sponsored members can directly trade with each other.

2.4 Money Market Segmentation

The phenomenon "market segmentation" typically refers to the fact that some investors cannot or find it very costly to buy assets in a particular market, due to various reasons such as regulatory restrictions or a lack of expertise or infrastructure to trade. In this paper, we consider two sources of money market segmentation.

The first is institutional restriction. For example, depository institutions are the only group of financial intermediaries that hold accounts at the Fed and use the payment and settlement services provided by the Fedwire system. As a result, participants such as money market funds are naturally excluded from earning the IOR rate because they just don't have the access to it. Meanwhile, money market funds are restricted from issuing short-term debt other than MMF shares and can't trade in the Fed funds market. This regulatory restriction eliminates their ability to directly affect funding rates.

The second is policy-related segmentation. Although GSEs also have reserve balances with

[13]The SEC defines Registered Investment Companies as "an investment company that invests the money it receives from investors on a collective basis, and each investor shares in the profits and losses in proportion to the investor's interest in the investment company". Mutual funds, closed-end funds, and unit investment trusts are three basic types under this definition. In particular, the SEC excludes hedge funds from RICs. Source: `https://www.sec.gov/fast-answers/answersmfinvcohtm.html`.

[14]See `https://www.sec.gov/rules/sro/ficc/2017/34-80574.pdf` and `http://www.dtcc.com/clearing-services/ficc-gov/centrally-cleared-institutional-triparty` for details. By the end of 2019, CCIT members only include hedge funds operated by Citadel Securities.

[15]Source: `http://www.dtcc.com/~/media/Files/Downloads/legal/rule-filings/2018/Approval-OrderSR-FICC-2018-013.pdf`.

the Fed, they are not IOR-eligible. For the reverse repo facility, only a subset of large institutions in each group of participants are allowed to conduct reverse repo transactions with the central bank, and the counterparties are changing regularly.[16]

Table B.1 summarizes market segmentation in the current U.S. money market. As can be seen from the table, banks have access to various instruments in both long and short directions. In particular, the largest broker-dealers (also known as primary dealers) are affiliated with several large banks under the structure of a bank holding company. Therefore, we can generally treat banks as arbitrageuers and money market funds and GSEs as cash investors.

We can use a simple framework to represent market segmentation in the current U.S. money markets. There are J money market instruments traded in the market, indexed by j, and r^j_{t+1} is the net return of asset j from t to $t+1$. The Fed has two policy facilities that remunerate cash depositors at overnight risk-free rates r^{IOR}_t and r^{RRP}_t, respectively. There are I groups of investors indexed by $i = 1, 2, ..., I$. For each group of investors, there is a unique set of assets available for them to invest or use as funding instruments. Accordingly, we divide the asset space into an investment universe and a funding universe. The investment universe for group-i investors is

$$\mathcal{I}_i \subset \mathcal{I} \equiv \{\tilde{r}^j_t | j = 1, 2, ..., J\} \cup \{r^{IOR}_t, r^{RRP}_t\}$$

and the funding universe for group-i investors is

$$\mathcal{F}_i \subset \mathcal{F} \equiv \{f^k_t | k = 1, 2, ..., K\}$$

For the current U.S. money market, the aggregate investment and funding instruments can be defined as follows:

$$\mathcal{I} = \{\tilde{r}^{FF}_t, \tilde{r}^{DVP}_t, \tilde{r}^{GCF}_t, \tilde{r}^{TRP}_t, \tilde{r}^{CP}_t; \tilde{r}^{IOR}_t, \tilde{r}^{RRP}_t, \tilde{r}^{TB}_t\} \tag{2.2}$$

$$\mathcal{F} = \{\tilde{r}^{FF}_t, \tilde{r}^{DVP}_t, \tilde{r}^{GCF}_t, \tilde{r}^{TRP}_t, \tilde{r}^{CP}_t\} \tag{2.3}$$

where FF represents federal funds, DVP represents the FICC-cleared Delivery-versus-Payment Repo Service (a bilateral repo market with netting), GCF represents FICC's GCF Repo Service, TRP represents the tri-party repo, CP represents unsecured financing such as commercial papers, RRP represents the Federal Reserve's reverse repo facility, IOR represents the Federal Reserve's interest payment on reserves, and TB represents Treasury Bills. No participants can borrow at the policy rates and the Treasury Bill rats. In other words, private agents can only issue private money.

This setup is flexible enough to capture market segmentation and financial frictions in the current money market, as illustrated in Section 2.4. If $j \notin \mathcal{I}_i$, group-i investors are restricted from purchasing asset j, which is market segmentation in the traditional sense. If $k \notin \mathcal{F}_i$, group-i investors are constrained from using the k-th financing instrument. For example, only depository institutions and GSEs have access to the federal funds market. For the repo market, even though money market funds are dominant cash lenders in the tri-party repo market, they

[16] For a full list of current counterparties and historical replacements, see `https://www.newyorkfed.org/markets/rrp_counterparties`.

can only participate in the FICC-cleared DVP repo market through a sponsorship program. Hedge funds didn't get access to the FICC-cleared DVP repo market until January 2018. Based on Table B.1, we characterize $\mathcal{I}^i$ and $\mathcal{F}^i$ for different groups of participants in the U.S. money markets, as in Table 1.

An asset could be in the intersection of all three universes. For example, a financial commercial paper is an unsecured financing instrument for some investors, an investment instrument for those who buy invest cash in the commercial paper, and can be used as collateral to issue prime repurchase agreements. But for Treasury Bills, they only enter $\mathcal{I}$ and $\mathcal{F}^s$ since the U.S. Treasury is not within our participants. Similarly, the two monetary policy instruments can only be used as investment instruments.

Table 1. A Representation of U.S. Money Markets.

Notes: (+) means that the group of market participants under consideration can take long positions or reverse repo positions in the asset, while (−) means they can take short positions, repo positions, or borrow unsecuredly at the funding rate.

	$\tilde{r}_t^{FF}$	$\tilde{r}_t^{DVP}$	$\tilde{r}_t^{GCF}$	$\tilde{r}_t^{TRP}$	$\tilde{r}_t^{CP}$	$\tilde{r}_t^{IOR}$	$\tilde{r}_t^{RRP}$	$\tilde{r}_t^{TB}$
Banks	(+/-)	(+/-)	(+/-)	(+/-)	(+/-)	(+)	(+)	(+)
Broker-Dealers		(+/-)	(+/-)	(+/-)	(+/-)		(+)	(+)
GSEs	(+/-)	(+/-)	(+/-)	(+/-)	(+/-)		(+)	(+)
Money Market Funds		(+/-)		(+/-)	(+/-)		(+)	(+)
Mutual Funds		(+/-)		(+/-)	(+/-)		(+)	(+)
Hedge Funds		(-)	(+)	(+/-)	(+/-)			(+)

3 Data

3.1 Daily Interest Rate Indices

We obtain daily time-series data on major market interest rates from the H.15 table published by the Federal Reserve Board (FRB), including the effective federal funds rate, secondary-market Treasury Bill rates of various terms (4-week, 13-week, and 26-week), financial commercial papers of 30-day and 90-day maturities, and non-financial commercial papers of 30-day and 90-day maturities.[17] In addition to these aggregate daily time-series data, we also obtain security-level daily quotation data of U.S. Treasury securities from CRSP. The data covers all issues with maturity before 12/31/2018 and dates back to 1960s. The data contains information on bid prices, ask prices, maturity, coupon rates, coupon payment schedules, and amount outstanding, for each CUSIP and date. An appealing feature of this data is that we can construct an accurate measure of an overnight Treasury yield by sampling the quote prices just before a security

[17] The secondary-market T-bill rates are the daily secondary market quotation on the most recently auctioned Treasury Bills for each maturity tranche (4-week, 8-week, 13-week, 26-week, and 52-week) for which Treasury currently issues new Bills. Market quotations are obtained at approximately 3:30 PM each business day by the Federal Reserve Bank of New York. The Bank Discount rate is the rate at which a Bill is quoted in the secondary market and is based on the par value, amount of the discount and a 360-day year. Source: U.S. Treasury, Daily Treasury Bill Rates Data.

matures. We also use this data to calculate the market value of government securities outstanding by maturity on a daily frequency, which is not available through other sources.

3.2 Repo Rates

Our data on repo rates come from several sources. The Federal Reserve Bank of New York's provides several repo rate indices that measure funding costs at different layers of repo markets. One limitation of NY Fed's repo indices only goes back to 2015. To extend the sample, we use the tri-party repo rate indices published by the Bank of New York Mellon as an alternative candidate for tri-party repo rates, which start from 2012. In addition to the difference in sample period, the BNYM's repo indices calculate the volume-weighted average rate, while the NY Fed data records the volume-weighted median. For bilateral repo rates, the DTCC's GCF Repo Index is a direct measure of the average repo rates in the GCF market. Finally, the New York Fed recently published survey data on primary dealers' daily Treasury general collateral repo rates, which extends our measure of tri-party Treasury GC repo rates back to 1998. See appendix for details of these data.

3.3 Weekly Time Series of Public and Private Money Stock

Data on public money stock comes from the Fed Board's H.4.1 table. It contains weekly data on factors absorbing central banks reserves, including reserve balances of depository institutions, reverse repo transactions with foreign officials and others, reserves held in the Treasury General Account (TGA), and deposits held by other entities. Data on commercial banks' balance sheets comes from the H.8 table, both sampled at a weekly frequency.

3.4 Money Market Fund Holdings

Using self-written Python script, we collect a set of very detailed information of U.S. money market funds from the SEC N-MFP2 filings. The N-MFRP2 form is filed at the end of each month and our sample spans from October 2016 to June 2019. At the fund-level, our sample contains weekly information such as the dollar amount of total net assets, daily-liquid and weekly-liquid assets, and fund flows. Our sample also documents the security-level information of all securities held by each fund on the reporting day, including identification number, principal amount, yield, maturity date, name of the issuer, and information on collateral assets if the asset is a repurchase agreement.

Table B.4 presents the summary statistics of money market fund aggregate data and repo holdings. Money market funds heavily invest in short-term safe and liquid assets. The average share of daily and weekly liquid assets are 50% and 68%, respectively, which is well above the required minimum holdings of such assets.[18] There is also large heterogeneity across different

[18] In 2014, the SEC proposed a new rule to improve the risk management of money market funds. The new rule requires money funds to invest at least a certain percentage of total assets in liquid securities. In particular, a money market fund has to invest at least 10% of its total assets in "daily liquid assets", which includes cash, U.S. Treasury securities, or assets that become cash within one business day. A money market fund has to invest at least 30% of its total assets in "weekly liquid assets", including all daily liquid assets, government agency discount notes with less than 60 days to mature, or other assets that can be turned into cash within 5 business days.

types of funds. While the average share of daily liquid assets is 97% for Treasury money funds, the number is 34% for Prime funds and 12% for Single State funds. The average duration of portfolio securities is 25 days with a maximum duration 90 days.

This investment style makes money market funds the largest group of cash investors in the tri-party repo market.[19] As shown in Table B.4, the median size of Treasury repo contracts invested by money market funds can be as large as 100 million dollars. Meanwhile, the distribution of contract size is highly skewed, with the average size of Treasury repo contracts equal to 320 million dollars. Part of the reason is that the principal amount of the Fed's reverse repo contract is typically very large. To see this, we compute the statistics for each issuer in Table B.5, B.6, and B.7. The first observation is that almost all repo transactions are done with large financial institutions, including both domestic and foreign institutions. In particular, the total amount of Treasury repos issued by foreign institutions are almost three times than that of domestic institutions. Second, the average contract size of the Fed's RRP facility is 3.37 billion dollars, but for most financial institutions the number is smaller than 0.5 billion dollars. Another interesting fact is that Treasury repo contracts cleared by FICC also have large principal amounts, with an average of 1.08 billion dollars.

4 Stylized Facts about Post-crisis Monetary Policy

We now present some stylized facts about the transmission of post-crisis monetary policy. First, we will lay out a characteristics-based model of short-term interest rates. Next, we will show that the risk-free components of a wide range of short rates deviate from the complete-market benchmark. In particular, the deviation from complete-market benchmark is regime-shifting at a low frequency.

4.1 Decomposing Short-term Interest Rates

To measure the transmission of monetary policy, we first need to understand what determines the level of market interest rates. The most common approach in the literature is to decompose an interest rate into components that reflect the valuation of an asset's characteristics, such as risk premia and convenience yields. For money market instruments with sizable credit risk, such as financial commercial paper, movements in interest rates mainly reflects variation in risk premia. In contrast, for assets that provide monetary services, such as Treasury bills, movements in interest rates may be driven by the convenience yield (Krishnamurthy and Vissing-Jorgensen, 2012; Nagel, 2016). Define $\tilde{r}_t^j \equiv \mathbb{E}_t\, r_{t+1}^j$ as the expected return given period-t information, r_t^f as the risk-free rate, $\rho_t^j \geq 0$ as the risk premium, and $\xi_t^j \geq 0$ as the convenience yield, the expected return of asset j can be decomposed as[20]

$$\tilde{r}_t^j = r_t^f + \rho_t^j - \xi_t^j \tag{4.1}$$

[19]For information of repo market, see Appendix 2.3.

[20]Since assets with sizable risk premia do not provide monetary services, we can assume that $\rho_t^j \xi_t^j = 0$.

Equivalently, the above decomposition can be represented by a factor structure. Denote $\mathbf{f}_t \equiv [\rho_t, \xi_t]'$ as the aggregate factors of risk-free rate, risk premia, and liquidity factor, and β^j as a 2×1 vector of factor loadings, then the deviation from the complete-market benchmark can be represented as

$$\tilde{r}_t^j - r_t^f = \mathbf{f}_t' \beta^j + \varepsilon_t^j \tag{4.2}$$

From a friction-based perspective, interest rate spreads between assets with similar attributes reflect market frictions or transaction costs that limit the scale of arbitrage activities (Shleifer and Vishny, 1997; Gromb and Vayanos, 2002, 2018). Based on the framework introduced in Section 2.4, we can denote $\bar{r}_t^i \equiv \max_j \mathcal{I}_i$ as the highest rate of return within the investment universe of group-i investors and $\underline{f}_t^i \equiv \min_k \mathcal{F}_i$ as the lowest funding rate within the funding universe of group-i investors. As long as $\bar{r}_t^i > \underline{f}_t^i$, there is an arbitrage opportunity available for group-i investors. In a world without funding frictions, group-i investors will take long positions at $\bar{r}_t^i$ and short positions at $\underline{f}_t^i$, thereby pushing down $\bar{r}_t^i$ and pulling up $\underline{f}_t^i$ until $\bar{r}_t^i = \underline{f}_t^i$. Therefore, we can assume that the degree of market frictions faced by group-i investors, denoted by c_t^i, is proportional to the arbitrage spread:

$$c_t^i \propto \bar{r}_t^i - \underline{f}_t^i \tag{4.3}$$

A challenge in measuring c_t^i is that we need to observe the spectrum of rates in $\mathcal{I}_i$ and $\mathcal{F}_i$ in order to find $\bar{r}_t^i$ and $\underline{f}_t^i$. High-frequency interest rates data in our sample are either the median or the average of daily quoted rates.

For assets that do not have overnight yields at a daily frequency, such as Treasury bills and commercial papers, we follow Duffie and Krishnamurthy (2016) and correct the term premium using the overnight indexed swap rates

$$\tilde{r}_t^j(1) = \tilde{r}_t^j(m) - \left[r_t^{OIS}(m) - r_t^{OIS}(1) \right] \tag{4.4}$$

where $r_t^j(m)$ is the time t interest rate of instrument j with m days to mature. In our empirical exercise, we will use the IOR rate as a proxy for the overnight OIS rate.[21]

4.2 Measuring the Transmission Efficiency

To the extent that the Federal Reserve aims at tightly controlling the risk-free component of market interest rates using its policy instruments, we measure the transmission efficiency of monetary policy to asset j as the spread between the IOR rate and the risk-free component r_t^f of $\tilde{r}_t^j$. For the rest of our paper, we will call this interest rate spread the "IOR spread" or the deviation from complete-market benchmark interchangeably. Based on the previous section, the spread between the IOR rate and any other interest rate $\tilde{r}_t^j$ can be decomposed in the following

[21] Another way to account for the term premium is to include a variable indicating the number of days to the next FOMC meeting, consistent with what implied by the literature on the high-frequency identification of monetary shocks (Gürkaynak et al., 2007).

way:

$$r_t^{IOR} - \tilde{r}_t^j = \underbrace{r_t^{IOR} - r_t^{f,j}}_{\text{IOR spread}} + \underbrace{r_t^{f,j} - \tilde{r}_t^j}_{\text{risk attributes}} = c_t^j + \xi_t^j - \rho_t^j \tag{4.5}$$

Although this decomposition do not give any structural interpretation, as will be shown later, the spread between IOR and the risk-free component $r_t^{f,j}$ is largely driven by the funding cost.

In a complete-market economy, the law of one price would imply that assets with the same payoff share the same market price. Therefore, the price of a hypothetical risk-free asset that pays off $1 + r_t^{IOR}$ dollars for sure at date $t + 1$ should be 1 dollar at date t, which implies that the risk-free rate satisfies $r_t^f = r_t^{IOR}$. In other words, the IOR rate should serve as the complete-market benchmark for the risk-free rate.[22] Movements in expected rate $\tilde{r}_t^j$ only reflect movements in risk factors (since $c_t^j = 0$ in a complete market).

$$r_t^{IOR} - \tilde{r}_t^j = r_t^{f,j} - \tilde{r}_t^j = \xi_t^j - \rho_t^j \tag{4.6}$$

With various market frictions, however, monetary transmission may be hampered by the presence of these market frictions. For example, if most of the arbitrageurs are significantly constrained in borrowing using a type of short-term funding instrument, the corresponding IOR spread may be positive on that funding instrument. In this case, the spread $r_t^{IOR} - r_t^{f,j}$ is non-zero and is driven by the variation in funding constraints.

4.3 Time-varying IOR Spreads

So how do the IOR spreads appear in real data? To avoid large measurement errors in the IOR spread decomposition, we will mainly use Treasury and agency repo rates as our candidate rates for measuring IOR spreads, since they are safe and do not provide monetary services (ρ_t^j and ξ_t^j are small).[23] As an additional benefit, using repo rates also avoids adjusting term premia because repo contracts in our sample are concentrated at terms less than a week and overnight repo rates are readily available at a daily frequency.

If ρ_t^j and ξ_t^j are small and the degree of funding frictions remain constant over time, we would expect little time variation in the IOR spreads. However, our main empirical finding contradicts this prediction. Figure 5 plots the daily IOR spreads of four repo indices: the New York Fed TGCR and SOFR indices, the Bank of New York Mellon Treasury Repo Index, and the DTCC's GCF Repo Index. TGCR and BNYM repo indices measure tri-party repo rates, while SOFR and GCF repo indices measure bilateral repo rates. As shown by the graph, even though these repo contracts are safe and liquid, their spreads with the IOR rate deviate from the

[22]Note that we do not use the reverse repo rate as the risk-free benchmark rate because it is systematically lower than the IOR rate, which means that a profitable arbitrage opportunity would arise if investors use the RRP rate as the risk-free reference rate.

[23]Treasury and agency repos are safe because even if the borrower fails to repurchase the collateral asset, the cash provider can still sell the Treasury security at a price close to the repurchase price. Treasury repos do not provide monetary services because repo contracts cannot be traded in the secondary market. The funds invested in a repo contract is essentially locked up unless cash investors re-use the collateral security to obtain cash by issuing repo ("rehypothetication"). Consistent with this idea, Krishnamurthy and Vissing-Jorgensen (2012) uses the spread between term Treasury repo rates and Treasury bill rates with the same tenor as a measure of the convenience yield.

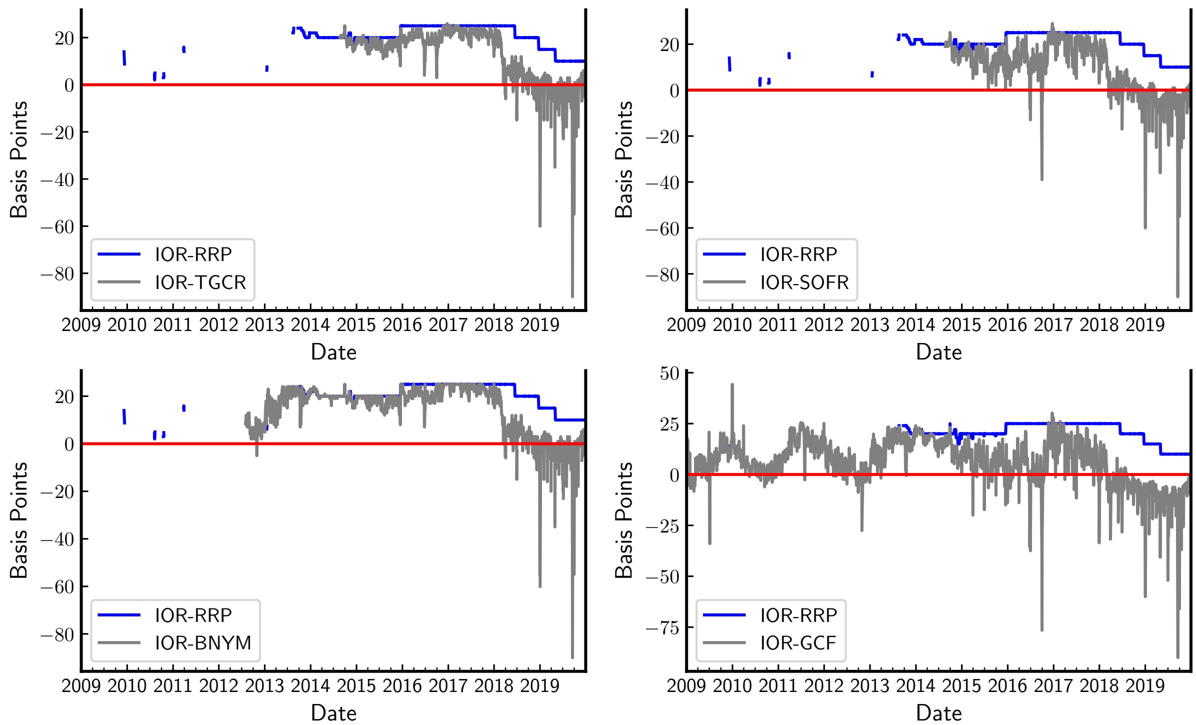


Figure 5. Daily spreads between the IOR rate and repo rates accessible to banks. See Section 3 for the definition of labels.

zero benchmark and greatly vary over time. If our simple decomposition model is correct, then these time-varying deviations from the complete-market benchmark implies that the degree of arbitrage activities, which might be driven by the degree of funding constraints, may be time-varying as well. In particular, a positive IOR spreads indicate that arbitrage activities are not enough to close the spreads.

