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Abstract

The Federal Reserve's "balance-sheet normalization," which reduced aggregate reserves between 2017 and September 2019, increased repo rate distortions, the severity of rate spikes, and intraday payment timing stresses, culminating with a significant disruption in Treasury repo markets in mid-September 2019. We show that repo rates rose above efficient-market levels when the total reserve balances held at the Federal Reserve by the largest repo-active bank holding companies declined and that repo rate spikes are strongly associated with delayed intraday payments of reserves to these large bank holding companies. Intraday payment timing stresses are magnified by early-morning settlement of Treasury security issuances. Substantially higher aggregate levels of reserves than existed in the period leading up to September 2019 would likely have eliminated most or all of these payment timing stresses and repo rate spikes.

Key words: repo rates, reserves, Treasuries, payments, central bank balance sheet

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https://www.newyorkfed.org/research/staff_reports/sr974.html.

1 Introduction

We show how post-crisis liquidity regulations and the Federal Reserve's "balance-sheet normalization" stressed the intraday management of reserve balances held at the Federal Reserve (Fed) by large bank holding companies (BHCs) that are active in repo markets. This led to spikes in Treasury repo rates during 2018-2019. After an especially large and prominently reported[1] disruption in repo markets during September 16-18, 2019, the Fed reversed its balance-sheet normalization. Despite this change in policy, our analysis implies that the reserve balances held at the Fed by the large BHCs that are active intermediaries in the Treasury repo market were still not sufficiently large to avoid repo liquidity crunches until the Fed created a large quantity of additional reserves in response to the Covid shock of March 2020. Whether the Fed should aim, over the long run, for a small or large balance sheet remains controversial. repos 3/2020

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

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

overdrafts on their reserve accounts at the Fed. We find that as balance sheet normalization reduced aggregate reserves, intraday payments to the large BHCs active in repo markets were significantly delayed and these BHCs quoted inefficiently high rates for wholesale overnight funding. These large BHCs avoided daylight overdrafts and the discount window, prioritizing regulatory liquidity requirements by maintaining a significant cushion of reserve balances at the Fed to manage intraday payments.

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

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

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

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

[3]See Pozsar (2019b). We checked this fact in conversations with multiple knowledgeable market participants and official-sector sources.

in the repo market.

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

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

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

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

or effectiveness of such policies in the future.”

Naturally, the FOMC’s views on these costs and benefits have evolved over time.[4] Section 8 summarizes policy tradeoffs associated with the ampleness of reserves.

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

2 Background and related work

The spread between U.S. 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), and regulatory liquidity requirements (Ihrig, 2019; d’Avernas and Vandeweyer, 2020). If the aggregate supply of reserves is ample for these combined purposes, then arbitrage would keep Treasury

[4]For example, consider the “Long-Run Monetary Policy Implementation Frameworks” discussion recorded in the minutes of the FOMC meeting of January 2019.

repo rates near IOR and wholesale funding markets would remain relatively liquid.[5]

The total quantity of reserves in the U.S. banking system has exceeded $1 trillion since the 2008-2009 financial crisis and reached a peak of $2.8 trillion in 2014 as a result 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 reserves declined, reaching a low of $1.4 trillion in early September 2019.

The Fed used Senior Financial Officer Surveys[7] to help ascertain the demand for reserves, asking banks about their "lowest comfortable level of reserves." In an April 2019 speech, Logan (2019) reported that one estimate of the banking system's demand for reserves based on the September 2018 and February 2019 responses ranged between $800 billion to $900 billion, well below the level of aggregate reserves supplied by the Fed at that time.[8] Logan (2019), however, noted that the aggregate amount of reserves needed to be supplied by the Fed is likely to be higher than this estimated range in order to account for survey error, changes in bank demand, and the possibility that there are frictions in the redistribution of reserves. Given the survey results and a wide range of other information available at that time, when reserves were around $1.6 trillion, it appeared that "reserves remain ample." Yet our analysis shows that with the decline in reserves from 2017 to September 2019, the spread between SOFR and IOR crept higher and occasionally spiked up, particularly on Treasury issuance dates. Appendix Table 11 lists dates on which Treasury repo rates spiked relative

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

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

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

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

to IOR.

