Reserves Were Not So Ample After All*

Adam Copeland, Darrell Duffie, and Yilin (David) Yang

FRBNY Stanford GSB Stanford GSB

March 8, 2021

Abstract

We document that the Federal Reserve's "balance-sheet normalization," which reduced aggregate reserves between 2017 and September 2019 is associated with increased repo rates as well as rate spikes, and intraday payment timing stresses, culminating with a significant disruption in Treasury repo markets in mid-September 2019. We show that repo rates rose above efficient-market levels when the total balances held at the Federal Reserve by the largest repo-active bank holding companies were reduced, and that repo rate spikes are strongly associated with delayed intraday payments of reserves to these bank holding companies. Further, intraday payment timing stresses are magnified by issuances of Treasury securities because of the need for the dealer entities of these bank holding companies to pay for newly issued Treasuries early in the day, and also because newly issued Treasury notes decrease the amount of reserves available to make payments. Our analysis implies that substantially higher aggregate levels of reserves than existed in the period leading up to September 2019 would likely have eliminated most or all of these payment timing stresses and repo rate spikes.

Keywords: Repo rates, reserves, Treasuries, payments, central-bank balance sheet.

JEL codes: G14, D47, D82

*Copeland is at the Federal Reserve Bank of New York. Duffie is at Stanford University's Graduate School of Business, the Stanford Institute for Economic Policy Research, and the National Bureau of Economic Research. Yang is in the Doctoral Program of Stanford Graduate School of Business. We are grateful for conversations with Gara Afonso, Sriya Anbil, David Andolfatto, Seth Carpenter, John Cochrane, Ricardo Correa, Lou Crandall, Wenxin Du, Bill English, Egemen Eren, Andy Filardo, Peter Fisher, Andy Filardo, Michael Fleming, Scott Freidenrich, Ken Garbade, Beth Hammack, Tom Harrop, Ben Hébert, Sebastian Infante, Peter Ireland, Frank Keane, Narayana Kocherlakota, Don Kohn, Arvind Krishnamurthy, Gabriele LaSpada, Jenn LeClair, Mickey Levy, Gordon Liao, Lorie Logan, Brian Madigan, Andrei Magasiner, Antoine Martin, Jamie McAndrews, Al Moffitt, Jamie McAndrews, Bill Nelson, Peter Nowicki, Patrick Parkinson, Monika Piazzesi, Simon Potter, Brian Sack, George Selgin, John Taylor, Mike Verdeschi, Josh Younger, John Williams, Stephen Williamson, and Amy Wang. The views expressed in this paper are those of the authors and do not necessarily reflect those of the Federal Reserve Bank of New York or the Federal Reserve System. Research assistance by Renhao Jiang is gratefully acknowledged.

1 Introduction

We show how post-crisis liquidity regulations and the Federal Reserve's "balance-sheet normalization" stressed the intraday management of balances held at the Federal Reserve (Fed) by large bank holding companies (BHCs) that are active in repo markets. This led to spikes in Treasury repo rates during 2018-2019. After an especially large and prominently reported[1] disruption in repo markets during September 16-18, 2019, the Fed reversed its balance-sheet normalization. Despite this change in policy, our analysis implies that the balances held at the Fed by the large BHCs that are active intermediaries in the Treasury repo market were still not sufficiently large to avoid repo liquidity crunches until the Fed created a large quantity of additional reserves in response to the Covid shock of March 2020. Whether the Fed should aim, over the long run, for a small or large balance sheet remains controversial.

Before the failure of Lehman Brothers in September 2008, a small aggregate supply of federal reserve balances, typically under $50 billion, was sufficient for large U.S. banks to manage trillions of dollars of daily payments and for wholesale overnight funding markets to function efficiently. Banks liberally exploited daylight overdrafts of their federal reserve accounts to manage intraday payments flows. The Fed's crisis and post-crisis quantitative-easing programs increased reserve balances to about $2.8 trillion in 2014. In late 2017, the Fed activated its policy of balance sheet normalization, by which aggregate reserves steadily declined, reaching about $1.4 trillion by September 2019, still far above pre-crisis levels. As part of its post-crisis regulatory reform, however, the Fed also introduced a battery of new liquidity requirements that provided incentives for large BHCs to maintain substantial balances at the Fed and which strongly discouraged them from incurring daylight overdrafts on their reserve accounts at the Fed. We find that as balance sheet normalization

[1] For examples of reporting, see "Fed Preps Second $75 Billion Blast With Repo Market Still On Edge," *Bloomberg,* September 17, 2019; "Why the U.S. Repo Market Blew Up and How to Fix It," *Bloomberg*, January 6, 2020; "Fed Plans Second Intervention to Ease Funding Squeeze," *Financial Times*, September 17, 2019; "New York Fed Examines Banks' Role in Money Market Turmoil," *Financial Times*, September 20, 2019; "Wall Street Is Buzzing About Repo Rates. Here's Why," *New York Times,* September 18, 2019; "Fed Intervenes to Curb Soaring Short-Term Borrowing Costs," *Wall Street Journal*, September 17, 2019.

reduced aggregate reserves, intraday payments to the large BHCs active in repo markets were significantly delayed and these BHCs quoted inefficiently high rates for wholesale overnight funding. These large BHCs avoided daylight overdrafts, prioritizing regulatory liquidity requirements by maintaining a significant cushion of reserve balances at the Fed to manage intraday payments flows.

In an efficient wholesale funding market, Treasury repo rates would be essentially equated by arbitrage with the overnight interest rate offered by the Fed on balances held at the Fed (IOR). This is so because Treasury repos and balances held at the Fed are nearly equivalent risk-free overnight investments available to banks. From 2015 to 2020, however, we find that the Secured Overnight Financing Rate (SOFR), a broad measure of overnight Treasury repo rates, was typically well above IOR whenever the total balances held at the Fed of the ten largest repo-active BHCs was below roughly $580 billion.

Low balances held at the Fed can lead to intraday cash hoarding by banks, raising concerns over market liquidity and sometimes even threatening financial stability.[2] Intraday payment delays can be exacerbated by self-fulfilling expectations. That is, whenever a bank believes that other banks will delay their payments because they have low balances, that bank also has an increased incentive to delay payments in order to conserve intraday balances. This feedback effect naturally leads to even higher jumps in repo rates (Yang, 2020).

Intraday payment timing stresses are also exacerbated by issuances of Treasuries because payment to the U.S. Treasury for these issuances must occur early in the day.[3] That is, Treasury issuances increase repo rates not only through the supply-of-reserves channel, but also through the intraday payment timing channel. Issuances also place upward demand-side pressure on repo rates because newly issued Treasury notes are particularly heavily financed in the repo market.

[2]See Hamilton (1996), McAndrews and Potter (2002), Bech and Garratt (2003), Ashcraft and Duffie (2007), Bech (2008), Ashcraft, McAndrews and Skeie (2011), Afonso, Kovner and Schoar (2011), Afonso and Shin (2011), and Yang (2020).

[3]We checked this fact in conversations with multiple knowledgeable market participants and official-sector sources.

Substantially higher aggregate levels of reserves than existed in the period leading up to September 2019 would likely have eliminated most of the upward impact of all of these factors on the excess of Treasury repo rates over IOR and on intraday delays in payments to the large, repo-active BHCs. Truly ample levels of reserves, however, implies a large balance sheet for the Federal Reserve, which is controversial and entails risks described in Section 8. An alternative approach to relieving these liquidity stresses would be a de-emphasis in BHC regulation and supervision on the importance of maintaining positive intraday balances at the Fed, or a de-stigmatization of the use of daylight overdrafts on accounts at the Fed.

Aside from the importance of ample reserves for the efficiency of money markets, Bush, Kirk, Martin, Weed and Zobel (2019) explain that ample reserves support financial stability, because reserves have special intra-day liquidity benefits above and beyond those of other forms of high quality liquid assets. They point to the potential for one-day stressed outflows of reserves from the largest systemically important banks to be in excess of $900 billion.

Commenting on the Fed's balance-sheet policy and its implications for the repo market disruption of September 2019, Gagnon and Sack (2020) wrote: "The minimum level of reserves is conceptually murky, impossible to estimate, and likely to vary over time. The best approach is to steer well clear of it, especially since maintaining a higher level of reserves as a buffer has no meaningful cost." Regarding the costs of maintaining a higher level of reserves, however, the minutes of the Federal Open Market Committee meeting of November 2018 stated that

"Potential drawbacks of an abundant reserves regime included challenges in precisely determining the quantity of reserves necessary in such systems, the need to maintain relatively sizable quantities of reserves and holdings of securities, and relatively large ongoing interest expenses associated with the remuneration of reserves. Some noted that returning to a regime of limited excess reserves could demonstrate the Federal Reserve's ability to fully unwind the policies used to respond to the crisis and might thereby increase public acceptance or effectiveness of such policies in the future.",

although naturally the FOMC's views on these costs and benefits evolved over time.[4]

[4]For example, consider the "Long-Run Monetary Policy Implementation Frameworks" discussion recorded

Section 8 summarizes policy tradeoffs associated with the ampleness of reserves.

When news of the Covid pandemic shocked financial markets in March 2020, the Fed quickly purchased trillions of dollars of assets to support the functionality of bond markets. Because these asset purchases were funded largely with additional reserves, they had the byproduct of increasing aggregate reserves to record levels, removing any strains on intraday payment timing and driving Treasury repo rates extremely close to IOR. Nevertheless, the Fed's past expressed preferences for balance sheet "normalization" may at some point in the future again raise tensions over an appropriate minimum aggregate level of reserves.

The remainder of this paper is organized as follows. Section 2 provides more background and discusses the relationship between our findings and prior research. Section 3 explains our key data sources. Section 4 describes how new liquidity rules and supervision dampen the incentives of large BHCs to provide liquidity to wholesale funding markets whenever there is a nontrivial risk that their buffers of intraday reserve balances may be depleted. Section 5 investigates the empirical relationships among Treasury repo rate distortions, the reserve balances of the largest BHCs active in repo markets, the reserve balances of other large banks, and delays in the intra-day payments to these large BHCs. We control for quarter-end regulatory capital requirements, the issuance of Treasury securities, and the total outstanding amount of Treasury bills, among other factors. Section 6 briefly considers the implications of regulatory capital requirements for funding market stress. Section 7 examines the role of other relevant factors, including the aggregate supply of Treasury bills and the concentration of reserves among the largest BHCs. Section 8 offers concluding remarks regarding key policy tradeoffs.

in the minutes of the FOMC meeting of January 2019.

2 Background and related work

In an efficient money market, the difference between economically equivalent risk-free overnight interest rates is zero. In practice, spreads between Treasury overnight repo rates and the rate of interest paid by the Federal Reserve to banks on their balances at the Fed (IOR) have often diverged substantially from zero. This is so despite the arbitrage by which a bank can invest reserves in Treasury repos whenever repo rates exceed IOR, and vice versa. [5] The total quantity of reserves in the U.S. banking system has exceeded $1 trillion since the 2008-2009 financial crisis and reached a peak of $2.8 trillion in 2014 as a result the Fed's quantitative easing programs. In late 2017, the Federal Open Market Committee began implementing its policy[6] of "balance sheet normalization," by which the Fed planned to reduce its assets and liabilities, including reserves, to the greatest extent consistent with "efficient and effective monetary policy." From late 2017, aggregate reserves declined, reaching a low of $1.4 trillion in early September 2019.

To help ascertain the demand for reserves in the financial system, the Fed surveyed banks about their "lowest comfortable level of reserves" using the Senior Financial Officer Surveys.[7] In a speech given in April 2019, Logan (2019) reports that one estimate of the banking system's demand for reserves based on the September 2018 and February 2019 responses ranged between $800 billion to $900 billion, well below the level of aggregate reserves supplied by the Fed at that time.[8] Logan (2019), however, notes that the aggregate amount of reserves needed to be supplied by the Fed is likely to be higher than this estimated

[5] Banks can engage in repos directly or, if they are part of a BHC, through an affiliated broker-dealer.

[6] See Board of Governors of the Federal Reseve System (2019) for an overview of the Fed's balance sheet normalization policies.

[7] According to the Federal Reserve Board's August 2019 Senior Financial Officer Survey, "satisfying internal liquidity stress metrics, meeting routine intraday payment flows, and meeting potential deposit outflows were "important or very important determinants" of the demands by banks of excess reserves. In a related BIP survey, over three-quarters of the banks for which Reg YY liquidity buffer is applicable indicated this regulation to be an important or very important consideration for the demand of reserves. For details of this regulation, see Liquidity Stress Test Requirements.

[8] See Keating, Martinez, Petit, Styczynski and Thorp (2019) for details behind this estimate. Andros, Beall, Martinez, Rodrigues, Styczynski and Thorp (2019) estimate that aggregate demand for reserves falls between $712 billion to $912 billion, after accounting for sampling and non-sampling error.

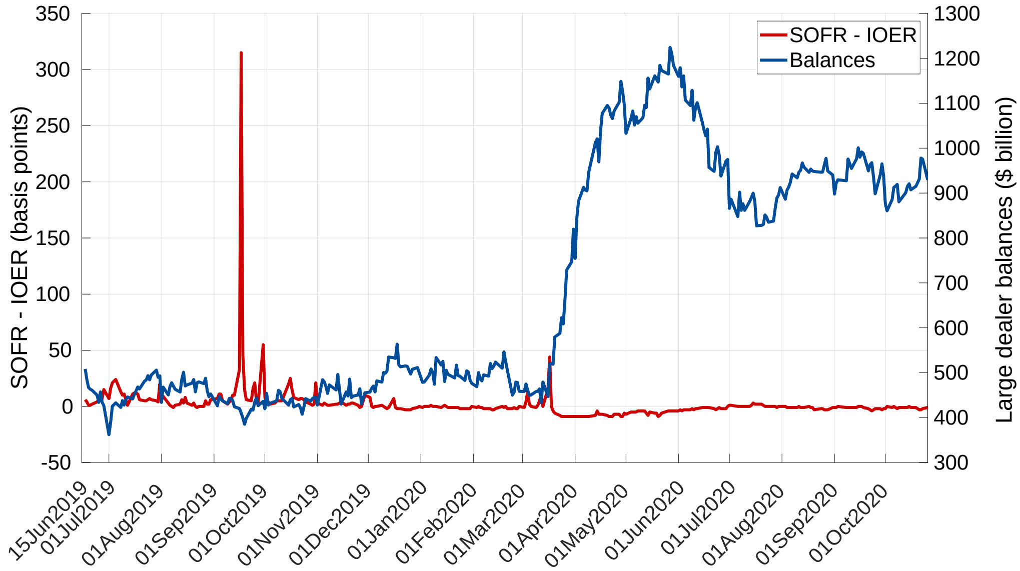


Figure 1: The reserve balances of ten large repo-active dealer banks (right axis, in blue) and SOFR-IOR spreads (left axis, in red). Data: Fedwire Funds Service, FRBNY.

range in order to account for survey error, changes in bank demand, and the possibility that there are frictions in the redistribution of reserves. Given the survey results, as well as a wide range of other information available at that time, when reserves were around $1.6 trillion, it appeared that "reserves remain ample." Yet our analysis shows that with the decline in reserves from 2017 to September 2019, spreads between SOFR and IOR crept higher and repo rates occasionally spiked well above IOR, particularly on Treasury issuance dates.

Our study focuses on the 100 largest U.S. banks in terms of balances held at the Fed. We find that the spread between SOFR and IOR is much more highly correlated with the sum of reserve balances associated with the ten largest BHCs active in repo markets than with the balances of the other 90 banks. Further, our analysis shows that the time by which these large repo-active BHCs accounts receive half of their daily incoming payments is a yet-more-powerful variable for explaining the spread between SOFR and IOR.

In addition to explaining the empirical relationship between rates, balances and the intraday timing of payments on average over our sample period of 2015 to 2020, our analysis also provides insights about the extraordinary repo rate spikes of September 2019 and March

2020.