Another interesting observation is that there are two regimes of IOR spreads after the initialization of the RRP facility. From September 2013 to January 2018, the IOR spreads are close to the IOR-RRP spread, with an average of 20 basis points. However, after January 2018, the average level of IOR spreads quickly moved down to zero and the volatility visibly spiked up.

Table B.8 presents some summary statistics of IOR spreads on various instruments. To account for possible regimes in our sample, we consider three sub-periods: January 2009 to September 2013, during which the Fed started paying interest on reserve balances; September 2013 to January 2018, after the initialization of the Fed's reverse repo facility, but before our conjectured shift to the third regime; and after January 2018. As shown in the first panel of Table B.8, the IOR spreads are sizable in the first two sub-samples, with average values around 10 basis points. However, after January 2018, the average spread reduced to almost zero, while the standard deviation were at least doubled for repo rates. For tri-party repo rate, the spread is on average 20 basis points and the standard deviation is 3 basis points from October 2013 to January 2018. But after January 2018, the average spread shrunk to 0.1 basis point and the

Table 2. Summary statistics of IOR-Repo spreads.

	Treasury Repo					Agency Repo				
	Mean	p50	p10	p90	N	Mean	p50	p10	p90	N
After Jan 2018	-6.4	-4.0	-20.0	6.0	32728	-9.3	-7.0	-25.0	3.0	22727
Before Jan 2018	19.2	20.0	11.0	24.0	25788	17.4	18.0	10.0	23.0	19337

standard deviation increased to 18.1 basis points.

Since daily repo rate indices are calculated using either the median or mean of the cross-section of all repo rates, it is possible that the observed regime shift is caused by extreme values. Using contract-level data of repurchase agreements held by money market funds, we show that this is not the case. For each reporting day, we calculate the spread between the IOR rate and the Treasury repo rate of contracts with one day to mature and plot the histogram of IOR-Repo spreads in Figure 6, categorized by the regime.[24] Consistent with the evidence from aggregate time series data, the cross-sectional distribution of IOR-Repo spreads also shifts after January 2018. In particular, the reduction of IOR spreads are similar across percentiles, as shown in Table 2. This implies that the regime shift happens to the cross-section of all repo contracts, instead of the effect of some extreme values.

Evidence of large variation in IOR spreads and especially the existence of regimes implies that the transmission of monetary policy is subject to significant inefficiency: the effective market interest rates increase by almost 25 basis points on top of any change in the target interest rate, which is equivalent to the size of a rate hike.

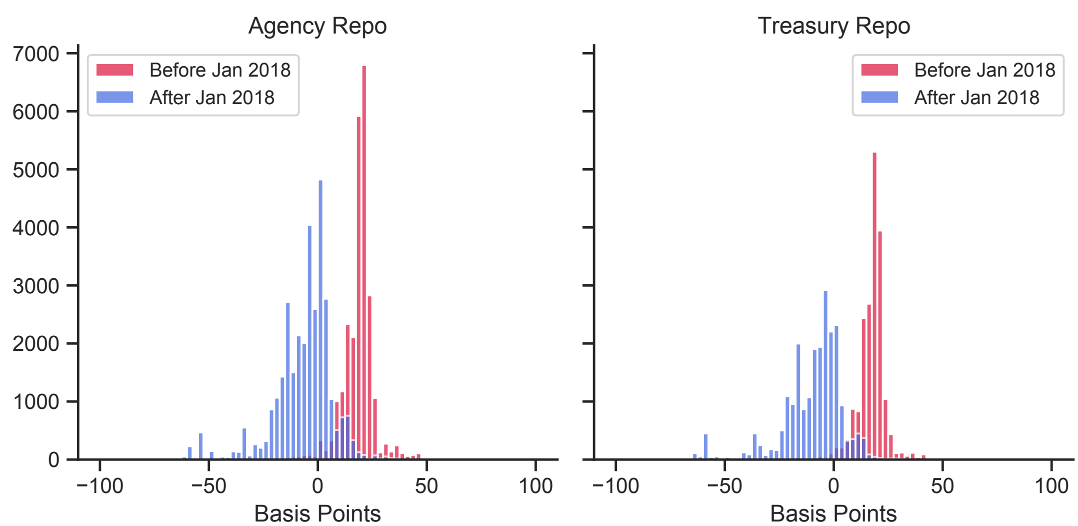


Figure 6. Histogram of IOR-Repo spread for tri-party repo contracts, categorized by collateral assets. We exlucde repo contracts issued by the Federal Reserve and contracts cleared by FICC from our computation. Sample period: 2016.10 - 2019.6. Source: N-MFP2 filings.

[24]Even though contracts with one day to mature do not correspond to overnight contracts, we still manage to exclude term repo contracts. Considering that repo contracts held by money market funds are often less than 7 days, even un-modified spreads won't have large measurement errors.

5 A Model of Segmented Money Markets

5.1 A Two-Period Model

To build intuitions, we first consider a simple two-period model with a minimal set of assumptions. There is only one asset in the financial market, investors are risk-neutral, and investors face short-sale/borrowing constraints. Even with a minimal set of assumptions, the model generates regimes of interest rates. We will use this simple model to derive the closed-form expression of the equilibrium bond yield and shed light on what triggers a shift from one regime to another.

5.1.1 Technology

Time is discrete and last for two periods, $t = 0, 1$. Suppose there are three types of investors, indexed by $\{A, B, C\}$. Type-i investor is endowed with ω_0^i initial wealth at time 0. All investors are risk-neutral and try to maximize the second period wealth ω_1^i. For monetary policy, the Fed sets up two deposit facilities for investors, which remunerate the depositor with overnight gross interest rates R_t^H and R_t^L, respectively.

Assumption 1 (*Market Segmentation*)**.** *We assume that investors have different access to the Fed's deposit facilities. In particular, type-A investors have access to policy rates R_t^H, type-B invetors have access to policy rates R_t^L, and type-C investors have no access to policy rates.*[25] *We assume the spread between two policy rates is positive,*

$$z_t \equiv R_t^H - R_t^L > 0 \tag{5.1}$$

5.1.2 Bond Market

Suppose the only asset in the market is a one-period bond with total supply $\bar{B}$. Each unit of bond pays one nominal wealth to the owner at date 1. The equilibrium price of each unit of bond, denoted by q_0, is set to clear the bond market. At date 0, type-i investors purchase b_0^i units of bond and deposit residual wealth x_0^i into the corresponding policy facility, subject to the budget constraint and two short-sale constraints:

$$q_0 b_0^i + x_0^i = \omega_0^i \tag{5.2}$$

$$b_0^i \geq 0 \tag{5.3}$$

$$x_0^i \geq 0 \tag{5.4}$$

Since the utility function is linear in (b_0^i, x_0^i), the optimal portfolio choice is a bang-bang solution, which depends on whether the equilibrium bond yield is larger than the rate of return on eligible policy instruments. For example, if the equilibrium bond yield is higher than R_0^A, type-A investors have the incentive to purchase as much government bond as possible, until either: 1) type-A investors run out of wealth, or 2) the equilibrium bond yield is equal to R_0^A.

[25] As we will see later, for each investor, it is the highest eligible policy rate that matters for the equilibrium result. So we ignore cases in which one type of investors have access to multiple policy facilities.

More formally, given the portfolio (b_0^i, x_0^i), the final period wealth is then $\omega_1^i = R_0^i x_0^i + b_0^i$. Let $\lambda_0^{b,i}$ and $\lambda_0^{x,i}$ be the Lagrangian multipliers for short-sale constraints, respectively. Then the first order condition for type-i investors is

$$q_0 = \frac{1+\lambda_0^{b,i}}{R_0^i + \lambda_0^{x,i}} \tag{5.5}$$

This formulation allows us to describe the optimal solution by values of the Lagrangian multipliers. First note that, for type-A and type-B investors, at least one Lagrangian multiplier is zero. Otherwise, their choices are not optimal since they can increase the final wealth by allocating some to the Fed's policy instrument. Without loss of generality, this also applies to type-C investors since they do not have an incentive to take short positions. If both $\lambda_0^{b,i}$ and $\lambda_0^{x,i}$ are zero, $q_0 = 1/R_0^i$ according to (5.5). So type-i investors are indifferent between bond and the i-th policy instrument. If $\lambda_0^{b,i} = 0$ and $\lambda_0^{x,i} > 0$, the equilibrium yield $1/q_0$ is greater than the outside option R_0^i, which induces type-i investors to allocate all wealth to bonds. Finally, if $\lambda_0^{b,i} > 0$ and $\lambda_0^{x,i} = 0$, the bond yield $1/q_0$ here is smaller than the policy rate R_0^i, which gives type-i investors an arbitrage opportunity. In this case, type-i investors have the incentive to allocate all wealth to the Fed's instrument, even by borrowing through the bond market by taking short positions (if they could).

Based on the above analysis, we can compactly express type-i investors' optimal portfolio choice as the following threshold strategy:

$$b_0^i(q_0|R_0^i, \omega_0^i) = \frac{\omega_0^i}{q_0}\mathbb{1}\{q_0 R_0^i < 1\} + \frac{\epsilon_0^i}{q_0}\mathbb{1}\{q_0 R_0^i = 1\} \tag{5.6}$$

$$x_0^i(q_0|R_0^i, \omega_0^i) = \omega_0^i \mathbb{1}\{q_0 R_0^i > 1\} + (\omega_0^i - \epsilon_0^i)\mathbb{1}\{q_0 R_0^i = 1\} \tag{5.7}$$

where ϵ_0^i is any real number in $[0, \omega_0^i]$ that clears the bond market at $q_0 = 1/R_0^i$. The optimal demand function illustrates that investors enter the bond market only when the bond yield is higher than their eligible policy rate (or zero when they are not eligible to any policy rate). Therefore, the policy rate sets a participation threshold, or the floor of bond yields, for policy-eligible investors (see Figure 7). This is the basic mechanism behind the so-called "floor system" of monetary policy.

This threshold strategy of bond market participation has interesting implications for the aggregate demand of government bonds. As the bond price decreases, investors of different types will gradually enter the bond market following the threshold strategy (see Figure 8a). When the bond price is high, type-C investors are marginal investors in the bond market since their participation threshold is zero. Type-A and type-B investors do not find it profitable to enter the bond market – doing so will make the bond yield even lower. This situation remains as the bond price decreases to the point that it is profitable for type-B investors to enter the market. Similarly, type-A investors enter the bond market when the equilibrium yield is greater or equal to R_0^H.

Formally, let $\mathcal{R}_0$ be the set of policy rates $\{R_0^H, R_0^L\}$ and $\mathcal{W}_0$ be the set of endowment wealth,

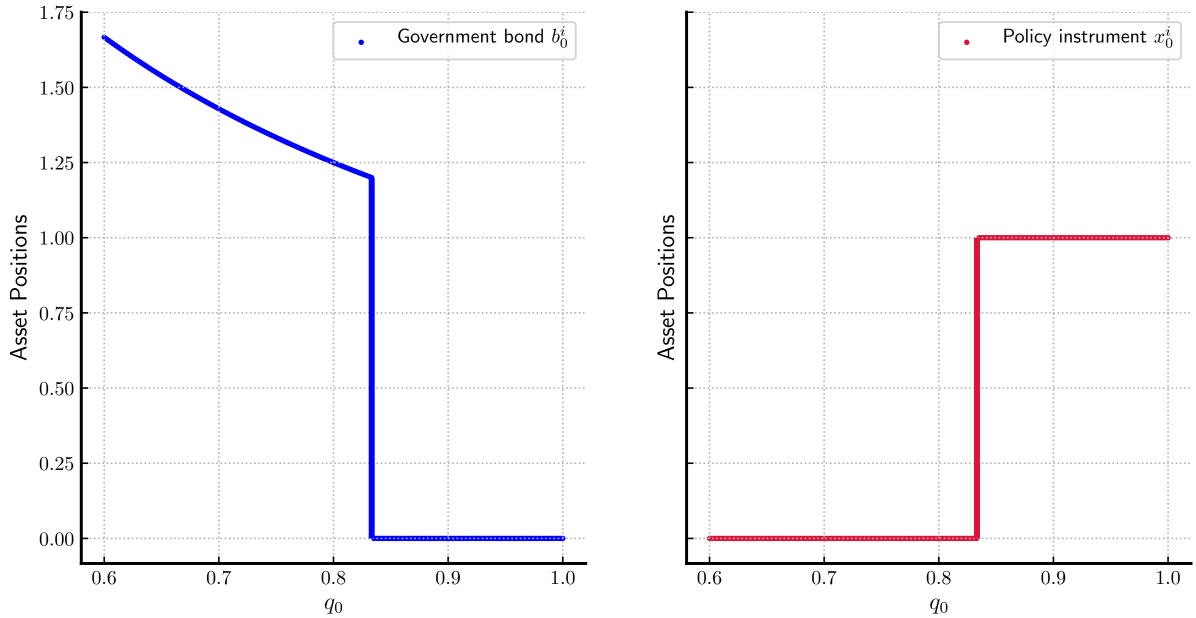


Figure 7. Optimal asset positions as functions of bond price. Parameters: $R_0^H = 1.2$, $R_0^L = 1.1$.

then the aggregate bond demand function is

$$B^d(q_0|\mathcal{R}_0, \mathcal{W}_0) = \sum_i \frac{\omega_0^i}{q_0} \mathbb{1}\{q_0 R_0^i < 1\} + \sum_i \frac{\epsilon_0^i}{q_0} \mathbb{1}\{q_0 R_0^i = 1\} \tag{5.8}$$

Note that the existence of the indicator functions, which is introduced by the market segmentation of the Fed's policy facilities, makes the demand function changes discontinuously at bond prices that induce entry or exit of policy-eligible investors. The inverse demand function $B^{-1}(x|\mathcal{R}_0, \mathcal{W}_0)$ is decreasing, which will guarantee that there is a unique equilibrium (see Figure 8b).

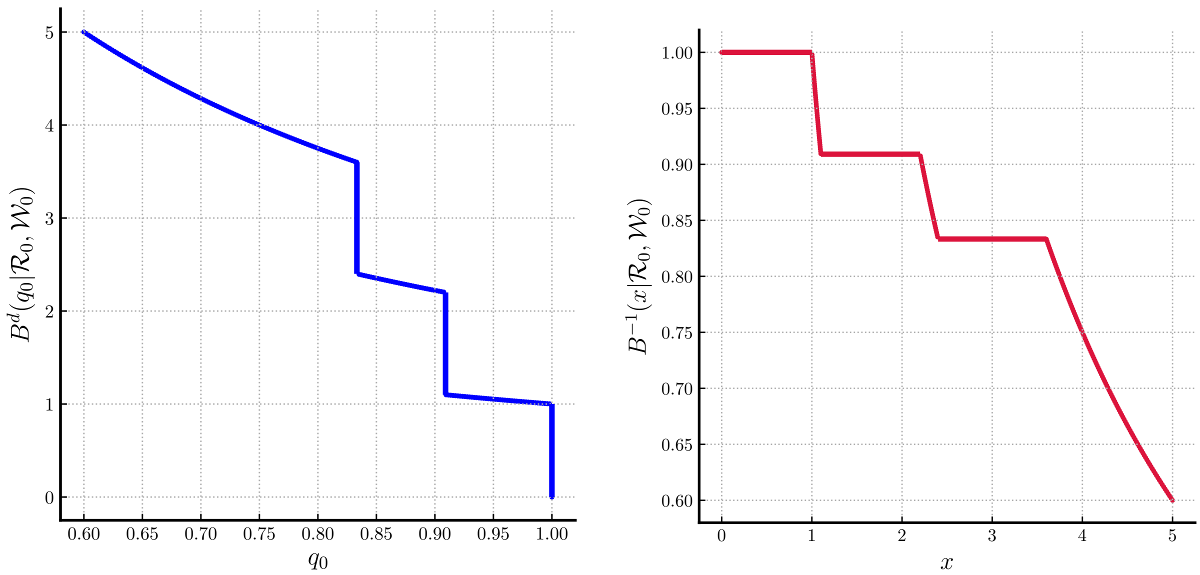
5.1.3 Equilibrium

We are seeking a general-equilibrium solution for our economy, in which the equilibrium bond price is set so that the bond market clears. Since the inverse aggregate bond demand is decreasing in bond price, there exists a unique equilibrium bond price q_0^* that solves the following market clearing condition:

$$B^d(q_0|\mathcal{R}_0, \mathcal{W}_0) = \bar{B} \tag{5.9}$$

The market clearing equation also implicitly defines a bond pricing function $q(x) \equiv B^{-1}(x|\mathcal{R}_0, \mathcal{W}_0)$ such that $q^*(\bar{B}) = q_0^*$, and a corresponding equilibrium yield function $R^*(x) \equiv 1/q^*(x)$.

If there is only one type of investors in this economy and they all get access to the same type of policy instrument, then in equilibrium the bond yield will be equal to the interest rate on policy instruments. Otherwise, either investors purchase more bonds until the bond yield reduces to the policy rate, or investors sell bonds until the bond yield rises to the policy rate.



(a) bond demand **(b)** inverse demand function

Figure 8. Aggregate bond demand and inverse demand function. Parameters: $R_0^H = 1.2$, $R_0^L = 1.1$.

However, with multiple types of investors with different policy rates, there are equilibria where the bond market is cleared by only a subset of investors, while others allocate all of their wealth into the policy instruments. We summarize the property of this equilibrium yield function in the following propositions.

Proposition 1 (*Characterization of the equilibrium bond yield*)**.** *Suppose there are N distinct policy rates and $N+1$ types of investors, indexed by $i = 0, 1, 2, ..., N$. Type-i investors have endowment ω^i and can save at the i-th smallest policy rate R^i. In particular, $R^0 = 1$. Let*

$$\mathcal{B}_k^I \equiv \left[R^k \sum_{i=0}^{k-1} \omega^i, R^k \sum_{i=0}^{k} \omega^i\right), 1 \leq k \leq N \tag{5.10}$$

$$\mathcal{B}_k^S \equiv \left[R^k \sum_{i=0}^{k} \omega^i, R^{k+1} \sum_{i=0}^{k} \omega^i\right), 0 \leq k \leq N-1 \tag{5.11}$$

$$\mathcal{B}_0^I \equiv \left[0, \omega^0\right) \quad \text{and} \quad \mathcal{B}_N^S \equiv \left[R^N \sum_{i=0}^{N} \omega^i, \infty\right) \tag{5.12}$$

Then, the equilibrium yield R^* as a function of bond supply b is

$$R^*(b) = \begin{cases} R^k & \text{if } b \in \mathcal{B}_k^I, \quad 0 \leq k \leq N \\ \dfrac{b}{\sum_{j=0}^{k} \omega^j} & \text{if } b \in \mathcal{B}_k^S, \quad 0 \leq k \leq N \end{cases} \tag{5.13}$$

Figure 9 plots a numerical example of the net yield y_0^* as a function of bond supply. As shown by the graph, there are three closed intervals of bond supply such that within each interval: 1)

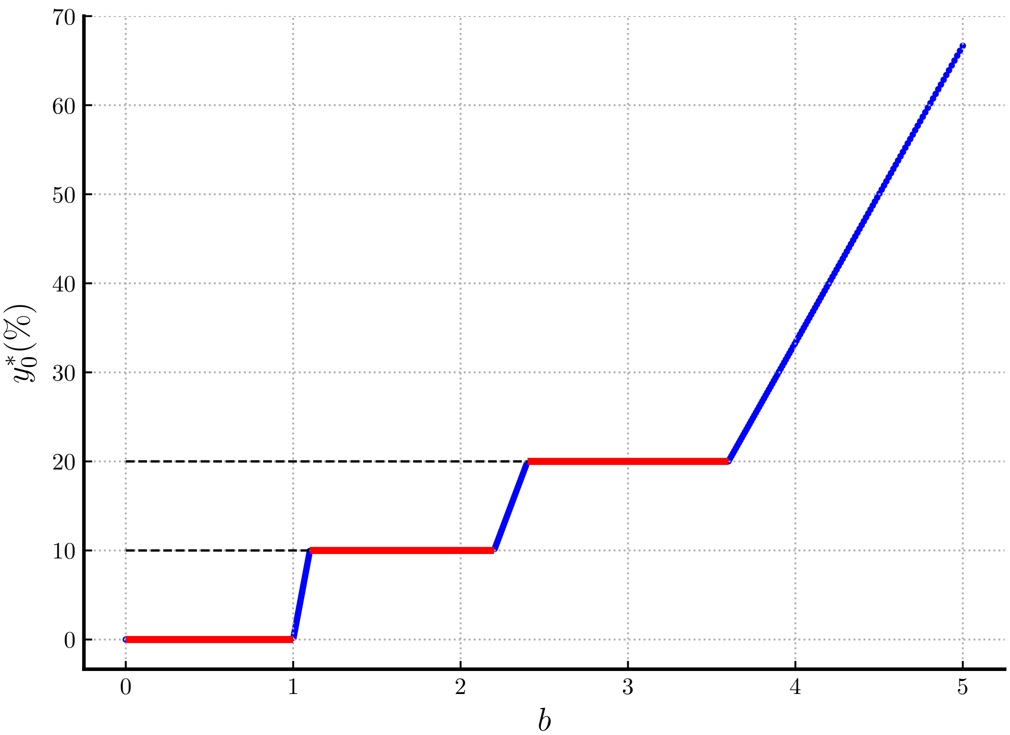


Figure 9. The equilibrium yield as a function of bond supply. Parameters: $R_0^H = 1.2$, $R_0^L = 1.1$.

a shock to the bond supply doesn't change the bond yield, as long as the shock doesn't move the aggregate bond supply out of that interval; 2) the bond yield is equal to the policy rate in each of the intervals. These intervals are connected by upward-sloping curves in which the bond yield is much more sensitive to the movement of bond supply.

