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Abstract

We show that the likelihood of a liquidity crunch in wholesale US dollar funding markets is highly dependent on levels of reserve balances at the financial institutions that are the most active intermediaries of these markets. Heightened risk of an imminent liquidity crunch is signaled by significant delays in intra-day payments to these large financial institutions over the prior two weeks. Our study contributes to the broader dialogue surrounding the Federal Reserve's ongoing quantitative tightening (QT).

Key words: repo rates, reserve balances, intra-day payments, central-bank balance sheet

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To view the authors' disclosure statements, visit
https://www.newyorkfed.org/research/staff_reports/sr974.html.

1 Introduction

What quantity of central bank deposits do financial institutions require? The Fed aims to provide banks with an "ample" supply of these deposits, called reserve balances. In effect, "ample" means enough for banks to efficiently process payments and provide funding to their customers. As the Fed brings down the size of its balance sheet, a process known as quantitative tightening, how will the Fed know the minimum ample level of reserve balances? In the Fed's previous round of quantitative tightening, reserve balances declined from a peak of around $2.8 trillion in 2014 to about $1.4 trillion in early September 2019. Suddenly, on September 16-17, 2019, interest rates negotiated in the largest wholesale funding market – the Treasury repo market – spiked by hundreds of basis points, as prominently reported in major news outlets.[1] We show that liquidity crunches caused by insufficient reserve balances can be predicted by delays in intra-day payments of reserves to the ten bank holding companies that are most active in the Treasury repo market, which we label "the dealer banks." More generally, we find a strong empirical relationship linking funding market rate spikes, intra-day payment delays, and the reserve balances of the largest banks.

In reaction to the liquidity crunch of September 2019, the Fed quickly supplied additional reserve balances to the banking system. Funding market liquidity and intra-day payment timing returned to near normal within a few days. Nevertheless, we find that the reserve balances held by the dealer banks did not increase significantly until the Fed created a much larger quantity of additional reserves in response to the Covid shock of March 2020, just after intra-day payments to the dealer banks were again significantly delayed and repo rates again spiked. This underscores the key role of reserve balances that are held by the dealer banks or are to be paid to the dealer banks throughout the day.

[1]For examples of reporting, see "Fed Preps Second $75 Billion Blast With Repo Market Still On Edge," *Bloomberg,* September 17, 2019; "Why the US 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.

Post-COVID reserve balances ultimately achieved a new peak of about $4.2 trillion in September 2021. In 2024, as the current round of quantitative tightening continues, Federal Reserve officials and market participants are again discussing the minimum desirable quantity of reserve balances (Logan, 2024; Waller, 2024; Perli, 2024; Abate, 2024; Cabana, 2024). Ongoing quantitative tightening at other central banks has triggered similar discussions (Gravelle, 2024; Bailey, 2024). This paper provides empirical analysis that supports an understanding of the quantity of reserve balances needed by the largest financial institutions to maintain an orderly financial system. In particular, we show that elevated delays in intraday payments to the largest repo market intermediaries signal imminent funding market liquidity risk.

Before the failure of Lehman Brothers in September 2008, a small aggregate supply of federal reserve balances, typically under $50 billion, was sufficient for US bank holding companies (BHCs) 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 their intraday payments. The Fed's GFC and post-GFC quantitative-easing programs increased reserve balances far above pre-crisis levels. As part of its post-crisis regulatory reform, however, the Fed also introduced a battery of new intraday liquidity requirements and supervisory standards that provided incentives for the largest BHCs to maintain substantial reserve balance and which strongly discouraged the largest banks from incurring daylight overdrafts on their reserve accounts at the Fed. Although reserve balances in September 2019 far exceeded pre-GFC levels, they were insufficient to avoid significant disruptions to funding markets.

The market for US Treasury repurchase agreements (repos) is by far the largest US dollar wholesale funding market, with a volume of over $3 trillion per day.[2] In an efficient wholesale funding market, Treasury repo rates would be essentially equated by arbitrage

[2]Primary dealers alone conduct over $5 trillion of repos and reverse repos per day, of which the majority are collateralized by US Treasuries (SIFMA data). Data collected by the Office of Financial Research imply that the bilateral (not centrally cleared) Treasury repo market alone provides over $3 trillion per day in funding.

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 extremely-low-risk 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 reserve balances of the ten largest repo-active BHCs was below roughly $580 billion.

Low aggregate levels of reserve balances can lead to intraday cash hoarding by banks, raising concerns over market liquidity and sometimes even threatening financial stability.[3] Yang (2020) theorizes that when banks perceive that other banks may have low opening balances at the Fed, there can suddenly be a self-fulfilling equilibrium expectation of later-than-normal payments by multiple banks, inciting spikes in repo rates. Even in the post-2008 period, when system-wide reserve balances 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.

Our study considers the 100 largest US banks as ranked by average reserve balances and focuses on the ten BHCs with the largest amount of repo activity, which we call "the dealer banks." We find that the spread between SOFR and IOR is much more highly correlated with the total quantity of reserve balances of these ten dealer banks than with the balances of the other 90 large banks. Further, our analysis shows that the time of day by which the dealer banks have received the first half of their daily incoming payments is a yet-more-powerful variable for explaining the spread between SOFR and IOR. We show that a two-week lagging average of this payment-delay variable could serve as a monitoring signal of the risk of an imminent liquidity crunch. Based on quantile regression analysis, during our sample period, a reduction of $100 billion dollars in the total opening-of-day balances of the ten dealer banks is estimated to increase the spread between SOFR and IOR at the 99%-ile by roughly

[3]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), d'Avernas and Vandeweyer (2020), and Afonso, Duffie, Rigon and Shin (2022a).

7 basis points.

Our probit-based estimate of the probability of a severe spike in SOFR−IOR on a given day is also highly sensitive to the reserve balances of the dealer banks, delays in intraday payments to the dealer banks, and large Treasury security issuances. At quarter ends, when foreign banks are monitored for their adherence to regulatory capital requirements, the estimated probability of spike in this funding rate spread is estimated to increase much more dramatically, and even more so if the reserve balances of dealer banks are low. We will explain the incremental impacts of Treasury issuances, the stock of Treasury bills outstanding, and the total quantity of uninsured deposits held by customers of the dealer banks. Acharya and Rajan (2022), Acharya et al. (2022), and Lopez-Salido and Vissing-Jorgensen (2023) have shown that commercial bank deposits are a factor in the demand for reserve balances.

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 investigates the empirical relationships among Treasury repo rate distortions, the reserve balances of the largest BHCs active in repo markets, delays in the intraday payments to these large BHCs, and the reserve balances of other large banks. Section 5 suggests an approach to monitoring the sufficiency of reserve balances by using, as a warning signal, recent average delays in the time of day by which the most active intermediaries in the repo market have received the first half of their incoming payments. Section 6 incorporates additional factors related to the demand for reserves and liquidity in funding markets, including new bank liquidity rules and supervision, the quantity of commercial bank deposits, regulatory capital requirements, Treasury primary-market issuances, the aggregate supply of Treasury bills, and the concentration of reserves among the largest BHCs. Section 7 offers concluding remarks regarding key policy tradeoffs.

2 Background and related work

The market for overnight Treasury repurchase agreements underpins the financing of US Treasuries and, with a total volume exceeding $3 trillion per day, vastly exceeds the size of the federal funds market.[4] The spread between US Treasury overnight repo rates and the interest rate paid by Federal Reserve Banks on reserve balances (IOR) is a gauge of the sufficiency of reserve balances of large BHCs active in repo markets to meet counterparty funding and other "reserve draining" demands (Correa, Du and Liao, 2020), precautionary demands for reserves to meet intraday payment obligations (Ashcraft, McAndrews and Skeie, 2011; Yang, 2020), and regulatory liquidity requirements (Ihrig, 2019; d'Avernas and Vandeweyer, 2020). If the supply of reserves is ample for these combined purposes, then arbitrage would normally keep Treasury repo rates near IOR. Banks can engage in repos directly or, if they are part of a BHC, through an affiliated broker-dealer.[5]

The total quantity of reserves in the US banking system has exceeded $1 trillion since the 2008-2009 financial crisis and reached a pre-COVID peak of $2.8 trillion in 2014 as a result of 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 reserve balances declined, reaching a low of $1.4 trillion in early September 2019. With this decline, the spread between SOFR and IOR crept higher and occasionally spiked up, particularly on quarter ends and Treasury issuance dates. Appendix Table 10 lists dates on which Treasury repo rates spiked relative to IOR.

On September 17, 2019, SOFR suddenly jumped above IOR by 315 basis points and interdealer repo rates reached over 700 basis points above IOR during the course of the day,

[4] See SIFMA Research The US Repo Markets: A Chart Book, SIFMA, February 2022.

[5] Anbil, Anderson, Cohen and Ruprecht (2024) note the demand for money by shadow banks as a factor influencing reserve ampleness.

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

in response to a storm of supply and demand factors that exacerbated the main underlying cause, the low supply of reserve balances.[7]

The Fed reacted quickly[8] by supplying a large amounts of reserves, driving SOFR-IOR spreads back to moderately low levels. We document that on September 17, 2020, the total balances of all 100 largest banks in our sample reached a sample record low of $1.06 trillion. On the same day, the first half of payments of reserves to the ten dealer banks was later than average by a sample-record high, up to that date, of 151 minutes.

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.[9] The reserve balances of the ten repo-active banks remained near their low of September 2019 levels leading up to this event, as shown in Figure 1, despite the aforementioned increase in aggregate reserves between September 2019 and March 2020. Further, on March 17, the first half of daily incoming payments to the dealer banks arrived 155 minutes later than average, a new sample record high delay.

[7]See Afonso, Cipriani, Copeland, Kovner, La Spada and Martin (2020), Anbil, Anderson and Senyuz (2020a), Anbil, Anderson and Senyuz (2020b), Ihrig, Senyuz and Weinbach (2020), and Correa, Du and Liao (2020), among others. 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). 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). 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 conversion of reserves into TGA balances was exacerbated on September 16, 2019 by quarterly corporate tax payments due that day 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, money-market mutual funds had recently reduced their use of "sponsored repo" (Hüser et al., 2021; Afonso et al., 2020; Anbil et al., 2020b), 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 offsets a reduction in cash available via sponsored repos with an alternate source of cash, then the BHC would face a heightened regulatory capital commitment because 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 transactions that are more costly in terms of balance-sheet space, as measured by the associated regulatory capital requirements.

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

[9]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.

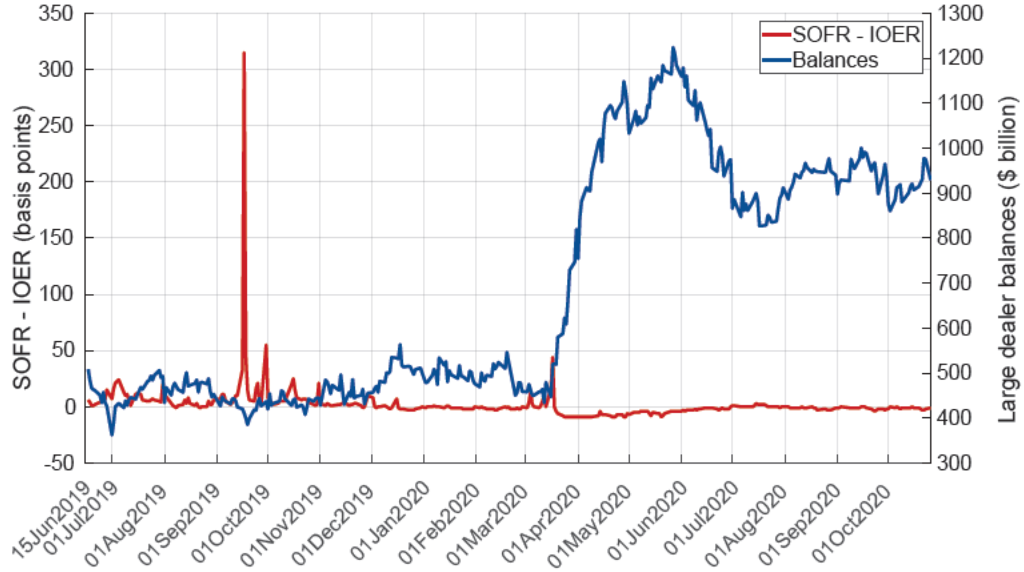


Figure 1: Reserve balances and the spread of SOFR over IOR
Note: SOFR is the Secured Overnight Financing Rate. IOR is the interest rate paid on reserves. The reserve balances of the large repo-active banks are shown in blue (right axis). The spread of SOFR from IOR is shown in red (left axis). Sources: Fedwire Funds Service, FRBNY.

Although the March 2020 shock to funding markets was triggered by severe macroeconomic pandemic news and is quite distinct in nature from the September 2019 disruption in repo markets, for both of these events our analysis shows that the level of reserves held by the dealer banks, the timing of intraday payments that they receive, and SOFR-IOR spreads are all near sample extremes. Leading up to these two quite different events, significantly higher levels of reserve balances of the dealer banks would have mitigated stresses on funding markets. Section 4 provides estimated relationships among repo rates, reserve balances, and intraday payment timing over the sample period, including a quantile regression analysis of repo-rate spreads and a probit analysis of the likelihood of repo-rate spikes.