On September 17, 2019, SOFR suddenly jumped above IOR by 315 basis points and interdealer repo rates reached over 700 basis points over IOR during the course of the day. The Fed reacted quickly,[9] by supplying a large amounts of reserves, and so driving SOFR-IOR spreads back to moderately low levels. We document that on Sept 17 the total balances of all banks in our sample reached a sample record low of $1.06 trillion and that intraday payments of reserves to the ten repo-active banks were significantly delayed, a sign of hoarding of reserves. Indeed, the time by which these ten banks had received half of their daily incoming payments hit a sample record high, up to that date, of 151 minutes later than average (the sample-period average of this daily half-received time).

A similar pattern is observed on March 17, 2020, when SOFR again spiked above IOR during the "dash for cash" induced by news of the Covid pandemic.[10] The reserve balances of the ten repo-active banks remained at their low Sept 2019 levels up until this event (see Figure 1), despite the aforementioned increase in aggregrate reserves between Sept 2019 and March 2020. Further, on March 17, the time by which half of daily incoming payments to the largest repo-active dealer banks had arrived reached the sample-record high of 156 minutes later than average.

Although the Covid-related shock is likely to be more of a tail-event shock compared to the Sept 2019 shock, for both of these events our analysis shows that the level of reserves held by the ten repo-active banks and the timing of intraday payments that they receive are important explanatory variables. We review the estimated relationship among repo rates, reserve balances, and intraday payment timing over the sample period as well as these repo-spike events in Section 5.

Because the March 2020 Covid-crisis news also caused severe illiquidity in the secondary

[9] See Ihrig, Senyuz and Weinbach (2020).

[10] SOFR exceeded IOR by 44 basis points on March 17, 2019. In mid-March 2020, as reported by Clark, Martin and Wessel (2020), term repo rates also jumped significantly, particularly for terms extending beyond the end of the quarter, because balance-sheet constraints of the dealer banks were sharply tightened by the flood of demands for liquidity in the secondary market for Treasury securities, among other markets.

market for Treasury securities, the Fed purchased enormous quantities of Treasuries and Agencies, expanding the total supply of reserves from mid-March by about $1 trillion in just three weeks. As a by-product of this huge asset purchase program, the total reserve balances of our sample of the ten largest repo-active dealer banks increased dramatically, as shown in Figure 1. With this and other aggressive actions by the Fed to restore market liquidity,[11] dealer banks provided reserves much more elastically[12] into the repo market and the spread between SOFR and IOR essentially disappeared, as shown in Figure 1.

The spread between U.S. Treasury overnight repo rates and the interest rate paid by Federal Reserve Banks on excess reserves (IOR) is a gauge of the sufficiency of dealer banks' reserve balances to meet counterparty funding and other "reserve draining" demands (Correa, Du and Liao, 2020), the precautionary demand for reserves to meet intra-day payment obligations (Ashcraft, McAndrews and Skeie, 2011), and regulatory liquidity requirements (Ihrig, 2019). If the aggregate supply of reserves is ample for these combined purposes, then arbitrage would keep Treasury repo rates near IOR and money markets would remain relatively liquid.

The SOFR-IOR spread was actually negative during most of 2015-2017 because of the large supply of federal reserve balances and the low outstanding amount of Treasury bills during most of this period.[13] Government money market funds substitute between Treasury bills and Treasury repos, which places downward pressure on the spread between Treasury

[11]The Fed also offered large amounts of repo funding to primary dealers and exempted reserves and Treasuries from a capital regulation known as the Supplementary Leverage Ratio (SLR).

[12]Lou Crandall, Wrightson Capital's money-market analyst, wrote, in the "Money Market Observer" of July 27, 2020: "As discussed last week, the supply of bank funding available to the repo market became much more elastic once the aggregate cash asset holdings of large domestic banks surged above $1.5 trillion this spring. When reserve availability was merely adequate in Q4 2019 and Q1 2020, GC rates had to rise significantly to induce large domestic banks to substitute RRPs for Fed balances in their HQLA portfolios. From October of last year through April 2020, it took a 15 basis point widening in the Treasury GCF index relative to IOR to induce a $100 billion increase in large domestic bank RRP investments. Between the last Wednesday in May and July 8, large domestic bank RRP positions increased by $271 billion while the Treasury GCF repo index widened by just three basis points, for a beta of just 1 basis point per $100 billion of repo funding provided by banks. We expect these relationships to be muddied to some extent in late July and early August due to tax-season flows, but the basic point still stands: when reserves are hyper-abundant, banks are likely to be willing to supply a large amount of cash to the repo market at only a modest yield pick-up over IOR."

[13]We are grateful to Lou Crandall for emphasizing this point in a private communication.

repo rates and IOR when the outstanding supply of Treasury bills is low (Duffie and Krishnamurthy, 2016). Money funds and most other investors cannot hold Federal reserves, whereas banks are subject to significant capital requirements for reserves.[14] So, when the supply of reserve balances is sufficiently large relative to the supply of Treasury bills, SOFR-IOR easily becomes negative. We explore this relationship in Section 7.

Among the limits to arbitrage between Treasury repo rates and IOR are (i) search frictions in funding markets (Afonso and Lagos, 2015), (ii) repo market segmentation (Han, 2020; Avalos, Ehlers and Eren, 2019; Duffie and Krishnamurthy, 2016), (iii) the cost to banks of mobilizing their repo trading operations (Avalos, Ehlers and Eren, 2019; Anbil, Anderson and Senyuz, 2020b), (iv) capital regulations that raise bank shareholder costs for allocating balance sheet space to repurchase agreements (Duffie, 2018; Correa, Du and Liao, 2020; Afonso, Cipriani, Copeland, Kovner, La Spada and Martin, 2020b), and (v) intra-day payment timing mismatches, which promote conservative payment timing and eventually the hoarding of reserves. When reserve balances are low enough, banks reach the self-fulfilling expectation that payments from other banks will be delayed to later in the day (Hamilton, 1996; McAndrews and Potter, 2002; Bech and Garratt, 2003; Ashcraft and Duffie, 2007; Bech, 2008; Ashcraft, McAndrews and Skeie, 2011; Afonso, Kovner and Schoar, 2011; Afonso and Shin, 2011; Acharya and Merrouche, 2013; Yang, 2020). While we offer support for the importance of all of these effects, our main marginal contribution is to estimate and interpret key relationships among the total reserve balances of the largest dealer banks, the total reserve balances of other large banks, intraday payment timing delays, and repo rate distortions.

The repo market phenomena addressed in this paper are best exemplified by the situation in mid-September 2019, which is described in detail by Afonso, Cipriani, Copeland, Kovner, La Spada and Martin (2020b), Anbil, Anderson and Senyuz (2020a), Anbil, Anderson and

[14] In the spring quarter of 2020, in stages, reserve balances were temporarily exempted from the Supplementary Leverage Ratio. Reserve balances continue to contribute to certain other capital requirements including those based on GSIB scores (Covas and Nelson, 2019).

Senyuz (2020b), Ihrig, Senyuz and Weinbach (2020), and Correa, Du and Liao (2020), among others. This was almost a perfect storm of supply and demand factors, beginning on the supply side with the lowest level of reserves ever achieved during the Fed's balance sheet normalization. Reserves had been depleted not only by the gradual process of balance-sheet normalization, but also by a significant shift of reserves into the Treasury General Account (TGA).[15] The Treasury Department does not supply funding to wholesale money markets, so the transfer of reserves from banks' Fed balances to the TGA reduces the supply of cash available to the repo market and other funding markets (Correa, Du and Liao, 2020). This shift of reserves into the TGA was exacerbated on September 16, 2019 by quarterly corporate tax payments due that day[16] and by an issuance of $54 billion of Treasury coupon securities, which was settled early that morning by a transfer of reserves to the TGA from the accounts of banks which have dealers as clients. This was not an unusually large Treasury settlement, but it came at a time of low balances held at the Fed by repo-active BHCs.

Meanwhile, as documented by Afonso, Cipriani, Copeland, Kovner, La Spada and Martin (2020b) and Anbil, Anderson and Senyuz (2020b), money market mutual funds had recently reduced their use of "sponsored repo,"[17] by which they had obtained repos that were centrally cleared through sponsoring dealers, thus reducing the amount of balance sheet space committed to repos by those dealers and, by extension, their BHC entity. As a result, if a BHC offset the reduction in cash available via sponsored repo with an alternate source of cash, the BHC would face a heightened regulatory capital committment as a nettable transaction would be replaced by one that is not nettable. As a consequence, the reduced use of sponsored repo leading up to mid-September 2019 could only be replaced by more balance-sheet costly transactions.

On the demand side of the repo market, large U.S. government fiscal deficits had caused

[15]In May 2015, the Treasury changed its policy around the management of TGA, deciding to establish a cash balance policy in which they hold sufficient cash for a week of outflows (Treasury Quarterly Refunding Statement, May 2015).

[16]We obtained corporate tax payment data from The Daily Treasury Statement.

[17]See also Hüser, Lepore and Veraart (2021)

a significant secular increase in the outstanding stock of marketable Treasury securities, which in turn increases the amount of Treasury securities for which dealers required repo financing. In particular, the Treasury issuances on September 16 and 17, 2020, increased the demand by dealers for repo financing. Further, the requirement by Treasury to be paid early in the morning results in early-morning transfers of reserve balances to the TGA, reducing the supply of reserves available to invest in repo. Newly issued Treasury coupon securities, especially notes, are in high demand in the repo market (Fleming, Hrung and Keane, 2010b). Anbil, Anderson and Senyuz (2020b) show that demand for repo financing of Treasuries in mid-September 2019 was highly inelastic.

Our research is most closely related to the work of Correa, Du and Liao (2020), who also examine, among other wholesale funding-market phenomena, how repo rate spreads respond to various funding-market pressures. In this respect, Correa, Du and Liao (2020) analyze how daily changes in repo rate spreads respond to Treasury issuances, daily changes in TGA balances, and daily changes in the Federal Reserve's holdings of Treasuries and Agencies in its System Open Market Account (SOMA), as reflected in their Table A5. By contrast, we focus on relationships among the total balances held at the Fed by large repo-active BHCs, the levels of repo rate spreads, and intraday payment delays to the largest repo-active BHCs. Correa, Du and Liao (2020) document the within-BHC flow of cash and securities, especially in response to repo rate spikes. This flow of reserves and securities between the bank and broker-dealer entities of the same BHC is an integral underlying assumption of our analysis.

Our work, like most of the research that we have cited, is relevant to the effectiveness of monetary policy transmission, the stability of the payment system, and funding market efficiency. Payment delays or a significant divergence between broad Treasury market repo rates and IOR can raise concerns over all three objectives, signaling potentially serious impediments to flows of funds between the central bank, key financial intermediaries, and other wholesale money market participants.

3 Data: Sources and Description

Our empirical work uses two types of information about balances held at the Federal Reserve Banks: daily opening balances held in individual accounts and the timing of cash transfers between accounts within each day.[18] The source of both of these types of information is the Fedwire Funds Service (Fedwire), a utility offering real-time gross settlement services to financial institutions holding an account at a Federal Reserve Bank.

There are over 6,000 accounts on Fedwire, the vast majority of which are managed by small domestic banks whose actions have at most second-order effects on the U.S. repo market. We therefore focus our attention on the largest 100 accounts managed by depository institutions.[19] We then identify ten of these accounts which are held by depository institutions owned by BHCs which have a large presence in U.S. repo markets.[20] Reflecting that the largest dealers active in repo are associated with large bank holding companies, these ten accounts hold relatively large balances, on average. Indeed, over 2018-19, the sum of the opening-day balances of these ten accounts is about 40 percent of total opening-day balances of all 100 accounts. For simplicity, we refer to these ten large repo-active account holders as "the dealer banks." This terminology reflects the fact that the bank entity of a bank holding company holds the Fedwire account, whereas the broker-dealer entity of the BHC tends to be more active in repo markets.[21] Given the requirement of data confidentiality, we do not identify individual account holders.

From the opening-day balances data for these 100 accounts, we produce two daily time series: the sum of opening-day balances for the ten specified dealer banks accounts, and the sum of all other opening-day balances. The daily reserve balances time series are shown in

[18] Our analysis is done at the master account level, which is the level at which the Fed tracks overdrafts.

[19] We consider the 100 largest accounts in terms of opening balances over 2018-19, excluding accounts held by the U.S. Treasury, by financial utilities,and a BHC which provides repo clearing and settlement services to most of the large broker-dealers.

[20] We use confidential repo data to generate a ranking of gross repo activity at the parent company level. Using this ranking we find that ten of the top eleven parent companies are associated with bank holding companies with Fedwire accounts. We use this set of ten bank holding companies to define our repo-active Fedwire accounts.

[21] Broker-dealers are not eligible to hold accounts on Fedwire.

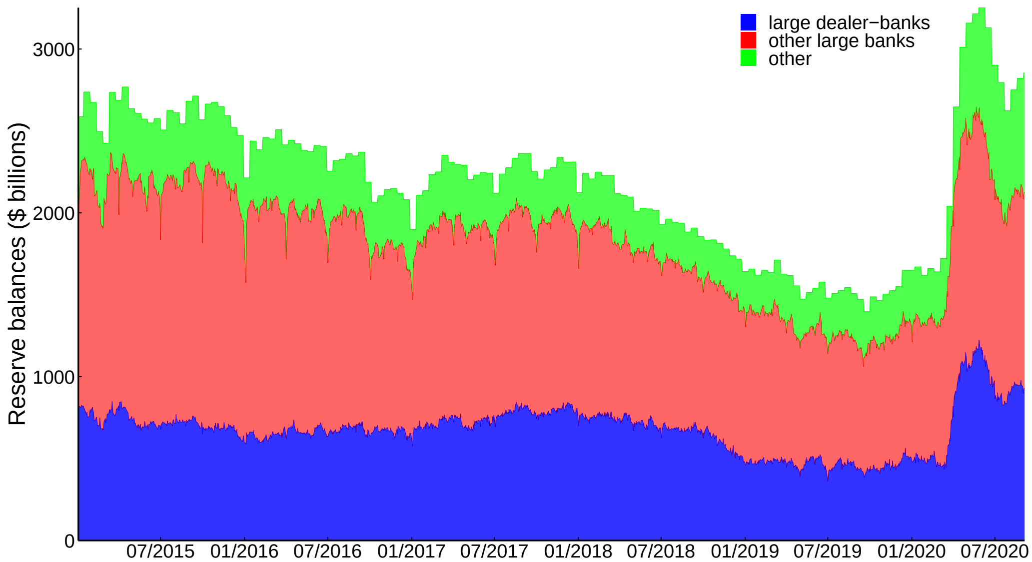


Figure 2: The total reserve balances of the ten large and repo-active account holders ("large dealer banks"), the total reserve balances of the other large account holders ("other large banks") in our sample of 100 accounts, and the total reserve balances of all other financial institutions ("other"). Data: Fedwire Funds Service, FRED (RESBALNS).

Figure 2, in blue and red, respectively, for our sample period of 2015 through late 2020. Our data capture a financial institution's account balance at the Federal Reserve rather than the amount of "reserves" that it holds, as defined by regulation. For the larger financial institutions on which we focus, this is not an important distinction. Indeed, we have checked and found that the opening-day balances of these accounts are quite close to the amount of reserves reported in Call Reports (FR Y-9C). For smaller banks, however, there could be a significant difference between balances held at the Fed and reserves. In the extreme, a small bank may enter into a correspondent banking relationship with another (typically larger) bank and place their reserves at that bank. The result of such an arrangement would be the small bank having a zero balance at the Fed, but still holding reserves. To provide a point of reference, the total balances of the 100 accounts in our analysis are equal to about 85 percent of total reserves held at Federal Reserve Banks over 2018-19. (The official calculation of reserves of an institution also includes its vault cash, which of course plays no role in our research.) The difference between the total system-wide reserve balances maintained at Federal Reserve Banks and the total balances of the 100 sample accounts is indicated in Figure 2 as "other."