Corollary 1. *$R^*(b)$ is continuous and semi-differentiable on $\mathbb{R}^+$. More specifically, $R^*(b)$ is differentiable on each $\mathcal{B}_k^I$ and $\mathcal{B}_k^S$. The derivatives are*

$$\partial R^*(b) = \begin{cases} 0 & \text{if } b \in \mathcal{B}_k^I, \quad 0 \leq k \leq N \\ \dfrac{1}{\sum_{j=0}^{k} \omega^j} & \text{if } b \in \mathcal{B}_k^S, \quad 0 \leq k \leq N \end{cases} \tag{5.14}$$

Since $\partial R^*(b)$ is positive on $\mathcal{B}_k^S$ and zero on $\mathcal{B}_k^I$, we call $\mathcal{B}_k^I$ a supply-insensitive regime $\mathcal{B}_k^I$ a supply-insensitive regime.

The equilibrium bond yield also helps to identify the marginal investor: in Regime I, type-C investors are marginal since the bond yield is too low for type-A and type-B investors to enter the bond market; in Regime II, type-B investors are marginal because their presence in the bond market anchors the market rate at R_0^L; similarly, type-A investors are marginal in Regime III.

Corollary 2. *There is a mapping $\Psi : [1, \infty) \longrightarrow \{k\}_{k=0}^N$ that identifies the marginal investor* *based on the equilibrium bond yield:*

$$\Psi(R^*) = \begin{cases} k & \text{if } R^* \in [R^k, R^{k+1}) \\ N & \text{if } R^* \in [R^N, \infty) \end{cases} \tag{5.15}$$

Furthermore, there is a mapping $\Phi : \{\mathcal{B}_k^I, \mathcal{B}_k^S\}_{k=0}^N \longrightarrow \{k\}_{k=0}^N$ that identifies the marginal investor based on aggregate bond supply:

$$\Phi(b) = k \quad \text{if } b \in \mathcal{B}_k^I \cup \mathcal{B}_k^S \tag{5.16}$$

We thus call $\mathcal{B}_k^I$ a type-k supply-insensitive regime.

Finally, compared to the supply-insensitive regions, the size of supply-sensitive regions is much smaller. For example, while the size of Regime I is ω_0^C, the size of adjacent supply-sensitive region is only $(R_0^L - 1)\omega_0^C$. For realistic values of R_0^L, say 1.02, the difference is 50 times. The implication is that bond yields are insensitive to the movement of bond supply for most of the time. But once bond supply reaches the upper boundary of supply-insensitive regions, a small positive shock can push the equilibrium yield to a higher level of policy rate.

Corollary 3. *The length of a type-k supply-insensitive regime is much larger than that of a type-k supply-sensitive regime. And the ratio of the two depends on*

$$\frac{|\mathcal{B}_k^I|}{|\mathcal{B}_k^S|} = \frac{R^k \omega^k}{(R^{k+1} - R^k) \sum_{i=0}^k \omega^i} \tag{5.17}$$

Corollary 4. *The equilibrium is invariant to the scale of the economy. Let $\theta_0^i \equiv \omega_0^i / \bar{B}$ be the normalized nominal wealth of type-i investors and let $\mathbf{\Theta}_0$ collects exogenous variables $\{\theta_0^i, r_0^i\}$ for all types. Then there is a unique mapping from $\mathbf{\Theta}_0$ to the equilibrium yield R^*, and the marginal investors can be uniquely identified by the state variable $\mathbf{\Theta}_0$.*

5.1.4 Discussion of model assumptions

The short-sale constraint is not a very strong assumption in our context. Many cash investors in the money market do not use short-term funding either because of they are restricted to do so (like money market funds), or they don't have the expertise to access the secured short-term funding market (like non-financial firms). From a modeling perspective, imposing short-sale constraints help us to clearly identify the effect of market segmentation without making additional assumption about the economy. See Cochrane (2011) for a discussion on the difference between "segmented markets" models and "intermediated markets" models. We will show that our result is robust to adding more relaxed funding constraints.

5.2 A Dynamic Model

We now extend our benchmark model to infinite horizon and multi-period bonds.

5.2.1 Model setup

Assume the government issues zero-coupon bonds up to K periods. There are two policy facilities with gross policy renumeration rates R_t^H and R_t^L, respectively. Accordingly, depending on the access to these two facilities, investors are divided into three groups, indexed by $i = N, L, H$. For type-i investors, let x_t^i be the position in the i-th policy facility at the *end* of period t, $b_{i,t}^{(\tau)}$ be the units of τ-period government bond at the beginning of period t, $Q_t^{(\tau)}$ be the competitive bond price, $\tilde{\omega}_t^i$ be the stochastic endowment process, and c_t^i be the amount consumed by type-i investors during period t. In particular, the stochastic endowment process can be decomposed into the sum of an idiosyncratic component with zero mean and a common component that follows a stationary process with positive mean.

Each period, investors allocate their nominal wealth over bonds of different maturities and the Fed's policy facilities in order to maximize the expected value of their life-time utility over a stream of consumption. Following He and Krishnamurthy (2013), we interpret consumption as compensation for managers or dividends for equity holders.[26] In our benchmark case, we will impose short-sale constraints on bonds and policy facilities, which is in contrast to many intermediary-based models. The short-sale constraints for bonds can be relaxed so that investors can obtain funds through secured financing. However, we will always keep the short-sale constraints for policy facilities since financial intermediaries cannot borrow from the Fed at these policy rates in the real world. Given the above model setup, type-i investors are solving the following problem:

$$\max_{\{b_{i,t+1}^{(\tau)}, x_t^i, c_t^i\}_{t=0}^{\infty}} \mathbb{E}_0 \left[\sum_{t=1}^{\infty} \beta^t u\left(c_t^i\right) \right] \tag{5.18}$$

subject to the budget constraint

$$c_t^i + \sum_{\tau=1}^{K} Q_t^{(\tau)} \left(b_{i,t+1}^{(\tau-1)} - b_{i,t}^{(\tau)} \right) + x_t^i \leq b_{i,t}^{(0)} + R_{t-1}^i x_{t-1}^i + \tilde{\omega}_t^i \quad \forall t \geq 0 \tag{5.19}$$

and short-sale constraints on bonds and policy instruments: 1) $x_t^i \geq 0$, $\forall t \geq 0$, x_{-1}^i given as an initial condition; 2) $b_{i,t}^{(\tau)} \geq 0$, $\forall t \geq 1$, and $b_{i,0}^{(\tau)} = 0$, $\forall 0 \leq \tau \leq K$. In our notation, $b_{t+1}^{(K-1)}$ is the purchase of K-period bonds issued at period t and we define $b_t^{(K)} = 0$ to make the expression more compact.[27] We assume that the government always repays debt, so the bond price for $b_t^{(0)}$ is one. We don't model how the total amount of injected reserves changes over time. Rather, we take it as given and study how the allocation of injected reserves affect asset prices.

[26] Maximizing the present value of expected utility over consumption also appears in representative-agent consumption-based models, such as Piazzesi and Schneider (2006). As the first few papers that develop intermediary-based asset-pricing models, He and Krishnamurthy (2012) and He and Krishnamurthy (2013) assume that financial intermediaries maximize the life-time utility over consumption subject to a leverage constraint micro-founded by an agency problem. In more recent works, researchers tend to explicitly model the portfolio choice problem faced by financial intermediaries and use the final period wealth/net worth as the objective (Gertler and Kiyotaki, 2010; Greenwood and Vayanos, 2014; Gertler et al., 2016; Drechsler et al., 2017a; Haddad and Sraer, 2019; Koijen and Yogo, 2019).

[27] Since our definition of $b_t^{(\tau)}$ restricts the interpretation of τ and t, we use $b_{t+1}^{(K-1)}$, instead of $b_t^{(K)}$, to represent the position of K-period bond issued at date t in order to avoid any conflict of notations. In other words, we keep track of the bond position at the beginning of every period without detailing the timing within a single period.

5.2.2 First-order conditions

To solve this dynamic programming problem, we define the following Lagrangian

$$\mathcal{L}^i \equiv \mathbb{E}_0 \left\{ \sum_{t=1}^{\infty} \beta^t \left[u(c_t^i) - \gamma_{i,t} F_t^i + \sum_{\tau=1}^{K} \mu_{i,t}^{b,\tau} b_{i,t+1}^{(\tau-1)} + \mu_{i,t}^x x_t^i \right] \right\} \tag{5.20}$$

$$F_t^i \equiv c_t^i + \sum_{\tau=1}^{K} Q_t^{(\tau)} (b_{i,t+1}^{(\tau-1)} - b_{i,t}^{(\tau)}) + x_t^i - b_{i,t}^{(0)} - R_{t-1}^i x_{t-1}^i - \tilde{\omega}_t^i \tag{5.21}$$

where $\gamma_{i,t} \geq 0$, $\mu_{i,t}^{b,\tau} \geq 0$, and $\mu_{i,t}^x \geq 0$ are the Lagrangian multipliers. The first-order conditions are as follows

$$u'(c_t^i) = \gamma_{i,t} \quad \forall t \tag{5.22}$$

$$-\gamma_{i,t} Q_t^{(\tau)} + \mu_{i,t}^{b,\tau} + \mathbb{E}_t \left[\beta \gamma_{i,t+1} Q_{t+1}^{(\tau-1)} \right] = 0 \quad \forall t, \tau \tag{5.23}$$

$$\mu_{i,t}^x - \gamma_{i,t} + \mathbb{E}_t \left[\beta \gamma_{i,t+1} R_t^i \right] = 0 \quad \forall t \tag{5.24}$$

Rearrange terms we get the standard Euler equations of incomplete-market models with occasionally binding borrowing constraints

$$\frac{\mu_{i,t}^{b,\tau}}{u'(c_t^i)} + \mathbb{E}_t \left[\Lambda_{t,t+1}^i Q_{t+1}^{(\tau-1)} \right] = Q_t^{(\tau)} \quad \forall t, \tau \tag{5.25}$$

$$\frac{\mu_{i,t}^x}{u'(c_t^i)} + \mathbb{E}_t \left[\Lambda_{t,t+1}^i \right] R_t^i = 1 \quad \forall t \tag{5.26}$$

$$\Lambda_{t,t+1}^i \equiv \beta \frac{u'(c_{t+1}^i)}{u'(c_t^i)} \tag{5.27}$$

where $\Lambda_{t,t+1}^i$ is the stochastic discount factor for type-i investors.

When the short-sale constraints on bond positions prevent type-i investors from borrowing funds by posting bonds as collateral, the equilibrium bond price is higher than the fair valuation of type-i investors. For discount factors, if type-i investors hold cash in the Fed's deposit facility, they discount future cash flows based on the policy rate they are eligible to. But when type-i investors withdraw all cash holdings from the Fed's deposit facility, either because of higher returns from government bonds or a negative income shock, their effective discount factor will become higher than what the policy rate, thereby affecting their valuation of government bonds.

Depending on which constraint is binding in equilibrium, bond yields could be higher or lower than the yield implied by the expectation hypothesis. While a binding constraint on bonds reduces the bond yield, a binding constraint on the Fed's policy facility increases the bond yield. It is also worth noting that the short-sale constraint on type-i investors' policy facility affects all bond pricing equations through its effect on $\Lambda_{t,t+1}^i$.

To get a better idea of how these two types of short-sale constraints affect bond pricing, we can express the bond price $Q_t^{(\tau)}$ as a function of the Lagrangian multipliers. Expanding the

Euler equation (5.25) forward for $h \geq 1$ days, we have

$$Q_t^{(\tau)} = \mathbb{E}_t \left[\left(\prod_{k=0}^{h} \Lambda_{t+k,t+k+1}^i \right) Q_{t+h+1}^{(\tau-h-1)} + \frac{1}{u'(c_t^i)} \sum_{k=0}^{h} \beta^k \mu_{i,t+k}^{b,\tau-k} \right] \tag{5.28}$$

Let $h = \tau - 1$, then we are pricing a risk-less asset since $Q_{t+\tau}^{(0)} = 1$. Denote the daily yield-to-maturity of this τ-day bond as $y_t^{(\tau)} \equiv -\log Q_t^{(\tau)}/\tau$, equation (5.28) becomes

$$y_t^{(\tau)} = -\frac{1}{\tau} \log \mathbb{E}_t \left[\left(\prod_{k=0}^{\tau-1} \mathbb{E}_{t+k}\, \Lambda_{t+k,t+k+1}^i \right) + \frac{1}{u'(c_t^i)} \sum_{k=0}^{\tau-1} \beta^k \mu_{i,t+k}^{b,\tau-k} \right] \tag{5.29}$$

where we make use of the law of iterated expectations. We can further replace stochastic discount factors using (5.26). Let $y_{t+k}^i \equiv \log R_{t+k}^i/365$ be the continuously-compounded daily yield of policy facility i, then (5.26) can be written as

$$\mathbb{E}_{t+k} \left[\Lambda_{t+k,t+k+1}^i \right] = \exp\left(-y_{t+k}^i - \psi_{t+k}^i \right) \quad \forall k \geq 0 \tag{5.30}$$

where

$$\psi_{t+k}^i \equiv -\log \left(1 - \frac{\mu_{i,t+k}^x}{u'(c_{t+k}^i)} \right) \geq 0 \tag{5.31}$$

is a measure of the shadow value of facility i. The assumption that $u'(c_t^i) > 0$ guarantees ψ_t^i is well-defined.[28] Also note that, when $\mu_{i,t+k}^x = 0$, $\psi_{t+k}^i = 0$; when $\mu_{i,t+k}^x > 0$, $\psi_{t+k}^i > 0$. Combine equation (5.29) and (5.30) we have

$$y_t^{(\tau)} = -\frac{1}{\tau} \log \mathbb{E}_t \left[\exp\left(-\sum_{k=0}^{\tau-1} (y_{t+k}^i + \psi_{t+k}^i) \right) + \sum_{k=0}^{\tau-1} \beta^k \tilde{\mu}_{i,t+k}^{b,\tau-k} \right] \tag{5.32}$$

where we define a new term $\tilde{\mu}_{i,t+k}^{b,\tau-k}$ by normalizing the Lagrangian multiplier $\mu_{i,t+k}^{b,\tau-k}$ using the marginal utility of consumption. Note that since $u'(c_t^i) > 0$, $\tilde{\mu}_{i,t+k}^{b,\tau-k}$ and $\mu_{i,t+k}^{b,\tau-k}$ has the same sign.

Type-i investors make a trade-off between the risk-less return of holding an n-day bond until maturity and the expected return of an actively traded portfolio. If type-i investors do not face any constraint so that $\mu_{i,t+k}^x = 0$ and $\mu_{i,t+k}^{b,n-k} = 0$, we have the expectation hypothesis. If type-i investors are expected to be constrained by either of the two constraints on any of the following n days with positive probability, the expectation hypothesis fails to hold. However, conditional on binding, these two types of short-sale constraints distort the equilibrium yield in opposite directions. While a binding constraint on the policy facility implies that the n-day bond is traded at a discount, a binding constraint on bonds implies that the n-day bond is traded at a premium. We can therefore identify the binding constraint based on the direction of mispricing.

[28] ψ_t^i is well-defined only if $\mu_{i,t+k}^x < u'(c_{t+k}^i)$. To check if this condition holds, suppose $\mu_{i,t+k}^x \geq u'(c_{t+k}^i)$, then from (5.26) we know that $\mathbb{E}_{t+k}\, \Lambda_{t+k,t+k+1}^i \leq 0$, which is contradicting to $u'(c_t^i) > 0$.

5.2.3 Equilibrium Characterization

Our definition of equilibrium follows a standard competitive general equilibrium with heterogeneous agents. Specifically, the equilibrium consists of a sequence of bond prices $\{Q_t^{(\tau)}\}_{t\geq 0}$ and quantities $\{c_t^i, b_{i,t+1}^{(\tau)}, x_t^i\}_{\forall i,t}$ such that: 1) given bonds prices, exogenous policy rates, endowment shocks, and asset holdings, investors choose their optimal policies according to first-order conditions (5.25) and (5.26); 2) bond prices adjust so that the aggregate bond demand is equal to the aggregate bond supply B_t, which is an exogenous process:

$$\sum_i b_{i,t+1}^{\tau} = B_t \tag{5.33}$$

We are not interested in fully solving the equilibrium policies since our model misses some important ingredients that are necessary for a serious quantitative calibration exercise.[29] Rather, we are interested in the high-frequency dynamics of interest rates given a relatively static macro condition. In this sens, our model can be mapped to the time window between two consecutive FOMC meetings or releases of macro statistics so that these low-frequency information of the macro economy do not affect investors' perception of the evolution of policy rates and bond supply.

However, we can still make some sharp predictions on what the equilibrium should look like. Since we express the equilibrium bond yield as a function of multipliers, we equivalently look for some restrictions on the realized values of Lagrangian multipliers in equilibrium. An important observation is that government bonds of the same tenor are traded at a single price, regardless of which types of investors are submitting the bid. This implies that in equilibrium the right hand side of the following first-order conditions should be equal to each other:

$$y_t^{(\tau)} = -\frac{1}{\tau}\log \mathbb{E}_t\left[\exp\left(-\sum_{k=0}^{\tau-1}(y_{t+k}^H + \psi_{t+k}^H)\right) + \sum_{k=0}^{\tau-1}\beta^k \tilde{\mu}_{H,t+k}^{b,\tau-k}\right] \tag{5.34}$$

$$y_t^{(\tau)} = -\frac{1}{\tau}\log \mathbb{E}_t\left[\exp\left(-\sum_{k=0}^{\tau-1}(y_{t+k}^L + \psi_{t+k}^L)\right) + \sum_{k=0}^{\tau-1}\beta^k \tilde{\mu}_{L,t+k}^{b,\tau-k}\right] \tag{5.35}$$

Case I: $\psi_{t+k}^H = 0$ and $\psi_{t+k}^L = 0$ The first case assumes that in equilibrium both banks and shadow banks hold positive positions in policy facilities throughout the life of the government bonds, which is consistent with what we observed before 2018. Since $y_{t+k}^H > y_{t+k}^L$, we have

$$\mathbb{E}_t\left[\sum_{k=0}^{\tau-1}\beta^k\left(\tilde{\mu}_{H,t+k}^{b,\tau-k} - \tilde{\mu}_{L,t+k}^{b,\tau-k}\right)\right] > 0 \tag{5.36}$$

[29] For example, we don't take a stand on how the aggregate bond supply or the stock of reserve balances evolve over time since the dynamics of these two variables are independent if monetary policy and fiscal policy are independent. It would also be interesting to explicitly model investors as financial intermediaries who issue short-term debt to households to raise funds. When the Fed raises interest rates, households tend to shift their funds to money market funds since the opportunity cost of holding low-yield bank deposits becomes higher (Xiao, 2018). This effectively changes the initial endowment wealth x_{-1}^i, which we take as exogenous.

This condition implies that it is impossible that banks participate in the bond market throughout the entire life of the τ-day bond, because otherwise we would have $\mu_{H,t+k}^{b,\tau-k} = 0$, which contradicts $\mu_{L,t+k}^{b,\tau-k} \geq 0$. In words, if both banks and shadow banks deposit in the Fed's policy facilities, banks must have the incentive to take short positions in government bonds for at least one period.

A direct implication is that for $\tau = 1$, $\mu_{H,t}^{b,1} > 0$ and thus $b_{H,t}^{(1)} = 0$ since it is the only Lagrangian multiplier in the pricing equation. Namely, for overnight bond yields, as long as both types of investors hold cash positions in the policy facilities, banks do not participate in the bond market.