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

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

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

A similar pattern is observed on March 17, 2020, when SOFR again spiked above IOR during the "dash for cash" induced by news of the Covid pandemic.[10] The reserve balances of the ten repo-active banks remained near their low September 2019 levels up until 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 time by which half of daily

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

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

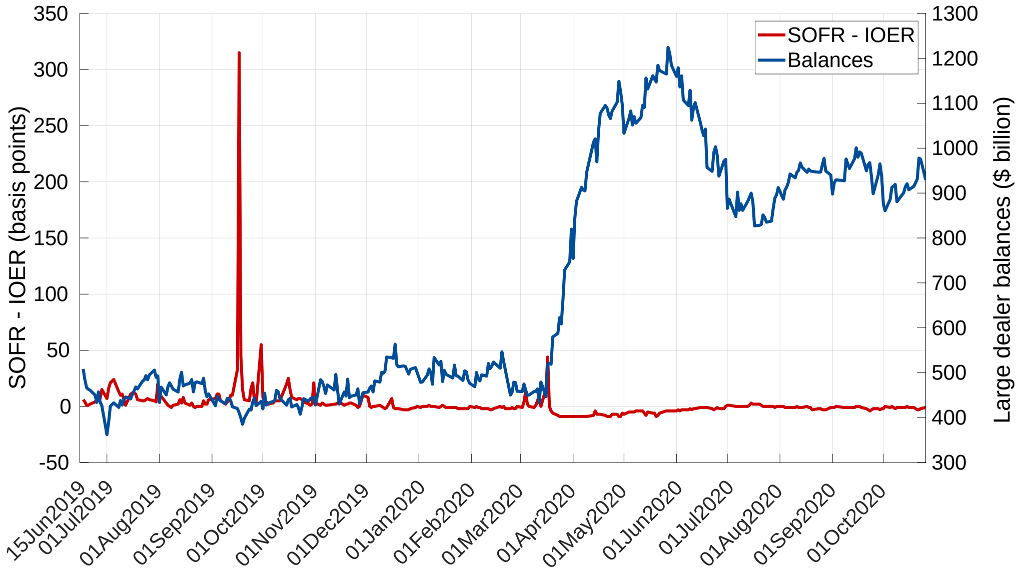

Figure 1: Reserve balances and the spread of SOFR over IOR

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.

incoming payments to the largest repo-active BHCs had arrived reached the sample-record high of 155 minutes later than average.

Although the Covid-related shock 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 ten repo-active BHCs, 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 ten large repo active BHCs would have mitigated stresses on funding markets and intra-day payment timing. Section 5 provides estimated relationships among repo rates, reserve balances, and intraday payment timing over the sample period, including a probit analysis of repo-spike events.

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

The SOFR-IOR spread was actually negative during most of 2015-2017 because of the large supply of federal reserve balances and the low outstanding amount of Treasury bills during most of this period.[13] Government money market funds substitute between Treasury bills and Treasury repos, which places downward pressure on the spread between Treasury repo rates and IOR when the outstanding supply of Treasury bills is low (Duffie and Krishnamurthy, 2016). Money funds and most other investors cannot hold Federal reserves, whereas banks are subject to significant capital requirements for reserves.[14] So, when the supply of reserve balances is sufficiently large relative to the supply of Treasury bills, SOFR-IOR easily becomes negative. We explore this relationship in Section 7.

Among the limits to arbitrage between Treasury repo rates and IOR are (i) search frictions in funding markets (Afonso and Lagos, 2015), (ii) repo market segmentation (Han, 2020; Avalos, Ehlers and Eren, 2019; Duffie and Krishnamurthy, 2016), (iii) the cost to banks of

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

[12]Lou Crandall, Wrightson Capital's money-market analyst, wrote, in the "Money Market Observer" of July 27, 2020: "As discussed last week, the supply of bank funding available to the repo market became much more elastic once the aggregate cash asset holdings of large domestic banks surged above $1.5 trillion this spring. When reserve availability was merely adequate in Q4 2019 and Q1 2020, GC rates had to rise significantly to induce large domestic banks to substitute RRPs for Fed balances in their HQLA portfolios. From October of last year through April 2020, it took a 15 basis point widening in the Treasury GCF 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."