In addition to daily opening-balance information, we compute statistics regarding the timing of payments sent over Fedwire within the day. Given our access to the confidential payments data on Fedwire, we observe every transfer of funds settled over Fedwire on a given day. Focusing on the ten repo-active accounts described above, we observe the flow of transfers received by these accounts as well as the flow of transfers sent by these accounts. Using this information, for each given day in our sample, we compute when in the day 25%, 50%, and 75%, respectively, of the total value of transfers to these these ten accounts has been received. Likewise, we compute when in the day these respective fractions of the total value of transfers have been sent by these ten accounts. For example, on February 20, 2019, half of the total transfers to the ten dealer banks had been received by 2:03 pm, and half of the total value sent by the ten dealer banks was sent by 12:54 pm. These statistics are based on standard payment timing metrics used in previous research on intra-day payments, such as Armantier, McAndrews and Arnold (2008), McAndrews and Kroeger (2016) and Copeland, Molloy and Tarascina (2019).

Our main source of repo rates is SOFR, a volume-weighted median of a broad set of overnight Treasury repo transaction rates which reflect the costs of funding for a broad range of market participants. This measure is computed and published daily by the Federal Reserve Bank of New York (FRBNY). SOFR is based on a large sample, often in excess of $1 trillion during our sample period, and is composed of data from tri-party repo, a dealer-to-client market segment, and two interdealer repo services offered by FICC: GCF Repo, and FICC DVP. For the portion of our sample period that precedes the availability of official SOFR fixings, we use unofficial estimates of SOFR published by FRBNY.[22]. Because SOFR is a mix of dealer-to-client and interdealer trades, we also use GCF Repo rates data published by FICC when we want a measure of rates which reflect the costs of funding in interdealer

[22]These unofficial estimates and the SOFR reference rates can be found at https://apps.newyorkfed.org/markets/autorates/SOFR

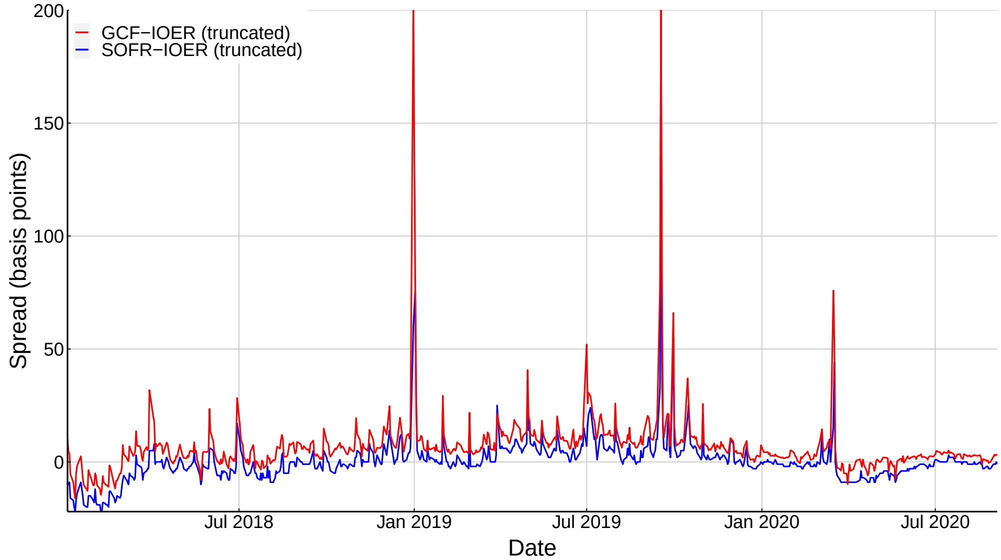


Figure 3: Spreads of SOFR over IOR and GCF over IOR, truncated at 200 basis points for better visualization of the spikes that are dominated by the large spike on September 17, 2019. Data: FRBNY and Tradition.

markets.[23]

Interdealer repo rates tend to be substantially higher than tri-party repo rates. This is so because the larger broker-dealers intermediate a component of the cash investments they receive in the tri-party market, by investing cash in repos with other dealers in the interdealer market (Copeland, Davis and Martin, 2015). This is illustrated in Figure 3 which compares SOFR (a mixture of dealer-to-client and interdealer rates) and GCF Repo (interdealer rates). Beyond the effect of this "bid-offer" spread between these two segments of the repo market, which averages about 7 basis points during our sample period, we also find that interdealer rates are much more sensitive to quarter-end capital requirements than is the case for tri-party rates. Indeed, the spread between interdealer repo rates and tri-party repo rates was much narrower, at 2 basis points or less, before the imposition of the supplementary leverage ratio capital requirement (Duffie and Krishnamurthy, 2016). Generally speaking,

[23]GCF Repo has by far the smallest volume when compared to tri-party repo and FICC DVP, as can been seen from the published volumes on FRBNY's SOFR website. Given its relatively small size, there is a concern that GCF Repo rates are not representative of interdealer rates. To check this, we compared the GCF Repo rates to those provided by Tradition, an interdealer broker, and found both sets of rates to be highly similar.

however, our results concerning the implications for repo rate spreads of the ampleness of reserve balances do not depend importantly on which of these two segments of the repo market is considered. We focus primarily on the spread between SOFR and IOR. Section 6 provides additional discussion of the implications of capital requirements for the spread between interdealer and tri-party repo rates.

In order to capture some of the intraday behavior of Treasury repo markets, we also use intraday general-collateral repo rate transaction-level data provided to us by Tradition, an interdealer broker, as captured by Tradition's brokering screen.[24]

We obtained Treasury issuance and redemption data from the Treasury Department. Our daily time series of Treasury bills outstanding was provided by Lou Crandall of Wrightson Capital, who created this series from daily issuance and redemption data. Primary dealer net Treasury positions are published by the Federal Reserve Bank of New York.

4 Intraday stress on balances held at Fed

A natural hypothesis is that when repo rates are above IOR, the repo-active dealer banks allocate their reserve balances based on the tradeoff between (a) holding balances at the Federal Reserve and (b) depleting these balances in order to obtain a higher rate of compensation in the repo market. Balances at the Federal Reserve are compensated at IOR, contribute to the option to make payments at any subsequent time during the day, and contribute to meeting regulatory liquidity requirements and maintaining the bank's reputation with regulatory supervisors for maintaining high levels of liquidity.

Jamie Dimon, the Chairman and CEO of JP Morgan, famously[25] commented on this tradeoff during J.P. Morgan's third-quarter 2019 earnings call, when he responded to a question[26] about "everything that went on in the repo markets" by saying

[24]For each transaction record, the fields includes whether the accepted rate is a bid or an ask, the size of the trade, and the collateral type. The data span 1/4/2016 to 2/27/2020. There are 202,062 overnight trade quotes with general Treasury collateral.

[25]Dimon's comments were covered by, for example, Bloomberg.

[26]Glenn Schorr, analyst at Evercore, questioned Dimon as follows. "Curious your take on everything that

"... we have a checking account at the Fed with a certain amount of cash in it. Last year [2018] we had more cash than we needed for regulatory requirements. So when repo rates went up, we went from the checking account, which was paying IOR into repo. Obviously makes sense, you make more money. But now the cash in the account, which is still huge. It's $120 billion in the morning and goes down to $60 billion during the course of the day and back to $120 billion at the end of the day. That cash, we believe, is required under resolution and recovery and liquidity stress testing. And therefore, we could not redeploy it into repo market, which we would have been happy to do. And I think it's up to the regulators to decide they want to recalibrate the kind of liquidity they expect us to keep in that account. Again, I look at this as technical; a lot of reasons why those balances dropped to where they were. I think a lot of banks were in the same position, by the way. But I think the real issue, when you think about it, is what does that mean if we ever have bad markets? Because that's kind of hitting the red line in the Fed checking account, you're also going to hit a red line in LCR, like HQLA, which cannot redeployed either. So, to me, that will be the issue when the time comes. And it's not about JPMorgan. JPMorgan will be fine in any event. It's about how the regulators want to manage the system and who they want to intermediate when the time comes."

To a follow-up question, Dimon replied:

"As I said, we have $120 billion in our checking account at the Fed, and it goes down to $60 billion and then back to $120 billion during the average day. But we believe the requirement under CLAR and resolution and recovery is that we need enough in that account, so if there's extreme stress during the course of the day, it doesn't go below zero. If you go back to before the crisis, you'd go below zero all the time during the day. So the question is, how hard is that as a red line? Was the intent of regulators between CLAR and resolution to lock up that much of reserves in the account with Fed? And that'll be up to regulators to decide. But right now, we have to meet those rules and we don't want to violate anything we've told them we're going to do."

Under post-crisis liquidity regulations and supervision, globally systemically important bank holding companies (GSIBs) appeared to have became extremely averse to the risk that their intraday reserve balances could approach zero, the "red line" described by Dimon. This conclusion is supported by our conversations with relevant senior managers at several GSIBs. A daylight overdraft at a large systemically important bank would cause a loss of reputation to the bank and thus to its line managers responsible for managing intraday balances. Given

went on in the repo markets during the quarter, and I would love it if you could put it in the context of maybe the fourth quarter of last year. If I remember correctly, you stepped in in the fourth quarter, saw higher rates, threw money at it, made some more money, and it calmed the markets down. I'm curious what's different this quarter that did not happen, and curious if you think we need changes in the structure of the market to function better on a go-forward basis."

the relatively unpredictable timing of incoming payments, it is natural for a large dealer bank to provide discretionary funding in the repo market very conservatively by quoting high repo rates whenever its balances are low and incoming payments seem likely to be delayed.

This is also what we find in the data. For example, the most powerful single explanatory variable in our data for the excess of SOFR over IOR is the time of day by which half of incoming payments to the large repo-active dealer banks have been received. A delay of one standard deviation (58 minutes) in this half-received payment time is predicted to increase SOFR−IOR by more than 8 basis points, after controlling for quarter-end fixed effects. The R^2 for this relationship is 36%. (This relationship is even stronger in the GCF repo market.) Moreover, the most extreme distortions in repo rates in our sample occur on days with the longest delays in these half-received payment times. We explore these relationships in more detail later in the next section.

The most immediately relevant liquidity rules, tests, and supervision are summarized as follows.

- The Fed's Large Institution Supervision Coordinating Committee (LISCC) supervises the intraday liquidity risk of large banks. In its May, 2019 Report on Supervisory Developments, the Federal Reserve Board stated: "In 2019, LISCC liquidity supervision is focusing on the adequacy of a firm's cash-flow forecasting capabilities, practices for establishing liquidity risk limits, and measurement of intraday liquidity risk." Ihrig (2019) describes the associated Comprehensive Liquidity Analysis and Review (CLAR), including the CLAR stress test mentioned by Dimon.

- The Federal Reserve Board's Regulation YY, Enhanced Prudential Standards, includes rules covering intraday liquidity exposures.[27] According to the Federal Reserve Board's

[27]The language for this rule in the Code of Federal Regulations includes: "If the bank holding company is a global systemically important BHC, Category II bank holding company, or a Category III bank holding company, these procedures must address how the management of the bank holding company will: (i) Monitor and measure expected daily gross liquidity inflows and outflows; (ii) Manage and transfer collateral to obtain intraday credit; (iii) Identify and prioritize time-specific obligations so that the bank holding company can meet these obligations as expected and settle less critical obligations as soon as possible; (iv) Manage the

August 2019 Senior Financial Officer Survey, "satisfying internal liquidity stress metrics, meeting routine intraday payment flows, and meeting potential deposit outflows were important or very important determinants" of banks' holdings of excess reserves. In a related BIP survey, over three-quarters of the banks to which the Regulation YY liquidity buffer is applicable indicated this to be an "important" or "very important" consideration.

- Under the Dodd-Frank Act, the Fed and FDIC implemented failure planning requirements for Resolution Liquidity Adequacy and Positioning (RLAP), which include the intraday "resolution" liquidity requirement mentioned by Dimon. The associated FDIC and Federal Reserve Board guidance states that banks must "ensure that liquidity is readily available to meet any deficits." "Additionally, the RLAP methodology should take into account (A) the daily contractual mismatches between inflows and outflows; (B) the daily flows from movement of cash and collateral for all inter-affiliate transactions; and (C) the daily stressed liquidity flows and trapped liquidity as a result of actions taken by clients, counterparties, key FMUs,[28] and foreign supervisors, among others." Pozsar (2019) outlines how RLAP impacts the intraday incentives for dealer banks to conserve reserve balances on days of Treasury issuances.

Even in the post-2008 period, when system-wide reserves have been much higher than pre-crisis, Copeland, Molloy and Tarascina (2019) and McAndrews and Kroeger (2016) showed a strong relationship between intraday payment timing and system-wide total reserve balances. Indeed, as shown in Figure 4, peak system-wide overdrafts have remained highly related to the reserve balances of the 100 largest banks during our post-2015 sample period, with an R^2 of 0.57 for this relationship. Figure 4 also shows that system-wide peak daylight overdrafts achieved their record high level in the two-week maintenance window ending September 25,

issuance of credit to customers where necessary; and (v) Consider the amounts of collateral and liquidity needed to meet payment systems obligations when assessing the bank holding company's overall liquidity needs."

[28] An FMU is a designated financial market utility, such as a designated payment system or a settlement system.

2019. This is also the two-week maintenance window in our sample that has the lowest average daily opening balances. This two-week window also contained the sample's second latest time of day by which the ten dealer banks had received 50% of their total daily payments, which occurred on September 17, 2019. On that day, this half-received payment time was 151 minutes later than normal (meaning 151 minutes after the sample average half-received time). Likewise, September 17, 2019 was the day on which the spread between SOFR and IOR achieved its record high. The only higher half-received payment time, at 154 minutes above average, occurred on March 17, 2020, during the Covid pandemic shock, when SOFR−IOR jumped to 44 basis points.

In short, it seems that new liquidity regulations had the unintended consequence of discouraging banks from providing liquidity to markets during stress periods, and have sometimes caused hoarding of reserve balances. While these adverse impacts of post-crisis financial regulations were predicted by regulators, they were not forecasted to be significant (Committee on the Global Financial System and Markets Committee, 2015). Gorton and Muir (2016) predicted that analogous inefficiencies would be caused by the liquidity coverage ratio (LCR) rule, which also ties down a bank's high quality liquid assets, such as reserves, as a liquidity backstop. Their analysis draws from the National Banking Era, when national banks ignored apparent arbitrages that would have required issuing new money because of the distortionary effect of the requirement to back private money issuance one-for-one with Treasuries.

As shown in Figure 5, a large fraction of interdealer repo transactions on the Tradition platform are conducted between 7:00am and 7:20am, Eastern time. Based on the empirical evidence and the institutional facts that we have described, when intermediating the Treasury repo market, the marginal value of holding balances at the Fed to a dealer bank is sensitive to anticipated stresses intra-day on these balances associated with payment timing. Figure 6 shows a strong relationship on stress days between Tradition repo rates spreads over IOR at the opening of the day, during the key period between 7:00am and 7:20am, and the half-

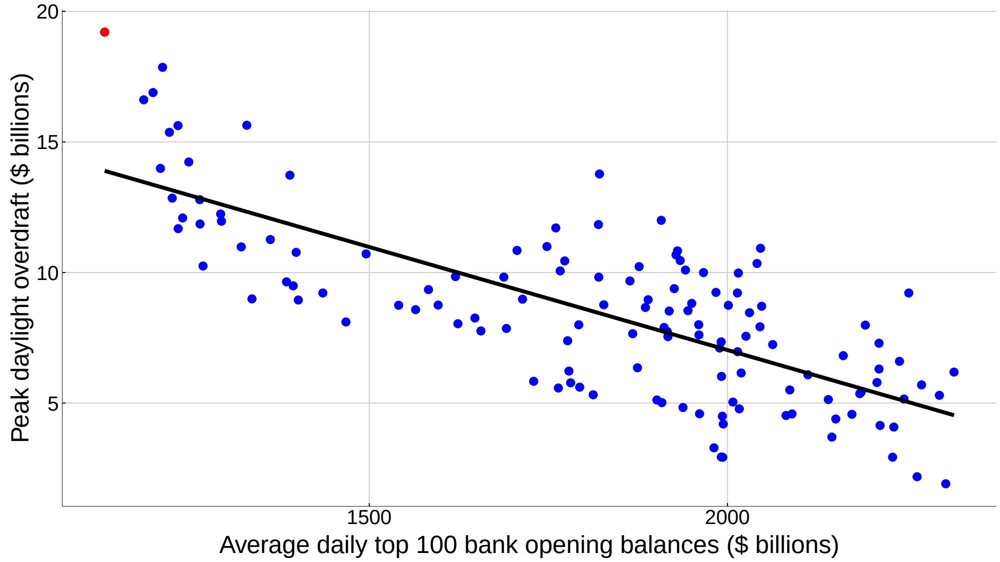


Figure 4: A scatter plot of peak intraday overdrafts over two-week periods, as reported by the Federal Reserve, and the average of the total opening reserve balances of top 100 bank reserves accounts during the same two-week periods. The R^2 for the linear relationship, plotted, is 0.57. The slope coefficient, -0.0079, is estimated with a standard error of 0.00061. The red dot corresponds to the observation for the 2-week maintenance period ending September 25, 2019. Data sources: Federal Reserve and Fedwire.

received payment time on the same day for the ten repo-active dealer banks. Stress on the intra-day balances held by these dealer banks is also related to our finding that their *outgoing* payments are actually *earlier* than normal on days of elevated repo rate spreads. The funding market stress associated with outgoing payments is exacerbated by the fact that dealers' payments to the Treasury General Account to purchase Treasuries at auction must be made early in the morning.