Case II: $\psi_{t+k}^H = 0$ and $\mu_{H,t+k}^{b,\tau-k} = 0$ If banks do hold positive amount of government bonds in equilibrium, the bond yield must satisfy the following equation

$$y_t^{(\tau)} = -\frac{1}{\tau} \log \mathbb{E}_t \exp \left[-\sum_{k=0}^{\tau-1} y_{t+k}^H \right] = -\frac{1}{\tau} \log \mathbb{E}_t \exp \left[-\sum_{k=0}^{\tau-1} \left(y_{t+k}^L + \psi_{t+k}^L \right) \right] \tag{5.37}$$

In equilibrium, type-H investors are marginal investors of bonds since the bond price is equal to their fair valuation. In comparison, type-L investors take long positions in bonds and short positions (zero position) on the reverse repo facility, thereby earning a positive premium over their policy rate by holding bonds. More generally, this is also the equilibrium solution in a model where only type-L investors face short-sale constraints on bonds, which is close to what we observe in the real world.

5.2.4 IOR Spreads

The IOR spreads in our model can be expressed as a function of the Lagrangian multipliers:

$$1 = \mathbb{E}_t \left[\exp \left(\tau y_t^{(\tau)} - \sum_{k=0}^{\tau-1} y_{t+k}^i \right) \exp \left(-\sum_{k=0}^{\tau-1} \psi_{t+k}^i \right) \right] + e^{\tau y_t^{(\tau)}} \mathbb{E}_t \left[\sum_{k=0}^{\tau-1} \beta^k \tilde{\mu}_{i,t+k}^{b,\tau-k} \right] \tag{5.38}$$

Equation (5.38) shows that the average arbitrage spread over the life of a τ-day bond depends on the expected values of Lagrangian multipliers on two types of short-sale constraints. However, the way that each type of short-sale constraint affects the arbitrage spread is different both qualitatively and quantitatively.

To simplify the exposition and excludes any effect from the expectation of future monetary policy, let's consider a case in which the bond matures before the next FOMC meeting so that $y_{t+k}^i = y_t^i$, for $1 \leq k \leq \tau - 1$. Then equation (5.38) becomes

$$y_t^i - y_t^{(\tau)} = -\frac{1}{\tau} \log \left(1 - e^{\tau y_t^{(\tau)}} \mathbb{E}_t \sum_{k=0}^{\tau-1} \beta^k \tilde{\mu}_{i,t+k}^{b,\tau-k} \right) + \frac{1}{\tau} \log \mathbb{E}_t \exp \left(-\sum_{k=0}^{\tau-1} \psi_{t+k}^i \right) \tag{5.39}$$

Variation in different types of Lagrangian multipliers delivers different impacts on the arbitrage spread. Qualitatively, a binding short-sale constraint on type-i investors' bond positions *raises* the spread by pushing down the equilibrium bond yield, while a binding short-sale constraint on type-i investors' policy facilities *reduces* the spread. Since the unconstrained arbitrage spread is zero, the impulse responses of these two types of short-sale constraint have *different signs*. A negative arbitrage spread for type-i investors implies that type-i investors do not reserves in the i-th deposit facility and the sum of multipliers ψ^i_{t+k} is greater than zero. In contrast, a positive arbitrage spread on asset j indicates that type-i investors are constrained from taking short positions on asset j. Therefore, if we observe a decline of positive arbitrage spreads while banks are actively holding reserve balances, it reflects a shift of equilibrium from Case I to Case II. Namely, banks are initially constrained from shorting bonds and all investors hold policy deposits, but the equilibrium soon transits to the one where banks take long positions and money market funds exit the Fed's reverse repo facility.

Quantitatively, the effect of a binding $\mu^{b,\tau-k}_{i,t+k}$ decreases as k increases, while the effect of a binding $\mu^{x,\tau-k}_{i,t+k}$ is invariant to k. To see this, we conduct a numerical exercise in which we compute the instantaneous response of current arbitrage spread on shocks to Lagrangian multipliers at different horizons. Specifically, we set parameters to reasonable values and solve the equilibrium arbitrage spread based on equation (5.39), given pre-specified values of Lagrangian multipliers. We consider a bond with $\tau = 100$ days to mature and give a shock to the multiplier on the k-th day only, $k = 0, 1, 2, ...99$. The arbitrage spread derived this way is essentially a time-0 impulse response to information shocks that change the expected value of Lagrangian multipliers.

6 Monetary Transmission in Repo Markets

In this section, we will empirically investigate the source of variation in IOR spreads using our transaction-level repurchase agreement data. Repurchase agreement, or "repo" for short, is a secured debt contract that enables the borrower to obtain cash from the lender by posting financial securities as collateral, with the promise that she/he will repurchase the security at a pre-specified price. The difference between the repurchase price and the principal amount reflects the risk-less rate of return conditional on the borrower repurchasing the security. If the borrower fails to repurchase the security, the security is owned by the cash lender. Since the term of a typical repo contracts is very short (around several days) and the collateral assets can be highly safe (e.g. Treasury bonds), the repo rate can be viewed as a good measure of risk-free rate. The repurchase agreement (repo) market is the most important source of secured funding in the modern financial system and the transmission of monetary policy in this market significantly affects the funding conditions of many financial institutions. During the 2008 financial crisis, it also played an important role in the collapse of Lehman Brothers, triggering a large literature on shadow banking and financial crises.[30] We will exploit the power of our detailed repo market data and shed light on some important aspects of monetary transmission, including the role of the RRP facility.

When we bring model to data, the short-sale/funding constraint we have in mind is similar to the supplementary leverage ratio rule implemented by Basel III because both of them operate on the extensive margin by limiting the amount of short positions that a financial institution can take, regardless of the risk profile of the institution's portfolio. Many papers argue that this

[30] See, for example, Gorton and Metrick (2012), Martin, Skeie, and Thadden (2014), and Copeland, Martin, and Walker (2014).

feature of the SLR severely hampers pricing efficiency in various markets, including the foreign exchange market (Du, Tepper, and Verdelhan, 2018), the corporate bond market (Bessembinder et al., 2018), and many short-term arbitrage transactions (Boyarchenko et al., 2018). We will show that the same thing happens for the repo market. In particular, due to the fact that repo contracts settled in a DVP manner are doubled-counted under the SLR, market making activities that channel funds from the tri-party repo market to bilateral repo market are even more costly for bank-affiliated dealers than other types of trade.[31]

For repo markets, funding constraints and repo issuance (or cash demand) are two sides of the same coin: allowing constrained banks to borrow more inevitably supplies more repos. Therefore, we can treat the variation in funding constraints as supply shocks to private debt. On the other hand, factors that increase the supply of other competing money market assets (e.g. Treasury bills) or decrease the level of reserves available for cash lenders (e.g. balance sheet normalization) are treated as shocks to reserves, or public debt. With this interpretation, we are able to answer questions such as whether the provision of government debt can crowd out private debt.[32] Also note that repo contracts can turn long-term securities (such as a 10-year Treasury bond) into short-term assets that are within the investment universe of money market funds. As such, the supply of Treasury notes and bonds also affects the supply of repo contracts to the extent that it helps relaxes the collateral constraint faced by repo issuers.

6.1 The Structure of Repo Markets

Demand-side participants in the repo market include financial institutions who wants to get secured funding, mainly banks, security dealers (or bank dealers if it is a subsidiary of a bank holding company), hedge funds, etc. Supply-side participants include cash lenders, including money market funds, government-sponsored enterprises (GSEs), and large corporations with abundant cash, security lenders with large cash balances.

Since collateral management and settlement are very sophisticated, gradually some large banks (i.e., JPMC and BNYM) start to act as the clearing agent for repo market participants. The clearing bank sets up cash and securities accounts for repo market participants on its own balance sheet, and facilitates the repo funding process by matching counterparties and settling repo transactions through its own infrastructure. Repo contracts issued in this way are called tri-party repos. In comparison, repo contracts issued via direct communication between two counterparties are called bi-lateral repos. Typically, bilateral repos transactions only happen between broker-dealers and hedge funds, or within broker-dealers.

Repo markets have different layers. Due to the technological limitation in conducting bilateral repo transactions, ultimate cash investors (e.g. MMFs) mainly lend to large bank dealers

[31]If a repo contract is treated as a secured loan, then the issuer expands its balance sheet for the same amount of what it borrows through repo, which pushed up the leverage ratio. Though such an accounting standard may seem unreasonable, it has its historical origin: if a repo contract is counted as a sale of security, then a bank can reduce the size of its balance sheet by using repo proceeds to pay down its liability, thereby lowering its leverage ratio. Lehman Brothers did exactly the same thing before 2008. See `https://www.fsgexperts.com/wp-content/uploads/2013/01/Lehman-and-Repo-105-Final-_2_.pdf`

[32]See Krishnamurthy and Vissing-Jorgensen (2015).

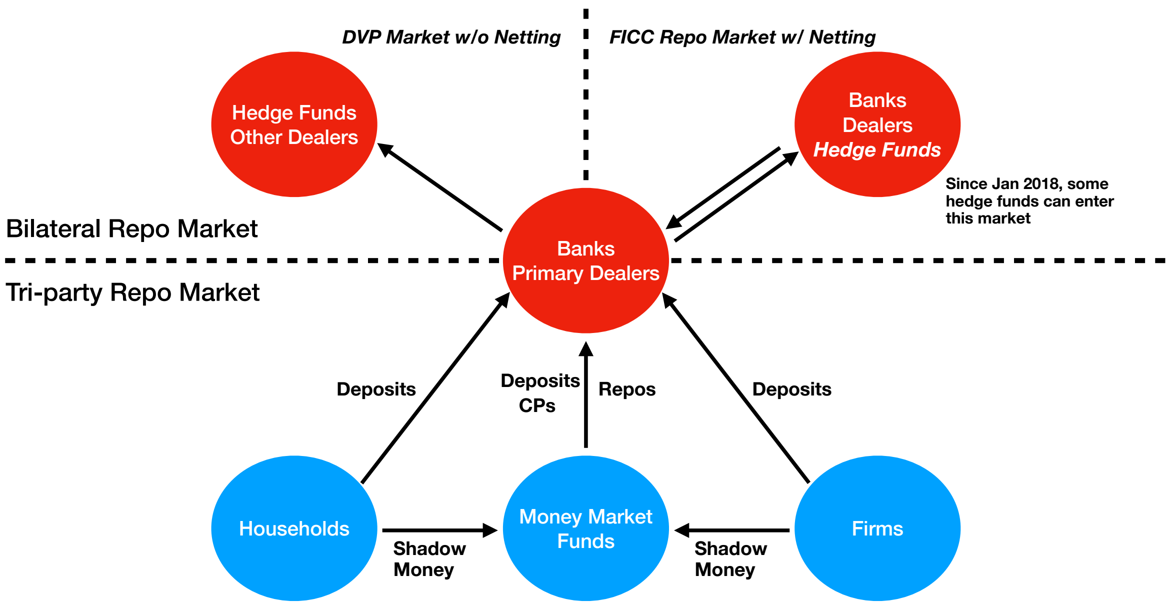


Figure 10. The structure of repo markets.

in the tri-party repo market.[33] Large banks and their securities dealer subsidiaries are the largest group of issuers in the tri-party repo market. A typical purpose of tri-party repo borrowing is to channel funds to smaller broker-dealers and hedge funds in the bilateral repo market.

Within the tri-party repo market infrastructure, there is a special platform that allows repo netting, operated by DTCC Fixed Income Clearing Corporation (FICC).[34] There are two segments in the FICC's platform: the General Collateral Financing (GCF) repo market, which is a blind-brokered general collateral repo market, and a bilateral market called the DVP (delivery-versus-payment) repo market. Participation in the FICC's repo markets requires membership, which are mainly assigned to large bank dealers, the major borrowers in the tri-party repo market. However, since 2005, other participants can also get access to these FICC-cleared markets through the FICC's Sponsored Repo Service, in which sponsoring banks intermediate trades on their balance sheets. Registered investment companies (e.g. mutual funds) are the only group of investors allowed by the SEC to get access to the sponsored repo market. But since January 2018, SEC approved that hedge funds are allowed to be sponsored members. Figure 4 illustrates how different segments are connected. See Appendix 2.3 for more details.

6.2 Identification Strategy

To identify exogenous variation in funding constraints, we exploit two unique events in the repo market. First, the difference in the regional implementation of Basel III leverage ratio rule

[33] In fact, within the 40 repo issuers with significant market exposure in my sample, there are only 4 nonbank issuers.

[34] Repo netting allows issuers and lenders to cancel out repo transactions with the same collateral but reverse directions. In this way, participants can greatly save their balance sheet capacity.

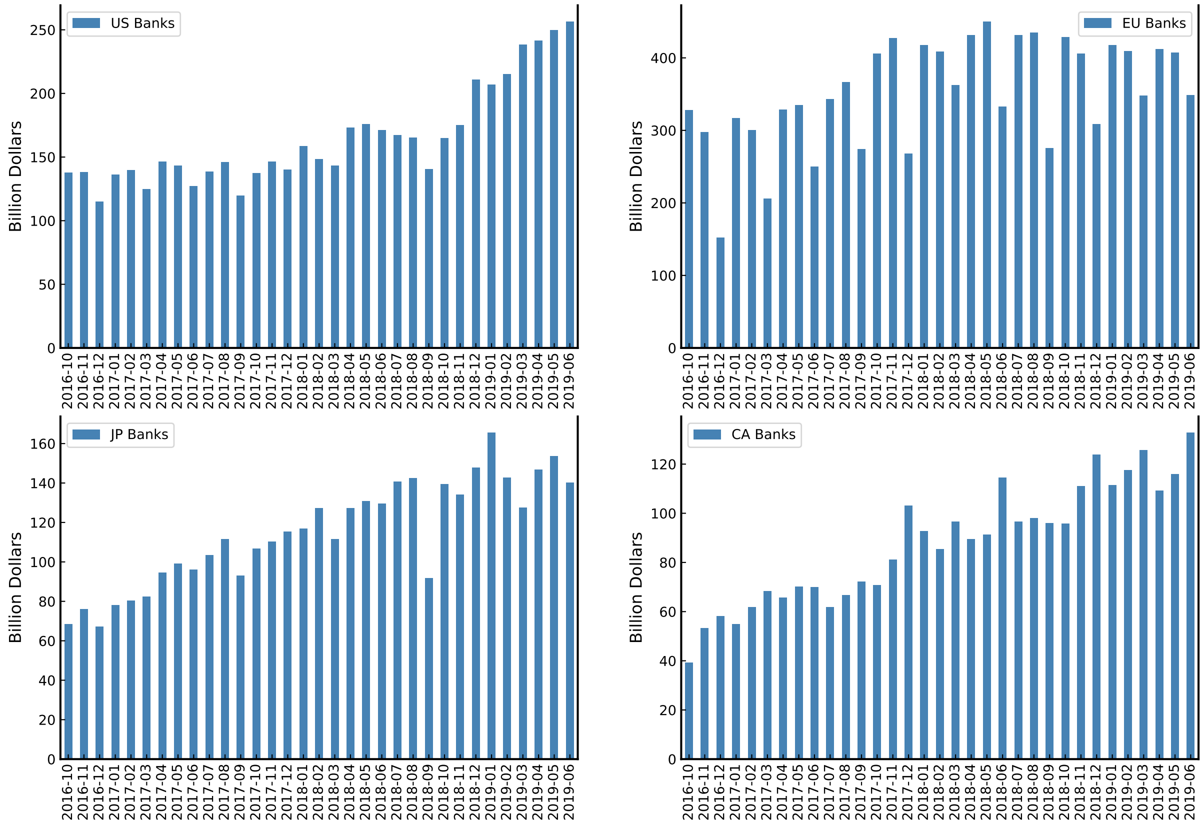


Figure 11. Window-dressing activities in the tri-party repo market.

generates a seasonal movement in repo supply (cash demand) that is driven by the variation in funding constrains. While U.S. bank holding companies have to report daily average statistics of their balance sheets, some foreign bank holding companies only need to report leverage ratios at the end of every quarter. In months that are not the end of each quarter, the effective leverage constraints faced by these foreign banks are less strict than U.S. banks. As a result, unconstrained foreign banks have a strong incentive to engage in window-dressing activities: they expand leverage above the maximum level during the quarter and gradually reduce leverage ratios below the maximum level by the end of each quarter (see Munyan (2015) and Anbil and Senyuz (2018)). The size of window-dressing is very large: the decline of outstanding repos issued by European dealers alone can be over 100 billion dollars. Since such window-dressing incentives are exogenous to other factors that affect repo supply in repo markets, we use the seasonal variation in repo issuance related to window-dressing to measure the degree of variation in funding constraints.

Note that whether a foreign bank is able to engage in window-dressing depends on the specific implementation details of Basel III in its country of domicile and the rules are changing over time. For example, from October 2016 to June 2019, French banks and Credit Suisse engaged in much more window-dressing activities compared to other European banks. Even banks within the same country might behave differently: Mizuho bank is the only Japanese bank that actively engages in window-dressing activities. Therefore, unlike previous works who

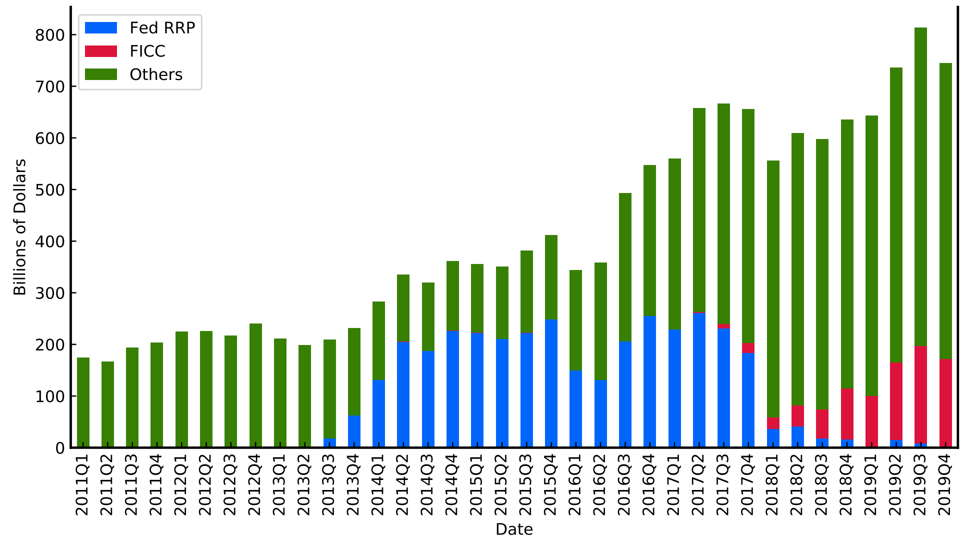


Figure 12. Monthly volume of tri-party repos held by money market funds. Source: N-MFP2 filings.

classify issuers using regions, in some exercises we will identify window-dressing eligibility at the issuer level.

The second event is an infrastructure reform affects the payment and clearing technology of a sub-group of repo market borrowers. On Jan 31st 2018, DTCC opened the FICC's sponsored repo market to hedge funds in order to alleviate the balance sheet constraint faced by bilateral repo market makers. The sponsored repo market is a tri-party Treasury repo market in which a sponsoring bank who has access to the FICC clearing platform acts as the intermediary between cash lenders and borrowers eligible to the sponsored repo program. Before Jan 2018, sponsored members are restricted to registered investment companies, including mutual funds and investment trusts, and sponsoring banks are limited to several large U.S. commercial banks that are FICC/GSD members. Since both legs in a sponsored repo transaction can be netted by FICC, in theory, the reform allows hedge funds and sponsoring banks to get around the SLR rule as long as their net positions comply with the SLR at the end of the trading day. We treat this event as an exogenous shock that relaxes the funding constraints for sponsoring banks, which generates an aggregate repo supply shock to tri-party repo market.[35]

6.3 Theoretical Mechanisms and Predictions

Our theoretical model predicts that when money market funds actively participate in the reverse repo facility, the equilibrium repo rate is insensitive to changes in repo borrowing because the excess cash demand can be fully absorbed by the reverse repo facility at the policy rate. Such a scenario is more likely to appear in an environment with relatively abundant bank reserves. Any factor that increases cash holdings by MMFs may contribute to the abundance of reserves, including, for example, the expansion of central bank balance sheet, or, limited supply of safe and

[35]Though DTCC does not provide updated information on sponsoring banks, all bank dealers in our sample are qualified for FICC repo netting service.