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

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

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), 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; Acharya and Merrouche, 2013; Yang, 2020). While we offer support for the importance of all of these effects, our main marginal contribution is to estimate and interpret key relationships among the total reserve balances of the largest dealer banks, the total reserve balances of other large banks, intraday payment timing delays, and repo rate distortions.

The repo market phenomena addressed in this paper are best exemplified by the situation in mid-September 2019, which is described in detail by Afonso, Cipriani, Copeland, Kovner, La Spada and Martin (2020), Anbil, Anderson and Senyuz (2020a), Anbil, Anderson and Senyuz (2020b), Ihrig, Senyuz and Weinbach (2020), and Correa, Du and Liao (2020), among others. This was almost a perfect storm of supply and demand factors, beginning on the supply side with the lowest level of reserve balances ever achieved during the Fed's balance sheet normalization. Reserves had been depleted not only by the gradual process of balance-sheet normalization, but also by a significant shift of reserves into the Treasury General Account (TGA).[15] The Treasury Department does not supply funding to wholesale money markets, so the transfer of reserves from banks' Fed balances to the TGA reduces the supply of cash available to the repo market and other funding markets (Correa, Du and Liao, 2020).

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

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, as documented by Afonso, Cipriani, Copeland, Kovner, La Spada and Martin (2020) and Anbil, Anderson and Senyuz (2020b), money market mutual funds had recently reduced their use of "sponsored repo,"[16] 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.[17]

On the demand side of the repo market, large U.S. government fiscal deficits had caused a significant secular increase in the outstanding stock of marketable Treasury securities, which in turn increases the amount of Treasury securities for which dealers required repo financing. In particular, the Treasury issuances on September 16 and 17, 2020, increased the demand by dealers for repo financing. Further, a requirement that the Treasury is paid for issuances early in the morning results in early-morning conversion of reserve balances to TGA balances, reducing the supply of reserves available that day for any purpose, including investment in repos and meeting intra-day payment needs. 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.

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

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

[17]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.

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 the work of Klingler and Syrstad (2021) which examines three alternative reference rate spreads, i.e. SOFR spread, SONIA (the sterling overnight index average) spread and ESTR (the euro short term rate) spread, and their empirical relationships to quarter end reporting dates, government debt outstanding and total bank reserves.

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

3 Data: Sources and Description

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

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

financial institutions holding an account at a Federal Reserve Bank.

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

From the opening-day balances data for these 100 accounts, we produce two daily time series: the sum of opening-day balances for the ten specified dealer banks accounts, and the sum of the opening-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 2015 through late 2020. Our data capture a financial institution's account balance at the Federal Reserve rather than the amount of "reserves" that it holds, as defined by regulation. For the larger financial institutions on which we focus, this is not an important distinction.[22]

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

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

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

[22] Indeed, we have checked and found that the opening-day balances of these accounts are quite close to the amount of reserves reported in Call Reports (FR Y-9C). For smaller banks, however, there could be a significant difference between balances held at the Fed and reserves. In the extreme, a small bank may enter into a correspondent banking relationship with another (typically larger) bank and place their reserves at