Yang (2020) suggests an additional impact of payment timing stress on repo rates, through the motive of a bank hoarding cash when it perceives that other banks may have low opening balances at the Fed. This induces a self-fulfilling equilibrium expectation of later-than-normal payments by multiple banks, inciting cash hoarding behavior and spikes in repo rates. Empirical work consistent with the importance of cash hoarding in funding markets includes Hamilton (1996), McAndrews and Potter (2002), Bech and Garratt (2003), Ashcraft and Duffie (2007), Bech (2008), Ashcraft, McAndrews and Skeie (2011), Afonso, Kovner and Schoar (2011), and Afonso and Shin (2011).

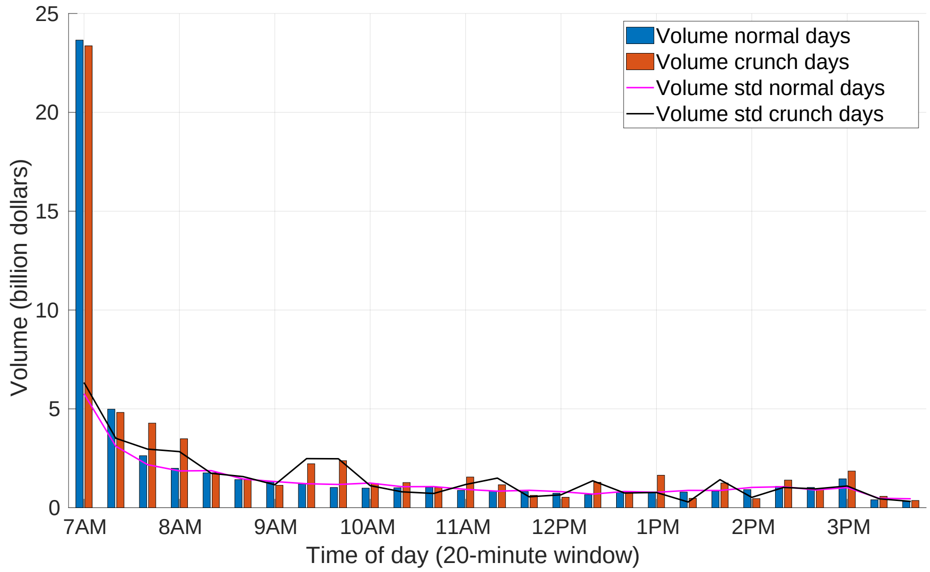


Figure 5: Average and standard deviation, across normal days and across crunch days, of total trading volume in each 20-minute time window. Data: Tradition.

In a February 2020 speech concerning the intra-day demand for reserves and the September 2019 stresses in the repo market, Federal Reserve Governor Randall Quarles mooted the idea of allowing banks to count the amount of credit available to them at the Discount Window toward their liquidity requirements.[29] If banks were not stigmatized by use of the Discount Window, funding market stresses could also be mitigated by drawing reserves from the Discount Window (Covas and Nelson, 2019). In practice, however, this is essentially never done, because of stigma concerns.

5 Liquidity stresses related to low balances at the Federal Reserve

In this section, we quantify key liquidity stresses associated with low levels of Fed balances. The simplest important natural relationships that we find in the data are summarized as follows.

[29]See Quarles (2020).

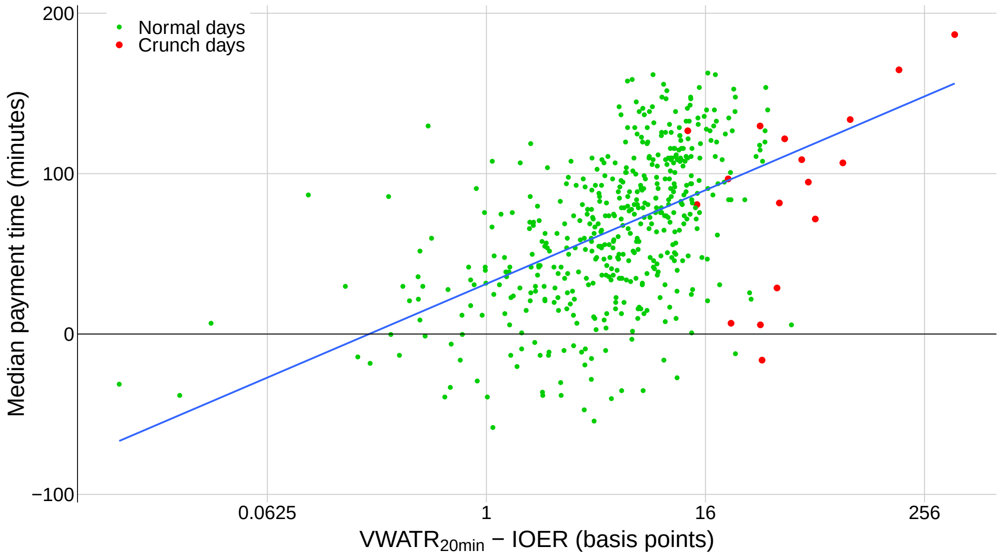


Figure 6: Scatter plot of the half-received payment time net of the ten large repo-active dealer banks and the spread between the volume-weighted average Tradition Treasury general collateral repo rate (VWATR) and IOR in the beginning 20 minutes of each day. Here, we drop the observations for which VWATR-IOR is negative and plot the repo rate spread on a log scale, with a corresponding prediction by OLS regression. Data sources: Fedwire and Tradition.

1. Dealer banks receive payments later in the day when other large banks have lower Fed balances, as illustrated in Figure 7. In a univariate regression, a one-standard-deviation reduction in other-large-bank opening balances ($231 billion) predicts a 48 minute delay in the dealer-bank half-received payment time (Table 1, column 2). The R^2 for this relationship is 69%.

2. Treasury repo rates rise further above efficient-market levels (IOR) when dealer banks receive their payments later in the day, as shown in Figure 8. A one-standard-deviation delay in the half-received time of dealer bank payments (58 minutes) predicts an elevation of SOFR−IOR of 8.2 basis points, with a standard deviation of approximately 0.6 basis points, after controlling for quarter-end fixed effects (Table 2, column 3). The R^2 for this relationship is 36%.

3. Large spikes in repo rates are much more likely on days with large issuances of coupon Treasuries and on days with much longer than normal intraday delays in payments to the large repo-active dealer banks. For example, on September 17, 2019, SOFR−IOR

spiked to 315 basis points and the half-received payment time for dealer banks was 151 minutes above its sample average, a record high to that point of our sample period. The estimated probit models shown in Appendix Tables 4 and 5 indicate that a spike in repo rates is much more likely to occur on days that (a) have a significantly delayed half-received time of payment to the repo active dealer banks, (b) have large Treasury coupon security issuances, (c) have low dealer balances, (d) are quarter ends, and (e) have combinations of one or more of these effects.

4. Each successive doubling of the difference between SOFR−IOR and its sample minimum predicts a delay in the half-received time of dealer banks of approximately 43 minutes, with a standard deviation of 2 minutes (Table 1, column 4).[30]

5. Treasury issuance settlements result in cash transfers from banks' accounts at the Fed to the TGA account, and moreover these transfers must occur near the beginning of the day, as we have verified from multiple authoritative sources. Issuance settlements also add to demands for financing in the repo market (Fleming, Hrung and Keane, 2010b), both of which elevate repo-rate distortions. For example, after controlling for other key factors (Table 2, column 7), a typical $50 billion issuance of coupon Treasuries predicts an increase of SOFR−IOR by 3.2 basis points (with a standard error of about 0.6 basis points). The analogous prediction for the interdealer market (GCF−IOR) is 5 basis points (Table 6, column 7). This issuance effect was previously reflected in the results of Correa, Du and Liao (2020), whose Table A5 shows that the amount of repo "lending" (reverse repurchases) conducted by U.S. globally systemically important banks (GSIBs) has risen significantly with increases in net Treasury issuance. Our sample is not restricted to U.S. dealer banks, and we focus on the role of new Treasury issuances, not issuances net of maturing securities, given the distinct role of new issuances on the repo market.[31]

[30]This is calculated by scaling the regression coefficient by $log(2)$, using the fact that the regressor is the natural logarithm of the excess of SOFR−IOR over its sample minimum (minus 1 basis point).

[31]Somewhat surprisingly, Correa, Du and Liao (2020) find that U.S. GSIB repo "borrowing" does not

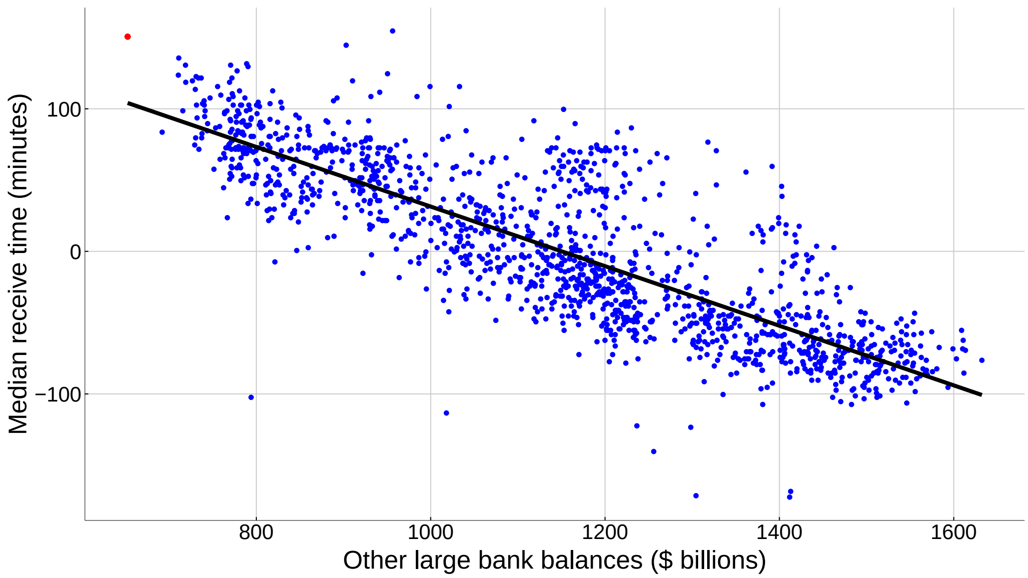


Figure 7: A scatter plot and regression fit of half-received time of payments to the ten dealer banks and opening balances of the remaining large banks in the 100-large-bank sample. The R^2 for the plotted linear relationship is 0.69. The slope coefficient, −0.209, is estimated with a standard error of 0.0037. The red dotted date is September 17, 2019. Data sources: Federal Reserve.

We are not claiming to estimate how much repo rates are causally determined by Fed balances held by dealer banks and other large banks. This would be challenging to do given the endogenous response of dealer bank balances to opportunities to profit from elevated repo rates. The coefficients associated with dealer bank balances in our basic regression models in Table 2, although large economically and highly statistically significant, are likely to underestimate the causal dependence of SOFR−IOR on the supply of dealer bank opening balances, given that dealer banks have an incentive to increase their Fed balances when they expect SOFR−IOR to be higher than normal, controlling for other determinants of balances. In an attempt to account for this endogeneity, we take an instrumental-variables (IV) approach. In a first-stage regression shown in Appendix Table 11, we use intraday payment timing variables on day $t-1$ and corporate tax payments[32] on day t to predict

depend significantly on net Treasury issuances (issuances net of redemption of Treasury securities). This may be related to the effect of net versus new issuance, or perhaps is related to the inclusion in issuance of bills and bonds, which do not circulate as heavily in the repo market as new note issuances.

[32] We obtained daily corporate tax payment data from https://fiscaldata.treasury.gov/datasets/daily-treasury-statement/federal-tax-deposits.

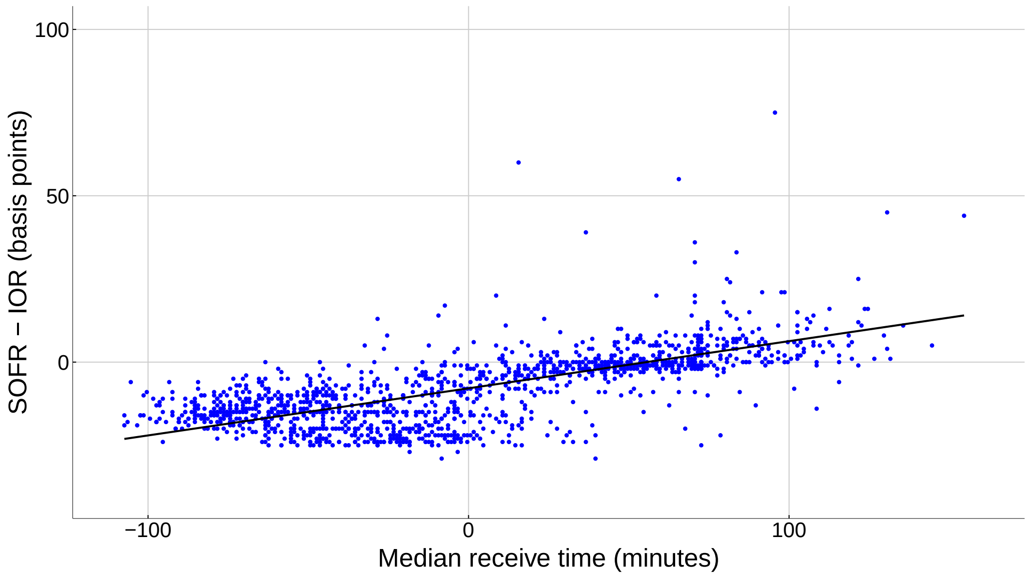


Figure 8: A scatter plot and regression fit of SOFR−IOR and half-received time of payments to the ten dealer banks. The R^2 for the linear relationship, plotted, is 0.35. The slope coefficient, 0.142, is estimated with a standard error of 0.0051. The scatter plot leaves out the single point corresponding to Sept. 17 2019 for better visualization, given the extreme level of 315 basis points for SOFR−IOR on that day. The regression estimation includes the effects of that one data point. Data sources: Federal Reserve.

dealer-bank opening balances on day t. In a second-stage regression shown in Appendix Table 12, we examine the linear relationship between SOFR−IOR and the predicted dealer-bank opening balances predicted by the first-stage model.

The intraday payment timing measures used in the first-stage IV prediction of dealer-bank opening balances on day t are the times on day $t-1$ by which day when dealer-banks had received 25%, 50%, and 75% of the value of payments sent to them by the remaining banks in our sample. With this construction, we aim to account for endogenous changes to dealer-bank Fed balances that are based on aggregate reserves and other factors unrelated to repo market shocks. The identifying assumption is that the timing of other banks' payments on date $t-1$ is unrelated to repo market activity on date t. Here, we also assume that the total value of corporate tax received by the Treasury on date t is independent of repo rates.