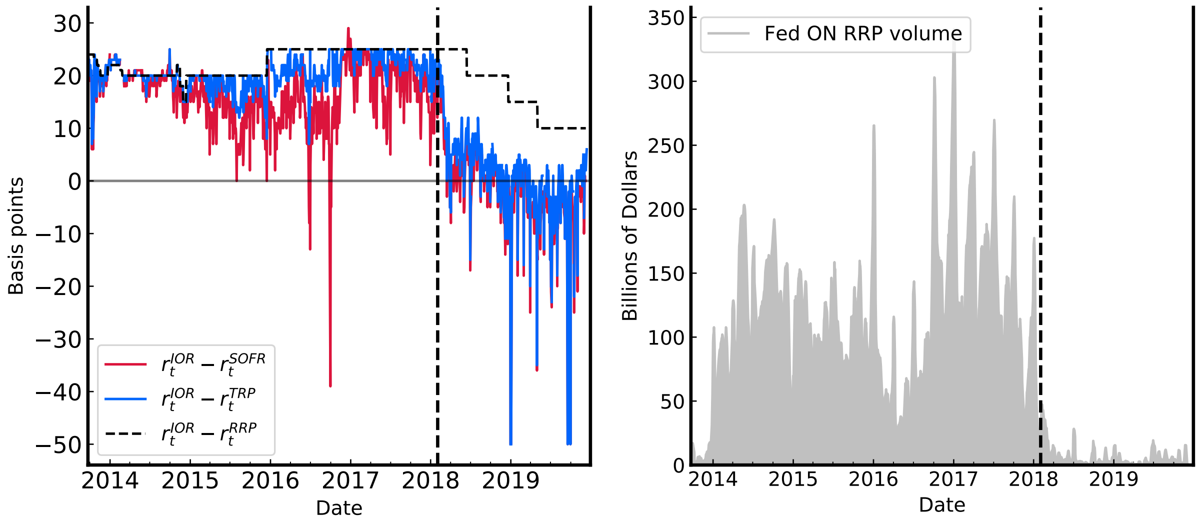


Figure 13. Regime shifts in interest rates and RRP participation. Left panel: daily time series of IOR spreads on BNYM Treasury tri-party repo rate index and the SOFR index, measured in basis points. Right panel: the daily volume of the Fed's reverse repo facility, billions of dollars. The vertical dashed line corresponds to Jan 31st 2018, which is the transition point of the estimated latent state in the benchmark Markov-switching dynamic regression. Source: BNYM, the Federal Reserve Bank of New York.

short-term assets. The latter could result from funding constraints or the scarcity of collateral assets, as argued by some authors. Also note that the stabilizing effect of the reverse repo facility applies to all markets within the investment universe of its participants. So a local market shock that causes reserve scarcity will also impact other markets, just as what we see in the theoretical model.

In an environment without the reverse repo facility, we expect that window-dressing would lower tri-party repo rates at the end of each quarter because it generates a large excess cash supply in the tri-party repo market that requires lower repo rates to clear the market. The extent of drop might depend on the availability of alternative assets such as Treasury bills. As an alternative theory, repo rates may drop because cash borrowers have more bargaining power at the end of each quarter (Bech and Klee, 2011). However, the HHI for both supply and demand side are smaller than 0.1, indicating a low level of concentration. So we still prefer a competitive market theory.

Before January 2018, money market funds were satiated with cash, which can be seen from the fact that the Fed's reverse repo facility had several hundred billion dollars of volume before the FICC's reform (see Figure 12). Therefore, despite the large variation in repo volumes driven by window-dressing, we do not expect to see much variation in tri-party repo rates across different months in a given quarter. But for the bilateral repo market (i.e. FICC's GCF and DVP), window-dressing inevitably generates a decline in cash supply, unless bank dealers intentionally shift more funds to this market. So we expect the bilateral repo rates to increase (GCF-repo spreads widen) at the end of each quarter. Note that this effect is independent of the abundance of reserves, but reserve scarcity does affect the degree of quarter-end liquidity tightening.

After the FICC reform, hedge funds who participate in the sponsored repo market may find it optimal to expand their bilateral repo borrowings because their sponsoring banks are not constrained in this segment of the repo market.[36] If large enough, this new source of cash demand can absorb all the residual cash supply in the tri-party repo market, which drains out the RRP facility and makes cash supply inelastic. With scarce reserves, the non-FICC segment of tri-party repo market has to be cleared on the intensive margin at the end of each quarter. However, window-dressing might not lead to lower tri-party repo rates at quarter ends. Rather, the aggregate demand shock can even exacerbate the quarter-end imbalance in the bilateral repo market and push up tri-party repo rates via competition for cash between sponsoring banks.

If the aggregate repo supply is large enough, banks can also enter the bilateral repo market as cash lenders using their excess reserve balances, which help anchor the bilateral repo rates at IOR. In an extreme case where banks also run out of excess reserve balances, repo rates would disentangle from policy rates and the Fed would lose control over this segment of the money market.

Prediction 1. *Let $\Delta\bar{B}_t$ denote the repo supply shock driven by window-dressing at time t, r_t^{TRP} the tri-party repo rate, and r_t^{BRP} the bilateral repo rate. Conditional on abundant MMF cash holdings, $\partial r_t^{TRP}/\partial\Delta\bar{B}_t$ is close to zero; conditional on scarce MMF cash holdings, the sign of $\partial r_t^{TRP}/\partial\Delta\bar{B}_t$ depends on the aggregate repo supply in the bilateral repo market. Fot the bilateral repo market, $\partial r_t^{BRP}/\partial\Delta\bar{B}_t < 0$ for both cases, but the absolute value is larger with scarce cash holdings.*

6.4 The Effects of Variation in Funding Constraints

6.4.1 Descriptive Evidence

Figure C.3 to C.8 plot a series of descriptive statistics of Treasury and agency repos issued by different groups of entities in the tri-party repo market.[37] The first observation is that window-dressing activities also appear in our first sub-sample. Before January 2018, European banks reduce their repo issuance by almost half at the end of each quarter, while other prime repo borrowers do not engage in window-dressing to such extent. However, the volume of the Fed's reverse repo facility is almost doubled at quarter ends. The average and median IOR-repo spreads do not experience visible variation across different months in a given quarter, but the quarter-end GCF-repo spreads significantly expand. We see these facts as supporting the view that RRP helps absorb the excess cash supply generated by window-dressing, which leaves the

[36] Boyarchenko et al. (2018) provides evidence that hedge funds cannot conduct certain arbitrage trades because bank dealers cannot supply enough funds to them, even though hedge funds do not face funding constraints by themselves.

[37] We manually match each issuer to its region of domicile. Bank dealers are aggregated to their parent company. "US Nonbanks" include several large buyside financial institutions and U.S. repo broker-dealers. "Others" includes borrowers that are not bank holding companies or are very inactive in the tri-party repo market. Each month is assigned to one of the three groups of months, depending on its order within a given quarter. Left panels show the sub-sample before the FICC's reform and the right panels show the sub-sample after the reform. Note that for aggregate repo volumes and the number of repo contracts, we drop the last two months so that the number of months in three subgroups remain the same.

tri-party repo rates unaffected. Nevertheless, the GCF repo market experiences less quarter-end cash supply, which needs to be cleared via higher repo rates.

The FICC's reform made several important changes to the repo market. Both the average and median level of IOR arbitrage spreads shifted downward for all non-Fed borrowers. More interestingly, IOR arbitrage spreads start exhibiting window-dressing patterns, indicating that the tri-party repo market also faces tightened liquidity condition at the end of each quarter. The GCF-repo spreads remain almost the same in months that are not quarter-end, but the quarter-end spreads increase by at least 100% for all non-FICC borrowers. The quarter-end imbalance greatly intensifies as FICC's reform increases the aggregate repo supply in the bilateral repo market.

The FICC's sponsored repo market might need some more analysis due to its unique features. Repo contracts issued via the FICC's sponsored repo program has an average principal amount of around 1 billion dollars, which is several times larger than those issued by banks and non-bank borrowers in the tri-party repo market. Before the FICC's reform, the market is not that active and the total volume is almost negligible compared to other borrowers. After the introduction of hedge funds, the aggregate volume gradually increased to almost 200 billion dollars by the end of 2019. This is accompanied by a decrease of RRP volumes to almost zero (see Figure 12).

6.4.2 Fixed-effects Regression

To quantify the effect of window-dressing and FICC's reform on interest rate spreads, we estimate the the following contrat-level regression with fixed effects

$$y_t^{ij} = \theta_0 + \theta_1' C^i + \theta_2' C^i Q_t + \theta_3' C^i G_t + \theta_4' C^i Q_t \times G_t + \beta' X_t^{ij} + \varepsilon_t^{ij} \tag{6.1}$$

where y_t^{ij} denotes a variable of interest for repo contracts issued by borrower i to fund j at time t, including the average GCF-repo spread, the average IOR-repo spread, and the total principal amount borrowed by an issuer. Based on our identification strategy, the explanatory variables include a quarter-end dummy Q_t, an FICC reform dummy G_t, region indicators C^i, and their interactions. We add a vector of exogenous controls in X_t^{ij}, which may include fund j's asset under management and fund fixed effects, etc. To account for correlation among observations within the same borrower or fund, standard errors are two-way clustered at the issuer and fund level. Table B.10 reports the estimation results and the base case is U.S. banks with $G_t = 0$ and $Q_t = 0$.

Our predictions in Section 6.3 are largely borne out in the data. While U.S. banks do not change their total amount of repo issuance across different months in a given quarter, foreign banks significantly expand their repo issuance during months that are not quarter-end and reduce repo borrowings at quarter ends. This pattern is most pronounced for European banks, whose repo issuance is twice as large as what U.S. banks issue during expansion and only half of what U.S. banks issue during window-dressing. However, on the intensive margin, we do not observe significant and economically meaningful differences in repo rates across issuers or months within a quarter. Except for Japanese banks, cross-region repo rate differentials are within 2 basis points for all months and subsamples. In comparison, the GCF-repo spread increases by

7.5 basis points at quarter ends due to the decline of cash supply, but we still do not observe cross-region differentials. These results imply that there is a strong common component that drives the level of tri-party repo rates and the tri-party repo market is closer to competitive.

The FICC's reform allows all banks to issue around 40% more Treasury repos and reduces IOR-repo spreads by around 25 basis points on average, consistent with our interpretation that such an event relaxes the funding constraints faced by borrowers. However, the FICC's reform also *intensifies* the quarter-end liquidity condition in both the tri-party and the GCF repo market. While we do not observe any impact on GCF-repo spreads during months that are not quarter-end, tri-party repo rates and GCF-repo spreads increase by around 11 and 34 basis points on average at quarter ends, respectively. These results indicate that the introduction of hedge funds into the sponsored repo market generates a large shock to the aggregate cash demand in the bilateral repo market that absorbs all residual cash supply in the tri-party repo market and makes repo rates in both markets more sensitive to window-dressing. In the next part, we will quantify the (time-varying) sensitivity using identified repo supply shocks.

6.5 Regime Shifts in the Supply elasticity of Repo Rates

We now investigate how repo rates respond to variation in the supply of repo contracts and test whether the FICC's reform makes such responses more sensitive. A challenge in this type of empirical exercises is how to identify exogenous variation in repo supply. To address this problem, we implement an instrumental variable approach. We will exploit the granularity of our transaction-level repo data and estimate the variation in repo issuance driven by window-dressing activities, which is arguably exogenous to many other factors that affect repo issuance. We then estimate the component of IOR spreads driven by the estimated variation in repo issuance.

6.5.1 Stage I: Identifying Cash Demand Shocks

Our identification exercises tries to implement the following theoretical framework. Suppose $B_t^{i,u}$ is the unconstrained optimal repo issuance of issuer i at time t and $B_t^{i,c}$ is the constrained optimal conterpart. For the group of banks that are eligible to do window-dressing, the econometrician only observes $B_t^{i,u}$ during months that are not quarter-end and $B_t^{i,c}$ at quarter ends. For other banks, the econometrician always observes $B_t^{i,c}$. Therefore, our goal is to estimate the level of repo borrowing that would be made by window-dressing banks if they were constrianed instead.

Simply assuming that U.S. banks serve as the control group may not uncover the true latent dynamics for window-dressing banks because the constrained repo borrowings as well as window-dressing activities can bear significant heterogeneity across banks. Some U.S. banks might also engage in window-dressing, possibly in order to improve quarter-end financial ratios. Some foreign banks could either find it not profitable to engage in window-dressing at all, or, such window-dressing behaviors are not accepted by their internal rules.

To account for such heterogeneity, we estimate the repo supply dynamics in a panel regression

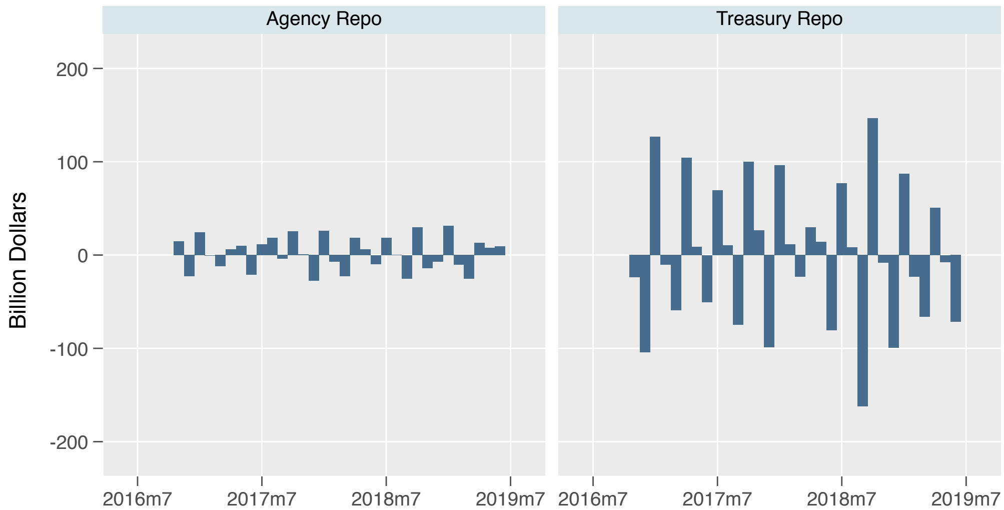


Figure 14. Variation in repo issuance driven by window-dressing activities. The series is constructed using the difference in monthly changes of repo issuance between foreign bank dealers and U.S. bank dealers. Foreign bank dealers include European and Japanese banks. Repo contracts are those held by money market funds and reported in the monthly N-MFP2 filings.

of the following form:

$$B_t^{ik} = \alpha + \sum_{h=1}^{3} \rho_h B_{t-h}^{ik} + \delta_{ik}' D_t + \eta_i + \phi_t + \varepsilon_t^{ik} \tag{6.2}$$

where B_t^{ik} is the total principal amount of repo contracts collateralized by type-k assets issued by firm i in month t, D_t is a vector of time dummies, η_i is the issuer fixed effect, and ϕ_t is the quarter time effect. We use δ_{ik}' to capture the variation in repo issuance that is driven by window-dressing activities. The simplest specification for D_t is a 3×1 vector of dummy variables that indicating the position of month t in its own quarter (window-dressing time dummies hereafter). Or, we could allow δ_{ik}' to vary across different years or regimes so that the estimates can captures the low-frequency variation of window-dressing activities for each issuer i. In our benchmark estimation, we will specify D_t as the interaction of window-dressing time dummies and year dummies. We use ρ_h to capture the latent dynamics of constrained repo supply, which is assumed to be common to all issuers. The common low-frequency shocks are captured by ϕ_t, while individual shocks are absorbed by residuals ε_t^i. We exclude Fed, U.S. repo brokers, and FICC from our estimation sample because they do not have the chance to engage in window-dressing and might have very different demand dynamics compared to other participants. By summing the estimated window-dressing coefficients across issuers and collateral, we construct a monthly time series of the aggregate component of repo supply driven by window-dressing activities: $B_t \equiv \sum_{i,k} \hat{\delta}_{ik}' D_t$. In the next section, we will use this estimate as an instrumental variable for exogenous variation in repo issuance and estimate the supply elasticity of repo rates.

6.5.2 Stage II: Estimating the Supply Elasticity of Repo Rates

Given the identified aggregate demand shocks, we estimate the supply elasticity of repo rates in a panel regression of the following form:

$$sp_t^{ijm} = \alpha + \theta' D_t + \gamma' D_t \Delta B_t + \eta_i + \psi_j + \beta' X_t^j + \varepsilon_t^{ijm} \tag{6.3}$$

where sp_t^{ijm} is the IOR-repo spread constructed using the m-th contract issued by issuer i and held by fund j at date t, η_i and ψ_j are fixed effects, and X_t^j is a vector of control variables, including fund-level variables such as monthly changes in cash holdings and net assets, and security-level variables such as days to maturity. Again, D_t is a vector of time dummy variables that helps us characterize the variation in elasticity across different states. For this regression, we define $D_t \equiv M_t \otimes G_t$, where M_t is a 3×1 vector of dummy variables indicating the month in a given quarter, and G_t is a 2×1 vector of FICC reform dummy variable.[38]

Note that we do not distinguish between variation in repo supply generated by foreign or domestic banks because all we care is whether the tri-party repo market is able to absorb repo supply shocks without large movements of repo rates, regardless of the source. The component of window-dressing done by foreign banks in excess of what a similar U.S. banks would do can serve as a better measure of the exogenous variation in funding constraints, but tends to overestimate the supply elasticity.

6.5.3 Estimation Results

We report the estimation results in Table B.11. With an abuse of notation, we will treat M_t and G_t as scalar indicator variables to facilitate labeling in our regression tables. Regression results are consistent with our theoretical predictions. Before the FICC's sponsored repo reform, repo rates do not respond to repo supply shocks are all, as reflected by an estimate of γ that is lose to zero and statistically insignificant: a repo supply shock of 1 billion dollars only moves the Treasury repo rates for contracts invested by RRP eligible funds by no more than 0.03 basis points on average for all months. This strongly supports our view that repo supply shocks can be fully absorbed by the Fed RRP facility without causing repo rates to move. After the reform, however, the estimates of γ become much larger and are statistically significant at 1% level.

During quarter ends, if repo supply declines by 1 billion dollars, Treasury repo rates for non-FICC issuers rise at least 0.94 basis points on average. Repos held by RRP ineligible funds and repos collateralized by agency securities tend to respond more sensitively. More interestingly, the supply elasticity of the FICC's sponsored repo rates is more than twice as large as that for Treasury repos issued by non-FICC entities, consistent with our theory that it is the large repo supply shock from the FICC-cleared bilateral repo market that drives the quarter-end rate spikes. As window-dressing reverses, repo rates fall back with slightly higher supply elasticity. Again, FICC-cleared repos respond the most to this relaxation of funding constraints.

Even though we do not treat variation in repo supply during the second month of a quarter as identified shocks, the estimates show that repo rates adjust lower in response to a decline in

[38] See regression results for details.

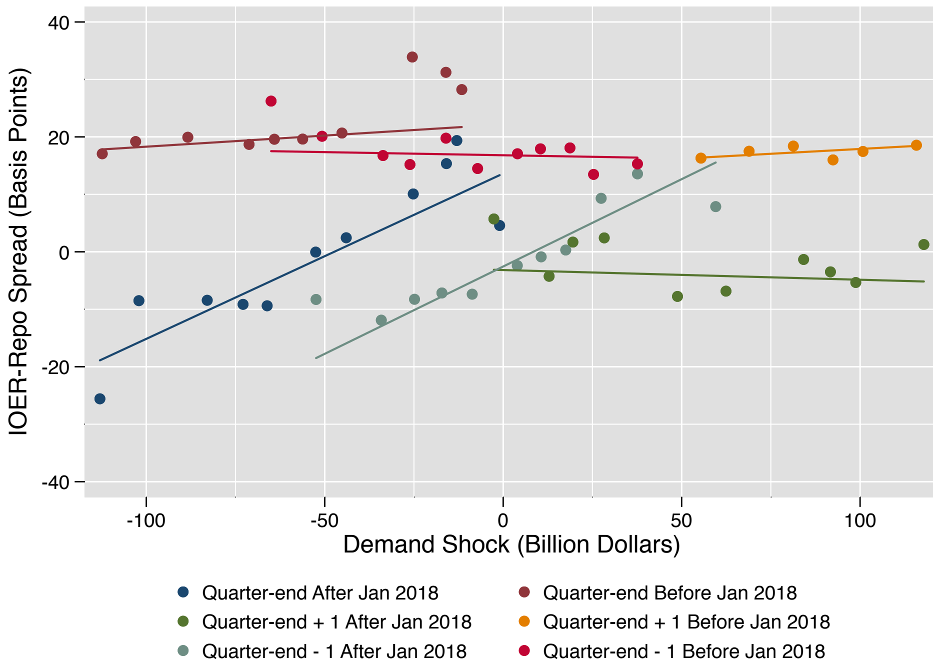


Figure 15. Binscatter plots of the supply elasticity of repo rates. Sample is restricted to Treasury repos issued by bank dealers from the United States, Europe, and Japan. The demand shock is constructed for each month by first taking the difference of total repo volumes between U.S. and foreign bank dealers and then taking the first difference. We include issuer-fund fixed effects and control for days to maturity and fund-level changes.

repo supply. This would happen if the tri-party repo market has to be cleared on the intensive margin but the supply-demand imbalance in the bilateral repo market is not severe, further supporting our argument that the observed response of tri-party repo rates at quarter ends are caused by the large excess repo supply in the bilateral repo market.

Finally, if a fund is eligible to the Fed's RRP facility, changes in cash positions do not correlate with repo rates. In contrast, changes in cash positions for RRP ineligible funds are negatively correlated with the IOR-repo spread. When their counterparties reduce cash demand, these funds cannot find alternative short-term investment opportunities equivalent to the RRP facility, which negatively impacts their bargaining power and investment returns.

6.6 Fed RRP as a Repo Rate Stabilizer

We complete our analysis by providing more evidence on the role of RRP facility. Our theory and previous results suggest that those funds who are eligible to the Fed's RRP facility is more flexible in dealing with repo supply shocks related to window-dressing. So a direct prediction is that declines of repo holdings at quarter ends are absorbed by the Fed's RRP facility. To test this prediction, we aggregate data to the region-fund level and run the following regression:

$$\Delta B_t^{jk} = \alpha + \beta_1 M_t \Delta B_t^{j,Banks} + \beta_2' X_t^j + \varepsilon_t^j \tag{6.4}$$

where ΔB_t^{jk} is the monthly change in fund j's repo holdings issued by borrowers of type k, X_t^j is a vector of controls for fund j. If $k = Banks$, the group represents European, Japanese, and U.S. banks who potentially engage in window-dressing activities. We do not attempt to conduct the same identification exercise as in the previous section because of the unobserved allocation effect of repo supply shocks. Therefore, $\Delta B_t^{j,Banks}$ can only be treated as weakly identified demand shocks at the fund level.