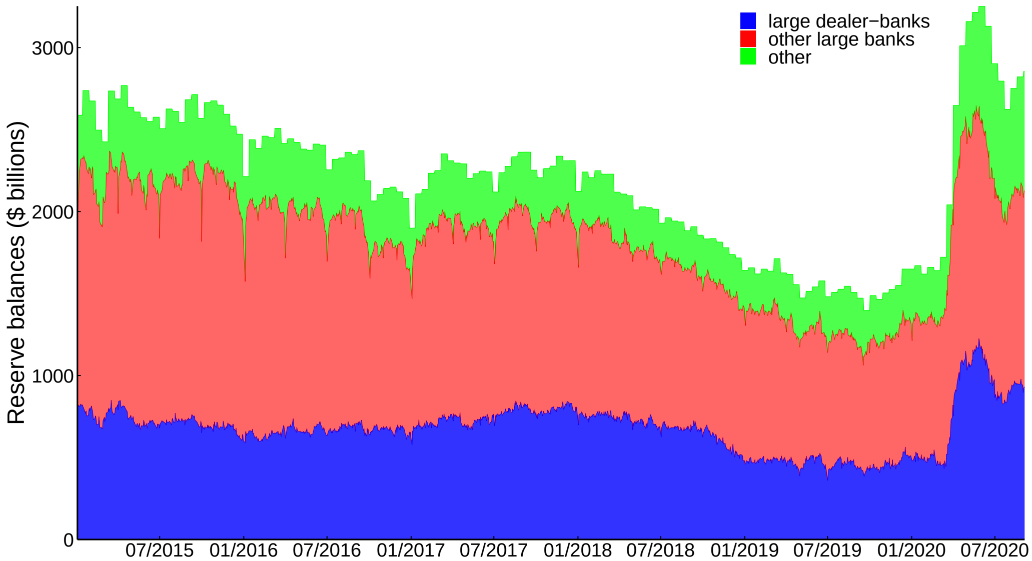

Figure 2: Reserve balances over time

Note: Large dealer banks are 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).

As a point of reference, 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 repo-active 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 given day in our sample, we compute

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

when in the day 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, half of the total transfers to the ten dealer banks had been received by 2:03 pm, and half of the total value sent by the ten dealer banks was sent by 12:54 pm. These statistics are based on standard payment timing metrics used in previous research on intraday payments, such as Armantier, McAndrews and Arnold (2008), McAndrews and Kroeger (2016), and Copeland, Molloy and Tarascina (2019).

Our main source of repo rates is SOFR, a volume-weighted median of 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 sample, often in excess of $1 trillion during our sample period, and is composed of data from tri-party repo (a dealer-to-client market segment) and two interdealer repo services offered by FICC: the General Collateral Finance Repo Service (GCF Repo®), and Fixed Income Clearing Corporation Delivery-vs-Payment Service (FICC DVP).[23] For the portion of our sample period that precedes the availability of official SOFR fixings, we use unofficial estimates of SOFR published by FRBNY.[24] Because SOFR is a mix of dealer-to-client and interdealer trades, we also use GCF Repo rates data published by FICC when we want a measure of rates that reflects the costs of financing Treasuries in interdealer markets.[25]

Interdealer repo rates tend to be higher than tri-party repo rates and are more sensitive to quarter-end capital requirements than are tri-party rates, as we discuss in Section 6.

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

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

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

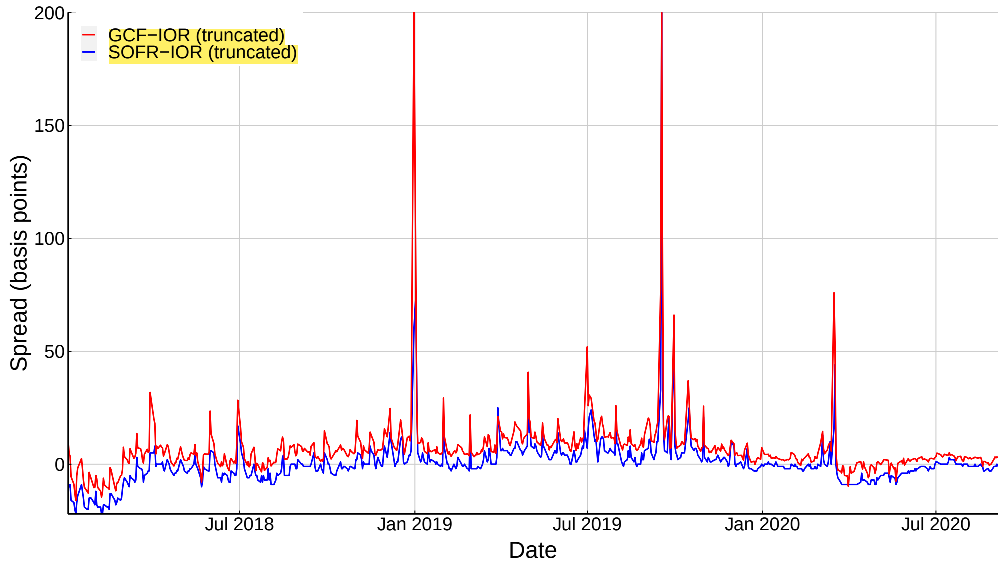

Figure 3: Repo rate benchmarks, spread to IOR

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.