This IV approach may not fully compensate for endogeneity. As suggested by endogeneity, however, the IV regression shows that the estimated linear relationship between SOFR−IOR and predicted dealer opening balances is roughly twice as steep as that re-

Table 1: Basic regression models for median time of receives. The units of the explanatory variables are trillions of dollars and log(basis points).

	Dependent variable: median time of receives							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
dealer opening balances	−144.0***		95.5***				98.3***	101.0***
	(11.3)		(7.87)				(6.02)	(6.27)
other large bank balances		−209.0***	−248.0***				−216.0***	−216.0***
		(3.05)	(4.0)				(3.70)	(3.70)
log (normalized SOFR-IOR)				62.7***		36.0***	28.2***	28.7***
				(2.82)		(2.45)	(1.66)	(1.71)
balances of 100 large banks					−120.0***	−93.7***		
					(3.43)	(3.90)		
net Treasury issuance								−73.9*
								(41.5)
Constant	98.4***	240.0***	220.0***	−185.0***	221.0***	65.9***	98.2***	95.4***
	(7.58)	(3.57)	(4.28)	(8.63)	(5.85)	(13.2)	(8.17)	(8.50)
Observations	1,464	1,464	1,464	1,454	1,464	1,451	1,451	1,450
R^2	0.14	0.691	0.728	0.381	0.515	0.632	0.808	0.809
Adjusted R^2	0.139	0.691	0.728	0.381	0.515	0.632	0.808	0.808
Residual Std. Error	53.8	32.2	30.2	45.0	40.4	34.7	25.1	25.0

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

flected by the linear relationship shown in Table 2 between SOFR−IOR and realized dealer bank opening balances.

During the balance sheet normalization, the total Fed balances of large financial institutions other than the ten dealer banks was much less related to repo rates, as indicated in Appendix Table 9. Again, this is not to suggest that other bank balances are not causally important to the determination of repo rate distortions. As we have discussed, other large bank balances are highly predictive of delayed payments to the dealer banks, which are in turn highly predictive of repo rate distortions. In any case, the distribution of opening balances between the dealer banks and the other large banks seems to play an important role in repo rates, as one might expect from lack of perfect-market competition and from imperfect mobility of reserve balances into the repo market.

Table 2: Basic regression models for market-wide (SOFR) Treasury repo spreads over IOR. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: SOFR - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-32.2^{***}	-32.1^{***}		-13.3^{***}	-50.6^{***}	-33.9^{***}	-31.4^{***}
	(3.53)	(3.52)		(1.92)	(3.51)	(2.15)	(3.07)
median time of receives			0.141^{***}	0.128^{***}		0.0642^{***}	0.0612^{***}
			(0.0102)	(0.00888)		(0.0156)	(0.0179)
quarter-end fixed effect		13.6^{***}	13.3^{***}	13.3^{***}	13.9^{***}	13.9^{***}	9.85^{**}
		(4.12)	(4.09)	(3.90)	(3.96)	(3.95)	(3.99)
Tbills outstanding					9.04^{***}	5.50^{***}	4.22^{***}
					(0.352)	(0.645)	(0.629)
net Treasuries inventory							13.2
							(11.6)
Treasuries redemption							-32.1^{***}
							(11.1)
Bill issuance							38.0^{***}
							(11.4)
Coupon issuance							63.8^{***}
							(11.1)
Observations	1,452	1,452	1,454	1,451	1,450	1,449	1,436
R^2	0.122	0.136	0.360	0.378	0.392	0.414	0.424
Adjusted R^2	0.121	0.135	0.360	0.377	0.391	0.412	0.421
Residual Std. Error	12.9	12.8	11.0	10.9	10.8	10.6	10.5

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

6 The role of capital requirements

Correa, Du and Liao (2020) and Wallen (2020) among others, examined the impact of quarter-end bank capital requirements on funding market arbitrage spreads. They included a focus on the cross-currency basis. Although reserves and overnight Treasury repos are essentially risk free, they are nevertheless assigned a capital requirement under various versions of the Basel III leverage-ratio rule. In several important non-U.S. jurisdictions, including the Eurozone, the leverage-ratio capital requirement applies to the quarter-end assets of bank holding companies (Egelhof, Martin and Zinsmeister, 2017; Correa, Du and Liao, 2020).

On quarter-end dates, we find that interdealer repo rates are substantially elevated, most likely because regulatory capital requirements on foreign bank holding companies cause them to reduce their provision of liquidity to interdealer markets, leaving the market to be intermediated mainly by U.S. dealer banks, which are subject to daily-average capital requirements rather than quarter-end requirements. Beyond the associated reduction in the supply of funding market liquidity on quarter ends, the quarter-end effect could be magnified by the associated reduction in the degree of competition facing U.S. dealer banks (Wallen, 2020). Correa, Du and Liao (2020) write that "on quarter-ends, we find that U.S. banks reduce their reserve balances by about $60 billion, and increase their net reverse repo positions by $40 billion and dollar lending in the FX swap market by $20 billion."

Our predicted quarter-end increase in GCF−IOR is 26 basis points, after controlling for other key factors. It is particularly important to control (Appendix Table 6, column 7) for Treasury issuances, which somewhat frequently occur at quarter ends (Appendix Table 10). Our estimated quarter-end fixed effect on GCF−IOR is substantially larger than that estimated by Correa, Du and Liao (2020). The tri-party repo predicted quarter-end effect is not statistically significant (Appendix Table 7, column 7) after controlling for Treasury issuances, which often occur on quarter ends.

This difference between tri-party repo and interdealer repo is likely due in part to U.S. Supplementary Leverage Ratio (SLR) constraints. When a large dealer bank invests cash in an interdealer repo, it is subject to the SLR, but when the dealer bank sources funds in the tri-party repo market, it is not subject to SLR as the tri-party repo transaction shows up on the balance sheet as a liability.[33] Given our quarter-end fixed-effect estimates, it is likely that the dealer banks demanded higher rates to invest cash in repo to compensate for their higher SLR-related balance-sheet costs. This represents an inefficient wedge in funding markets that reduces gains from trade, because balance-sheet costs are simply debt-

[33] Given the existence of a central counterparty in the interdealer repo market, a dealer bank's repo trading in this segment nets down. As such, our argument on the importance of SLR in this segment applies to strategies where the resulting transactions do not net down, such as a dealer bank investing cash in overnight repo to take advantage of high rates.

overhang frictions (Andersen, Duffie and Song, 2019). Before the imposition of SLR, the spread between GCF Repo rates and tri-party repo rates was typically under 2 basis points. In our sample period, under SLR, this spread averages 7 basis points (Appendix Table 15), rising to an estimated 19.5 basis points[34] on quarter ends (Appendix Table 8) after controlling for Treasury issuances and other effects.

There is also a non-trivial upward impact of capital requirements on intra-quarter repo-IOR spreads, mainly because the U.S. SLR rule applies to the large U.S. dealer banks on a daily-averaging basis. (In stages, beginning in April and May 2020, Treasuries and reserve balances were temporarily exempted from SLR. Treasury repos were not exempted.) For this reason, sponsored repo, which reduces SLR-based asset measures through netting long and short sponsored repo positions at the FICC, had a downward impact on repo-IOR spreads (Afonso, Cipriani, Copeland, Kovner, La Spada and Martin, 2020b; Anbil, Anderson and Senyuz, 2020b). We have not estimated this effect. Capital requirements based on "GSIB scores" also impinge on balance sheet space for repo market intermediation (Covas and Nelson, 2019).

7 Other factors relevant to repo rate spreads

Duffie and Krishnamurthy (2016) and Martin, McAndrews, Palida and Skeie (2019) consider the impact of substitution among Treasury bills, IOR, Treasury repos, the Fed's Reverse Repurchase Facility, and unsecured bank deposits, suggesting a key role for the supply of short-term Treasury securities. Martin, McAndrews, Palida and Skeie (2020) show "that a trillion dollars of additional reserves tends to reduce the fed funds rate by 8 basis points relative to the IOR rate, while an additional trillion dollars of Treasuries with less than a year to maturity tends to increase the fed funds rate by about 3 basis points, confirming the opposing effects these two variables impart on short-term rates."

As we have discussed, because of the option of non-bank investors, especially govern-

[34] This coefficient estimate has a large standard error, of about 10 basis points.

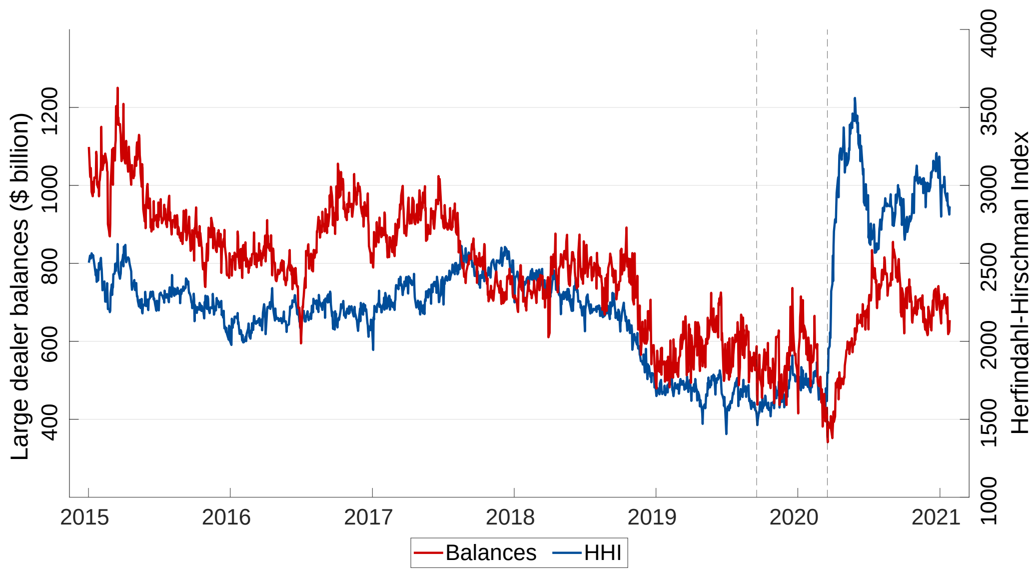


Figure 9: In blue, as measured on the left-hand axis, is the total of the beginning-of-day reserve balances of the ten dealer banks. In red, as measured on the right-hand axis, is the Herfindahl-Hirschman index (HHI) of concentration of beginning-of-day reserve balances across the ten dealer banks. The vertical black dashed lines corresponds to the dates of the repo rate spikes on September 17, 2019 and March 17, 2020. Data: Fedwire Funds Service.

ment money market funds, to substitute between Treasury bills and Treasury repos, an increase in the outstanding supply of Treasury Bills is strongly associated with an increase in SOFR−IOR (Table 2, Columns 5-7). Depending on the regression model, the estimated effect is 4 to 9 basis points per trillion dollars of outstanding Treasury bills, the sample standard deviation of which is \$0.84 trillion. From minimum to maximum during our sample period, Treasury bills outstanding vary by \$3.6 trillion, suggesting a large estimated effect on SOFR−IOR.

We next consider how the concentration of Fed balances among the 10 dealer banks effects repo rates. Figure 9 shows how, as the Fed balances of the dealer banks fluctuated over our sample period, the concentration of balances across these 10 firms varied. Concentration is measured with the Herfindahl-Hirschman index.[35] As shown, when dealer-bank Fed balances

[35] The HHI is the sum of the squares of the percentage shares of each firm. For example, if five firms each have a share of 20%, the HHI is $5 \times 20^2 = 2000$, which is roughly the level of HHI in March 2020. If concentration rises, so that two firms share the entire pool of balances equally, HHI rises to $2 \times 50^2 = 5000$.

are higher, the concentration of balances among dealer banks tends to rise. Perhaps sharing their Fed balances more efficiently, thus more evenly, becomes less valuable to the large dealer banks as their aggregate reserves gets more plentiful. This empirical relationship may alleviate concerns that large spikes in repo rates are caused by the exercise of pricing power by a small subset of the dealer banks that holds a large fraction of all dealer banks' Fed balances.

8 Concluding policy-related remarks

Our results demonstrate that the minimum amount of reserves needed to maintain stability in intraday payments and to avoid stresses in key wholesale funding markets is difficult to gauge, in part because it is highly variable given a number of factors such as the timing and composition of Treasury issuance. As balance sheet normalization proceeded and the total quantity of reserves declined, we document there were adverse impacts on Treasury repo markets. This raises potential alternative policy approaches, including the following.

1. Maintain a balance sheet that achieves clearly abundant reserve balances, with a focus on the resulting quantity of reserve balances chosen by the largest dealer banks. In 2018, the FOMC outlined its views on the costs of this approach, the most obvious of which is the potentially large associated interest expense to the Fed. Cavallo, Negro, Frame, Grasing, Malin and Rosa (2019) consider the political-economy costs to the Fed of large interest payments to banks. Holding balances at the Fed also impinge on bank capital requirements, and thus, when sufficiently large, crowd out other forms of intermediation by banks (Covas and Nelson, 2019). Plosser (2018) points to the risk that the Fed could use a large balance sheet for purposes distinct from monetary policy, such as credit policy, or that Congress could exploit the Fed for this purpose, thus reducing the independence of the Fed's monetary policy. Filardo (2020) adds concerns over dampening the incentives of private market participants to allocate reserves and

monitor counterparties when a large balance sheet implies a large footprint of the Fed on money markets.

2. Establish a standing repo facility, which would offer financing to a designated set of repo market participants at a rate slightly above IOR.[36] The facility rate could be set high enough that the Fed's balance sheet expands only as needed to address temporary liquidity crunches.

3. Relax post-crisis liquidity rules and supervision, which significantly increase the incentive of large banks to maintain thick intraday buffers of reserve balances, and thus significantly reduce the elasticity with which they provide liquidity to funding markets when those buffers are low enough. Because of the March 2020 Covid shock to bond and repo markets, in April 2020 the Fed eliminated reserve requirements, encouraged banks to use their liquidity buffers, and temporarily suspended restrictions and fees on the use of daylight overdrafts.

4. Offer greater incentives for banks to utilize the Discount Window for backstop funding. Alternatively, as mooted by Quarles (2020), the Fed could relax the amount of high quality liquid assets that banks must keep on their balance sheets under liquidity regulations by counting Discount Window access as a substitute for HQLA. Taking a related approach,[37] the Reserve Bank of Australia offers a Committed Liquidity Facility (CLF). Australian banks can access the CLF by paying a fee for a committed line of credit that counts toward their regulatory liquidity requirements.

Because of the huge pace of asset purchases by the Fed in response to the Covid pandemic, which continue,[38] the total amount of reserve balances is at an all-time high and continues

[36] See Andolfatto and Ihrig (2019); Gagnon and Sack (2020) for arguments for the creation of such a facilty.

[37] The RBA's CLF is motivated by the limited outstanding amount of Australian government securities.

[38] At its meeting of December 2020, The FOMC stated that "the Federal Reserve will continue to increase its holdings of Treasury securities by at least $80 billion per month and of agency mortgage-backed securities by at least $40 billion per month until substantial further progress has been made toward the Committee's maximum employment and price stability goals. These asset purchases help foster smooth market functioning and accommodative financial conditions, thereby supporting the flow of credit to households and businesses."