Table B.12 reports the regression results. Columns (1) and (2) report how demand shocks are absorbed by the Fed's RRP facility. We restrict the sample to months before Feb 2018 since after this date there is almost no participation in the RRP. Consistent with our prediction, around quarter ends, over 80% of the demand shocks are absorbed by the RRP facility. During the middle of a quarter, this proportion reduces to 50%. Another interesting observation is that changes in net assets are also absorbed by the RRP facility and the proportion is 54%. This suggests that the RRP facility also plays an important role in buffering fund-level liquidity shocks, but also suggests that money market funds do not have many alternative investment opportunities that can serve as a substitute for RRP.

To see if the FICC's sponsored repo can serve a similar role, we also run a similar regression using changes in the FICC's sponsored repo holdings. The sample is restricted to dates after January 2018 since there was almost no volume before this date. Columns (3) and (4) show that only around 10% are absorbed by the FICC's sponsored repos and such effects are largely insignificant. Changes in cash holdings and net assets also do not correlate with changes in FICC repo holdings.

7 Concluding Remarks

Even though it has been more than a decade since the Fed started to implement interest rate target with its new policy tools, theory and evidence on the effectiveness of these policy tools are still limited. The limitation poses challenges in understanding the mechanism of post-crisis monetary policy for both market participants as well as policy makers. For example, in September 2019, the Federal Reserve lent several hundred billion dollars via its liquidity facility in order to alleviate the tightening condition in repo markets, which seems puzzling because the outstanding amount of reserves was still over one trillion dollars.

As an attempt to fill some gap in this field, this paper presents theory and evidence on the mechanism of post-crisis monetary policy instruments. Our results point to the importance of market structure in the implementation of monetary policy. Maintaining the abundance of liquidity in key money market segment, such as the repo market, is important for the Fed to implement its floor system. Whether the level of reserves is abundant or not does not depend on its absolute value, but should be measured by the supply elasticity of repo rates. More coordination between different policy agencies are needed to improve the implementation of monetary policy and financial stability.

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A Markov-switching Estimation

In this section, we estimate a Markov-switching model of post-crisis interest rates and show that the model can identify a regime shift point at early 2018. Let s_t^j represent the policy rate used to price asset j at date t, which takes value from $\{H, L\}$. We interpret state H as the one where the risk-free component is equal to the IOR rate. Define $\theta(s_t^j)$ as an indicator function that is equal to 1 if $s_t^j = H$, and 0 vice versa. Then, based on Section 4.1, the expected return $\tilde{r}_t^j$ and the IOR spread can be expressed as

$$\tilde{r}_t^j = r_t^{RRP} + \theta(s_t^j)(r_t^{IOR} - r_t^{RRP}) + \rho_t^j - \xi_t^j - c^j \tag{A.1}$$

$$r_t^{IOR} - \tilde{r}_t^j = [1 - \theta(s_t^j)](r_t^{IOR} - r_t^{RRP}) - \rho_t^j + \xi_t^j + c(s_t^j) \tag{A.2}$$

We assume that s_t^j follows a two-state Markov process with an exogenous transition matrix and estimate equation (A.2) using Markov-switching dynamic regression with the following model specification

$$sp_t^j = \alpha(s_t^j) + [1 - \theta(s_t^j)]z_t + \Xi(s_t^j)\mathbf{x}_t + \sigma(s_t^j)\varepsilon_t^j \tag{A.3}$$

where $sp_t^j \equiv r_t^{IOR} - r_t^j$ is the IOR spread of asset j, $z_t \equiv r_t^{IOR} - r_t^{RRP}$, $\mathbf{x}_t$ is a vector of exogenous variables, including a month-end indicator controlling for window-dressing effect in the tri-party repo market and a variable controlling for funding stress in the repo market. The transition matrix is

$$P = \begin{bmatrix} p_{HH} & 1 - p_{HH} \\ 1 - p_{LH} & p_{LH} \end{bmatrix} \tag{A.4}$$

where $p_{HH} \equiv \mathbb{P}(s_{t+1}^j = H | p_t^j = H)$ and $p_{LH} \equiv \mathbb{P}(s_{t+1}^j = H | p_t^j = L)$ are the conditional transition probability from one state to another.

For the benchmark estimation, we use the spread between the GovPX overnight GC repo rate and the BNYM tri-party Treasury repo rate as a proxy of funding stress. In a competitive market, this spread reflects the cost that broker-dealers have to bear in order to channel funds from cash investors to end borrowers, such as hedge funds. During market stress, counterparty risk and the spiking demand for repo financing from cash borrowers widen this spread, which in turn raises the tri-party repo rate via competition. We also let the volatility to be state-dependent so that regime shifts in conditional volatility doesn't affect the identification of regime shifts in conditional mean. We estimate the parameters $\{\alpha(s_t^j), \theta(s_t^j), \Xi(s_t^j), \sigma(s_t^j); p_{HH}, p_{LH}\}$ via maximum likelihood and the estimation result is presented in Table 3.

Estimates of θ show that the risk-free component of T-bill rate seems to shift from the RRP rate to the IOR rate, while for two repo rates the risk-free component remains at the RRP rate across two regimes. In particular, conditional on $s_t^j = H$, the point estimate of θ is equal to 1, which is perfectly consistent with the interpretation that the IOR rate is used as the risk-free rate when pricing Treasury bills. But for repo rates, estimates of θ are very close to zero and are statistically significant at 1% level, indicating that money market funds are marginal investors across two regimes. This result supports our assumption that different asset j might have different marginal investors.

Table 3. Markov-switching Dynamic Regression

Estimation results of the benchmark Markov-switching dynamic regression. θ: an state-dependent parameter that represents the identity of marginal investors, constructed by taking the difference between one and the estimated coefficient on the IOR-RRP spread; Ξ_D: the effect of the month-end dummy variable; Ξ_{FS}: the effect of funding stress. If the original time series is at daily frequency, we take the weekly average. For month-end dummy, we set it to 1 if the week contains the last business day of the month.

	sp_t^{TB}		sp_t^{SOFR}		sp_t^{TRP}	
	$s_t^j = H$	$s_t^j = L$	$s_t^j = H$	$s_t^j = L$	$s_t^j = H$	$s_t^j = L$
θ	1	0.51 ***	0.2 ***	0.076 ***	0.087 ***	0.19 ***
Ξ_D	0.0098 *	0.0044	-0.026 ***	0.0051	-0.024 **	0.0074 **
Ξ_{FS}	-0.17 ***	0.0044	-0.99 ***	-0.67 ***	-0.94 ***	-0.15 ***
α	0.045 ***	0.0057	-0.042 **	0.035 ***	-0.043 **	0.038 ***
σ^2	0.00049 ***	0.0012 ***	0.0012 ***	0.00045 ***	0.0014 ***	0.00032 ***
p_{HH}	0.99	0.99	0.98	0.98	0.98	0.98
p_{LH}	0.0077	0.0077	0.0065	0.0065	0.0074	0.0074
AIC	-1236.71	-1236.71	-1357.91	-1357.91	-1420.65	-1420.65
BIC	-1192.07	-1192.07	-1313.26	-1313.26	-1376.01	-1376.01
N	305	305	305	305	305	305

Estimates of $\{\Xi_D, \Xi_{FS}, \alpha\}$ point to more relaxed balance sheet constraints conditional on $s_t^j = H$. IOR spreads are 8 basis points lower on average and 3 basis points lower at the end of each month, which together account for about half of the reduction in the average IOR spreads documented in Table B.8. In comparison, T-bill rates do not have economically significant changes across two regimes. Since the month-end effect is related to the balance sheet cost of broker-dealers when they borrow in the wholesale funding market, it is reasonable that only funding rates such as repo rates are impacted by such an effect. Finally, in the H state, IOR spreads are smaller under funding stress, indicating that broker-dealers and banks can raise more funds in the tri-party repo market when the demand for bilateral repo financing is high. This result further supports the view that in the H state broker-dealers and banks face more relaxed funding constraints. In particular, the relaxation is more likely on the extensive margin, such as more balance sheet capacity, rather than the intensive margin, such as transaction costs.

The estimated model also successfully capture the switching point that we found out in the preliminary results. In Figure 16, we plot the filtered probability of being in the H state at each week in our sample. For repo rates, there is only one shift in our sample from state L to state H, which happens around January 2018. For Treasury bill rate, the state first switches from H to L state in mid 2014, and then switches back to H state in January 2018. This further confirms that there are multiple latent processes that govern interest rates in different markets, which we interpret as the presence of different marginal investors.

Despite its appealing performance, the Markov switching model is just one way to characterize regime shifts. The assumption that state transitions are governed by a first-order Markov process with constant transition probabilities has two potential problems. First, the true driving

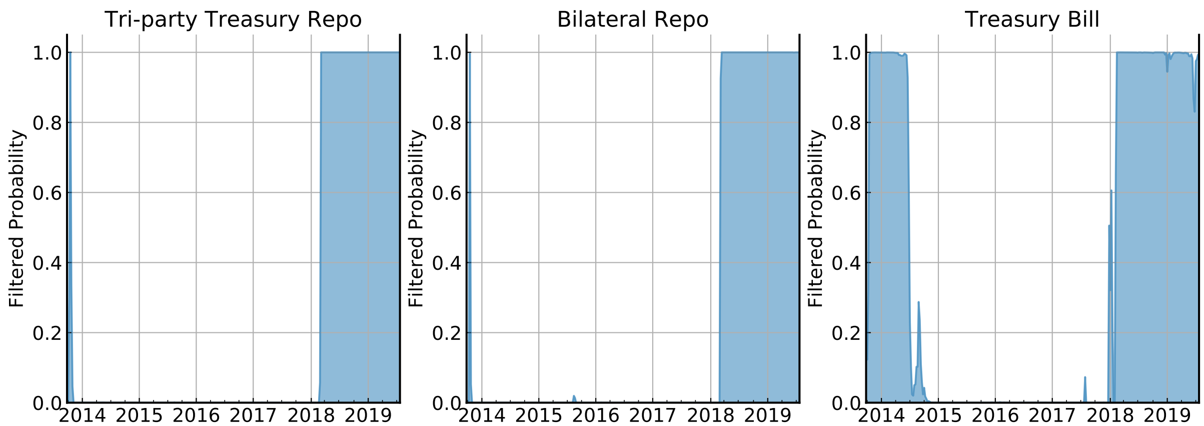

Figure 16. Filtered probability of $s_t^j = H$ in the benchmark Markov-switching estimation.

forces of the observed regime shift might not be re-occuring at all. Considering that there is only one shift in repo rates, it is also possible that such shift is triggered by a permanent structural change, which should be simply modeled as a structural change. The fact that θ does not change significantly across two states also indicate such possibility. Second, even if such regime shifts are re-occuring, the economic forces that trigger the transition from one state to another might not be exogenous. For example, the transition probability might depend on a set of exogenous variables so that regime shifts are internally related to some fundamental factors, rather than purely statistical processes. One can also motivate such a time-varying model using theoretical model with deeper structure. In section 5.1, we will show that discrete entry-exit choices made by investors can map the equilibrium risk-free rate to different policy rates, thereby generating two regimes of conditional distribution of IOR spreads. In that model, the aggregate bond supply serves as the exogenous state variable that drives state transitions.

B Additional Tables

Table B.1. The Segmentation of U.S. Money Markets

The symbol ✓means that the participant in consideration has access to the financial instrument, while $\star$ means that only a subset of designated participants has access. By "have access", we mean that participants can take long positions in investment instruments or borrow cash via funding instruments. In particular, "unsecured debt" includes commercial papers, bank deposits, asset-backed securities, and money market fund shares. For the full list of FICC/GSD members, see `http://www.dtcc.com/client-center/ficc-gov-directories`.

Panel A: Investment Instruments

	Banks	Money market funds	Broker-dealers	GSEs
Federal funds	✓			✓
IOR	✓			
ONRRP	$\star$	$\star$	$\star$	✓
Treasury bills	✓	✓	✓	✓
Unsecured debt	✓	✓	✓	✓
Tri-party GC repo	✓	✓	✓	✓
FICC DVP Repo	$\star$	$\star$	$\star$	✓
FICC GCF Repo	$\star$	$\star$	$\star$	$\star$

Panel B: Funding Instruments

	Banks	Money market funds	Broker-dealers	GSEs
Federal funds	✓			✓
IOR				
ONRRP				
Treasury bills				
Unsecured debt	✓	✓	✓	✓
Tri-party GC repo	✓	✓	✓	✓
FICC DvP Repo	$\star$	$\star$	$\star$	✓
FICC GCF Repo	$\star$	$\star$	$\star$	$\star$

Table B.2. Central Counterparty (CCP) Clearing Platforms Operated by DTCC

"NSCC": National Securities Clearing Corporation, "FICC": Fixed Income Clearing Corporation, "GSD": Government Securities Division. "DVP": Delivery-versus-Payment. FICC/GSD members include banks, broker-dealers, issuers of government and agency securities. FICC/GSD sponsored members include mutual funds, close-end funds, unit investment trust, and hedge funds. Note that JPMorgan Chase stopped settling government securities since 2019.

	Securities	Types of Transactions	Participants	Clearing & Settlement Agent	Netting?	Payment System
NSCC	Equities Corporate debt Municipal debt ETFs		Broker-dealers	DTC	Yes	NSS
FICC/GSD	Treasury securities Agency securities	Treasury auctions CCP buy and sell DVP Treasury repos GCF repos	FICC/GSD members Sponsored members	Clearing banks: BNYM JPMC (-2018.12) Fedwire Securities	Yes	Clearing banks Fedwire Funds DTC-NSS

Table B.3. The Structure of U.S. Repo Markets

Notations: "DVP": Delivery-versus-Payment; "GC": general collateral; "FICC": Fixed Income Clearing Corporation; "GCF": FICC's General Collateral Finance Repo Service; "FICC/GSD": FICC Government Securities Division; "Blind-brokered": counterparties do not know the identity of each other; "BNYM": Bank of New York Mellon; "JPMC": JPMorgan Chase Bank. FICC/GSD members include banks, broker-dealers, issuers of government and agency securities. FICC/GSD sponsored members include mutual funds, close-end funds, unit investment trust, and hedge funds. Note that JPMorgan Chase stopped settling government securities since 2019.

Segment	Cash lenders	Cash borrowers	Collateral Type	Clearing & Settlement Platforms and Types		Payment System
DVP Tri-party	Money funds Securities lenders GSEs	Primary dealers	GC	Clearing banks: - BNYM - JPMC (-2018.12)	DVP	Clearing banks
FICC's GCF	Banks Primary dealers Hedge funds: (since 2017.5)	Secondary Dealers	GC	Clearing banks: - BNYM - JPMC (-2018.12) FICC GSD Fedwire Securities DTC	Blind-brokered netting	Clearing banks (GCF Intrabank) Fedwire Funds (GCF Interbank) DTC-NSS (non-Fedwire collateral)
FICC's DVP	FICC/GSD members: - Large banks - Primary dealers FICC Sponsored members: - RICs (since 2005)	FICC/GSD members: - Large banks - Primary dealers FICC Sponsored members: - RICs (since 2005) - Hedge funds (since 2018.1)	Treasury securities Agency securities	Clearing banks: BNYM JPMC (-2018.12) FICC GSD Fedwire Securities	DVP2	Clearing banks (DVP Intrabank) Fedwire Funds (DVP Interbank)

Table B.4. Summary Statistics of Money Market Fund Holdings

Notes: Panel A: Summary statistics of SEC N-MFP2 money market fund data. The data is aggregated at the month-fund level. Panel B: Summary statistics of money market fund repo positions. Each observation represents a repo contract held by a money market fund on the reporting day of SEC's N-MFP2 form. Sample period: 2016.10 - 2019.6.

	Mean	Std	Median	Min	5%	95%	Max	N
Panel A: Series-level Information								
AUM (Billion $)	7.7	18	1.1	0	.033	40	166	14458
Daily Liquid Assets (Billion $)	5	10	.7	0	.011	25	82	12312
% Daily Liquid	.5	.29	.41	0	.13	1	1	12313
Weekly Liquid Assets (Billion $)	5.5	12	.86	0	.026	26	105	14458
% Weekly Liquid	.68	.21	.68	0	.35	1	1	14458
NAV	.86	.24	1	0	0	1	1.2	14458
Seven-day Gross Yield (%)	.014	.022	.013	0	0	.025	2	14458
Average Life (days)	52	36	51	0	1	107	129	14458
Average Duration (days)	25	15	26	0	1	49	90	14458
Panel B: Repo Holdings								
Treasury Repo								
Principal (Billion $)	0.32	0.83	0.10	0.00	0.00	1.13	21.39	61038
Repo Rate (%)	1.61	0.75	1.71	0.00	0.43	2.61	5.50	61038
Days to Maturity	6.73	13.62	3.00	1.00	1.00	31.00	372.00	61038
Share of AUM	0.02	0.04	0.01	0.00	0.00	0.10	1.00	61038
Agency Repo								
Principal (Billion $)	0.25	0.49	0.10	0.00	0.00	1.00	13.20	42092
Repo Rate (%)	1.61	0.77	1.71	0.00	0.42	2.65	8.00	42092
Days to Maturity	7.73	15.84	3.00	-29.00	1.00	43.00	372.00	42092
Share of AUM	0.02	0.05	0.01	0.00	0.00	0.09	1.00	42092
Prime Repo								
Principal (Billion $)	0.07	0.11	0.04	0.00	0.00	0.28	2.56	15455
Repo Rate (%)	1.89	0.69	1.90	0.00	0.77	2.94	3.61	15455
Days to Maturity	19.51	30.11	4.00	1.00	1.00	91.00	185.00	15455
Share of AUM	0.01	0.01	0.01	0.00	0.00	0.03	0.21	15455

Table B.5. Summary Statistics of Repo Contracts: Domestic Issuers

Summary statistics of repurchase agreements held by money market funds on the reporting dates of SEC N-MFP2 form. For each domestic issuer, we compute the average repo rate, the average principal amount of the repo contract, and the total principal amount of repurchase agreements. Average repo rates are rounded to the nearest basis point and principal amounts are denominated in billion of dollars. FICC represents the Fixed Income Clearing Corporation, a subsidiary of DTCC. Fed RRP represents the Federal Reserve's reverse repo facility.

	Treasury Repo			**Agency Repo**			**Prime Repo**		
	Average Volume	Total Volume	Average Rate	Average Volume	Total Volume	Average Rate	Average Volume	Total Volume	Average Rate
US Banks	0.18	1940	1.54	0.26	3497	1.62	0.08	512	1.96
BMO Harris Bank	0.07	166.71	1.45	0.10	72.95	2.12	0.07	24.53	1.99
Bank of America	0.09	46.50	1.57	0.31	380.68	1.73	0.20	20.24	2.39
Bank of New York Mellon	0.32	12.34	2.16	0.15	49.13	1.56	0.01	0.04	0.87
Citigroup	0.16	294.25	1.55	0.19	435.23	1.60	0.07	90.70	2.20
Goldman Sachs	0.26	214.90	1.53	0.19	407.61	1.50	0.04	0.61	1.24
JPMorgan Chase & Co.	0.29	568.45	1.82	0.36	635.35	1.87	0.08	122.88	1.93
Merrill Lynch	0.15	201.92	1.40	0.15	355.68	1.57	0.11	107.21	1.96
Morgan Stanley	0.16	22.47	2.01	0.18	29.65	1.21	0.20	2.94	2.34
State Street	0.13	31.74	0.66	0.52	3.64	0.87			
Wells Fargo	0.30	380.40	1.51	0.44	1126.21	1.45	0.06	143.34	1.84
US Nonbank Institutions	0.18	475	1.65	0.14	273	1.74	0.04	5	1.78
Cantor Fitzgerald	0.04	1.01	2.47	0.10	11.57	2.52			
Guggenheim Securities				0.08	3.17	2.63			
Metlife	0.19	55.01	1.66						
Prudential Financial	0.19	240.70	1.69	0.21	8.96	1.34	0.10	0.52	1.07
TD Ameritrade	0.16	173.75	1.58	0.18	197.42	1.57	0.03	3.02	1.76
US Repo Brokers	0.12	4.55	1.62	0.09	51.84	1.89	0.07	1.13	2.11
Others									
FICC Sponsored Repo	1.04	1441	2.06	0.81	21	1.97			
Fed RRP	3.37	3822	0.98	7.15	14	0.62	0.54	1	1.25
Unidentified	0.26	286.65	1.77	0.13	21.99	1.84	0.12	0.62	1.63

Table B.6. Summary Statistics of Repo Contracts: European Issuers

Summary statistics of repurchase agreements held by money market funds on the reporting dates of SEC N-MFP2 form. For each foreign issuer, we compute the average repo rate, the average principal amount of the repo contract, and the total principal amount of repurchase agreements for the whole sample. Average repo rates are rounded to the nearest basis point and principal amounts are denominated in billion of dollars. Sample period: October 2016 – June 2019.