Because the March 2020 Covid-crisis news also caused severe illiquidity in the secondary market for Treasury securities, the Fed purchased enormous quantities of Treasuries and Agency securities, expanding the total supply of reserves from mid-March 2020 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 ten dealer banks increased dramatically, as shown in

Figure 1. With this and other aggressive actions by the Fed to restore market liquidity,[10] dealer banks provided reserves much more elastically[11] into the repo market and the spread between SOFR and IOR essentially disappeared, as shown in Figure 1.

Among the limits to arbitrage between Treasury repo rates and IOR are (i) search frictions in funding markets (Afonso and Lagos, 2015; Bianchi and Bigio, 2022), (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, 2020; Gerba and Katsoulis, 2021), and (v) intraday payment timing mismatches, which promote conservative payment timing that can ultimately lead to 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; Afonso, Duffie, Rigon and Shin, 2022a; Acharya and Merrouche, 2013; Yang, 2020). While we offer support for the importance of all of these effects, our main marginal contribution is our predictive analysis of disruptions in wholesale dollar funding markets based on the quantity of reserve balances

[10]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).

[11]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 Repo 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."

held by the most important financial intermediaries in repo markets and based on intra-day delays in the payments of reserve balances to these dealer banks.

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 total balances held by other large banks, intraday payment delays to the largest repo-active BHCs, and levels of repo rate spreads over IOR. 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 is also related to Klingler and Syrstad (2021), which examines how risk-free reference rates including SOFR respond to quarter-end reporting dates, government debt outstanding, and total reserve balances.

Our work is relevant to the effectiveness of monetary policy transmission,[12] 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.[13]

[12] Afonso, Giannone, La Spada and Williams (2022b) examine the demand for reserves as reflected by the spread between the federal funds rate and IOR, with a focus on shifts over time in this demand curve, which is assumed to be linear in the short run. They control for shifts in the demand for reserves by normalizing the aggregate supply of reserves by the aggregate amount of bank assets.

[13] There is in addition intrinsic value of conducting arbitrage. For example, Dávila, Graves and Parlatore (2021) show that any degree of arbitrage that makes the spread between two risk free rates smaller will always generate Pareto improvements for all traders. They also define a specific measure of the value of arbitrage.

3 Data: Sources and Description

We use 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.[14] 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 US repo market. We therefore focus our attention on the largest 100 accounts managed by depository institutions.[15] We then identify ten of these accounts held by depository institutions owned by BHCs that have a large presence in US repo markets.[16] Reflecting that the largest dealers in the repo market 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-of-day balances of these ten accounts is about 40 percent of total opening-of-day balances of the accounts of the 100 largest banks. 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.[17] Given the requirement of data

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

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

[16] We use confidential repo data to generate a ranking of gross repo activity at the parent company level over 2018-2019. 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. This set of top ten active firms is stable over our sample period with seven out of 10 firms always being in the top 10 in terms of gross repo activity. The other three firms, for a couple of years at the beginning of our sample, are just outside of the top ten.

[17] Broker-dealers are not eligible to hold accounts on Fedwire. We analyze Fedwire accounts at the depository institution level. If a bank holding company contains two depository institutions, each with its own account, we consider the accounts separately. This lack of aggregation is not a concern for our analysis, because bank holding companies tend to concentrate their reserves into one account naturally (note the concentration statistics reported in Section 6). We checked and found that concentration of reserves into one account holds for the ten repo-active dealer banks on which we focus.

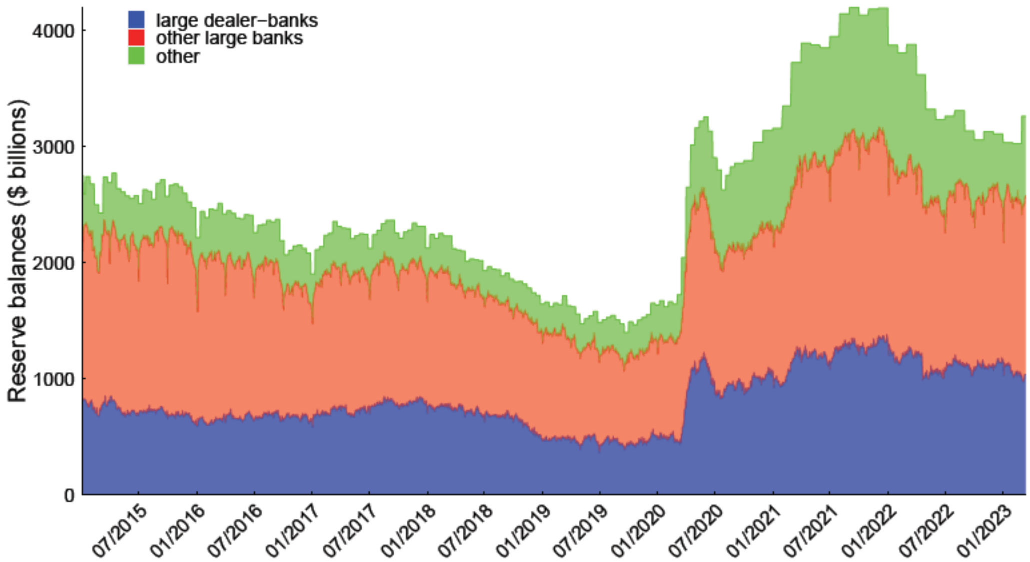


Figure 2: Reserve balances over time

Note: "Large dealer banks" refers to the total reserve balances of the ten large and repo-active account holders, Other large banks are the total reserve balances of the other large account holders in our sample of 100 accounts, and Other is the remaining total reserve balances of all other financial institutions.
Source: Fedwire Funds Service, FRED (RESBALNS).

confidentiality, we do not identify individual account holders.[18]

From the opening-of-day balances data for these 100 accounts, we produce two daily time series: the sum of opening-of-day balances for the ten specified dealer banks accounts, and the sum of the opening-of-day balances of the other large banks. The daily reserve balances time series are shown in Figure 2, in blue and red, respectively, for our sample period of January 1, 2015 through March 13, 2023. 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.[19]

[18]Mergers and acquisitions have the potential to dramatically change the size of a bank holding company and so its reserve balances. An examination of the history of banking applications over our sample period reveals that none of the top ten repo-active dealer banks were involved in mergers or acquisitions that significantly affected their reserve balances. These banking applications can be found at https://www.federalreserve.gov/newsevents/pressreleases.htm.

[19]Indeed, we have checked and found that the opening-of-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

The total balances of the 100 accounts in our analysis are 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 confidential payments data on Fedwire, we observe every transfer of funds settled over Fedwire on a given day. Focusing on the ten dealer-bank accounts described above, we can observe the intraday flow of transfers received by these accounts as well as the flow of transfers sent by these accounts. Using this information, for each day in our sample, we compute when in the day the first 25%, 50%, and 75%, respectively, of the total value of transfers to 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, the first half of the total transfers to the ten dealer banks had been received by 1:32 pm, and the first half of the total value sent by the ten dealer banks was sent by 1:04 pm.[20]

Our main source of repo rates is SOFR, a volume-weighted median of overnight Treasury repo transaction rates, reflecting the costs of funding for a broad range of repo market participants. This measure is computed and published daily by the Federal Reserve Bank of New York (FRBNY). SOFR is based on a large daily sample, often in excess of $1 trillion during our sample period, and is composed of data from tri-party repo (a dealer-to-client

at that bank. The result of such an arrangement could leave the small bank with a zero balance at the Fed while still holding reserves.

[20]These statistics are based on standard payment timing metrics used in previous research on intraday payments, such as Armantier, McAndrews and Arnold (2008), McAndrews and Kroeger (2016), and Copeland, Molloy and Tarascina (2019). Another service through which reserves can be transferred between accounts at Federal Reserve Banks is the Fedwire Securities Service, a delivery-versus-payment system. With this service, account holders can deliver securities and simultaneously receive cash. The account holder sending the securities initiates the transaction, and so the intraday liquidity incentives dictate that account holders deliver securities over this service as early as possible (the service opens at 8am). Because there are no gains to delay, the intraday timing of these transactions do not have information about the scarcity of reserves.

market segment) and two interdealer repo services offered by FICC: the General Collateral Finance Repo Service (GCF Repo®), and Fixed Income Clearing Corporation Delivery-vs-Payment Service (FICC DVP).[21] 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] Appendix Figure 10 compares the SOFR and GCF repo rate benchmarks during our sample period.

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.[23]

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

Summary statistics of the key variables used in our study are provided in Appendix Tables 4 and 5.

4 Stresses related to low reserve balances

We now describe our main results relating stress in funding markets to low reserve balances and to intra-day delays in payments to the ten dealer banks. When payments to the dealer banks are delayed and the dealer banks themselves have low opening-of-day reserve balances, in some combination, repo rates can rise precipitously.

As shown in Figure 3, the time of day by which dealer banks have received the first half

[21] GCF Repo® Service (hereinafter, "GCF Repo") is a registered service mark of the Fixed Income Clearing Corporation.

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

[23] 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. Figures 14 and 15 highlight the importance of early-morning trade in the interdealer Treasury repo market.

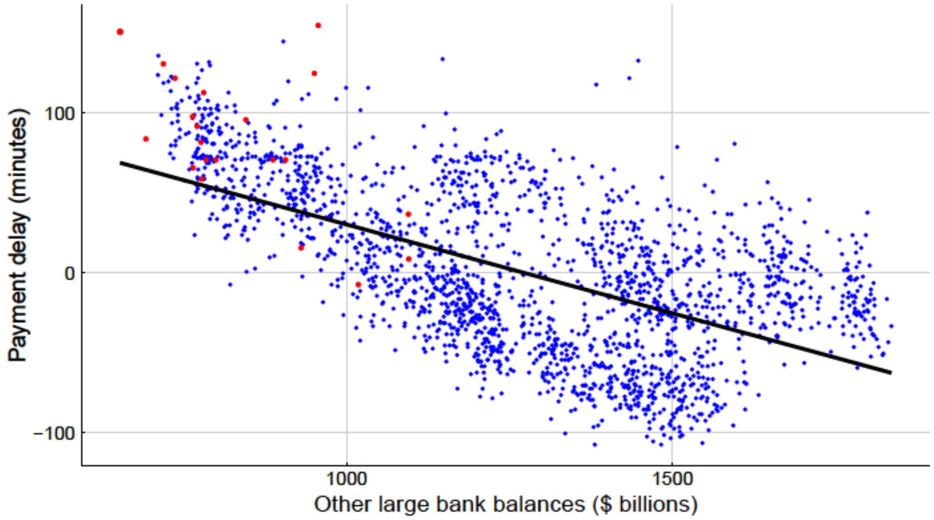


Figure 3: Non-dealer bank reserve balances and the timing of payments to dealer banks
Note: "Other large bank balances" for a given day is the total of the opening-of-day reserve balances of all accounts in our sample, except for the ten dealer banks. The payment timing measure is the half-received time of payments to the dealer banks. The solid line is the estimated linear relationship, which has an R^2 of 0.36. The slope coefficient, −0.11, is estimated with a standard error of 0.00325. The red dots in the scatter plot correspond to the observations for the 20 dates on which SOFR−IOR attained the highest 20 levels of those in the list of rate "spikes" shown in the Table 10. The date corresponding to the red dot in the upper left corner is September 17, 2019, on which SOFR−IOR spiked to its sample-record high and the total opening balances of the other large banks reached its sample-record low. Data source: Fedwire Funds Service.

of their incoming payments from the other large banks in our sample is well explained by the opening-of-day reserve balances of the other 90 large banks in our sample. The red dot in Figure 3 shows that the second latest time of day at which the ten dealer banks had received 50% of their total daily payments occurred on September 17, 2019. On that day, this half-received payment time was 151 minutes later than its sample average. 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 155 minutes above average, occurred on March 17, 2020, during the Covid pandemic shock, when SOFR−IOR jumped to 44 basis points. Appendix Table 6 offers a more detailed regression analysis of how payment delays are explained by the reserve balances of the ten dealer banks largest and the balances of the other 90 large banks in our sample.