Generally speaking, however, our results concerning the implications for repo rate spreads of the ampleness of reserve balances do not depend importantly on which of these two segments of the repo market is considered, as shown in a parallel set of results for other repo benchmarks found in the Appendix. We focus primarily on the spread between SOFR and IOR, which is illustrated in Figure 3 alongside the the spread between GCF Repo and IOR.

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.[26]

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 Table 6.

[26]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.

4 Intraday stress on balances held at the Fed

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

Jamie Dimon, the Chairman and CEO of JP Morgan, famously[27] commented on this tradeoff during J.P. Morgan's third-quarter 2019 earnings call, when he responded to a question[28] about "everything that went on in the repo markets" during the September 2019 repo market disruption by saying

". . . 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."

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

[28] 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 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."

Under post-crisis liquidity regulations and supervision, globally systemically important bank holding companies (GSIBs) appeared to have become extremely averse to the risk that their intraday reserve balances could approach zero, the "red line" described by Dimon.[29] This conclusion is supported by our conversations with relevant senior managers at several GSIBs. A daylight overdraft at a large systemically important bank would cause a loss of reputation to the bank and thus to its line managers responsible for managing intraday balances. Given the uncertain timing of incoming payments, it is natural for a large dealer bank to be conservative when providing discretionary funding in the repo market by quoting high repo rates whenever its balances are low and incoming payments could be delayed.[30]

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

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

[29] 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."

[30] 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 0.57 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.

follows.

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

- The Federal Reserve Board's Regulation YY, Enhanced Prudential Standards, includes rules covering intraday liquidity exposures.[31] 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 a related BIP survey, over three-quarters of the banks to which the Regulation YY liquidity buffer is applicable indicated this to be an "important" or "very important" consideration.

- Under the Dodd-Frank Act, the Fed and FDIC implemented failure planning requirements for Resolution Liquidity Adequacy and Positioning (RLAP), which include the intraday "resolution" liquidity requirement mentioned by Dimon. The associated FDIC and Federal Reserve Board guidance states that banks must "ensure that liquidity is readily available to meet any deficits." "Additionally, the RLAP methodology should

[31] 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."

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,[32] and foreign supervisors, among others." Pozsar (2019a) outlines how RLAP impacts the intraday incentives for dealer banks to conserve reserve balances on days of Treasury issuances.

Even in the post-2008 period, when system-wide reserves have been much higher than pre-crisis, Copeland, Molloy and Tarascina (2019) and McAndrews and Kroeger (2016) showed a strong relationship between intraday payment timing and system-wide total reserve balances. Indeed, as shown in Figure 4, the half-received time of payments to the dealer banks is highly related to the opening-of-day reserve balances of the other large banks in our sample. The red dot in Figure 4 shows the sample's second latest time of day by which the ten dealer banks had received 50% of their total daily payments, which occurred on September 17, 2019. On that day, this half-received payment time was 151 minutes later than 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.