	Treasury Repo			**Agency Repo**			**Prime Repo**		
	Average Volume	Total Volume	Average Rate	Average Volume	Total Volume	Average Rate	Average Volume	Total Volume	Average Rate
Europe Banks	0.29	8178	1.59	0.23	3448	1.59	0.08	482	1.85
ABN AMRO Bank	0.19	54.09	1.46	0.22	146.78	1.51	0.05	6.38	1.50
BNP Paribus	0.28	2314.45	1.58	0.25	921.29	1.62	0.07	110.91	1.87
Bank of Nova Scotia	0.26	344.78	1.50	0.30	326.17	1.43	0.07	16.98	1.75
Barclays	0.41	966.67	1.70	0.23	233.33	1.74	0.12	28.42	2.46
Credit Suisse	0.46	273.06	1.39	0.31	86.41	1.22	0.07	66.01	1.76
Crédit Agricole	0.31	918.10	1.58	0.22	243.62	1.55	0.08	0.50	0.77
DNB ASA	0.45	57.49	1.99						
Deutsche Bank	0.21	440.19	1.60	0.21	158.09	1.46	0.11	2.38	0.89
HSBC	0.29	778.09	1.50	0.25	336.63	1.74	0.07	83.73	1.80
ING Group	0.27	210.13	1.81	0.13	400.63	1.61	0.04	34.06	1.84
Lloyds Bank	0.12	176.45	1.81	0.22	5.16	1.95			
Natixis	0.43	590.35	1.86	0.28	206.23	1.69	0.13	0.25	1.39
Royal Bank of Scotland	0.35	290.70	1.49	0.35	30.02	1.57	0.18	12.58	2.04
Société Générale	0.25	691.34	1.35	0.35	353.30	1.45	0.14	111.16	1.92
Standard Chartered	0.18	27.49	2.11				0.15	0.15	1.22

Table B.7. Summary Statistics of Repo Contracts: Japanese and Canadian Issuers

Summary statistics of repurchase agreements held by money market funds on the reporting dates of SEC N-MFP2 form. For each foreign issuer, we compute the average repo rate, the average principal amount of the repo contract, and the total principal amount of repurchase agreements for the whole sample. Average repo rates are rounded to the nearest basis point and principal amounts are denominated in billion of dollars. Sample period: October 2016 – June 2019.

	Treasury Repo			**Agency Repo**			**Prime Repo**		
	Average Volume	Total Volume	Average Rate	Average Volume	Total Volume	Average Rate	Average Volume	Total Volume	Average Rate
Japan Banks	0.22	1895	1.74	0.38	1904	1.66	0.04	83	1.87
Daiwa Securities Group	0.27	77.77	2.18	1.40	135.77	2.13			
MUFG Bank	0.13	510.07	1.75	0.19	384.35	1.58	0.06	32.11	1.74
Mizuho Bank	0.25	203.19	1.72	0.14	197.29	1.51	0.03	50.14	1.92
Nomura Holdings	0.71	528.69	1.49	1.02	791.40	1.77	0.14	0.55	1.49
Norinchukin Bank	0.12	267.10	1.81						
SMBC	0.50	308.08	1.64	0.57	395.38	2.00			
Canada Banks	0.20	1392	1.59	0.23	1509	1.55	0.08	53	1.51
Bank of Montreal	0.18	298.78	1.46	0.12	53.55	1.57	0.05	1.10	1.00
Bank of Toronto	0.12	41.70	1.41	0.18	42.47	1.52	0.05	0.40	0.31
CIBC	0.39	255.35	2.09	0.38	143.08	2.17	0.14	1.30	1.27
RBC Capital Markets	0.18	796.21	1.59	0.23	1270.20	1.51	0.08	50.18	1.56

Table B.8. Descriptive Statistics of Monetary Transmission: Daily Time Series

Summary statistics of various interest rate spreads at daily frequency, measured in basis points. IOR: the Federal Reserve's interest payment on reserves; TB: 3-month Treasury bill rate; $EFFR$: effective federal funds rate; TRP: overnight tri-party repo rate collateralized by Treasury securities, cleared by the Bank of New York Mellon; DVP: GovPX bilateral Treasury repo index; GCF: DTCC's overnight GCF Treasury repo index; $SOFR$: secured overnight funding rate. The sample frequency is daily and all term interest rates are converted to overnight rates using overnight indexed swap rates. Source: the Federal Reserve Bank of New York, DTCC, the Bank of New York Mellon, and Datastream.

	2009.1 - 2013.9				**2013.10 - 2018.1**				**2018.2 - 2019.8**			
	Mean	Median	Std	N	Mean	Median	Std	N	Mean	Median	Std	N
IOR Spreads												
r_t^{IOR}-r_t^{EFFR}	10.95	10.00	4.25	1232	12.61	12.00	3.27	1137	0.94	0.00	4.35	434
r_t^{IOR}-r_t^{SOFR}	11.45	11.00	6.99	1172	16.62	17.00	5.71	1116	-2.32	0.00	17.98	434
r_t^{IOR}-r_t^{TB}	5.20	5.40	2.83	1178	10.85	11.00	4.76	1086	0.77	1.20	3.78	420
r_t^{IOR}-r_t^{TRP}	13.79	13.00	7.33	285	20.48	20.00	2.97	1077	0.11	2.00	18.12	418
Repo-Fed Funds												
r_t^{DVP}-r_t^{EFFR}	7.54	8.00	5.56	1232	3.41	2.00	9.69	1137	12.35	10.00	15.24	434
r_t^{GCF}-r_t^{EFFR}	2.04	1.80	4.97	1232	2.50	1.70	9.03	1137	9.64	8.00	18.26	239
r_t^{SOFR}-r_t^{EFFR}	-0.52	-1.00	3.90	1172	-4.10	-4.00	6.51	1116	3.25	2.00	16.12	434
Repo Market Making												
r_t^{DVP}-r_t^{TRP}	7.96	8.00	3.16	285	11.37	10.00	9.05	1077	11.14	11.00	9.20	418
r_t^{GCF}-r_t^{TRP}	4.50	4.20	2.23	285	10.39	9.60	8.11	1077	10.48	9.10	14.19	230
r_t^{SOFR}-r_t^{TRP}	0.82	1.00	0.62	284	3.82	3.00	4.64	1077	2.27	2.00	1.35	418

Table B.9. Descriptive Statistics of Monetary Transmission: Tri-party Repo Transactions

Descriptive statistics of repurchase agreements held by money market funds on the reporting dates of SEC N-MFP2 form, grouped by the country of origin of a dealer's parent bank, the indicator variable for the end of a quarter, and sample periods. For each group of repo contracts, we compute the median IOR-Repo spread, the median GCF-Repo spread, and the total principal amount. Interest rate spreads are rounded to the nearest 1/100-th basis point and principal values are denominated in billion of dollars. FICC represents the repo contracts issued via the FICC's sponsored repo market. Fed RRP represents the Federal Reserve's reverse repo facility. Quarter-end means that the reporting day is at the end of March, June, September, or December. For non quarter-end months, we present the monthly average value of total repo volumes for easier comparison.

	Total Repo Volume				**Median IOR-Tri-party Spread**				**Median GCF-Tri-party Spread**			
Regime	After Jan 2018		Before Jan 2018		After Jan 2018		Before Jan 2018		After Jan 2018		Before Jan 2018	
Quarter-end?	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Panel A: Treasury Repo												
Fed RRP	43.57	169.36	918.94	1682.83	20.00	20.00	25.00	25.00	32.70	44.20	19.50	27.50
FICC	312.89	363.93	29.41	54.61	-4.00	-23.00	74.00	17.00	10.00	16.93	64.40	38.60
US Banks	328.60	337.34	264.42	193.53	-2.00	-5.00	20.00	21.00	10.70	18.93	14.10	24.60
EU Banks	1538.19	1159.46	1340.32	749.30	-1.00	-5.00	20.00	20.00	11.60	20.93	13.10	25.50
JP Banks	361.75	297.84	259.81	216.61	-2.00	-8.00	18.00	18.00	10.00	24.93	10.40	24.50
CA Banks	230.74	270.58	180.36	187.20	-1.00	-1.00	21.00	21.00	12.30	25.20	14.00	26.50
US Nonbanks	77.38	74.45	74.76	66.33	-4.00	-18.00	18.00	14.00	7.70	9.30	12.00	18.60
Other	60.68	33.01	48.31	11.40	-6.00	-15.50	15.00	15.00	7.70	13.93	9.40	17.50
Panel B: Agency Repo												
Fed RRP			7.15				25.00				15.05	
FICC	4.52	5.82	0.01	0.03	-7.00	-40.00	113.00	113.00	10.00	165.80	109.50	108.30
US Banks	587.76	566.33	519.40	432.70	-3.00	-12.00	19.00	18.00	8.70	14.70	12.10	21.50
EU Banks	576.09	466.45	592.53	400.53	-4.00	-10.00	18.00	19.00	9.00	14.93	11.10	22.50
JP Banks	336.92	310.28	263.08	237.45	-5.00	-10.00	17.00	18.00	7.60	18.93	10.40	20.60
CA Banks	272.09	286.25	178.80	184.59	-2.00	-5.00	18.00	20.00	10.00	17.92	12.00	24.50
US Nonbanks	39.96	40.79	45.84	45.52	-7.00	-17.00	18.00	17.00	6.70	8.05	10.40	18.23
Other	5.11	2.74	3.23	0.81	-2.00	-25.00	18.00	7.00	10.70	3.90	10.33	18.60

Table B.10. The Effects of Funding Constraints: Fixed-effects Regression

This table reports the effects of funding constraints on IOR-repo spreads. Dependent variables include average IOR-repo spreads and the total issuance of tri-party repo contracts, aggregated at the borrower-lender level. Explanatory variables include region fixed effects C^i, the quarter-end dummy Q_t, and the FICC reform dummy G_t. The base group is U.S. banks in months that are not quarter-end before February 2018. Estimation is based on OLS with fund fixed effects. Standard errors are two-way clustered at the borrower and fund level and presented in parentheses. *, **, and *** represent statistical significance at the 10%, 5%, and 1% levels, respectively.

	Treasury Repo			Agency Repo		
	(1) GCF-Repo	(2) IOR-Repo	(3) Volume	(4) GCF-Repo	(5) IOR-Repo	(6) Volume
Base-case Average	16.04***	21.18***	0.26***	16.14***	16.68***	0.39***
	(2.159)	(1.756)	(0.032)	(4.221)	(1.070)	(0.076)
Q_t	7.44***	0.18	-0.01	8.48***	-0.47	-0.03
	(0.983)	(0.907)	(0.020)	(0.529)	(0.345)	(0.015)
G_t	-1.91	-25.24***	0.11**	-1.91*	-24.83***	0.05
	(1.854)	(1.977)	(0.040)	(0.708)	(0.869)	(0.037)
$Q_t \times G_t$	33.63***	-10.79***	0.03	31.78***	-8.28***	0.04*
	(2.137)	(1.396)	(0.043)	(2.117)	(1.046)	(0.016)
CA Banks	-0.80	-1.41	0.11*	1.22	0.95	0.15
	(1.375)	(1.379)	(0.054)	(1.010)	(0.934)	(0.135)
EU Banks	-1.63	-1.72	0.31**	0.50	0.41	-0.02
	(1.463)	(1.453)	(0.086)	(0.869)	(0.742)	(0.088)
JP Banks	-4.79*	-4.05	0.19	0.51	0.03	0.14
	(2.080)	(2.041)	(0.147)	(0.922)	(0.867)	(0.211)
US Nonbanks	-1.96	-2.31	-0.06	1.61	1.87*	-0.17*
	(1.693)	(1.631)	(0.038)	(1.047)	(0.923)	(0.079)
CA Banks $\times Q_t$	2.59*	1.27	0.04	0.80	1.33*	0.07*
	(1.142)	(1.215)	(0.023)	(1.031)	(0.570)	(0.030)
EU Banks $\times Q_t$	2.12	-0.74	-0.12**	0.33	0.55	-0.03
	(1.213)	(1.039)	(0.045)	(0.869)	(0.628)	(0.022)
JP Banks $\times Q_t$	2.86	-1.23	0.06	-0.54	-0.21	0.03
	(1.763)	(1.211)	(0.031)	(0.802)	(0.746)	(0.021)
US Nonbanks $\times Q_t$	-0.18	-3.80***	0.01	-3.51***	-2.40***	0.03
	(1.124)	(0.940)	(0.022)	(0.553)	(0.344)	(0.018)
CA Banks $\times G_t$	0.88	1.82	-0.01	1.50	1.78	0.08
	(1.702)	(1.886)	(0.081)	(1.013)	(1.301)	(0.081)
EU Banks $\times G_t$	0.89	1.60	-0.03	-0.20	0.08	-0.01
	(1.912)	(2.032)	(0.048)	(0.893)	(1.003)	(0.038)
JP Banks $\times G_t$	1.69	2.05	-0.02	-1.47	-0.75	0.01
	(2.237)	(2.409)	(0.114)	(0.760)	(0.877)	(0.099)
US Nonbanks $\times G_t$	-0.81	-0.13	-0.12**	-2.79**	-3.67**	-0.04
	(2.015)	(2.149)	(0.039)	(0.898)	(1.254)	(0.066)
CA Banks $\times Q_t \times G_t$	-4.61	4.12*	0.00	2.80	-0.31	-0.05
	(3.985)	(1.840)	(0.043)	(2.681)	(1.212)	(0.033)
EU Banks $\times Q_t \times G_t$	-0.83	2.20	0.03	3.44	-1.66	-0.01
	(2.510)	(1.621)	(0.053)	(3.080)	(1.009)	(0.019)
JP Banks $\times Q_t \times G_t$	4.61	3.05	-0.07	10.18***	-0.51	-0.05
	(3.030)	(2.137)	(0.081)	(2.438)	(1.903)	(0.062)
US Nonbanks $\times Q_t \times G_t$	-3.60	0.85	-0.05	0.16	-0.86	-0.03
	(4.389)	(1.426)	(0.047)	(4.232)	(0.858)	(0.018)
Observations	29946	29946	29946	25231	25231	25231
Adjusted R^2	0.161	0.558	0.338	0.159	0.529	0.407

Table B.11. Estimating the Supply Elasticity of Repo Rates

This table reports the estimated supply elasticity of repo rates. Column (1), (2), (4), and (5) report results based on repo contracts issued by entities other than FICC, Fed RRP, and U.S. repo brokers. Column (3) reports Treasury repos issued via FICC after Jan 2018. Dependent variables are the spread between IOR and contract-level tri-party repo rates. Explanatory variables are aggregate cash demand shocks, indicator variables, and their interaction. Indicator variables include month dummy M_t and the FICC dummy G_t. For month dummy, $M_t = 0$ if $t = 3, 6, 9, 12$, $M_t = 1$ if $t = 1, 4, 7, 10$, and $M_t = -1$ if $t = 2, 5, 8, 11$. $G_t = 1$ if t is after January 2018. The base case is $G_t = 0$ and $M_t = -1$. Estimation is based on OLS with issuer and fund fixed effects. Standard errors clustered at issuer-month and fund levels are presented in parentheses. *, **, and *** represent statistical significance at the 10%, 5%, and 1% levels, respectively.

	Treasury Repos			Agency Repos	
	(1) Fed RRP Eligible	(2) Fed RRP Ineligible	(3) FICC	(4) Fed RRP Eligible	(5) Fed RRP Ineligible
ΔB_t	0.00	0.04		0.01	-0.00
	(0.050)	(0.036)		(0.048)	(0.039)
$[M_t = 0] \times \Delta B_t$	0.03	0.01		0.02	0.05
	(0.051)	(0.034)		(0.049)	(0.037)
$[M_t = 1] \times \Delta B_t$	-0.01	-0.04		-0.01	-0.00
	(0.051)	(0.037)		(0.049)	(0.041)
$[G_t = 1] \times \Delta B_t$	-1.06***	-1.16***	-2.04***	-1.26***	-1.43***
	(0.198)	(0.231)	(0.443)	(0.173)	(0.188)
$[M_t = 0] \times [G_t = 1] \times \Delta B_t$	0.94***	1.07***	2.24***	1.28***	1.58***
	(0.205)	(0.252)	(0.522)	(0.182)	(0.197)
$[M_t = 1] \times [G_t = 1] \times \Delta B_t$	1.39***	1.54***	2.60***	1.60***	1.86***
	(0.225)	(0.279)	(0.483)	(0.188)	(0.214)
$[M_t = -1]$	18.09***	20.44***		17.31***	17.53***
	(1.622)	(1.514)		(1.559)	(1.665)
$[M_t = 0]$	5.70**	4.79**		4.35**	4.92***
	(1.878)	(1.472)		(1.504)	(1.228)
$[M_t = 1]$	2.15	0.19		0.45	0.87
	(1.585)	(1.277)		(1.502)	(1.265)
$[M_t = -1] \times [G_t = 1]$	-64.91***	-70.45***	-82.50***	-73.73***	-82.36***
	(8.207)	(10.081)	(16.279)	(6.901)	(7.940)
$[M_t = 0] \times [G_t = 1]$	25.85**	30.33**	79.93***	45.00***	59.87***
	(8.287)	(10.534)	(21.647)	(7.881)	(9.638)
$[M_t = 1] \times [G_t = 1]$	1.90	-1.20	11.41	7.10	4.58
	(7.215)	(6.269)	(15.736)	(7.579)	(7.822)
$Days\ to\ Maturity$	-0.11***	-0.08	0.05	-0.06	-0.10**
	(0.025)	(0.042)	(1.680)	(0.031)	(0.029)
$\Delta Cash_t^j$	-0.07	-1.17*	1.81	-0.11	-0.38
	(0.365)	(0.573)	(1.463)	(0.325)	(0.482)
ΔAUM_t^j	-0.17	0.55	-0.36	-0.15	0.55*
	(0.091)	(0.339)	(0.380)	(0.112)	(0.259)
Observations	39276	14248	1034	23602	13641
Adjusted R^2	0.558	0.649	0.499	0.522	0.464

Table B.12. Fed RRP as a Repo Market Stabilizer

This table reports the relationship between variation in cash demand by banks and other repo borrowers, such as Fed RRP and FICC. Data is aggregated at the fund-month level. For each fund and month, dependent variables include monthly changes in total repo issuance by different types of issuers, as shown on the column names. Explanatory variables include monthly changes in total repo issuance by all banks for the same fund, interacted with month dummy variables M_t, and fund-level controls such as monthly changes in cash positions, net assets, and average IOR-repo spreads for the same fund. For month dummy, $M_t = 0$ if $t = 3, 6, 9, 12$, $M_t = 1$ if $t = 1, 4, 7, 10$, and $M_t = -1$ if $t = 2, 5, 8, 11$. Estimation is based on OLS with fund fixed effects. Standard errors clustered by fund are presented in parentheses. *, **, and *** represent statistical significance at the 10%, 5%, and 1% levels, respectively.

	(1) Fed RRP	(2) Fed RRP	(3) FICC	(4) FICC	(5) CA	(6) CA
$[M_t = 0] \times \Delta B_t^j$	-0.78***	-0.85***	-0.08	-0.11*	-0.02	-0.03
	(0.123)	(0.102)	(0.047)	(0.049)	(0.015)	(0.014)
$[M_t = 1] \times \Delta B_t^j$	-0.95***	-0.89***	-0.12	-0.14	-0.06***	-0.06***
	(0.099)	(0.094)	(0.071)	(0.069)	(0.014)	(0.015)
$[M_t = -1] \times \Delta B_t^j$	-0.38**	-0.49*	-0.07	-0.10	-0.02	-0.03
	(0.115)	(0.164)	(0.071)	(0.077)	(0.019)	(0.020)
$\overline{sp}_t^j$		0.04		-0.00		0.00
		(0.031)		(0.001)		(0.000)
$\Delta Cash_t^j$		0.43		0.11		-0.09*
		(0.315)		(0.091)		(0.035)
ΔAUM_t^j		0.54***		0.07		0.03*
		(0.082)		(0.040)		(0.013)
RRP Ineligible $\times [M_t = 0] \times \Delta B_t^j$			0.05	0.02	0.07*	0.04*
			(0.040)	(0.034)	(0.025)	(0.019)
RRP Ineligible $\times [M_t = 1] \times \Delta B_t^j$			0.13	0.11	0.02	0.01
			(0.071)	(0.062)	(0.018)	(0.019)
RRP Ineligible $\times [M_t = -1] \times \Delta B_t^j$			0.10	0.12	-0.03	-0.03
			(0.072)	(0.092)	(0.058)	(0.057)
Constant	0.10	-0.85	0.05*	0.03	0.02*	0.02
	(0.230)	(0.688)	(0.023)	(0.016)	(0.009)	(0.009)
Observations	1063	1063	3594	3594	6642	6642
Adjusted R^2	0.539	0.643	0.016	0.048	0.008	0.027

C Additional Figures

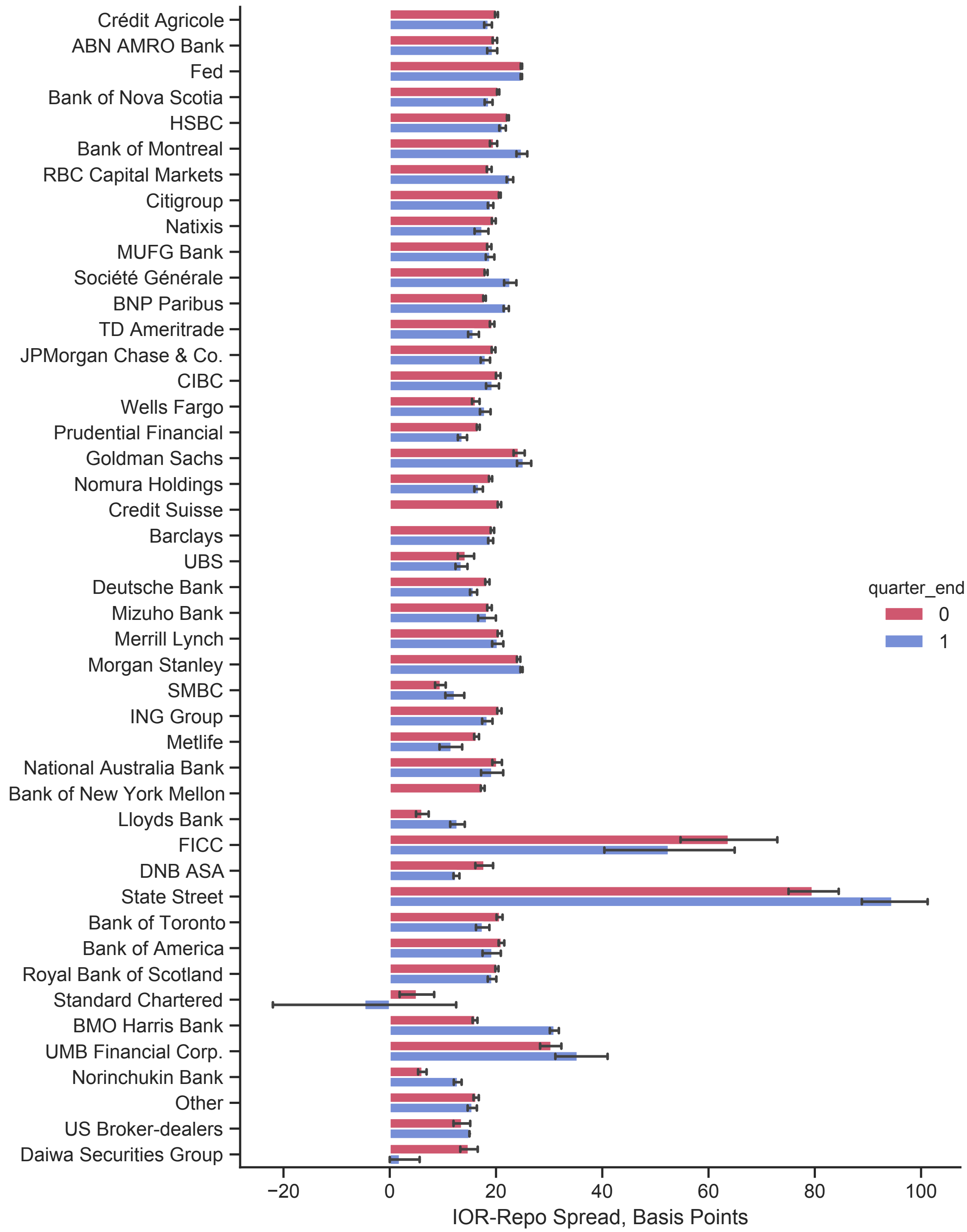

Figure C.1. The cross-section of average IOR-repo spreads constructed using repo contracts issued by bank dealers in the tri-party repo market before February 2018.