The theoretical model of Yang (2020) implies that fluctuations in reserve balances could

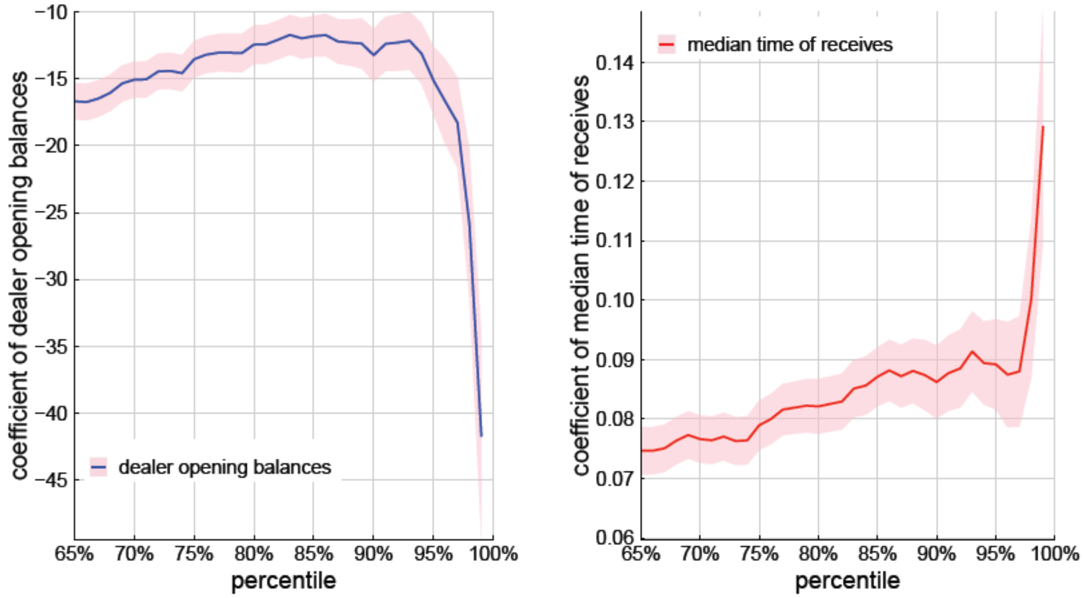


Figure 4: Quantile regression results for dealer-bank balances and payments timing
This figure plots the estimated coefficients from a quantile regression estimated for percentiles ranging from 65% to 99% of the spread of SOFR to IOR, in basis points. The spread of SOFR to IOR is the dependent variable. The independent variables are dealer-bank balances, median time of received payments by the dealer-banks, stock of Treasuries outstanding, amount of Treasuries redeemed, amount of Treasury Bills issued, amount of Treasury Coupons issued, amount of uninsured deposits issued by the dealer banks, corporate tax flows to the Treasury, quarter-end fixed effects, and a constant term. For each percentile at which the quantile regression is estimated (the x-axis in these charts), the coefficient for total dealer-bank reserve balances, in trillions of dollars, is plotted in the left panel and the coefficient for the time, in minutes, at which the first half of payments to the dealer banks is received is plotted in the right panel. The shaded regions are estimated one-standard-deviation error bands around the point estimates.

have highly non-linear or even discontinuous impacts on SOFR, especially when the total supply of reserves is sufficiently low. This is an equilibrium effect of self-fulfilling hoarding of reserves. Based on this concept, whenever dealer balances are well above levels that cause funding market stress, we anticipate only a muted relationship between funding rate distortions and changes in balances. As anticipated, Figure 4 shows that the spread between SOFR and IOR predicted by quantile regressions is increasingly sensitive to dealer balances and to payment delays whenever funding markets are increasingly stressed, that is, at higher quantiles of SOFR−IOR. Quantile regressions for the 95th and 99th percentiles are reported in Appendix Tables 7 and 8, respectively. These show that SOFR−IOR is far more sensitive to dealer-balances and payment delays at the 99th percentile than at the 95th percentile.

The opening-of-day balances of the dealer banks may increase endogenously whenever funding market stresses on a given day are anticipated. The magnitudes of the coefficients shown in the left panel of Figure 4 could therefore understate the elasticity of funding rate spreads to dealer-bank balances. In order to estimate the casual response of SOFR-IOR spreads to dealer balances, we use the instrumental-variables (IV) quantile regression approach of Kaplan and Sun (2017). For this purpose, we instrument for dealer balances using the timing of payments sent by small banks to large banks other than the dealer banks.[24] The timing of this subset of payments is likely to satisfy the exclusion restriction of being orthogonal to repo market shocks for two reasons. First, in the Fedwire Funds payment system, the bank sending a payment controls its timing. Because the small banks whose outbound payments determine our instrument do not participate in the repo market, the times at which they send these payments in the day are unlikely to be influenced by repo market shocks. Second, our instrument is further restricted to payments sent to banks other than the ten dealer banks. These "non-dealer banks" are not influential in the repo market. Taking these two reasons together, information about repo market shocks should play essentially no role in the timing of payment flows from small banks to non-dealer banks. We further reduce the likelihood that these payment-time instruments reflect contemporaneous repo market shocks by lagging these payment-time statistics by seven days. Finally, these payment-timing statistics are strong instruments because they reflect whatever tightness exists in the overall level of reserves in the banking system, which in turn is correlated with dealer-bank balances. We also include as an instrument the total value of corporate taxes received by the US Treasury. This variable is independent of repo rates and shocks to the total reserve balances of banks.[25]

[24] These instruments are the times in the day at which non-dealer-banks received the first 25%, 50%, and 75% of the value of payments sent to them from small banks. We define small banks using the payments data from 2018. For that year, we first gather all payments sent excluding those sent by the dealer banks. In this set of payments, we find that the largest 62 accounts make up 85% of activity in terms of value. The accounts which make up the remaining 15% of activity (a little over 5,500 accounts) are defined to be the set of small banks.

[25] We obtained daily corporate tax payment data from https://fiscaldata.treasury.gov/datasets/daily-treasury-statement/federal-tax-deposits. By itself, we find that this corporate tax-flow variable is a weak

The estimated IV model has SOFR−IOR as the dependent variable. Dealer-bank balances are the main independent variable of interest. Controls include the quantity of uninsured deposits of dealer banks (Acharya and Rajan, 2022; Acharya et al., 2022; Lopez-Salido and Vissing-Jorgensen, 2023) and a number of variables related to Treasury security issuances, whose impact on the tightness of reserve balances is explained in Section 6. The estimated coefficients for this quantile regression of the 99th percentile of SOFR−IOR, with and without instrumenting for dealer-bank balances, are reported in Table 1.

The quantile IV results tell us that a $100 billion reduction in dealer-bank balances has an estimated casual effect on SOFR−IOR of about 7.4 basis points at the 99th percentile. We estimate this quantile IV regression for percentiles of SOFR−IOR between 65% and 99%. The estimated coefficients for the instrumented dealer-balances are reported in Appendix Figure 11 for each percentile, illustrating that the estimated causal coefficient has a more muted response at quantiles below about 90%.[26]

Complementing our quantile analysis, we use a probit-based approach to estimate the probabilities of a spike in repo rate spreads. A spike is defined as a day on which at least one of the major repo-rate benchmarks exceeded IOR by at least 15 basis points on average for the previous two weeks, or was exceptionally high on a given day (at least 20 basis points for SOFR and Tri-Party General Collateral Repo, and at least 30 basis points for the more volatile benchmark, GCF Repo). Details and a list of "spike days" are provided in Appendix Table 10. The coefficient estimates are reported in Appendix Table 11. The probit-based estimates of the probability of a repo rate spike are displayed in Figure 5 for a selection of scenarios. As shown, spikes in repo rates are much more likely to occur on days that (a) have a significantly delayed half-received time of payments to the repo active dealer banks, (b) have large Treasury coupon security issuances, (c) have low dealer balances, (d) are quarter ends, and (e) combine two or more of these effects.

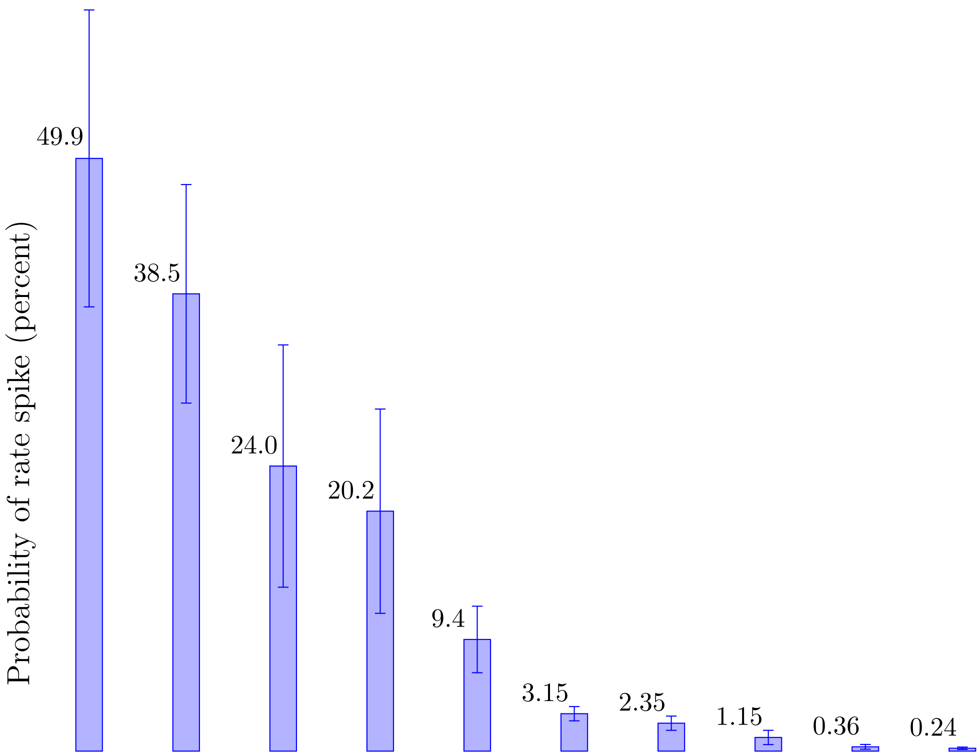
instrument for dealer-bank balances.

[26]In Appendix section D additional results are provided on the robustness of the IV quantile results and the strength of the instruments.

Table 1: Quantile regression of 99th percentile SOFR−IOR, with and without instrumenting for dealer-bank opening balances

	Dependent variable: SOFR−IOR	
	(non-IV)	(IV)
dealer opening balances	-77.3^{***}	
	(12.4)	
predicted dealer opening balances		-74.1^{***}
		(20.5)
quarter-end fixed effect	29.2	31.5^{***}
	(22.1)	(6.7)
T-bills outstanding	3.01	3.22
	(2.65)	(1.38)
Treasuries redemption	−25.1	−13.7
	(36.7)	(24.2)
T-Bill issuance	30.6	23.2
	(33.0)	(27.1)
coupon issuance	52.4	38.8
	(35.6)	(26.2)
dealer-bank uninsured deposits	26.5^{***}	24.1^{**}
	(8.54)	(11.3)
corporate tax to US treasury	−34.3	15.2
	(209.0)	(120.4)
constant	4.76	6.34
	(6.59)	(21.7)
observations	2,043	2,031
$R^1(0.99)$	0.347	0.253

Note: The Non-IV column lists the estimated coefficients of a quantile regression. The IV column lists the estimated coefficients from an instrumental-variables quantile regression, estimated using the method of Kaplan and Sun (2017). SOFR-IOR is measured in basis points. The units of the explanatory variables are trillions of dollars and minutes. The date range is January 1, 2015 to March 13, 2023. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$. The goodness-of-fit statistic $R^1(\tau)$ is an analogue of R^2 for quantile regressions (Koenker and Machado, 1999).



Scenario	1	2	3	4	5	6	7	8	9	10
payment delay			•		•	•			•	
dealer balances	•				•	•	•			
Treasury issuance		•			•			•		
quarter end	•	•	•	•						

Figure 5: Probit estimated probabilities (percent) of a spike in repo rates for selected scenarios. The definition of a spike in repo rates and a list of dates on which there was a spike are provided in Appendix Table 10. Spike probabilities are estimates from the probit model (column (7) of Table 11) at various levels of the explanatory variables. Standard errors are shown with error bars. For each scenario, bullet symbols indicate those explanatory variables set at adverse levels, with respect to funding market stress. "Payment delay" is the time of day by which the ten largest repo-active bank holding companies received the first half of their incoming payments-an adverse shock is a 51 minute delay above the sample mean. "Dealer balances" is the total quantity of opening-of-day reserve balances of the ten largest repo-active bank holding companies-an adverse shock is an aggregate balance that is $251 billion below the sample mean. "Treasury issuance" is the quantity of issuance of Treasury coupon securities-an adverse shock is a level of issuance that is $97.4 billion above the sample mean. Quarter end is included in a scenario wherever indicated by a bullet.

5 Late payments to dealer banks are a warning sign

We have focused to this point on contemporaneous relationships among repo-rate distortions, dealer-bank reserve balances, and the timing of intra-day payments to the dealer banks. Even armed with an understanding of these relationships, it may be challenging to estimate the level of reserve balances at which funding market stresses could suddenly appear, as, for example structural changes in the banking system may shift the minimum ample level of reserves. The Federal Reserve Board conducts Senior Financial Officer Surveys that ask banks whether their estimates of the lowest comfortable level of reserves (LCLOR) has changed since the last survey and, if so, why this estimate has changed. For example, in the May 2024 survey, respondents noted that important factors driving changes to their LCLOR estimate were "changes to broader market conditions, changes in retail deposit outflow assumptions, and changes in the composition or level of liabilities." In this section, we explore the use of payment-timing variables as early warning signals of impending liquidity crunches.