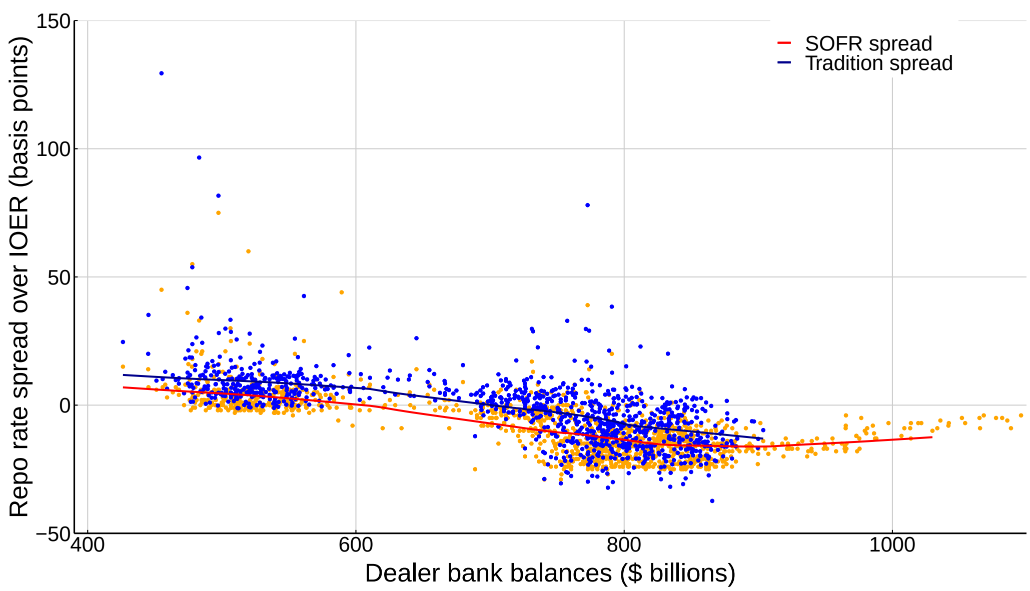
to grow rapidly. Although the FOMC has not re-stated its principles with respect to balance sheet normalization, it may not again need to confront the costs associated with less-than-ample reserve balances for a significant period of time.

Appendix

A Additional figures

The scatter plot in Figure 10 illustrates the relationship[39] between dealer-bank reserve balances and spreads between Treasury repo rates and IOR. The cloud of dots corresponding to total dealer bank reserve balances below $600 billion shows that when dealer bank balances fall into this range, repo rates tend be significantly above IOR. The figure also shows a nonlinear (piece-wise linear) fit of repo rate spreads to dealer-bank reserve balances, for each of the two spread measures.

Figure 10: A scatter plot of dealer balances and the difference between overnight Treasury repo rate indices and IOR. The blue dots indicated spreads associated with the volume-weighted daily average estimated midpoints associated with inter-dealer transactions conducted on the Tradition platform. The green dots indicate spreads corresponding to daily SOFR observations. Dealer bank balances are the beginning-of-day reserve balances of our sample of ten large dealer-bank account holders. (Our sample period SOFR time series begins earlier than that for Tradition data, when reserve balances were higher.) The plotted green and blue line segments correspond to linear regressions restricted to several respective ranges of dealer bank reserve balances, for SOFR and Tradition data respectively. Data: Fedwire Funds Service, FRBNY, Tradition.



[39] This figure is based on a preliminary sample of nine repo-active dealer banks.

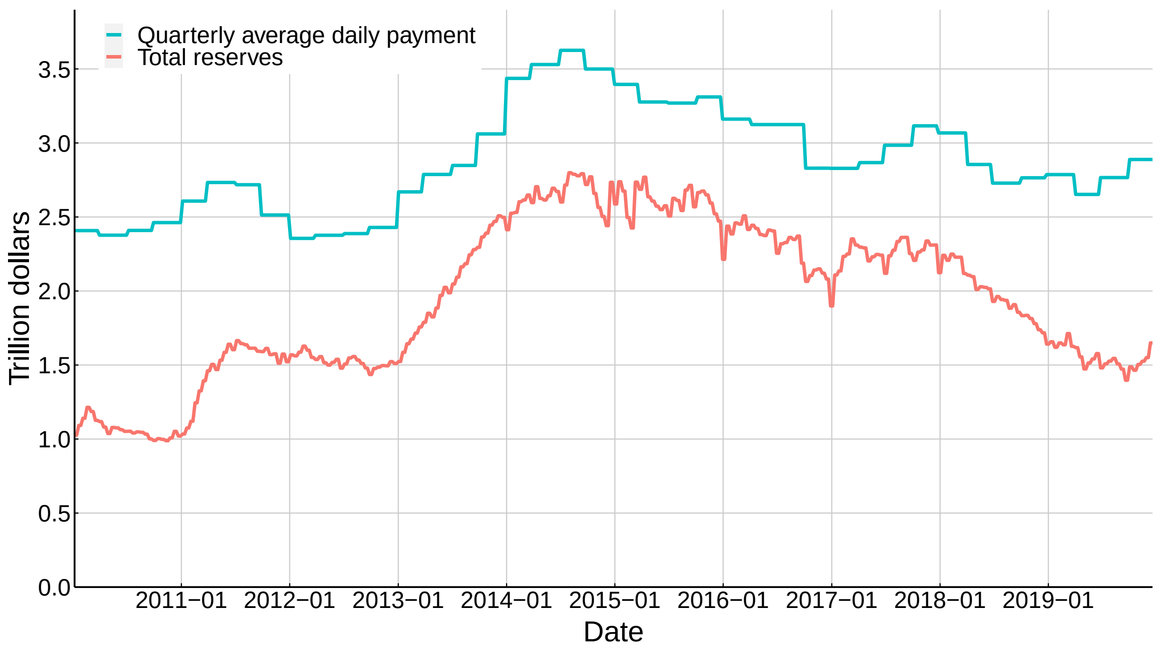


Figure 11: Data: Fedwire Funds Service, FRBNY.

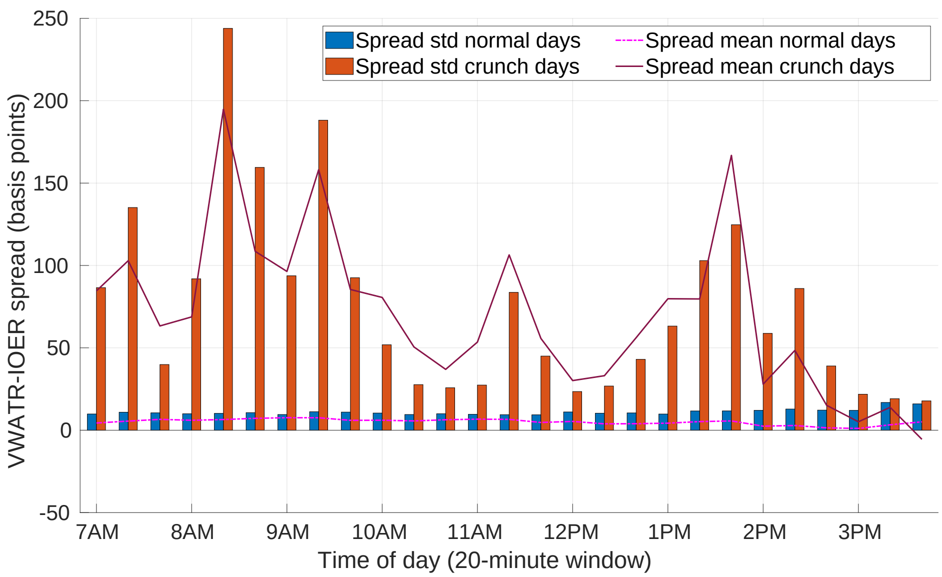


Figure 12: Intraday mean and volatility of VWATR-IOR. Data: Tradition.

B Additional tables

Table 3: Definitions of key regressors

Variable	Definition
dealer opening balances	Sum of daily opening reserve balances, 10 dealer banks ($ trillions). These 10 accounts are associated with entities active in repo markets.
balances of 100 large banks	Sum of daily opening reserve balances of top 100 accounts ($ trillions).
other large bank balances	Sum of daily opening balances in other top 100 accounts, excluding 10 accounts associated with large entities active in repo markets ($ trillions).
median time of receives	Time at which 50% of the day's total incoming payment value has been received by the 10 dealer banks, net of sample mean (minutes).
Tbills outstanding	Treasury bills outstanding ($ trillions).
Bill issuance	Daily quantity of Treasury bills issued ($ trillions).
Coupon issuance	Daily quantity Treasury bonds and notes issued ($ trillions).
Treasuries redemptions	Daily quantity of Treasury securities redeemed ($ trillions).
net Treasuries inventory	Total of primary-dealer net positions in Treasury securities ($ trillions).
QuarterEnd	Indicator (0 or 1) of the quarter end date.
log(normalized SOFR-IOR)	natural logarithm of the excess of SOFR−IOR over the sample minimum of: SOFR−IOR minus one basis point.
$Q(p)$ receive time from other banks	The time at which the fraction p of the value of payments from 100 accounts other than those of the 10 dealer banks was received by the 10 large dealer-bank accounts (minutes).
corporate tax payments	Total daily corporate tax payments to the U.S. Treasury ($ trillions).
BeforeQE	Indicator (0 or 1) of the day before the quarter end.
AfterQE	Indicator (0 or 1) of the day after the quarter end.

Table 4: Estimated probit models of the likelihood of a repo rate spike. These models are of the form $P\left(Repo\,Spike = 1 \mid X_1, X_2, \ldots, X_k\right) = \Phi\left(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k\right)$, where Φ is the standard normal cumulative distribution function. Events of repo rate spikes are defined to have occurred on the dates shown in Table 10, as determined by the criteria stated in the caption of that table. The units of the explanatory variables are minutes and trillions of dollars.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
median time of receives	0.00569***		0.00342**		0.00628***	0.00372**	0.00499**
	(0.00126)		(0.00154)		(0.00144)	(0.00173)	(0.00199)
dealer opening balances		−2.52***	−1.47**			−1.62**	−1.78**
		(0.545)	(0.636)			(0.673)	(0.772)
Coupon issuance				10.1***	10.2***	10.6***	7.05***
				(1.37)	(1.41)	(1.44)	(1.71)
quarter-end fixed effect							2.02***
							(0.323)
Constant	−1.98***	−0.289	−1.0**	−2.13***	−2.25***	−1.18***	−1.19**
	(0.0782)	(0.336)	(0.419)	(0.0847)	(0.101)	(0.441)	(0.506)
Observations	1,418	1,417	1,416	1,415	1,414	1,412	1,412
Log Likelihood	-178.0	-177.0	-174.0	-164.0	-153.0	-150.0	-129.0
Akaike Inf. Crit.	359.0	358.0	355.0	332.0	312.0	307.0	267.0

Note: *p<0.1; **p<0.05; ***p<0.01

Table 5: Estimated likelihoods of a spike in SOFR−IOR based on probit model (7) of Table 4 at various levels of the explanatory variables. These levels are at the sample mean or at the sample mean plus or minus one sample standard deviation of the explanatory variables. The units are the explanatory variables are minutes (time) and bllions of dollars (opening balances and issuances).

spike probability	median receive time	dealer opening balances	coupon issuance	quarter end
0.00962	−0.375	0.686	0.0102	0
0.0201	57.6	0.686	0.0102	0
0.019	−0.375	0.536	0.0102	0
0.0383	−0.375	0.686	0.0911	0
0.373	−0.375	0.686	0.0102	1
0.486	57.6	0.686	0.0102	1
0.477	−0.375	0.536	0.0102	1
0.597	−0.375	0.686	0.0911	1

Table 6: Basic regression models for interdealer (GCF) Treasury repo spreads over IOR. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: GCF - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-38.6^{***}	-38.4^{***}		-18.3^{***}	-50.5^{***}	-31.7^{***}	-30.2^{***}
	(4.60)	(4.51)		(2.87)	(4.66)	(4.76)	(4.40)
median time of receives			0.137^{***}	0.117^{***}		0.0731^{***}	0.0728^{***}
			(0.0132)	(0.0116)		(0.0216)	(0.0246)
quarter-end fixed effect		31.0^{**}	30.8^{**}	30.7^{**}	32.5^{**}	32.4^{**}	26.1^{**}
		(12.5)	(12.8)	(12.6)	(12.9)	(13.0)	(12.8)
Tbills outstanding					8.26^{***}	4.06^{***}	2.69^{***}
					(0.514)	(1.10)	(0.926)
net Treasuries inventory							8.53
							(17.0)
Treasuries redemption							-46.3^{**}
							(18.2)
Bill issuance							54.6^{***}
							(18.8)
Coupon issuance							100.0^{***}
							(18.1)
Observations	1,419	1,419	1,420	1,418	1,417	1,416	1,413
R^2	0.105	0.151	0.251	0.270	0.266	0.283	0.298
Adjusted R^2	0.104	0.150	0.250	0.268	0.264	0.281	0.294
Residual Std. Error	16.5	16.0	15.1	14.9	14.9	14.8	14.6

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

Table 7: Basic regression models for triparty (TGCR) Treasury repo spreads over IOR. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: TGCR - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-31.5^{***}	-31.5^{***}		-10.6^{***}	-52.0^{***}	-33.1^{***}	-31.1^{***}
	(3.66)	(3.66)		(1.96)	(3.56)	(2.10)	(2.99)
median time of receives			0.153^{***}	0.143^{***}		0.0726^{***}	0.0693^{***}
			(0.0102)	(0.00886)		(0.0156)	(0.0178)
quarter-end fixed effect		9.26^{**}	8.88^{**}	8.88^{**}	9.39^{***}	9.39^{***}	5.99
		(4.10)	(3.88)	(3.73)	(3.57)	(3.63)	(3.66)
Tbills outstanding					10.0^{***}	6.01^{***}	4.81^{***}
					(0.359)	(0.636)	(0.588)
net Treasuries inventory							13.2
							(11.6)
Treasuries redemption							-50.3^{***}
							(10.2)
Bill issuance							53.3^{***}
							(10.8)
Coupon issuance							67.2^{***}
							(10.3)
Observations	1,452	1,452	1,454	1,451	1,450	1,449	1,436
R^2	0.116	0.123	0.408	0.419	0.433	0.460	0.470
Adjusted R^2	0.115	0.121	0.407	0.418	0.432	0.459	0.467
Residual Std. Error	13.0	13.0	10.6	10.6	10.4	10.2	10.1

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

Table 8: Regression models for interdealer (GCF) Treasury repo spread over triparty (TGCR) Treasury repo. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: GCF - TGCR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	−2.80	−2.65		−6.81***	0.892	1.91	1.99
	(1.83)	(1.72)		(1.67)	(1.91)	(3.62)	(2.60)
median time of receives			−0.0166***	−0.0241***		0.00396	0.00534
			(0.00382)	(0.00366)		(0.00962)	(0.0112)
quarter-end fixed effect		21.7**	21.8**	21.8**	22.5**	22.5**	19.5*
		(10.0)	(10.1)	(10.0)	(10.5)	(10.5)	(10.3)
Tbills outstanding					−2.36***	−2.58***	−2.69***
					(0.236)	(0.673)	(0.574)
net Treasuries inventory							−1.94
							(8.88)
Treasuries redemption							4.68
							(13.4)
Bill issuance							1.03
							(13.2)
Coupon issuance							31.4**
							(13.4)
A constant was included							
Observations	1,418	1,418	1,419	1,417	1,416	1,415	1,412
R^2	0.0023	0.0972	0.107	0.118	0.138	0.138	0.154
Adjusted R^2	0.0016	0.0959	0.106	0.116	0.136	0.135	0.149
Residual Std. Error	8.51	8.10	8.05	8.01	7.92	7.93	7.87

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

Table 9: Estimated regressions of SOFR−IOR, restricted to the sample period ending September 19, 2019, including as a regressor the total of the opening reserve balances of those accounts other than those of the ten large repo-active banks.