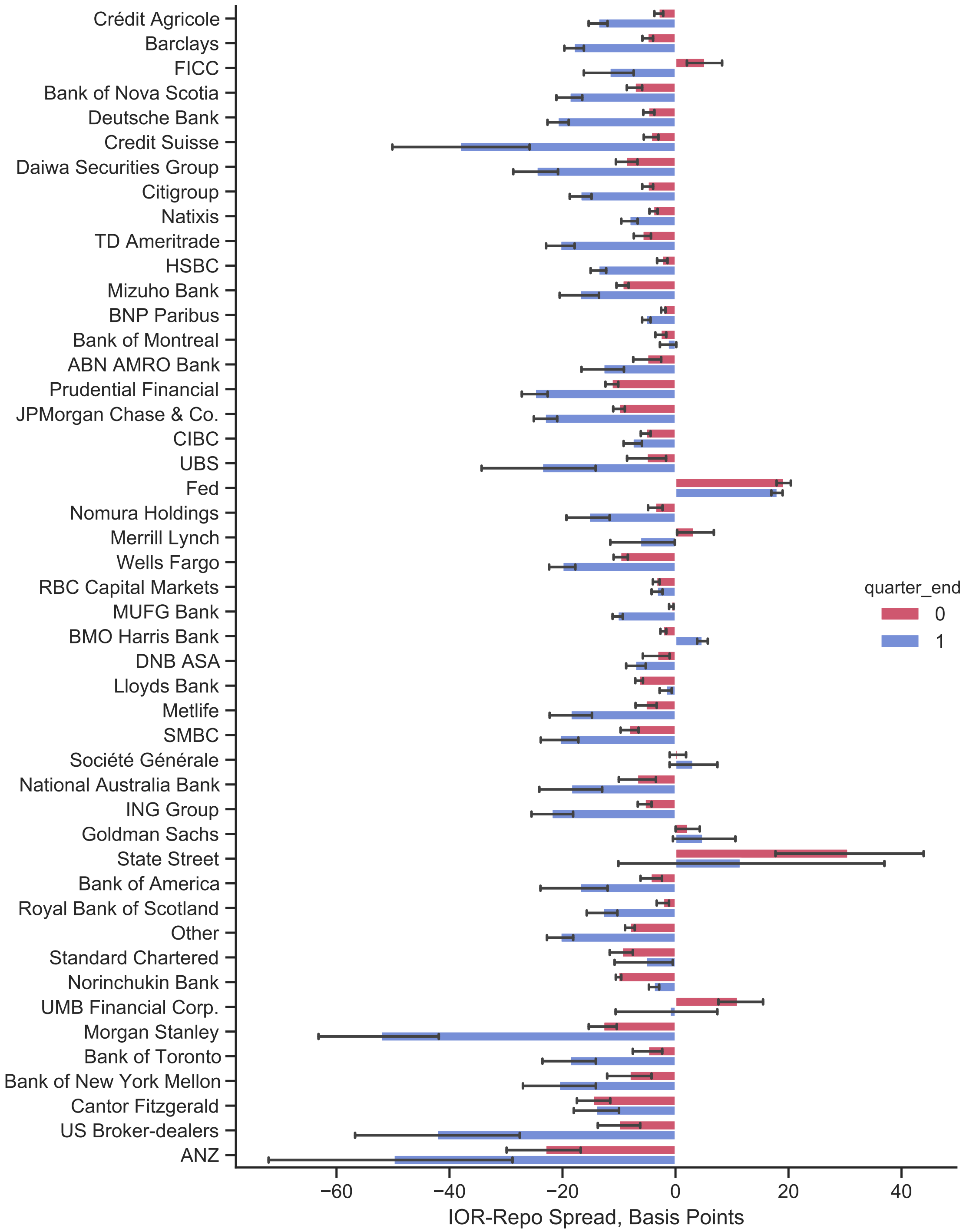

Figure C.2. The cross-section of average IOR-repo spreads constructed using repo contracts issued by bank dealers in the tri-party repo market after January 2018.

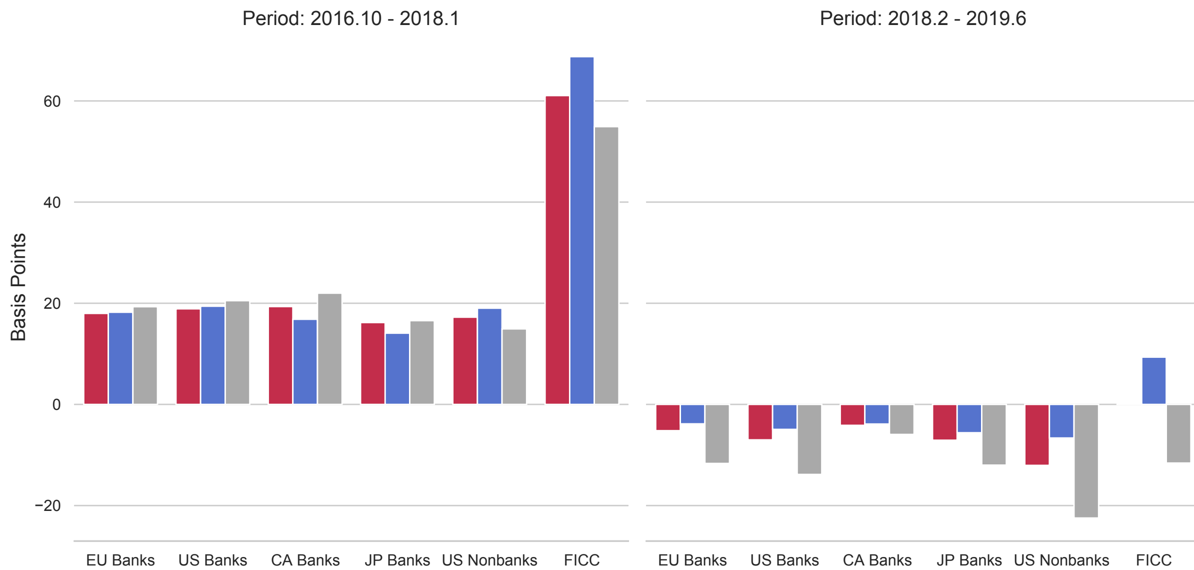

Figure C.3. Average spread of IOR rate over repo rate of Treasury and agency repo contracts issued by different groups of borrowers in the tri-party repo market. Red, blue, and gray bars represent 2, 1, and 0 months before the quarter-end month, respectively. Source: N-MFP2 filings.

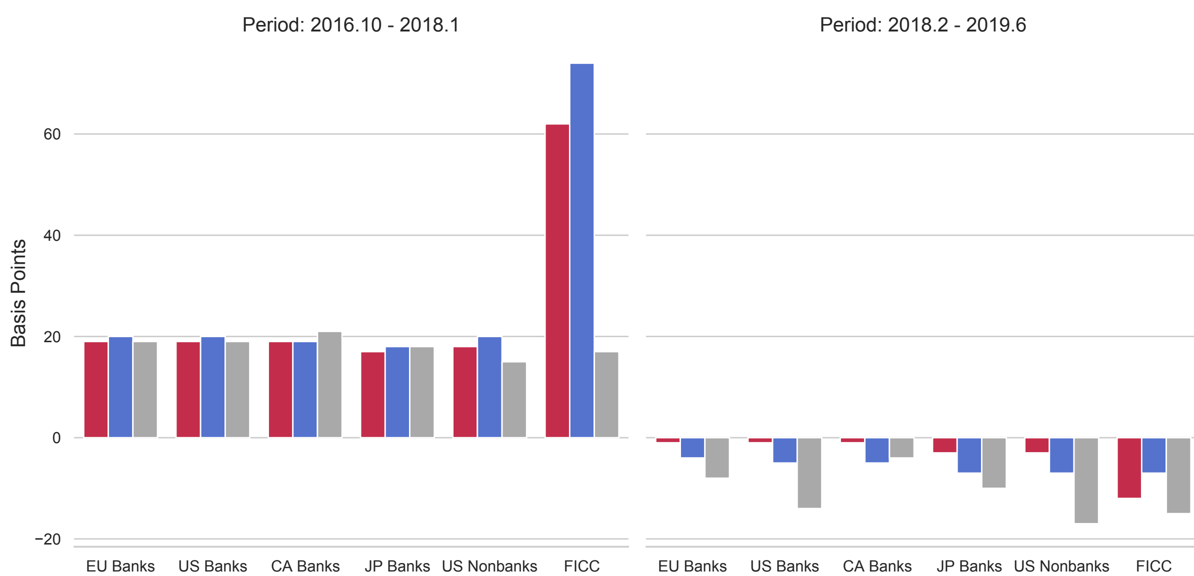

Figure C.4. Median spread of IOR rate over repo rate of Treasury and agency repo contracts issued by different groups of borrowers in the tri-party repo market. Red, blue, and gray bars represent 2, 1, and 0 months before the quarter-end month, respectively. Source: N-MFP2 filings.

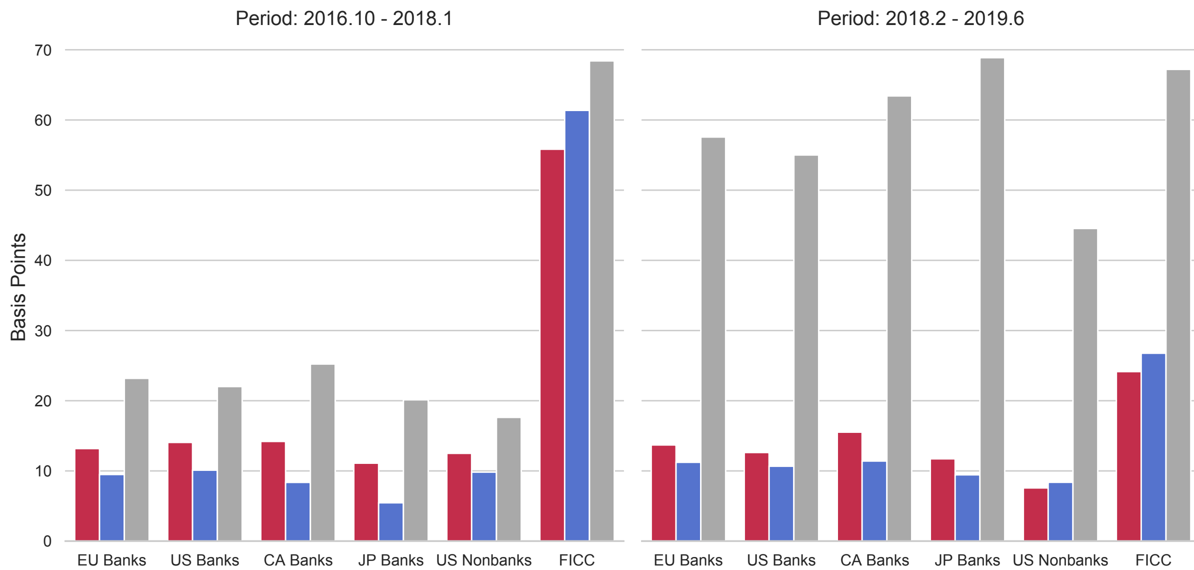

Figure C.5. Average spread of the DTCC's GCF Repo Index over repo rate of Treasury and agency repo contracts issued by different groups of borrowers in the tri-party repo market. Red, blue, and gray bars represent 2, 1, and 0 months before the quarter-end month, respectively. Source: N-MFP2 filings.

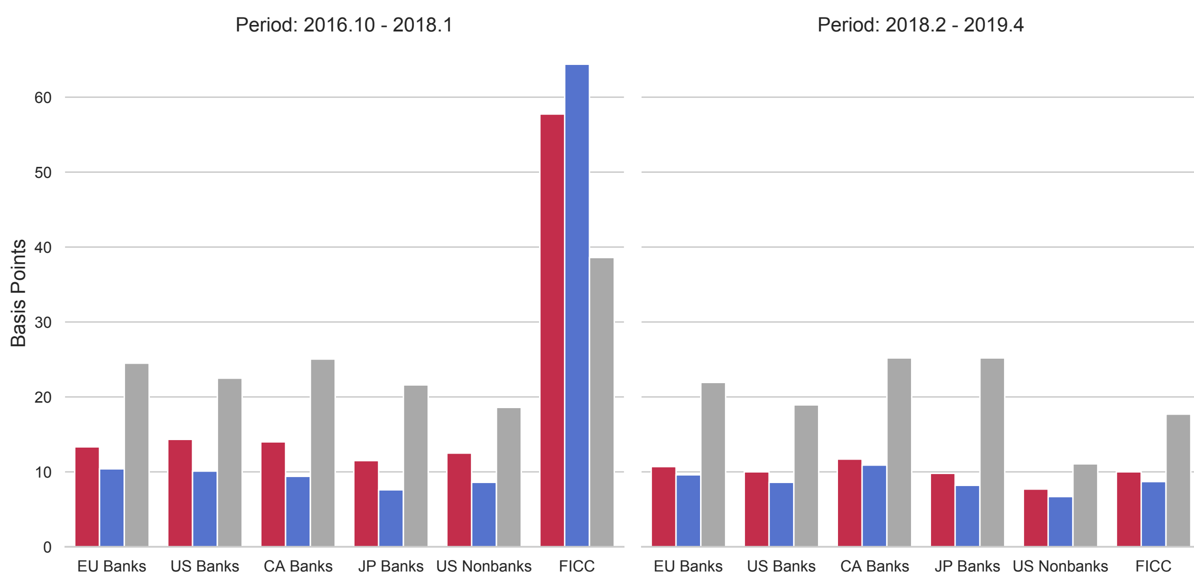

Figure C.6. Median spread of the DTCC's GCF Repo Index over repo rate of Treasury and agency repo contracts issued by different groups of borrowers in the tri-party repo market. Red, blue, and gray bars represent 2, 1, and 0 months before the quarter-end month, respectively. Source: N-MFP2 filings.

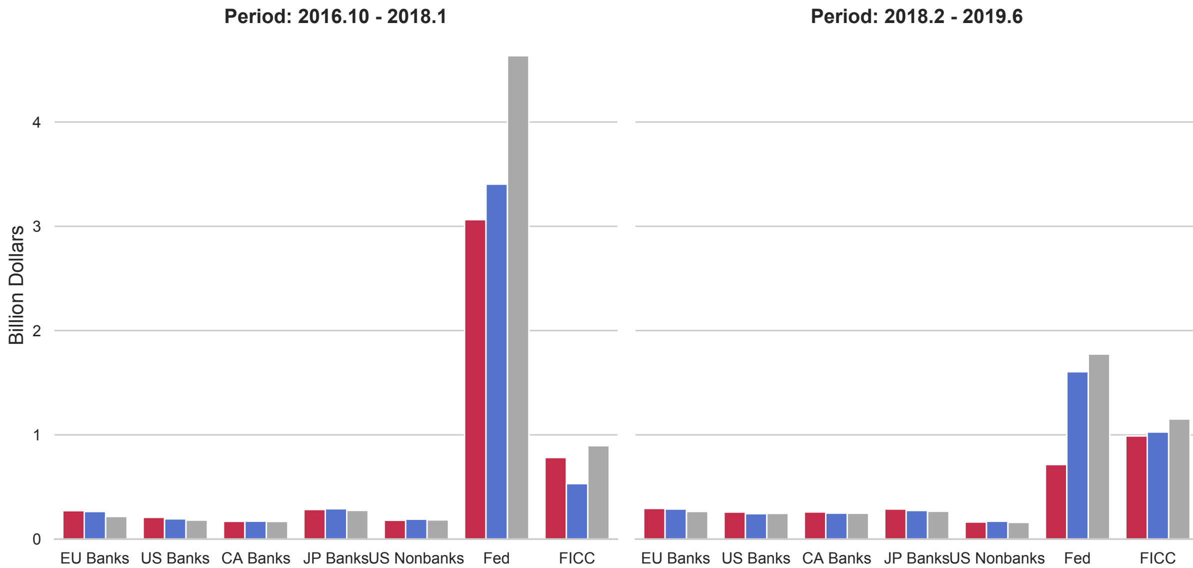

Figure C.7. Average principal amount of Treasury and agency repo contracts issued by different groups of borrowers in the tri-party repo market. Red, blue, and gray bars represent 2, 1, and 0 months before the quarter-end month, respectively. Source: N-MFP2 filings.

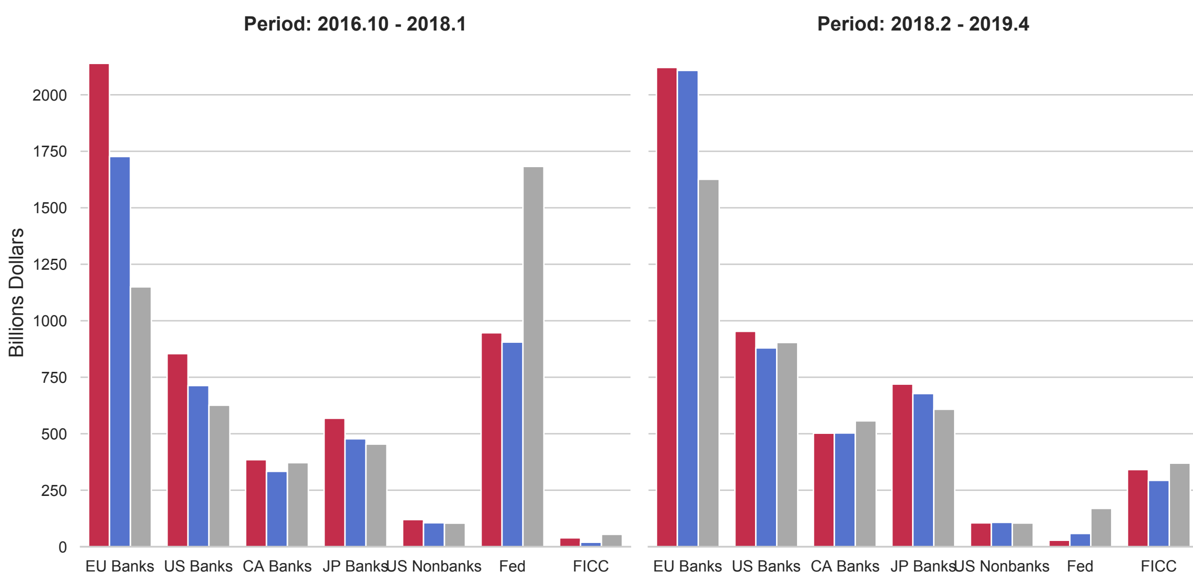

Figure C.8. Total principal amount of Treasury and agency repo contracts issued by different groups of borrowers in the tri-party repo market. Red, blue, and gray bars represent 2, 1, and 0 months before the quarter-end month, respectively. Source: N-MFP2 filings.