Exploring the dynamics underlying the demand for reserve balances, Acharya and Rajan (2022) and Acharya, Chauhan, Rajan and Steffen (2022) find that a large supply of reserve balances may induce banks to provide their customers with larger quantities of demandable liquidity, including deposits and credit lines. They find that this, in turn, increases the reliance of banks on reserves to manage the risks of sudden large liquidity draws. This suggests a ratchet effect. That is, a larger supply of reserves may induce higher subsequent demand by banks for reserves. Lopez-Salido and Vissing-Jorgensen (2023) provide additional evidence that the demand for reserve balances depends on the quantity of commercial bank deposits. They also find structural shifts over time in the demand for reserves. An additional important change to money markets in recent years that is likely to affect the demand for reserves is the demand for money by non-banks such as money-market mutual funds (Anbil, Anderson, Cohen and Ruprecht, 2024)

Because of the difficulty of directly contemporaneously estimating the minimum ample level of reserves, we focus in this section on using delays in the intra-day payment to the largest repo-active dealer banks as a warning signal of the risk of insufficiently ample reserves. Figure 6 shows that the liquidity crunch of September 2019 was preceded by increasingly late times of day by which the dealer banks received the first half of their incoming payments.

The left panel of Figure 7 illustrates the clear relationship between repo-rate spreads and times of day at which dealer banks had received the first half of their incoming payments, especially in the right tails of their sample distributions.[27] The right panel, however, shows no strong relationship between repo-rate spreads and times of day at which dealer banks had made the first half of their *outgoing* payments. Appendix Figures 12 and 13 show that most of the relevant payment timing pressure on the dealer banks is associated with large payments, those with values of at least \$100 million.[28] The time of day by which the dealer banks received the first half these large value payments shifted by about 150 minutes from the beginning of 2017 to September 2019. However, the time of day by which the dealer banks had *sent* their large-value payments remained steady over this period. Roughly speaking, receive times for large payments were sensitive to system-wide reserve balances, whereas send times were not. By contrast, for payments with values of less than \$100 million, Appendix Figure 13 shows, during our sample period, there were no important differences between the timing variables for received and sent payments.

The OLS regression results reported in Table 2 imply substantial predicted economic distortions of repo-rate spreads whenever dealer banks have been receiving the first half of their daily incoming payments much later than normal over the previous 10 days. Quantile regressions reported in Appendix Table 9 show substantially larger estimated predicted impacts at the 99-th percentile of SOFR−IOR.

[27] The standard deviation of the dealer banks incoming payment delay (half-received time) is 51.1 minutes. The difference between the sample minimum and sample maximum is 262 minutes. The standard deviation of the average payment delay over 9 days is approximately 47 minutes. The minimum of average payment delay over 9 business days is −89.4 minutes; the maximum is 119.2 minutes.

[28] Appendix Figure 12 illustrates the ten-day lagged average of the median time by which the dealer banks had received the first half of their incoming payments with a size of \$100 million or more and the analogous measure for their sent payments of \$100 million or more. Appendix Figure 13 shows the corresponding payment timing measures for payments of less than \$100 million.

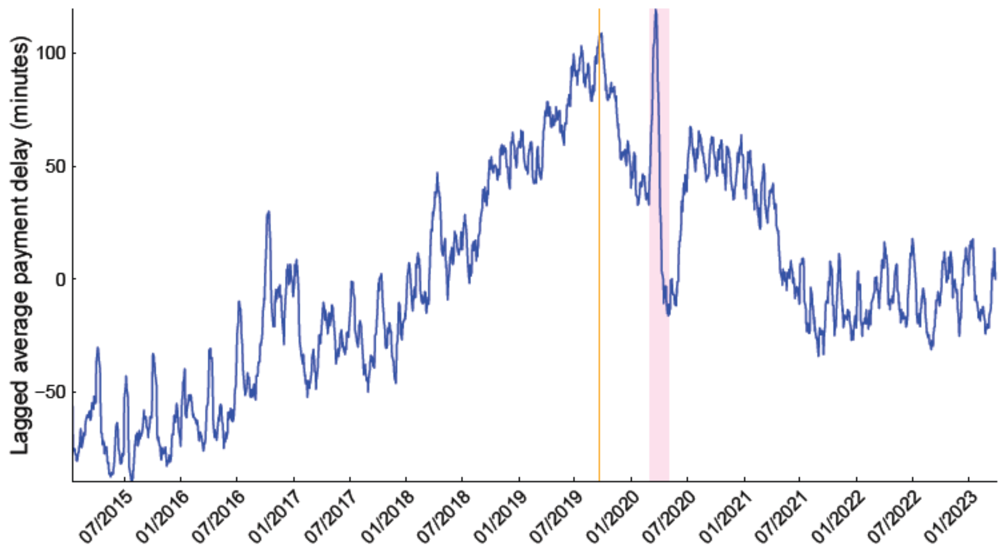


Figure 6: Incoming payment delays to repo-active banks. The lagged average of the time of day by which the ten largest repo-active bank holding companies received the first half of their incoming payments, relative to the sample mean, in minutes. The observation shown for date t is the average delay for business days $t-10$ through $t-2$ (inclusive). A vertical line is marked at September 18, 2019, the end of the three-day repo-market liquidity crunch of September 2019. A shaded bar marks the COVID shock period of March-April 2020. Data source: Fedwire Funds Service.

In principle, an alternative early warning signal could be the spread between SOFR and IOR. A higher spread should be a sign that reserve balances are getting closer to the minimum ample level (Afonso et al., 2022b, 2023). However, as illustrated in Figure 1, the SOFR-IOR spreads can jump suddenly from low trailing levels, with seemingly little advance warning, as in September 2019. By contrast, the trailing payment delay "warning signal" plotted in Figure 6 was clearly rising to multi-year record-high levels in advance of the liquidity crunch of September 2019.

Table 2: Ordinary least squares regression of SOFR−IOR on lagged 10-day average payment delays and other variables.

	Dependent variable: SOFR−IOR			
	(1)	(2)	(3)	(4)
dealer opening balances $t-2$	-5.63^{***}		-21.5^{***}	-21.7^{***}
	(0.860)		(1.64)	(1.64)
average payment delay $t-10$ to $t-2$	0.141^{***}	0.147^{***}	0.0891^{***}	0.0885^{***}
	(0.00718)	(0.00804)	(0.010)	(0.00989)
T-bills outstanding			2.94^{***}	2.84^{***}
			(0.454)	(0.472)
Treasuries redemption				−0.985
				(7.73)
T-Bill issuance				7.62
				(7.16)
coupon issuance				17.1^{**}
				(6.81)
dealer-bank uninsured deposits			2.33^{**}	2.34^{**}
			(1.04)	(1.04)
corporate tax to US treasury				53.9^{*}
				(31.1)
quarter-end fixed effect	8.46^{***}	8.36^{***}	9.37^{***}	7.41^{**}
	(2.96)	(3.09)	(3.02)	(3.15)
constant	-3.93^{***}	-8.52^{***}	-4.03^{***}	-4.06^{***}
	(0.879)	(0.207)	(0.942)	(0.947)
Observations	1998	2002	1996	1994
R^2	0.361	0.347	0.377	0.381
Adjusted R^2	0.360	0.346	0.375	0.379
Residual standard error	9.49	9.58	9.38	9.35

Note: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$. Average payment delay is the lagged average of the time of day by which the ten largest repo-active bank holding companies had received the first half of their incoming payments, relative to the sample mean, in minutes, averaged for business days $t-10$ through $t-2$.

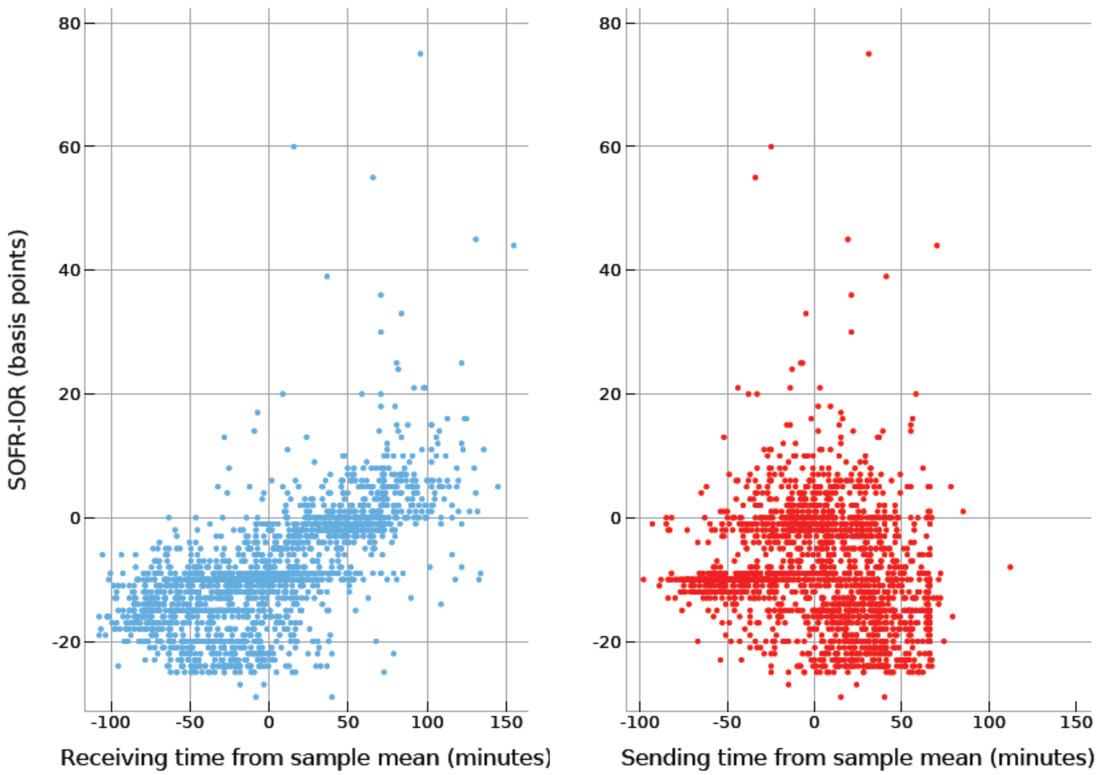


Figure 7: Repo rates and dealer-bank payment timing

Note: SOFR is the secured overnight financing rate. IOR is the interest rate paid by the Fed on reserves. Receiving time is the time by which half of the total of the ten repo-active dealer banks' incoming payments have been received. Sending time is the time by which half of these dealer banks' outgoing payments have been sent. For better visualization, the observation for September 17, 2019, with SOFR−IOR at 315 basis points, is not shown. Data: Fedwire Funds Service and FRBNY.

6 Factors that affect the demand for reserves

We turn to a discussion of institutional factors that affect the demand for reserve balances and therefore can exacerbate the severity or likelihood of a liquidity crunch in funding markets when reserve balances decline sufficiently.

6.1 Liquidity regulations and supervision

Post-GFC liquidity rules and supervision 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. Jamie Dimon, the Chairman and CEO of JP Morgan, famously commented about the importance of maintaining a buffer of reserves balances that meets regulatory and supervisory liquidity objectives, even at the cost of forgoing the opportunity to invest reserve balances in repos at highly elevated SOFR-IOR spreads during September 2019 repo market disruption. (See Appendix E for Dimon's verbatim remarks.)

Given the uncertain timing of incoming payments, it is natural for a dealer bank to be conservative when providing discretionary funding to counterparties in the repo market whenever its reserve balances are not abundant. A dealer bank would quote high repo rates, relative to IOR, whenever its balances are low and there is a high risk that its incoming payments could be significantly delayed.[29]

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

[29] Small to medium size banks seem to still use daylight overdraft facility to make their payments whenever total reserve balances are low. Indeed, as shown in Figure 9, peak system-wide overdrafts have remained highly related to the opening-of-day reserve balances of the 100 largest banks during our post-2015 sample period, with an R^2 of 0.63 for this relationship. Figure 9 also shows that system-wide peak daylight overdrafts achieved their record high level in the two-week maintenance window ending September 25, 2019. This is also the two-week maintenance window in our sample that has the lowest average daily opening balances.

limits, and measurement of intraday liquidity risk." Ihrig (2019) describes the associated Comprehensive Liquidity Analysis and Review (CLAR), including the CLAR stress test mentioned in Dimon's remarks.

The Federal Reserve Board's Regulation YY, Enhanced Prudential Standards, includes rules covering intraday liquidity exposures.[30] 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 banks' holdings of excess reserves. In the May 2023 Senior Financial Officer Survey Results, a majority of participating banks reported that "satisfying liquidity-testing metrics" is an "important or very important" factor in determining their institution's lowest comfortable level of reserves.[31]

Under the Dodd-Frank Act, the Fed and FDIC implemented failure planning requirements for Resolution Liquidity Adequacy and Positioning (RLAP), which include intraday "resolution" liquidity requirements.[32]

6.2 Uninsured bank deposits generate a demand for reserves

Acharya and Rajan (2022) and Acharya, Chauhan, Rajan and Steffen (2022) emphasize that once the supply of reserves becomes large, banks react by offering greater amounts of

[30] 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 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."

[31] Similar expressions can be found in almost all recent Senior Financial Officer Survey Results.