	Dependent variable: SOFE - IOER				
	(1)	(2)	(3)	(4)	(5)
dealer opening balances	-51.1^{***}	-51.1^{***}	-55.7^{***}	-52.4^{***}	-43.6^{***}
	(4.69)	(4.48)	(5.60)	(5.05)	(11.2)
other large bank balances	-3.47	-4.98^{**}	-14.1^{***}	-5.22^{**}	-0.643
	(2.14)	(2.24)	(1.83)	(2.21)	(3.83)
median time of receives from non-dealer banks	0.0544^{***}	0.0454^{***}		0.0455^{***}	0.042^{***}
	(0.0125)	(0.0142)		(0.0142)	(0.0162)
median time of sends			0.021	0.0212	0.0274^{**}
			(0.0144)	(0.0145)	(0.0116)
TBills outstanding	103.0^{***}	98.9^{***}	91.3^{***}	101.0^{***}	61.6
	(27.5)	(26.7)	(26.6)	(26.8)	(41.6)
Bill issuance		45.9^{***}	45.2^{***}	49.5^{***}	47.3^{***}
		(15.1)	(15.6)	(15.2)	(15.3)
Coupon issuance		67.7^{***}	79.2^{***}	73.9^{***}	73.1^{***}
		(19.4)	(17.7)	(18.1)	(17.7)
Treasuries redemption		-33.5^{*}	-33.9^{*}	-37.2^{**}	-35.2^{**}
		(17.3)	(17.4)	(16.8)	(16.3)
net Treasuries inventory					34.7
					(27.4)
quarter-end fixed effect	12.9^{***}	9.91^{**}	9.95^{**}	9.92^{**}	10.3^{***}
	(4.19)	(4.08)	(4.07)	(4.06)	(3.94)
Constant	27.2^{***}	28.2^{***}	41.6^{***}	29.2^{***}	14.6
	(4.29)	(3.85)	(5.43)	(4.10)	(14.1)
Observations	1,176	1,176	1,176	1,176	1,176
R^2	0.357	0.365	0.362	0.366	0.369
Adjusted R^2	0.354	0.361	0.358	0.361	0.364
Residual Std. Error	11.6	11.5	11.6	11.5	11.5

Note: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
Constant included for each specification.

Table 10: Days on which repo rates spiked. The table shows spreads, in basis points (bps) over IOR, of the Secured Overnight Financing Rate (SOFR), of the General Collateral Finance (GCF) repo rate, and the Tri-Party General Collateral Rate (TGCR), for all days in our sample on which at least one of these repo rate spreads was above its previous 14 days rolling average by at least 15 basis points. The table also includes days for which SOFR or TGCR spread is above 20 basis points and for which GCF spread is above 30 basis points. Also shown are three key covariates: issuance and redemption of Treasuries and total opening reserve balances of the sample of ten large repo-active dealer banks. Data: Fedwire Funds Service, FRBNY, and Tradition.

date	SOFR −IOR (bps)	GCF −IOR (bps)	TGCR −IOR (bps)	dealer balances ($ billions)	other bank balances ($ billions)	Treasury issuance ($ billions)	Treasury redemptions ($ billions)
3/31/15	−5	20	−13	822.39	1398.82	103.00	78.42
6/30/15	−8	17.3	−15	700.86	1330.73	97.00	74.13
9/30/15	−2	10.2	−15	708.49	1424.81	103.00	69.10
12/16/15	0	15	−8	650.46	1430.73	0.00	0.00
3/31/16	−8	13.9	−20	658.48	1272.05	244.59	219.70
6/24/16	5	35.5	−4	683.58	1271.25	13.00	0.00
6/27/16	8	26.1	−7	650.60	1226.38	0.00	0.00
6/30/16	13	37.5	−10	635.46	1208.89	213.57	190.91
9/27/16	4	18.1	−13	677.23	1136.14	0.00	0.00
9/28/16	14	29	−10	655.81	1135.62	0.00	0.00
9/29/16	20	39.1	−8	671.38	1095.33	116.00	102.00
9/30/16	39	76.6	−3	648.08	1094.85	118.83	94.60
10/3/16	−5	24.7	−16	635.48	957.59	−0.02	0.00
10/4/16	5	24.9	−12	654.90	1058.81	0.00	0.00
1/17/17	−16	1.3	−21	699.42	1119.99	59.10	50.66
3/31/17	−15	2.5	−20	763.73	1161.05	125.56	94.91
6/30/17	−5	11.6	−16	764.70	1054.70	118.88	92.25
12/29/17	−3	33.6	−12	807.56	1065.96	26.99	0.00
3/29/18	5	31.8	4	737.83	1079.62	196.00	161.01
5/31/18	6	23.5	3	703.68	1046.11	259.11	231.07
6/29/18	17	28.3	15	689.84	1018.07	21.00	0.00
12/6/18	14	24.7	11	580.69	892.63	171.00	160.01
12/31/18	60	274.9	55	481.36	930.31	126.99	94.39
1/2/19	75	83.1	70	459.59	845.31	70.00	70.00
1/3/19	30	24.2	30	461.32	886.90	101.01	109.98
1/31/19	18	29.3	15	468.76	906.32	253.01	245.72
2/28/19	18	21.8	15	487.01	926.52	239.83	200.11
3/29/19	25	21.1	18	500.81	846.48	29.00	0.00
4/30/19	36	40.7	35	414.68	799.44	236.91	223.96
7/1/19	7	52	3	362.03	778.73	119.46	93.46
7/3/19	21	30.6	20	425.21	770.52	0.00	0.00
7/5/19	24	29.2	23	432.94	776.43	72.00	81.00
9/16/19	33	77.6	32	420.27	691.97	78.00	59.00
9/17/19	315	390.7	315	410.63	652.37	90.04	90.01
9/18/19	45	90	40	399.19	718.76	0.00	0.00
9/25/19	21	21	20	434.84	715.67	0.00	0.00
9/30/19	55	66	55	436.37	764.10	137.99	93.24
10/15/19	20	37	15	427.78	777.80	168.03	114.01
10/16/19	25	26.9	22	439.93	736.79	0.00	0.00
10/31/19	21	25.7	18	445.40	763.68	252.68	204.02
3/16/20	16	75.9	13	446.84	950.51	78.07	24.00
3/17/20	44	53.8	40	519.74	956.32	95.57	88.89

Table 11: First Stage of IV regression: Prediction of dealer opening balances.

	Dependent variable: dealer opening balances
lag $Q(0.25)$ receive time from other (non-dealer) banks	-0.0029^{***}
	(0.00023)
lag $Q(0.5)$ receive time from other (non-dealer) banks	-0.00186^{***}
	(0.00014)
lag $Q(0.75)$ receive time from other (non-dealer) banks	0.00181^{***}
	(0.00013)
corporate tax payments	-0.0375
	(0.57)
Constant	0.686^{***}
	(0.00302)
Observations	1,461
R^2	0.439
Adjusted R^2	0.437
Residual Std. Error	0.112

Notes: Lagged variables are lagged by one day. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table 12: Second stage of IV regression: Prediction of SOFR−IOR (basis points). Explanatory variables are measured in trillions of dollars.

	Dependent variable: SOFR - IOR					
	(1)	(2)	(3)	(4)	(5)	(6)
predicted dealer opening balances	-59.5^{***}	-59.3^{***}	-59.3^{***}	-60.2^{***}	-60.2^{***}	-36.3^{***}
	(6.67)	(6.66)	(6.66)	(6.46)	(6.46)	(7.36)
quarter-end fixed effect		13.1^{***}	13.1^{***}	13.8^{***}	13.8^{***}	10.3^{**}
		(4.25)	(4.25)	(4.47)	(4.47)	(4.11)
Tbills outstanding				5.81^{***}	5.81^{***}	−0.0433
				(0.224)	(0.224)	(0.418)
net Treasuries inventory						79.7^{***}
						(5.38)
Treasuries redemption						12.1
						(11.4)
Bill issuance						−3.46
						(10.4)
Coupon issuance						32.1^{***}
						(11.8)
Observations	1,449	1,449	1,449	1,447	1,447	1,436
R^2	0.184	0.198	0.198	0.321	0.321	0.390
Adjusted R^2	0.184	0.197	0.197	0.319	0.319	0.387
Residual Std. Error	12.5	12.4	12.4	11.4	11.4	10.8

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

Table 13: Second stage of IV regression. Prediction of GCF−IOR (basis points). Explanatory variables are measured in trillions of dollars.

	Dependent variable: GCF - IOR					
	(1)	(2)	(3)	(4)	(5)	(6)
predicted dealer opening balances	-66.4^{***}	-66.0^{***}	-66.0^{***}	-64.8^{***}	-64.8^{***}	-44.6^{***}
	(8.66)	(8.54)	(8.54)	(8.39)	(8.39)	(9.38)
quarter-end fixed effect		30.8^{**}	30.8^{**}	32.7^{**}	32.7^{**}	26.5^{**}
		(12.5)	(12.5)	(13.0)	(13.0)	(12.4)
Tbills outstanding				5.07^{***}	5.07^{***}	-0.842
				(0.317)	(0.317)	(0.665)
net Treasuries inventory						71.0^{***}
						(8.43)
Treasuries redemption						-8.26
						(17.0)
Bill issuance						19.1
						(16.5)
Coupon issuance						74.7^{***}
						(18.8)
Observations	1,417	1,417	1,417	1,415	1,415	1,413
R^2	0.143	0.189	0.189	0.238	0.238	0.283
Adjusted R^2	0.143	0.188	0.188	0.237	0.237	0.28
Residual Std. Error	16.1	15.7	15.7	15.2	15.2	14.8

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

Table 14: Second stage of IV regression: Prediction of TGCR−IOR (basis points). Explanatory variables are measured in trillions of dollars.

	Dependent variable: TGCR - IOR					
	(1)	(2)	(3)	(4)	(5)	(6)
predicted dealer opening balances	-61.9^{***}	-61.7^{***}	-61.7^{***}	-62.7^{***}	-62.7^{***}	-38.6^{***}
	(6.77)	(6.77)	(6.77)	(6.52)	(6.52)	(7.37)
quarter-end fixed effect		8.75^{**}	8.75^{**}	9.30^{**}	9.30^{**}	6.47^{*}
		(4.05)	(4.05)	(4.10)	(4.10)	(3.72)
Tbills outstanding				6.70^{***}	6.70^{***}	0.728^{*}
				(0.232)	(0.232)	(0.399)
net Treasuries inventory						81.8^{***}
						(5.21)
Treasuries redemption						−4.91
						(10.3)
Bill issuance						11.0
						(9.47)
Coupon issuance						34.8^{***}
						(10.8)
Observations	1,449	1,449	1,449	1,447	1,447	1,436
R^2	0.198	0.204	0.204	0.364	0.364	0.433
Adjusted R^2	0.197	0.202	0.202	0.363	0.363	0.430
Residual Std. Error	12.4	12.4	12.4	11.1	11.1	10.5

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

Table 15: Summary statistics

Variable	N	Mean	St. Dev.	Min	$Q(0.25)$	$Q(0.75)$	Max
dealer opening balances ($ billions)	1,465	686.0	150.0	362.0	619.0	759.0	1,224.0
other large bank balances ($ billions)	1,465	1,153.0	231.0	652.0	960.0	1,335.0	1,632.0
Tbills outstanding ($ billions)	1,522	2,137.0	841.0	1,233.0	1,557.0	2,312.0	4,802.0
Bill issuance ($ billions)	1,463	33.0	56.8	−0.017	0	75.0	273.0
Coupon issuance ($ billions)	1,463	10.2	31.8	−0.011	0	0	218.0
TBills position ($ billions)	1,507	24.0	20.5	−2.10	13.5	26.1	106.0
Treasuries redemption ($ billions)	1,463	37.9	56.8	0	0	84.7	259.0
net Treasuries inventory ($ billions)	1,507	138.0	77.3	9.26	82.4	224.0	295.0
median time of receives from non-dealer banks	1,467	−0.129	53.0	−115.0	−40.1	34.9	161.0
median time of receives	1,467	−0.375	58.0	−172.0	−49.4	49.6	155.0
SOFE - IOER (basis points)	1,455	−7.84	13.8	−29	−16	−1	315
GCF - IOER (basis points)	1,421	−0.724	17.4	−30.2	−9	5.3	391.0
TGCR - IOER (basis points)	1,455	−11.1	13.8	−26	−20	−3	315
Treasuries issuance ($ billions)	1,463	43.2	64.3	−0.017	0	87.0	365.0
quarter-end fixed effect	1,524	0.0164	0.127	0	0	0	1
corporate tax paid to US treasury ($ billions)	1,467	0.00117	0.00516	−6e-05	5e-05	0.00028	0.0595
Note issuance ($ billions)	1,463	9.27	29.5	−0.011	0	0	199.0
log (normalized SOFR-IOR)	1,455	2.95	0.563	0	2.64	3.37	5.84

Table 16: Summary statistics for selected other variables. The Broad General Collateral Rate (BGCR) is a volume-weighted median of overnight Treasury general collateral tri-party repo data published by the New York Fed.

Variable	N	Mean	St. Dev.	Min	$Q(0.25)$	$Q(0.75)$	Max
SOFR (basis points)	1,455	99.3	85.3	1	17	175	525
TGCR (basis points)	1,455	96.0	85.8	1	11	170	525
GCF (basis points)	1,421	109.0	85.9	0.2	27.7	183	601.0
IOER (basis points)	1,464	107.0	78.8	10	25	175	240
BGCR (basis points)	1,455	96.1	85.7	1	11	170	525
BGCR−IOER (basis points)	1,455	−11	13.8	−27	−20	−3	315
Bond issuance ($ billions)	1,463	0.959	4.09	−0.005	0	0	41.5
Bill redemptions ($ billions)	1,463	30.6	51.9	0	0	75.0	207.0
Bond redemptions ($ billions)	1,463	0.116	1.25	0	0	0	18.9
Note redemptions ($ billions)	1,463	7.20	24.7	0	0	0	155.0
Coupon redemptions ($ billions)	1,463	7.32	25.1	0	0	0	155.0
Bonds position ($ billions)	1,507	97.9	61.7	−7.38	54.8	158.0	227.0
Notes position ($ billions)	1,507	6.30	3.55	−0.729	3.75	8.09	20.3
TIPs position ($ billions)	1,507	9.35	3.74	−0.699	6.71	12.4	17.8
AGYMBS position ($ billions)	1,507	85.0	18.5	49.0	70.7	99.0	134.0
net total inventory ($ billions)	1,507	223.0	85.6	104.0	158.0	312.0	428.0
quarter end -1	1,523	0.0164	0.127	0	0	0	1
quarter end +1	1,524	0.0171	0.130	0	0	0	1
Q1 time of receives from non-dealer banks (minutes)	1,467	0.0221	21.8	−123.0	−14.6	14.4	59.4
Q3 time of receives from non-dealer banks (minutes)	1,467	−0.260	45.2	−166.0	−27.6	33.4	116.0
median time of receives and sends (minutes)	1,453	−3.36	30.2	−153.0	−22.9	16.1	115.0
Q1 time of receives and sends (minutes)	1,453	−2.89	17.2	−72.5	−13.5	7.48	102.0
Q3 time of receives and sends (minutes)	1,453	0.576	13.5	−143.0	−6.07	7.93	174.0
median time of sends (minutes)	1,467	0.14	28.6	−155.0	−18.7	20.3	69.3
Q1 time of sends (minutes)	1,467	0.257	26.1	−94.0	−21.0	20.0	86.0
Q3 time of sends (minutes)	1,467	−0.0211	12.0	−120.0	−5.13	5.87	158.0
Q1 time of receives (minutes)	1,467	−0.029	21.4	−111.0	−17.1	13.9	79.9
Q3 time of receives (minutes)	1,467	−0.148	22.2	−225.0	−14.6	16.4	177.0
dealer opening balance - balance drop ($ billions)	1,464	0.552	0.152	0.174	0.479	0.638	1.04

C Main regressions without spike days

Table 17: Basic regression models for market-wide (SOFR) Treasury repo spreads over IOR for the subsample without spike days

	Dependent variable: SOFR - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-24.7^{***}	-24.7^{***}		-9.03^{***}	-43.1^{***}	-33.0^{***}	-29.2^{***}
	(1.99)	(1.99)		(1.11)	(0.985)	(1.59)	(1.95)
median time of receives			0.123^{***}	0.114^{***}		0.0396^{***}	0.0349^{***}
			(0.00268)	(0.00276)		(0.00482)	(0.00541)
quarter-end fixed effect		5.09	2.13	2.49	1.30	1.52	-3.12
		(3.66)	(2.97)	(2.83)	(3.14)	(3.02)	(3.47)
Tbills outstanding					8.52^{***}	6.34^{***}	4.67^{***}
					(0.170)	(0.306)	(0.449)
net Treasuries inventory							20.2^{***}
							(5.43)
Treasuries redemption							-36.1^{***}
							(9.14)
Bill issuance							36.0^{***}
							(8.08)
Coupon issuance							61.8^{***}
							(9.51)
Observations	1,409	1,409	1,411	1,408	1,407	1,406	1,393
R^2	0.147	0.149	0.528	0.544	0.622	0.639	0.658
Adjusted R^2	0.146	0.148	0.527	0.543	0.621	0.638	0.656
Residual Std. Error	8.84	8.84	6.58	6.47	5.89	5.76	5.63

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

Table 18: Basic regression models for interdealer (GCF) Treasury repo spreads over IOR for the subsample without spike days.