[32] These are also reflected in Dimon's remarks. 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, and foreign supervisors, among others." (An FMU is a designated financial market utility, such as a designated payment system or a settlement system.) Pozsar (2019) outlines how RLAP impacts the intraday incentives for dealer banks to conserve reserve balances on days of Treasury issuances.

products, such as credit lines and uninsured deposits, that expose banks to liquidity shocks. This increases the desire by banks to maintain significant reserve balances to mitigate the associated liquidity risks of sudden large draws on credit lines and deposit redemptions. The resulting increased demand by banks for reserve balances can elevate funding-market spreads when reserve balances reach sufficiently low levels. Table 3, for example, shows that the quantity of uninsured deposits of the dealer banks plays a significant role in explaining repo-rate spreads, after controlling for other effects. From the quantile regressions shown in Table 1, a one-standard-deviation increase in dealer-bank uninsured deposits ($478 billion) is estimated to increase 99th percentile SOFR-IOR spreads by approximately 12 basis points.

6.3 Capital requirements

Treasury repos are assigned a capital requirement under various versions of the Basel III leverage-ratio rule. In several important non-US jurisdictions, including the Eurozone, the leverage-ratio capital requirement applies only to the quarter-end assets of bank holding companies (Egelhof, Martin and Zinsmeister, 2017; Correa, Du and Liao, 2020). Our empirical findings align with the effects of capital requirements. On quarter-end dates, interdealer repo rates significantly increase, with an average effect around 7 to 9 basis points depending on the least-squares regression model shown in Table 3. At the 99th percentile level, Appendix Table 9 shows an estimated quarter-end effect on SOFR−IOR of around 30 basis points. Quarter-end 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 US 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 US dealer banks (Wallen, 2020; Eisenschmidt, Ma and Zhang, 2021). Correa, Du and Liao (2020) write that "on quarter-ends, we find that US 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."

There is also a non-trivial upward impact of capital requirements on intra-quarter repo-IOR spreads, mainly because the US SLR rule applies to the large US dealer banks on a daily-averaging basis.[33] 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, 2020; 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).

6.4 The supply of T-bills, a substitute for Treasury repos

SOFR was actually below IOR during most of 2015-2017 because of the large supply of reserves and the low outstanding amount of Treasury bills during most of this period.[34] Government money market funds substitute between Treasury bills and Treasury repos (including through the Fed's Reverse Repurchase Facility).[35] This places downward pressure on the spread between Treasury repo rates and IOR when the outstanding supply of Treasury bills is low (Duffie and Krishnamurthy, 2016). Money funds and most other investors cannot open accounts at Federal Reserve Banks and so cannot directly hold reserves and earn IOR. Furthermore, banks cannot seamlessly intermediate for these investors because banks are subject to significant capital requirements for reserves.[36] As a result, when the supply of reserve balances is sufficiently large relative to the supply of Treasury bills, SOFR−IOR easily becomes negative. Martin, McAndrews, Palida and Skeie (2020) estimate "that a trillion dollars of additional reserves tends to reduce the fed funds rate by 8 basis points

[33] In stages, beginning in April and May 2020, Treasuries and reserve balances were temporarily exempted from SLR. Treasury repos were not exempted.

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

[35] See Afonso, Cipriani and La Spada (2022c).

[36] 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).

Table 3: OLS prediction of SOFR−IOR

	Dependent variable: SOFR−IOR							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
dealer opening balances	-10.9^{***}	-10.9^{***}		-5.96^{***}	-22.5^{***}	-22.6^{***}	-26.0^{***}	-26.3^{***}
	(1.26)	(1.26)		(0.835)	(1.44)	(1.60)	(1.58)	(1.55)
median time of receives			0.132^{***}	0.126^{***}	0.0756^{***}	0.0916^{***}	0.0715^{***}	0.0711^{***}
			(0.00921)	(0.0085)	(0.0131)	(0.00987)	(0.0127)	(0.0125)
quarter-end fixed effect		9.57^{***}	9.07^{***}	9.10^{***}	9.72^{***}	9.2^{***}	9.7^{***}	7.88^{**}
		(3.19)	(3.15)	(3.01)	(3.01)	(2.97)	(3.01)	(3.15)
T-bills outstanding					4.21^{***}		3.39^{***}	3.33^{***}
					(0.448)		(0.533)	(0.545)
Treasuries redemption								-15.2^{**}
								(7.28)
T-Bill issuance								18.2^{***}
								(6.95)
coupon issuance								24.2^{***}
								(6.34)
dealer-bank uninsured deposits						9.53^{***}	3.83^{***}	3.86^{***}
						(0.887)	(0.940)	(0.943)
corporate tax to US treasury								69.0^{**}
								(33.1)
constant	0.648	0.499	-8.55^{***}	-3.66^{***}	-1.46^{**}	-11.0^{***}	-4.85^{***}	-4.88^{***}
	(1.24)	(1.23)	(0.205)	(0.846)	(0.713)	(1.21)	(0.884)	(0.888)
Observations	2046	2046	2046	2042	2040	2042	2040	2039
R^2	0.0547	0.0648	0.336	0.352	0.385	0.373	0.388	0.392
Adjusted R^2	0.0542	0.0639	0.336	0.351	0.384	0.372	0.386	0.389
Residual standard error	11.4	11.4	9.59	9.49	9.24	9.33	9.23	9.21

Note: SOFR is the secured overnight financing rate and IOR is interest on reserves. SOFR-IOR is in basis points. The units of the explanatory variables are trillions of dollars and minutes. Standard errors are adjusted for heteroskedasticity. The date range is January 1, 2015 to March 13, 2023. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

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." Consistent with this, Columns 5-7 of Table 3 show estimated impacts on SOFR-IOR spreads of 3 to 4 basis points per trillion dollars of outstanding Treasury bills. From minimum to maximum during our sample period,[37] the quantity of Treasury bills outstanding varied by \$3.7 trillion, suggesting a large impact on SOFR−IOR of variation in the supply of T-bills.

[37] The sample standard deviation of Treasury bills outstanding is \$0.84 trillion.

6.5 Issuance of Treasury securities

An issuance of Treasury securities is settled with a transfer of reserve balances from a bank to the Treasury's Federal Reserve account, known as the Treasury General Account (TGA). These transfers therefore extinguish reserves from the system. Moreover, these transfers to the TGA must occur near the beginning of the issuance day, ruling out the timing options available to banks for many other outgoing payments.[38] After controlling for other key factors (Table 3, column 8), we estimate that a typical \$50 billion issuance of coupon Treasuries is associated with an estimated increase of SOFR−IOR of about 1.2 basis points.

Large US government fiscal deficits have caused a significant secular increase in the quantity of Treasury securities that require financing in the repo market. In particular, Treasury issuances occurred on September 16 and 17, 2020. Newly issued Treasury coupon securities, especially notes, are in high demand in the repo market (Fleming, Hrung and Keane, 2010). Anbil, Anderson and Senyuz (2020b) show that demand for repo financing of Treasuries in mid-September 2019 was highly inelastic. 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 US GSIBs has risen significantly with increases in net Treasury issuance. Compared to that work, our sample is not restricted to US 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 in the repo market.[39]

6.6 Concentration of reserve balances among dealer banks

With frictions and heterogeneity across financial intermediaries in the provision of liquidity in funding markets, the distribution of reserve balances across financial institutions could exacerbate liquidity strains when total balances are low (Logan, 2024). Figure 8 illustrates

[38] We verified this fact in conversations with multiple authoritative market participants.

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

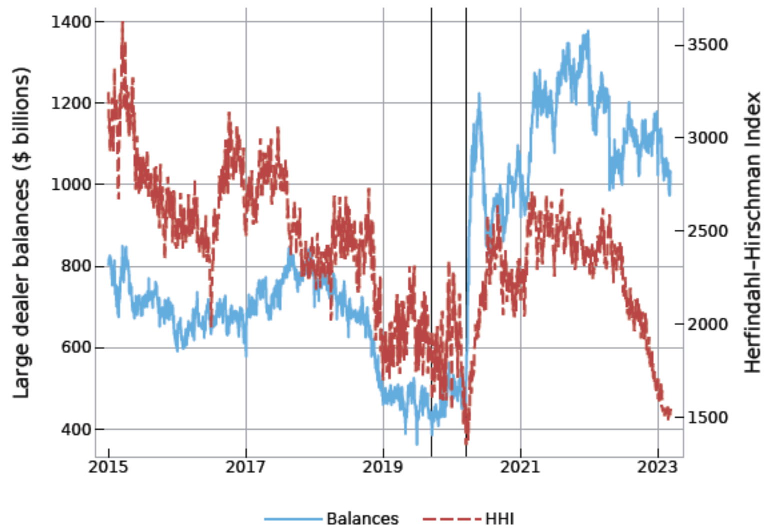


Figure 8: Concentration of dealer bank balances over time

Note: The solid blue line is the total reserve balances of the dealer banks (left axis) and the dashed red line is the concentration of dealer bank balances as measured by the Herfindahl-Hirschman Index (HHI) (right axis). The vertical black dashed lines corresponds to the dates of the repo rate spikes on September 17, 2019 and March 17, 2020. Source: Fedwire Funds Service.

the relationship between the concentration of reserve balances across the ten dealer banks in our sample and their total quantity of reserve balances. Concentration is measured with the Herfindahl-Hirschman Index.[40] As shown, when total dealer-bank balances are lower, the concentration of balances among dealer banks tends to be lower. This may also alleviate concerns that large spikes in repo rates are caused by a failure for balances to be shared more evenly when they are more scarce.

7 Concluding remarks

The November 2018 minutes of the Federal Open Market Committee[41] state:

"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 inter-

[40] 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 $2 \times 50^2 = 5000$.

[41] See Federal Open Market Committee (2018).

est 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."

However, commenting on the Fed's balance-sheet policy in light of 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."[42]

The FOMC's views on how to maintain sufficient reserve balances have evolved over time. The March 2024 minutes of the FOMC[43] reflect a cautious new approach:

"In light of the uncertainty regarding the level of reserves consistent with operating in an ample-reserves regime, slowing the pace of balance sheet runoff sooner rather than later would help facilitate a smooth transition from abundant to ample reserve balances. Slower runoff would give the Committee more time to assess market conditions as the balance sheet continues to shrink. It would allow banks, and short-term funding markets more generally, additional time to adjust to the lower level of reserves, thus reducing the probability that money markets experience undue stress that could require an early end to runoff. Therefore, the decision to slow the pace of runoff does not mean that the balance sheet will ultimately shrink by less than it would otherwise. Rather, a slower pace of runoff would facilitate ongoing declines in securities holdings consistent with reaching ample reserves. A few participants, however, indicated that they preferred to continue with the current pace of balance sheet runoff until market indicators begin to show signs that reserves are approaching an ample level."

Cavallo, Negro, Frame, Grasing, Malin and Rosa (2019) and Plosser (2018) consider the political-economy costs to the Fed of a large balance sheet. Holding balances at the Fed also impinges on bank capital requirements, and thus, when sufficiently large, crowds out other forms of intermediation by banks (Covas and Nelson, 2019; Diamond, Jiang and Ma, 2020). Acharya and Rajan (2022) and Acharya, Chauhan, Rajan and Steffen (2022) emphasize that once the supply of reserves becomes large, banks react by offering greater

[42] Yang (2020) proposes a theoretical framework and develops a quantitative model to estimate the minimum reserves necessary for financial stability, offering an initial step in analyzing minimum level of sufficient reserves.

[43] See Federal Open Market Committee (2024).

amounts of products, such as credit lines and demand deposits, that expose banks to liquidity shocks, increasing the financial stability risks associated with a subsequent reduction in the supply of reserves. 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.

Alternative policy approaches to relieving liquidity stresses that can arise with lower levels of reserve balances could include a de-emphasis in BHC regulation and supervision of the imperative that banks are self-sufficient with respect to intraday liquidity under all circumstances, a de-stigmatization of the use of the discount window and daylight overdrafts on accounts at the Fed, and the Fed's new Standing Repo Facility (SRF), at which banks and primary dealers get repo financing directly from the Fed at a rate only slightly above IOR. The SRF has yet to be used, except in testing, and its use may also suffer from stigmatization (Nelson and Parkinson, 2022).

Our research contributes to an understanding of the dynamics determining the quantity of reserve balances needed to maintain orderly money markets and timely interbank payments. We also find that when payments to the largest bank holding companies that are active on wholesale funding markets begin to arrive later than normal, there is a rising risk of a liquidity crunch in wholesale financing markets.

References

Abate, Joseph, "US Money Markets Monthly Update," Barclays, US Money Markets Monthly Update, March March 2024.

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.

_ **and Raghuram Rajan**, "Liquidity, Liquidity Everywhere, Not a Drop to Use: Why Flooding Banks with Central Bank Reserves May Not Expand Liquidity," New York University, NBER Working Paper 29680 May 2022.

_ **, Rahul Chauhan, Raghuram Rajan, and Sascha Steffen**, "Liquidity Dependence: Why Shrinking Central Bank Balance Sheets is an Uphill Task," Jackson Hole Symposium Paper, Federal Reserve Bank of Kansas City August 2022.

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.

_ **, Darrell Duffie, Lorenzo Rigon, and Hyun Shin**, "How Abundant Are Reserves? Evidence from the Wholesale Payment System," Federal Reserve Bank of New York Staff Report 1040, November, Federal Reserve Bank of New York March, 2022.

_ **, Domenico Giannone, Gabriele La Spada, and John Williams**, "Scarce, Abundant, or Ample? A Time-Varying Model of the Reserve Demand Curve," Staff Report 1019, Federal Reserve Bank of New York, May 2022.

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

__ , __ , **and Gabriele La Spada**, "Banks? Balance-Sheet Costs, Monetary Policy, and the ON RRP," Federal Reserve Bank of New York Staff Report 1041 December 2022.

__ , **Thomas Mertens, Gabriele La Spada, and John Williams**, "The Optimal Supply of Central Bank Reserves under Uncertainty," Staff Report 1077, Federal Reserve Bank of New York, May 2023.

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.

__ , __ , **Ethan Cohen, and Romina Ruprecht**, "Stop Believing in Reserves," Working paper, Federal Reserve Board, May 2024.

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.

Bailey, Andrew, "The Importance of Central Bank Reserves," Speech, Bank of England, May 2024.

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.

Bianchi, Javier and Saki Bigio, "Banks, liquidity management and monetary policy," *Econometrica*, 2022, *90*, 391–454.

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.

Cabana, Mark, "Fed balance sheet: Tax date tweaks," US Rates Watch, Bank of America Global Research, February 14 2024.

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.

Chernozhukov, Victor and Christian Hansen, "Notes and Comments: An IV Model of Quantile Treatment Effects," *Econometrica*, 2005, *73(1)*, 245–261.

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.

Copeland, Adam, 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.

d'Avernas, Adrien and Quentin Vandeweyer, "Intraday Liquidity and Money Market Dislocations ," Working Paper November 2020.

Diamond, William, Zhengyang Jiang, and Yiming Ma, "The reserve supply channel of unconventional monetary policy," Working Paper, 2020.

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.

Dávila, Eduardo, Daniel Graves, and Cecilia Parlatore, "The Value of Arbitrage ," Working Paper July 2021.

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.

Eisenschmidt, Jens, Yiming Ma, and Anthony Lee Zhang, "Monetary Policy Transmission in Segmented Markets," Working Paper, January 2021.

Federal Open Market Committee, "Minutes," Board of Governors of the Federal Reserve Board, November 2018.

_ , "Minutes," Board of Governors of the Federal Reserve Board, March 2024.

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," *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.

Gerba, Eddie and Petros Katsoulis, "The repo market under Basel III," Technical Report 2021.

Gravelle, Toni, "Balance Sheet Reduction: Progress to Date and a Look Ahead," Speech, Federal Reserve Bank of New York, May 2024.

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.

Kaplan, David M and Yixiao Sun, "Smoothed estimating equations for instrumental variables quantile regression," *Econometric Theory*, 2017, *33* (1), 105–157.

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.

Klingler, Sven and Olav Syrstad, "Life after LIBOR," *Journal of Financial Economics*, 2021, *141*, 783–801.

Koenker, Roger and Jose A. F. Machado, "Goodness of Fit and Related Inference Processes for Quantile Regression," *Journal of the American Statistical Association*, 1999, *94* (448), 1296–1310.

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.

_ , "Discussion of 'Quantitative Tightening Around the Globe: What Have We Learned?' by Wenxin Du, Kristin Forbes and Matthew Luzzetti," Federal Reserve Bank of Dallas, March March 2024.

Lopez-Salido, David and Annette Vissing-Jorgensen, "Reserve Demand, Interest Rate Control, and Quantitative TighteningBalance Sheet Policy Above the ELB," Technical Report, Federal Reserve Board, Working Paper, October 2023.

Martin, Antoine, James McAndrews, 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.*

Nelson, Bill and Pat Parkinson, "A Major Limit on the Fed?s Crisis Toolkit: Shame," Bank Policy Institute, January 2022.

Perli, Roberto, "Balance Sheet Reduction: Progress to Date and a Look Ahead," Speech, Federal Reserve Bank of New York, May 2024.

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.

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

Waller, Christopher, "Thoughts on Quantitative Tightening, Including Remarks on the Paper "Quantitative Tightening around the Globe: What Have We Learned?"," Federal Reserve Board, March 2024.

Yang, Yilin (David), "What Quantity of Reserves Is Sufficient?," SSRN Working Paper 2020.

Appendices

A Additional tables

Table 4: Summary statistics: Key variables.

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Median	Pctl(75)	Max
dealer opening balances ($ billions)	2,046	819.3	251.3	362.0	664.4	744.4	1,051.3	1,378.0
other large bank balances ($ billions)	2,046	1,266.6	277.5	652.4	1,067.3	1,265.9	1,477.9	1,836.1
100 large banks ($ billions)	2,046	2,085.9	504.3	1,063.0	1,777.1	2,036.5	2,483.3	3,165.5
T-Bills outstanding ($ billions)	2,059	2,711.9	1,166.9	1,233.0	1,742.0	2,274.0	3,810.7	4,984.4
T-Bill issuance ($ billions)	2,059	40.1	61.7	−0.03	−0.001	0.0	92.0	272.9
coupon issuance ($ billions)	2,059	12.6	40.4	−0.02	0.0	0.0	0.0	301.3
T-Bills position ($ billions)	2,058	29.7	22.5	−4.0	15.1	22.0	36.3	110.3
Treasuries redemption ($ billions)	2,059	47.1	65.6	0.0	0.0	0.0	101.5	342.6
net Treasuries inventory ($ billions)	2,058	144.0	69.6	9.3	93.0	130.2	213.8	294.7
median time of receives (minutes)	2,046	0.7	51.1	−107.4	−36.4	−4.4	39.6	154.6
median time of sends (minutes)	2,046	0.5	36.6	−97.9	−26.9	4.1	29.1	112.1
Q1 time of receives for small banks (minutes)	2,046	0.1	29.1	−98.1	−15.8	2.9	19.9	82.9
median time of receives for small banks (minutes)	2,046	0.1	46.7	−186.6	−10.6	11.4	27.4	159.4
Q3 time of receives for small banks (minutes)	2,046	−0.2	49.2	−330.4	−10.4	1.6	20.6	98.6
SOFR - IOR (basis points)	2,061	−8.3	11.7	−29	−15	−10	−2	315
Treasuries issuance ($ billions)	2,059	52.7	73.2	−0.03	0.0	0.0	107.6	470.1
quarter-end fixed effect	2,060	0.02	0.1	0	0	0	0	1
corporate tax to US treasury ($ billions)	2,060	1.3	5.5	−0.1	0.1	0.1	0.4	63.7
dealer-bank uninsured deposits ($ billions)	2,061	2,214.0	478.2	1,685.8	1,828.7	1,933.3	2,773.1	3,039.9
log (normalized SOFR-IOR)	2,061	3.0	0.5	0.0	2.7	3.0	3.3	5.8
average Payment Delay $t-10$ to $t-2$ (minutes)	2,051	0.7	46.7	−89.5	−30.0	−4.9	40.4	119.2

Table 5: Summary statistics: Selected other variables.

Statistic	N	Mean	St. Dev.	Min	Max
IOR (basis points)	2,061	112.4	111.1	10	490
TGCR - IOR (basis points)	2,057	−10.9	11.8	−26	315
GCF - IOR (basis points)	2,059	−3.1	15.1	−47.4	390.7
Bond issuance ($ billions)	2,059	1.4	5.5	−0.005	41.5
Note issuance ($ billions)	2,059	11.2	36.1	−0.02	272.7
Bill redemption ($ billions)	2,059	38.9	59.6	0.0	230.1
Bond redemption ($ billions)	2,059	0.1	1.4	0.0	30.6
Note redemption ($ billions)	2,059	8.1	28.1	0.0	220.4
net total inventory ($ billions)	2,058	222.9	76.7	103.7	427.5
median time of receives and sends (minutes)	2,046	0.6	32.0	−129.5	110.5
Q1 time of receives and sends (minutes)	2,046	0.2	18.2	−69.5	112.5
Q3 time of receives and sends (minutes)	2,046	0.4	10.3	−43.8	168.2
Q1 time of sends (minutes)	2,046	0.1	26.1	−60.8	94.2
Q3 time of sends (minutes)	2,046	0.5	13.8	−71.9	163.1
Q1 time of receives (minutes)	2,046	0.3	19.2	−69.1	81.9
Q3 time of receives (minutes)	2,046	0.6	17.9	−68.7	175.3

Table 6: OLS estimation of dealer-bank median receive and send times

	median receive time				median send time				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
100 large banks	-43.4^{***}				-33.2^{***}				
	(1.76)				(1.38)				
dealer-bank opening balances		183.0^{***}	27.1^{***}	16.2		-122.0^{***}	56.8^{***}	58.0^{***}	51.1^{***}
		(3.87)	(8.08)	(11.3)		(4.04)	(9.2)	(8.99)	(8.97)
other large bank balances		-246.0^{***}	-171.0^{***}	-169.0^{***}		46.5^{***}	-18.0^{***}	-17.7^{***}	54.9^{***}
		(3.54)	(3.77)	(4.72)		(3.88)	(4.14)	(4.17)	(5.86)
log (normalized SOFR-IOR)			22.6^{***}				-0.738		
			(1.61)				(1.37)		
SOFR - IOR				0.778^{***}				0.00402	-0.330^{**}
				(0.30)				(0.0503)	(0.167)
Treasuries issuance			-112.0^{***}	-98.1^{***}			-111.0^{***}	-112.0^{***}	-70.2^{***}
			(27.5)	(29.7)			(24.4)	(24.3)	(24.3)
Treasuries redemption			153.0^{***}	139.0^{***}			121.0^{***}	122.0^{***}	62.2^{**}
			(30.1)	(31.5)			(27.3)	(27.3)	(26.7)
median time of receives									0.429^{***}
									(0.0267)
dealer-bank uninsured deposits			57.5^{***}	64.9^{***}			-74.9^{***}	-75.7^{***}	-104.0^{***}
			(3.30)	(5.77)			(3.61)	(3.43)	(3.30)
constant	91.3^{***}	163.0^{***}	0.193	63.2^{***}	69.6^{***}	41.6^{***}	145.0^{***}	143.0^{***}	116.0^{***}
	(3.85)	(3.44)	(5.91)	(5.54)	(3.05)	(3.22)	(5.39)	(4.53)	(5.15)
Observations	2042	2042	2041	2041	2042	2042	2041	2041	2041
R^2	0.184	0.631	0.782	0.774	0.208	0.343	0.545	0.545	0.626
Adjusted R^2	0.184	0.631	0.781	0.774	0.208	0.342	0.544	0.544	0.625
Residual standard error	46.2	31.0	23.9	24.3	32.6	29.7	24.7	24.7	22.4

Note: Payment timing measures are in minutes. The units of the explanatory variables are trillions of dollars, log(basis points), and basis points. Standard errors are adjusted for heteroskedasticity. The date range is January 1, 2015 to March 13, 2023. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table 7: Quantile regressions of SOFR-IOR spreads at the 95th percentile

	Dependent variable: SOFR - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	−24.1***	−23.4***		−12.4***	−15.2***	−15.4***	−15.6***
	(0.958)	(0.85)		(1.11)	(2.84)	(2.32)	(2.29)
median time of receives			0.128***	0.101***	0.0914***	0.0886***	0.0878***
			(0.00722)	(0.00729)	(0.00893)	(0.00662)	(0.00715)
T-bills outstanding					1.07*	1.05***	0.822**
					(0.562)	(0.356)	(0.382)
Treasuries redemption						−1.97	−1.05
						(6.24)	(4.48)
T-Bill issuance						2.60	2.83
						(5.89)	(4.53)
coupon issuance						55.8***	55.1***
						(6.04)	(7.89)
dealer-bank uninsured deposits					−0.544	0.103	0.528
					(1.65)	(1.46)	(1.45)
corporate tax to US treasury							39.8
							(44.4)
quarter-end fixed effect		43.2***	46.3***	44.0***	43.9***	37.3***	37.4***
		(11.3)	(13.8)	(10.6)	(9.09)	(8.8)	(8.65)
constant	23.0***	22.0***	0.287	9.77***	10.2***	8.40***	8.09***
	(1.13)	(1.01)	(0.363)	(1.17)	(1.74)	(1.37)	(1.29)
Observations	2046	2046	2046	2042	2040	2039	2039
$R^1(0.95)$	0.217	0.249	0.305	0.374	0.378	0.396	0.396

Note: The goodness-of-fit statistic $R^1(\tau)$ is an analogue of R^2 for quantile regressions (Koenker and Machado, 1999).