	Dependent variable: GCF - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-27.8^{***}	-27.8^{***}		-11.8^{***}	-39.6^{***}	-28.2^{***}	-25.8^{***}
	(1.94)	(1.94)		(1.23)	(1.07)	(1.87)	(2.41)
median time of receives			0.111^{***}	0.0983^{***}		0.0449^{***}	0.0431^{***}
			(0.00303)	(0.00323)		(0.00588)	(0.0064)
quarter-end fixed effect		4.72	2.38	2.61	2.32	2.26	-3.11
		(4.96)	(5.14)	(4.84)	(5.28)	(5.38)	(5.86)
Tbills outstanding					7.47^{***}	4.90^{***}	3.24^{***}
					(0.233)	(0.396)	(0.601)
net Treasuries inventory							14.5^{**}
							(6.65)
Treasuries redemption							-44.3^{***}
							(10.8)
Bill issuance							48.7^{***}
							(9.59)
Coupon issuance							78.8^{***}
							(11.2)
Observations	1,376	1,376	1,377	1,375	1,374	1,373	1,370
R^2	0.171	0.173	0.415	0.440	0.468	0.489	0.515
Adjusted R^2	0.171	0.172	0.414	0.439	0.467	0.487	0.512
Residual Std. Error	8.88	8.87	7.46	7.30	7.12	6.98	6.81

Notes: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
A constant was included for each specification.

D Tradition repo transactions data

Tradition has provided transaction level quote data captured throughout the day by Tradition's brokering screen. For each transaction record, the fields includes whether the accepted rate is a bid or an ask, the size of the trade, and the collateral type. The data span 1/4/2016 to 2/27/2020. There are a total of 609691 observations, which contains 453136 trade quotes with Treasury and Government Agency as collateral. Our paper focuses on the overnight general Treasury collateral repo rates. There are 202062 overnight trade quotes with general Treasury collateral, and 33622 special overnight repo.

We consider only transactions between t_0 = 7:00 am and T = 4:00 pm. The Tradition data consist of bid and ask rates. We first calculate the mid point rate in the following way.

For general collateral (GC) transactions, let r_t be the rate for a transaction at time t and m_t be the estimated midpoint of the bid and offer rate, in that for a GC trade, $r_t = m_t + q_t c_t$, where c_t is the estimated half bid-offer spread and q_t is 1 for a bid and -1 for an offer. Let c_{t_0} be the ending estimated half bid-offer spread of previous day and let m_{t_0} be the ending estimated midpoint of previous day. We estimates the midpoint and the half-spread at time t using previous estimates, r_t and q_t. Specifically, at time t, let m_{t-} and c_{t-} denote the previous midpoint and half-spread estimates, respectively. For a GC transaction at time t, if $q_t = q_{t-}$, let

$$\begin{aligned} m_t =& r_t - q_t c_{t-} \\ c_t =& c_{t-}. \end{aligned}$$

If $q_t = -q_{t-}$, let

$$\begin{aligned} c_t =& \frac{r_t - m_{t-}}{q_t} \\ m_t =& m_{t-} \end{aligned}$$

We replace negative estimates of the bid-offer spread c_t with zero.

Next, we adjust for repo specialness for specific-collateral (SC) transaction. Let

$$y_t = m_{t-} + q_t c_{t-} - r_t$$

denote the estimated specialness of a specific-collateral (SC) transaction rate r_t at time t.

If $y_t > 20$ basis points, the specialness is "too large" and the transaction is not considered. Otherwise, the transaction is accepted as close enough to GC. For each accepted SC transaction, if $q_t = q_{t-}$

$$\begin{aligned} c_t =& c_{t-} \\ m_t =& r_t - q_t c_t + k, \end{aligned}$$

where k is the average estimated repo specialness of accepted transactions on the previous day. If $q_t = -q_{t-}$

$$\begin{aligned} c_t =& \frac{r_t - m_{t-}}{q_t} \\ m_t =& m_{t-}. \end{aligned}$$

The daily volume-weighted transaction rate (VWATR) is the volume weighted average of midpoint rates between 7:00 am and 4:00 pm each day.

$$\text{VWATR}(t) = \frac{\sum_s \hat{m}_s \cdot V_s}{\sum_s V_s},$$

where V_s is the volume of any transaction at time s. For some applications we use intraday VWATR. For example, VWATR_{20min} is the volume-weighted average of midpoint rates between 7:00 am and 7:20 am.

References

Acharya, Viral and Ouarda Merrouche, "Precautionary Hoarding of Liquidity and Interbank Markets: Evidence from the Subprime Crisis," *Review of Finance*, 2013, *17* (1), 107–160.

Afonso, Gara and Hyun Song Shin, "Precautionary Demand and Liquidity in Payment Systems," *Journal of Money, Credit and Banking*, 2011, *43*, 589–619.

_ **and Ricardo Lagos**, "Trade Dynamics in the Market for Federal Funds," *Econometrica*, 2015, *83*, 263–313.

_ **, Anna Kovner, and Antoinette Schoar**, "Stressed, Not Frozen: The Federal Funds Market in the Financial Crisis," *Journal of Finance*, 2011, *66*, 1109–1139.

_ **, Kyungmin Kim, Antoine Martin, Ed Nosal, Simon Potter, and Sam Schulhofer-Wohl**, "Monetary Policy Implementation with an Ample Supply of Reserves," Staff Report 910, Federal Reserve Bank of New York January 2020.

_ **, Marco Cipriani, Adam Copeland, Anna Kovner, Gabriele La Spada, and Antoine Martin**, "The Market Events of Mid-September 2019," FRB of New York Staff Report 918, Federal Reserve Bank of New York March, 2020.

Anbil, Sriya, Alyssa Anderson, and Zeynep Senyuz, "Are Repo Markets Fragile? Evidence from September 2019," Working Paper, Federal Reserve Board, October 2020.

_ **,** _ **, and** _ **,** "What Happened in Money Markets in September 2019?," FEDS Notes, Board of Governors of the Federal Reserve System, February, 2020.

Andersen, Leif, Darrell Duffie, and Yang Song, "Funding Value Adjustments," *Journal of Finance*, 2019, *74*, 145–192.

Andolfatto, David and Jane Ihrig, "Why the Fed Should Create a Standing Repo Facility," Federal Reserve Bank of St. Louis, *On the Economy Blog*, March 6, 2019.

Andros, Joseph, Michael Beall, Francis Martinez, Tony Rodrigues, Mary-Frances Styczynski, and Alex Thorp, "Approaches to Estimating Aggregate Demand for Reserve Balances," FEDS Notes, October 17, 2019.

Armantier, Olivier, James McAndrews, and Jeffrey Arnold, "Changes in the Timing Distribution of Fedwire Funds Transfers," *Economic Policy Review*, 2008, *14* (2).

Ashcraft, Adam and Darrell Duffie, "Systemic Illiquidity in the Federal Funds Market," *American Economic Review*, 2007, *97*, 221–225.

_ , James McAndrews, and David Skeie, "Precautionary Reserves and the Interbank Market," *Journal of Money, Credit and Banking*, 2011, *43*, 311–348.

Avalos, Fernando, Torsten Ehlers, and Egemen Eren, "September Stress in Dollar Repo Markets: Passing or Structural?," *BIS Quarterly Review*, December 8, 2019.

Baklanova, Viktoria, Adam Copeland, and Rebecca McCaughrin, "Reference Guide to US Repo and Securities Lending Markets," Staff Report 740, September, 2015.

Bech, Morten, "Intraday Liquidity Management: A Tale of Games Banks Play," *Economic Policy Review*, 2008, *14*.

_ and Rod Garratt, "The Intraday Liquidity Management Game," *Journal of Economic Theory*, 2003, *109*, 198–219.

Board of Governors of the Federal Reseve System, "History of the FOMC's Policy Normalization Discussions and Communications," Federal Reserve Board, Washington, D.C., October 2019.

_ , "Financial Stability Report," Federal Reserve Board, Washington, D.C.. May 2020.

Bush, Ryan, Adam Kirk, Antoine Martin, Philip Weed, and Patricia Zobel, "Stressed Outflows and the Supply of Central Bank Reserves," *Liberty Street Economics*, February 20, 2019.

Cavallo, Michele, Marco Del Negro, Scott Frame, Jamie Grasing, Benjamin Malin, and Carlo Rosa, "Fiscal Implications of the Federal Reserve's Balance Sheet Normalization," *International Journal of Central Banking*, 2019, *15*, 255–306.

Clark, Kevin, Antoine Martin, and Timothy Wessel, "The Federal Reserve's Large-Scale Repo Program," *Liberty Street Economics*, Federal Reserve Bank of New York, August 2020.

Committee on the Global Financial System and Markets Committee, "Regulatory Change and Monetary Policy," CGFS Working Paper Number 54, Bank for International Settlements 2015.

Copeland, Adam, Isaac Davis, and Antoine Martin, "An Empirical Analysis of the GCF Repo Service," *FRBNY Economic Policy Review*, 2015, *21(2)*, 25–37.

_ , Linsey Molloy, and Anya Tarascina, "What Can We Learn From the Timing of Interbank Payments?," *Liberty Street Economics*, Federal Reserve Bank of New York February, 2019.

Correa, Ricardo, Weixin Du, and Gordon Liao, "US Banks and Global Liquidity," Working Paper, Federal Reserve Board and University of Chicago, March, 2020.

Covas, Francisco and Bill Nelson, "Bank Regulations and Turmoil in Repo Markets," Bank Policy Institute September 2019.

Duffie, Darrell, "Post-Crisis Bank Regulations and Financial Market Liquidity," Baffi Lecture, Banca d'Italia, March, 2018.

— **and Arvind Krishnamurthy**, "Passthrough Efficiency in the Fed's New Monetary Policy Setting," in Richard A. Babson, ed., *Designing Resilient Monetary Policy Frameworks for the Future, A Symposium Sponsored by the Federal Reserve Bank of Kansas City*, Jackson Hole, Wyoming, August 25-27, 2016, Federal Reserve Bank of Kansas City, August 2016, pp. 21–102.

Egelhof, James, Antoine Martin, and Noah Zinsmeister, "Regulatory Incentives and Quarter-End Dynamics in the Repo Market," Federal Reserve Bank of New York, *Liberty Street Economics*, Federal Reserve Bank of New York, August 2017.

Federal Open Market Committee, "Statement Regarding Monetary Policy Implementation and Balance Sheet Normalization," Press release, Board of Governors of the Federal Reserve System, Washington, DC, January, 2019.

Filardo, Andrew, "Monetary Policy Operating Frameworks: Are Reforms Heading in the Right Direction?," *Cato Journal*, Spring/Summer 2020.

Fleming, Michael, Warren Hrung, and Frank Keane, "Repo Market Effects of the Term Securities Lending Facility," Federal Reserve Bank of New York Staff Report 426, January 2010.

— , — , and — , "Repo Market Effects of the Term Securities Lending Facility," *American Economic Review*, 2010, *100*, 591–596.

Gagnon, Joseph and Brian Sack, "Recent Market Turmoil Shows That the Fed Needs a More Resilient Monetary Policy Framework," Peterson Institute for International Economics, *Realtime Economic Issues Watch*, June 18, Peterson Institute for International Economics, 2020.

Gorton, Gary and Tyler Muir, "Mobile Collateral versus Immobile Collateral," NBER Working paper 22619 September 2016.

Hamilton, James, "The Daily Market for Federal Funds," *Journal of Political Economy*, 1996, *104*, 26–56.

Han, Yangjue, "Monetary Policy Transmission Before and After the Crisis," Working Paper, New York University, May 2020.

Hüser, Anne-Caroline, Caterina Lepore, and Luitgard Veraart, "How do secured funding markets behave under stress? Evidence from the gilt repo market," Technical Report, Bank of England 2021.

Ihrig, Jane, "Banks' Demand for Reserves in the Face of Liquidity Regulations," *On the Economy Blog*, Federal Reserve Bank of St. Louis, March 5, 2019.

_ , Zeynep Senyuz, and Gretchen Weinbach, "The Fed's "Ample-Reserves" Approach to Implementing Monetary Policy," Technical Report, Board of Governors of the Federal Reserve System, February 2020.

Infante, Sebastian and Zack Saravay, "What Drives U.S. Treasury Reuse?," Federal Reserve Board working paper, Federal Reserve Board June 2020.

_ and _ , "Treasury Market Functioning During the COVID-19 Outbreak: Evidence from Collateral Re-use," FEDS Notes. Washington: Board of Governors of the Federal Reserve System December 4 2020.

Keating, Thomas, Francis Martinez, Luke Petit, Mary-Frances Styczynski, and Alex Thorp, "Estimating System Demand for Reserve Balances Using the 2018 Senior Financial Officer Survey," FEDS Notes, April 9, 2019.

Logan, Lorie, "Observations on Implementing Monetary Policy in an Ample-Reserves Regime," Remarks before the Money Marketeers of New York University, Federal Reserve Bank of New York, April 2019.

Martin, Andrew, James McAndrews, Ali Palida, and David Skeie, "Federal Reserve Tools for Managing Rates and Reserves," Federal Reserve Bank of New York Staff Report 642, August 2019.

Martin, Antoine and James McAndrews, "Liquidity-Saving Mechanisms," *Journal of Monetary Economics*, 2008, *55*, 554–567.

_ , _ , Ali Palida, and David Skeie, "Explaining the Puzzling Behavior of Short-Term Money Market Rates," *Liberty Street Economics*, Federal Reserve Bank of New York, August 24, 2020.

McAndrews, James and Alexander Kroeger, "The payment system benefits of high reserve balances," *Journal of Payments Strategy & Systems*, 2016, *10* (1), 72–83.

_ and Simon Potter, "Liquidity Effects of the Events of September 11, 2001," *Economic Policy Review*, 2002, *8.*

Munyan, Benjamin, "Regulatory Arbitrage in Repo Markets," Office of Financial Research Working Paper, August 2017.

Nicolae, Laura, "The Effects of Liquidity Regulation on Bank Demand for Reserves and Federal Reserve Balance Sheet Policy," Working Paper, May 2020.

Plosser, Charles, "The Risks of a Fed Balance Sheet Unconstrained by Monetary Policy," in Michael Bordo, John Cochrane, and Amit Seru, eds., *The Structural Foundations of Monetary Policy*, Hoover Institution Press, Stanford California, 2018, pp. 1–16.

Pozsar, Zoltan, "Collateral Supply and o/n Rates," Global Money Notes 22, Credit Suisse Economics, May 2019.

Quarles, Randall, "The Economic Outlook, Monetary Policy, and the Demand for Reserves," Speech Vice Chair for Supervision Randal K. Quarles At the Money Marketeers of New York University, New York, New York, Federal Reserve Board, February 2020.

Ranaldo, Angelo, Patrick Schaffner, and Michalis Vasios, "Regulatory Effects on Short-Term Interest Rates," *Journal of Financial Economics*, 2020, *forthcoming.*

Treasury Market Practices Group, "Clearing and Settlement in the Secondary Market for U.S. Treasury Securities," White Paper July 2019.

Wallen, Jonathan, "Markups to Financial Intermediation in Foreign Exchange Markets," Working Paper, Stanford Graduate School of Business, January 2020.

Yang, Yilin (David), "Why Repo Spikes," Working paper, Graduate School of Business, Stanford University, December 2020.

Younger, Joshua, Henry St. John, and Sejal Aggarwal, "If It's Not One Thing, It's Another. The Payment System Risks of a Repo Shock," J.P. Morgan North America Fixed Income Strategy Report 2020. July, 14, 2020.