Table 8: Quantile regressions of SOFR-IOR spreads at the 99th percentile

	Dependent variable: SOFR - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	−40.3***	−34.2***		−19.9***	−40.2***	−42.0***	−41.8***
	(8.63)	(4.04)		(4.43)	(14.6)	(15.0)	(12.4)
median time of receives			0.188***	0.189***	0.135***	0.127***	0.129***
			(0.0293)	(0.0283)	(0.0391)	(0.0414)	(0.0415)
T-bills outstanding					−0.763	−1.09	−0.645
					(3.43)	(3.13)	(2.98)
Treasuries redemption						−4.85	1.52
						(53.6)	(61.8)
T-bill issuance						17.2	11.4
						(50.5)	(55.4)
coupon issuance						22.1	18.0
						(47.3)	(51.6)
dealer-bank uninsured deposits					12.3	14.5	13.4*
					(9.67)	(9.50)	(7.86)
corporate tax to US treasury							−12.4
							(189.0)
quarter-end fixed effect		39.8**	48.1***	41.6***	38.8***	37.4***	37.1***
		(17.4)	(5.48)	(4.59)	(5.18)	(2.96)	(5.1)
constant	44.8***	36.6***	8.96***	25.1***	16.0*	12.5	13.8*
	(10.6)	(4.88)	(1.77)	(4.81)	(8.50)	(8.37)	(7.83)
Observations	2046	2046	2046	2042	2040	2039	2039
$R^1(0.99)$	0.214	0.289	0.310	0.373	0.380	0.384	0.384

Note: The goodness-of-fit statistic $R^1(\tau)$ is an analogue of R^2 for quantile regressions (Koenker and Machado, 1999).

Table 9: Quantile regression of SOFR−IOR at the 99th percentile on lagged 10-day average payment delays and other variables.

	Dependent variable: SOFR - IOR			
	(1)	(2)	(3)	(4)
dealer opening balances $t-2$	-24.9^{***}		10.3	-4.80
	(4.59)		(8.05)	(11.5)
average payment delay $t-10$ to $t-2$	0.164^{***}	0.181^{***}	0.287^{***}	0.240^{***}
	(0.0393)	(0.0485)	(0.0473)	(0.0596)
T-Bills outstanding			-7.32^{***}	-6.48^{**}
			(2.36)	(2.66)
Treasuries redemption				0.209
				(40.0)
T-Bill issuance				12.1
				(39.8)
coupon issuance				50.5
				(49.2)
dealer-bank uninsured deposits			-6.84	1.42
			(6.24)	(5.46)
corporate tax to US treasury				-129.0
				(180.0)
quarter-end fixed effect	35.7	40.3	33.9^{**}	29.2
	(42.1)	(37.5)	(15.9)	(31.2)
constant	27.7^{***}	9.32^{***}	35.0^{***}	25.5^{***}
	(5.26)	(2.50)	(7.31)	(7.14)
Observations	1998	2002	1996	1994
$R^1(0.99)$	0.356	0.272	0.360	0.368

Note: Standard errors are adjusted for heteroskedasticity. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$. Average payment delay is the lagged average of the time of day by which the ten largest repo-active bank holding companies had received the first half of their incoming payments, relative to sample mean, in minutes, averaged for business days $t-10$ through $t-2$. The goodness-of-fit statistic $R^1(\tau)$ is an analogue of R^2 for quantile regressions (Koenker and Machado, 1999).

B Additional figures

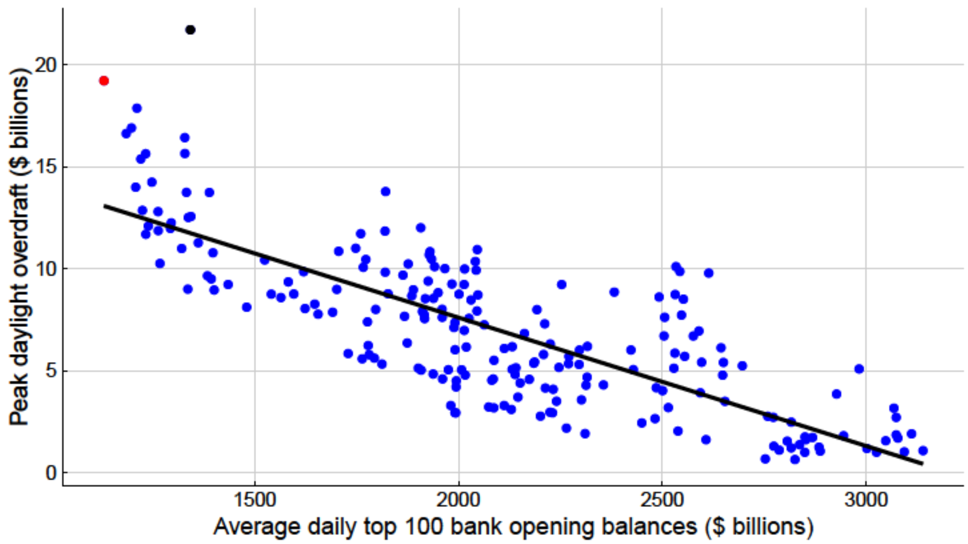


Figure 9: Peak intraday overdrafts and reserve balances

Note: Peak intraday overdrafts are calculated over two-week periods and published by the Federal Reserve. Average total reserve balances in our sample are computed over the same two-week periods. The R^2 of the linear relationship, plotted, is 0.63. The slope coefficient, -0.0063, is estimated with a standard error of 0.00033. The red dot corresponds to the observation for the 2-week maintenance period ending September 25, 2019. The black dot corresponds to the observation for the 2-week maintenance period ending March 11, 2020. The data period is from January 1, 2015 to March 22, 2023. Sources: Federal Reserve and Fedwire Funds Service.

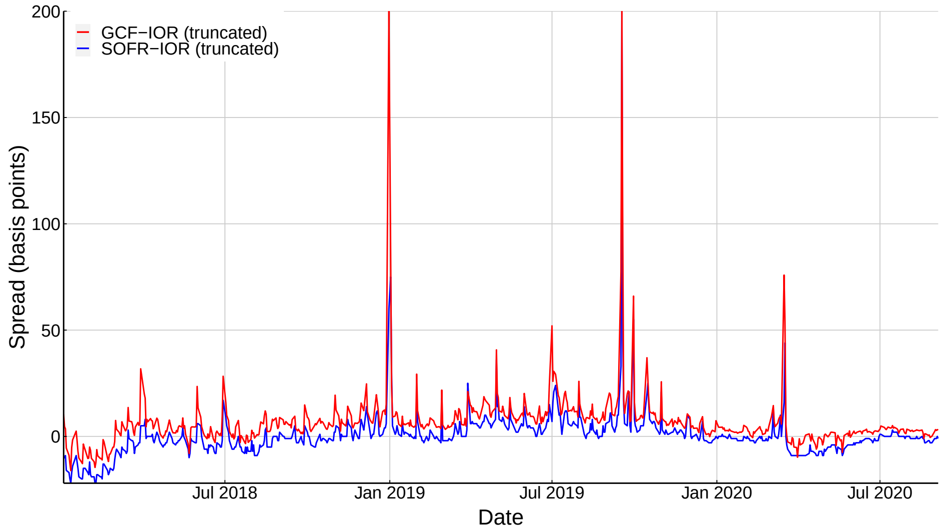


Figure 10: Repo rate benchmarks, spread to IOR, 2018-2020
Note: SOFR is the secured overnight financing rate and IOR is interest on reserves. SOFR−IOR is shown in blue. GCF Repo−IOR is shown in red. Both spread plots are truncated at 200 basis points for improved visualization. Source: FRBNY and FICC.

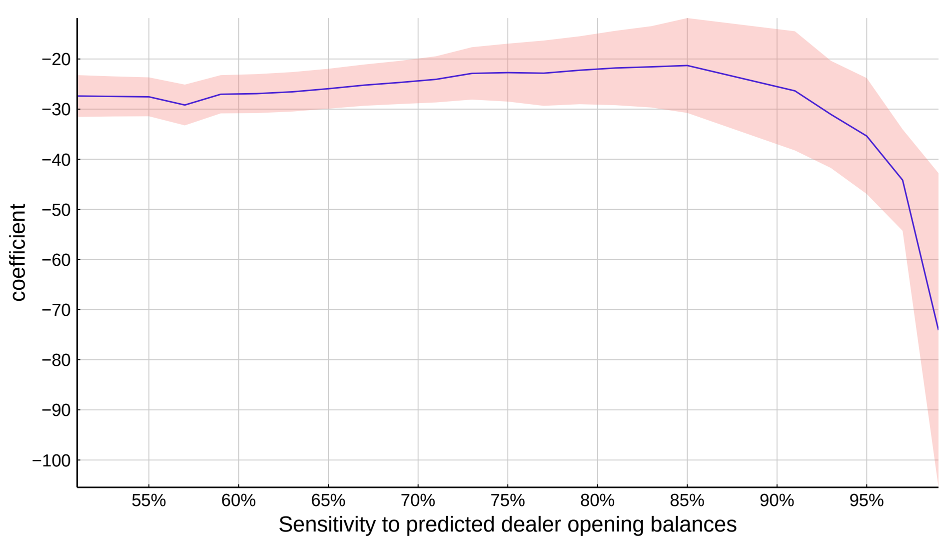


Figure 11: Sensitivity of SOFR-IOR to dealer reserve balances from IV quantile regressions.
Note: The blue line is the estimated coefficient of predicted dealer opening balances, in trillions of dollars. The shadow region represents the plus and minus one standard deviation around the point estimates. At each percentile of 51, 53, $\cdots$, 99, we estimate the quantile regression analogous to that of column (2) of Appendix Table 1. Coefficients corresponding to the 87th and 89th percentiles are omitted because of non-convergence of the numerical procedure of Kaplan and Sun (2017).

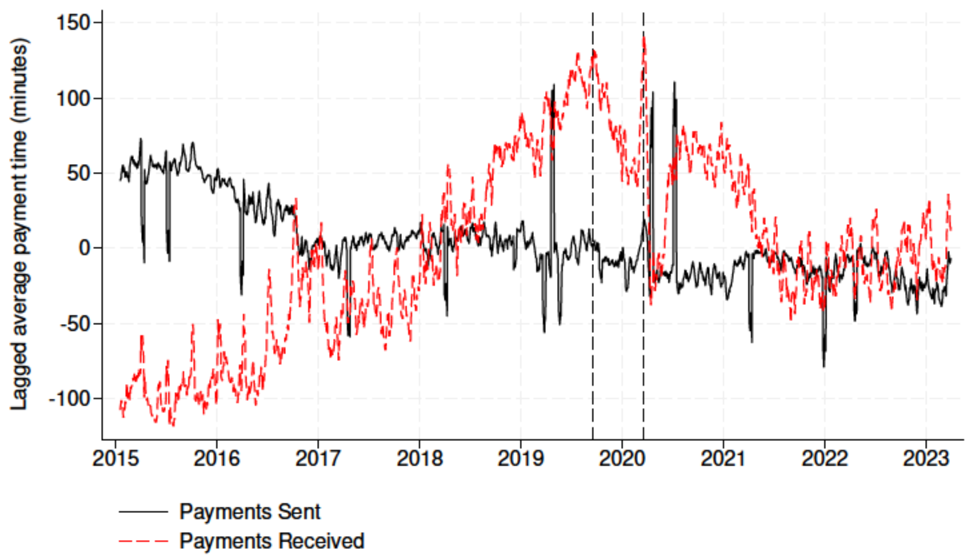


Figure 12: Timing of payments over $100 million to and from dealer banks

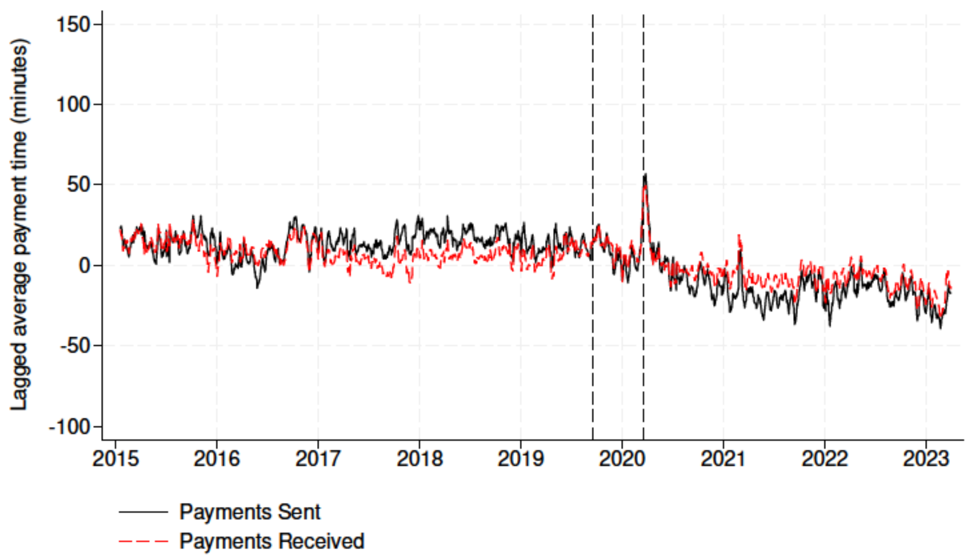


Figure 13: Timing of payments less than $100 million to and from dealer banks

Note: These two figures show the times of day by which the dealer banks received half of their incoming payments and sent half of their incoming payments, relative to the sample mean, in minutes, for those payments weakly greater than $100 million (Figure 12) and for those less than $100 million (Figure 13). (An increase in minutes means later in the day.) The observation for date t is the average over the past ten business days, inclusive of date t. The vertical lines mark September 17, 2019 and March 17, 2020. Data source: Fedwire Funds Service.

C Analysis of the likelihood of repo rate spikes

Table 10: Days on which repo rates spiked.

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

Note: Spreads are, in basis points (bps) over IOR, of the Secured Overnight Financing Rate (SOFR), General Collateral Finance (GCF) repo rate, and 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. Source: Fedwire Funds Service, FRBNY, and Tradition.

Table 11: Estimated coefficients of a probit model of repo rate spikes

	Dependent variable:						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
median time of receives	0.0063***		0.0024*		0.00682***	0.0017	0.00247
	(0.0013)		(0.0014)		(0.00143)	(0.00158)	(0.00181)
dealer opening balances		−2.73***	−2.17***			−2.91***	−3.30***
		(0.466)	(0.488)			(0.557)	(0.686)
Coupon issuance				6.04***	6.20***	9.15***	5.54***
				(0.948)	(0.972)	(1.32)	(1.66)
quarter-end fixed effect							1.98***
							(0.313)
constant	−2.13***	−0.152	−0.551*	−2.19***	−2.32***	−0.320	−0.184
	(0.0748)	(0.293)	(0.331)	(0.074)	(0.0915)	(0.355)	(0.429)
Observations	2046	2046	2042	2059	2045	2041	2041
Log Likelihood	−199.0	−184.0	−183.0	−196.0	−183.0	−160.0	−137.0
Akaike Inf. Crit.	402.0	373.0	372.0	397.0	371.0	328.0	284.0

Note: The probit model is $P\left(Repo\,Spike = 1 \mid X_1, X_2, \ldots, X_k\right) = \Phi\left(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k\right)$, where Φ is the standard normal cumulative distribution function. Repo rate spike dates are listed in Table 10, and determined by the criteria stated in the table note. The units of the explanatory variables are minutes and trillions of dollars. The date range is January 1, 2015 to March, 13, 2023. *p<0.1; **p<0.05; ***p<0.01.

D Additional IV analysis

This appendix section provides additional IV analysis. Table 12 shows OLS prediction of SOFR−IOR, with and without instrumenting for dealer opening balances. As anticipated, the coefficients on dealer opening balances and IV-predicted dealer balances are lower than the corresponding coefficients of the high-quantile regressions. Further, the coefficient on predicted dealer balances is larger than that for the model in which dealer balances are not instrumented, consistent with endogenous increases in balances when SOFR−IOR is higher. Table 13 shows the first stage of the IV regression. The associated F-statistics of 574 demonstrates the strength of the instruments.

Table 14 provides additional results at the 99th percentile. The rightmost column of this table provides the results used in the paper, using the method described in Kaplan and Sun (2017). The remaining columns in the table report the results using the method described in Chernozhukov and Hansen (2005) with grid points numbers of 500, 700, 900, and 1100. The estimated coefficients and, to a larger extent, the standard errors, change somewhat with different numbers of grid points. The magnitude of the coefficient on dealer balances is relatively stable, however, at approximately -77 basis points per trillion dollars of balances. The standard errors imply that this coefficient is significantly different from zero for all but one choice of the number of grid points.

Table 12: Estimated coefficients of OLS models of SOFR-IOR spreads with and without IV prediction of dealer-bank opening balances

	Dependent variable: SOFR−IOR		
	OLS	IV	IV
dealer opening balances	-26.3^{***}		
	(1.55)		
median time of receives	0.0711^{***}		
	(0.0125)		
predicted dealer-banks opening balances		-46.0^{***}	-23.3^{*}
		(4.85)	(13.79)
residual of median receive time on opening balances			0.0836^{***}
			(0.0272)
quarter-end fixed effect	7.88^{**}	8.21^{***}	7.85^{**}
	(3.15)	(3.15)	(3.52)
T-bills outstanding	3.33^{***}	5.83^{***}	3.02^{***}
	(0.545)	(0.328)	(0.895)
Treasuries redemption	-15.2^{**}	−11.8	−15.3
	(7.28)	(7.99)	(21.8)
T-Bill issuance	18.2^{***}	17.3^{**}	17.9
	(6.95)	(7.38)	(20.5)
coupon issuance	24.2^{***}	21.7^{***}	24.3
	(6.34)	(7.16)	(16.8)
dealer-bank uninsured deposits	3.86^{***}	8.56^{***}	1.50
	(0.943)	(2.60)	(5.17)
corporate tax to US treasury	69.0^{**}	80.2^{**}	63.8
	(33.1)	(33.9)	(198.8)
constant	-4.88^{***}	-5.92^{***}	−1.19
	(0.888)	(1.56)	(2.53)
Observations	2039	2031	2026
R^2	0.392	0.355	0.388
Adjusted R^2	0.389	0.353	0.385
Residual standard error	9.21	9.48	9.25

Note: The first column present the results of an ordinary least squares (OLS) regression. The second column, IV, presents the results of a two-stage least squares regression, where dealer bank balances have been instrumented from a first stage regression (see Appendix Table 13). The third column mimics the second column, except that an additional dependent variables has been added. SOFR-IOR is in basis points and the units of the explanatory variables are trillions of dollars and minutes. A constant was included for each specification but is not reported. Standard errors are adjusted for heteroskedasticity. The date range is January 1, 2015 to March 13, 2023. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table 13: First stage of IV regression: Prediction of dealer opening balances.

	Dependent variable: dealer opening balances
Q1 time of receives for small banks $t-7$	-0.00022
	(0.00015)
median time of receives for small banks $t-7$	-0.00059^{***}
	(0.00013)
Q3 time of receives for small banks $t-7$	0.00088^{***}
	(0.00011)
T-Bills outstanding	-0.0563^{***}
	(0.0064)
Treasuries redemption	-0.347^{**}
	(0.161)
T-Bill issuance	0.293^{*}
	(0.157)
coupon issuance	0.0932
	(0.138)
quarter-end fixed effect	-0.00779
	(0.0254)
dealer-bank uninsured deposits	0.535^{***}
	(0.0154)
corporate tax to US treasury	1.06^{**}
	(0.540)
constant	-0.209^{***}
	(0.0206)
Observations	2031
R^2	0.740
Adjusted R^2	0.738
Residual Std. Error	0.129
F Statistic	574.0^{***}
Notes:	$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table 14: Robustness of IV quantile prediction of SOFR-IOR at the 99th percentile.

Method	Chernozhukov and Hansen (2006)				Kaplan and Sun (2017)
Grid points	1100	900	700	500	
predicted dealer balances	-77.75802	-77.83352	-77.24437	-78.06266	-73.25041
	(18.18609)	(16.55381)	(62.23318)	(16.76075)	(39.17101)
quarter-end fixed effect	29.51487	29.54318	29.32223	29.62912	33.28292
	(3.298832)	(3.226688)	(17.24483)	(3.583235)	(13.76293)
T-bills outstanding	2.995394	3.030637	2.755629	3.137601	3.222659
	(1.068315)	(0.8838553)	(33.9007)	(0.5591909)	(1.892072)
Treasuries redemptions	-24.84351	-24.5969	-26.52123	-23.84844	-14.96246
	(14.58203)	(12.18771)	(297.5446)	(8.972999)	(24.58671)
T-bill issuance	30.4733	30.28878	31.72865	29.72874	24.08455
	(12.89701)	(11.24421)	(199.6474)	(9.194063)	(20.5541)
coupon issuance	46.76542	46.29506	49.96535	44.86751	30.44799
	(26.10531)	(21.37337)	(264.6824)	(11.0142)	(35.25005)
corporate tax to US treasury	-34.33891	-34.97266	-30.0274	-36.89609	31.51947
	(47.77225)	(43.13383)	(172.1301)	(28.34876)	(163.9801)
dealer-bank uninsured deposits	26.01943	25.71187	28.11182	24.77842	23.68129
	(9.984596)	(8.940665)	(134.0081)	(8.27471)	(19.83468)
constant	5.571819	5.752031	4.345801	6.298979	6.536006
	(4.331995)	(3.525758)	(155.2013)	(2.326463)	(9.029197)

Note: The first four columns present the estimated coefficients of a quantile IV regression at the 99th percentile for various number of grid points using the method of Chernozhukov and Hansen (2005). The fifth column presents the estimated coefficients for the same quantile IV regression using the method of Kaplan and Sun (2017) . Robust standard errors included in parenthesis. These estimates were computed using the **ivqregress** command in STATA.

E Jamie Dimon comments on September 2019 event

Dimon's comments during J.P. Morgan's third-quarter 2019 earnings call were covered by Bloomberg. Glenn Schorr, analyst at Evercore, questioned Dimon as follows. "Curious your take on everything that 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 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." Dimon responded:

"... 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."

F Analysis of inter-dealer transaction-level repo 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 453,136 trade quotes with Treasury and Government Agency as collateral. Our paper focuses on the overnight general Treasury collateral repo rates. There are 202,062 overnight trade quotes with general Treasury collateral, and 33,622 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.

Stress on the intraday balances held by these dealer banks is also related to our finding that dealer banks delay their *outgoing* payments to a much lesser extent than the delay in their incoming payments, as we discuss in Section 4. This relationship holds in general throughout our sample period, including days on which repo rates spiked. On the repo-stress days of September 17, 2019 and March 17, 2020, for example, the delay in half-time of payments received reached the highest two levels in the sample, 151 and 155 minutes respectively, whereas the delays in half-sent time were only 6 and 54 minutes, respectively. Contributing to the lower responsiveness of the timing of outgoing payments is the fact that payments to the Treasury General Account for the settlement of Treasuries purchased at auctions must be made early in the morning.

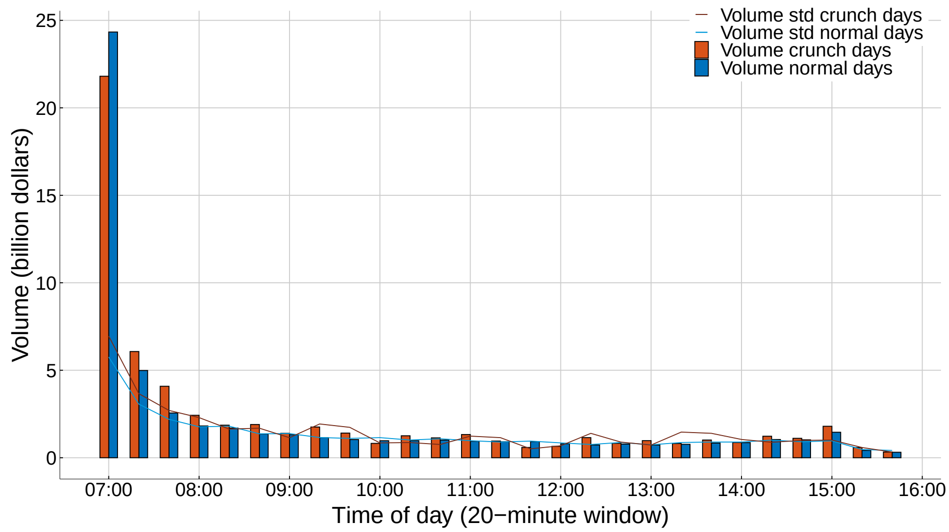


Figure 14: Average and standard deviation, across normal days and across crunch days, of total trading volume in each 20-minute time window. Source: Tradition.

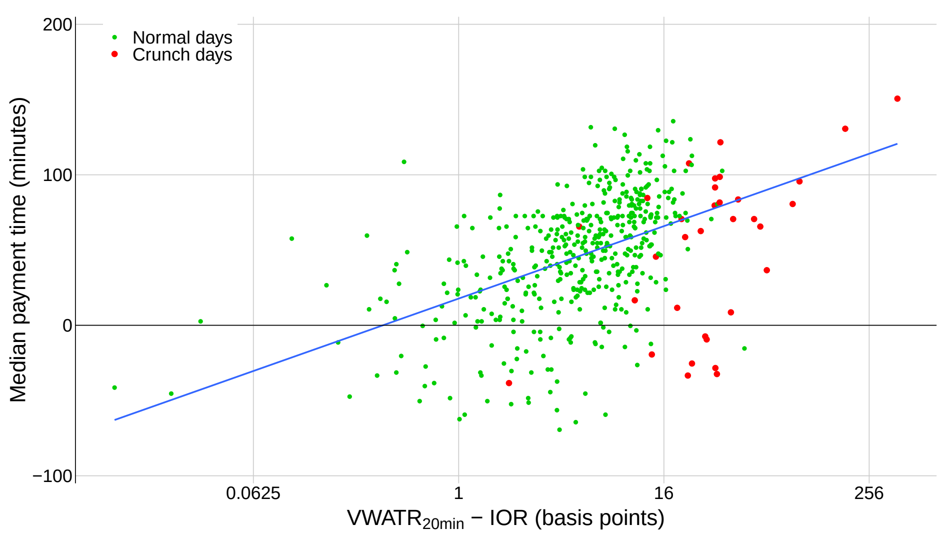


Figure 15: Interdealer repo rates and payments timing

Note: The repo rate spread shown in the value-weighted average of Treasury general collateral repo rates, in excess of IOR, over the first 20 minutes of the day. Because of the log scale, we drop the observations for which this rate spread is negative. "Crunch days" are those for which the rate spread is at least 15 basis points above the average rate spread over the previous 14 days. The solid line is the estimated linear relationship between the two variables. Data sources: Fedwire Funds Service and Tradition.