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

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

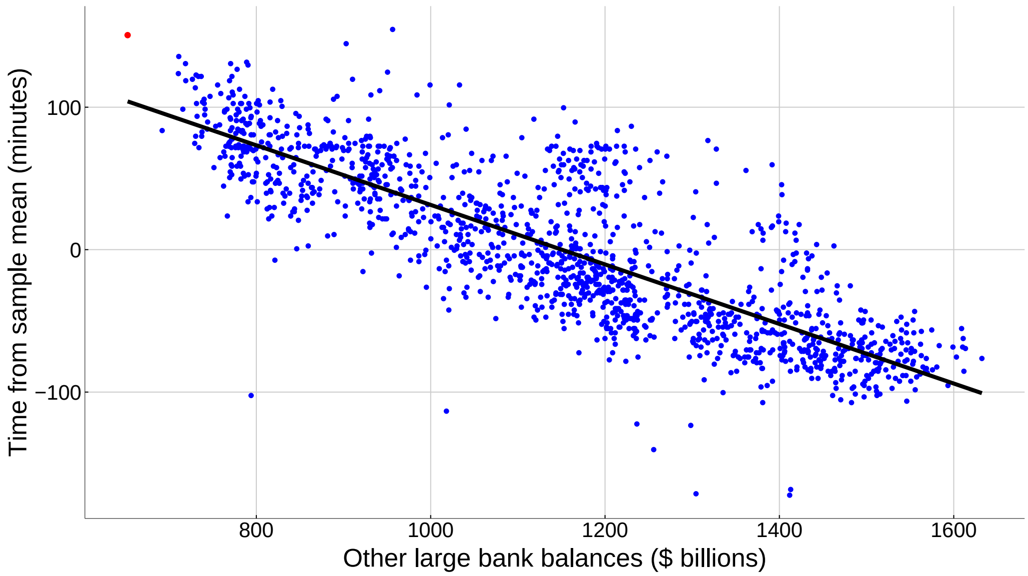

Figure 4: Non-dealer bank reserve balances and the timing of payments to dealer banks
Note: Reserve balances are the total opening-of-day reserve balances of all accounts in our sample, except for the ten dealer banks. The payment timing measure is the half-received time of payments to the dealer banks. The solid line is the estimated linear relationship, which has an R^2 of 0.69. The slope coefficient, -0.209, is estimated with a standard error of 0.0037. The date corresponding to the red dot in the upper left corner is September 17, 2019, when SOFR-IOR spiked to its sample-record high. Source: Fedwire Funds Service.

banks ignored apparent arbitrages that would have required issuing new money because of the distortionary effect of the requirement to back private money issuance one-for-one with Treasuries.

The new liquidity regulations may have an especially large impact in repo markets because the majority of repo transactions are executed early in the business day. For example, transaction level data from Tradition's repo platform demonstrate that a large fraction of interdealer repo trades are conducted between 7:00am and 7:20am, Eastern time (Appendix Figure 8). Based on the empirical evidence and the institutional facts that we have described, when intermediating the Treasury repo market, the marginal value to a dealer bank of holding balances at the Fed is sensitive to anticipated intraday payment stresses on these balances. Figure 5 shows a strong relationship on stress days between Tradition repo rates spreads over IOR at the opening of the day, during the key period between 7:00am and 7:20am, and the half-received payment time on the same day for the ten repo-active dealer banks.

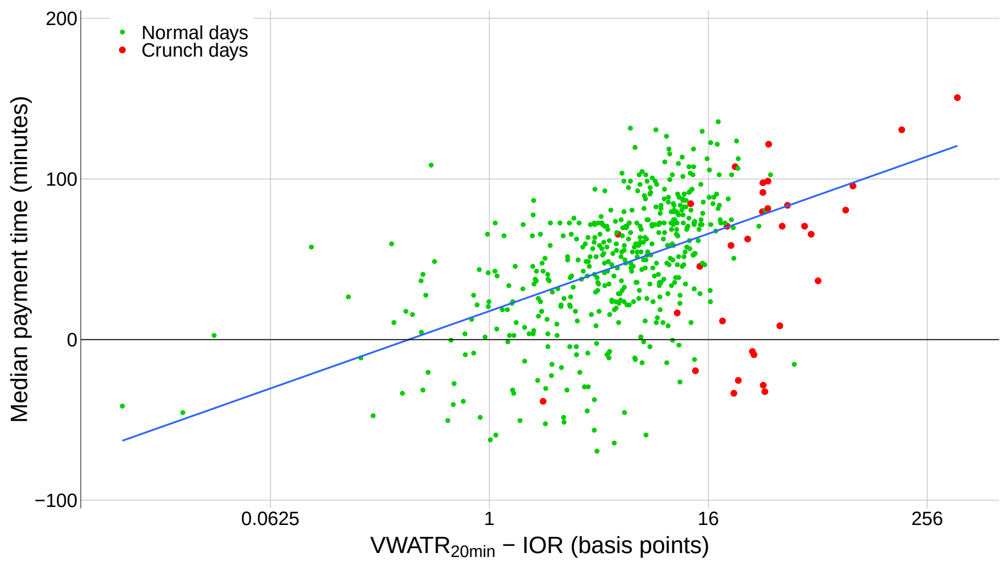

Figure 5: Interdealer repo rates and payments timing

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.

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 5. 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.

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

Another factor that may contribute to a high shadow cost to dealer banks of providing intraday funding with reserves is the risk that an intraday overdraft at the Fed is converted into an overnight overdraft, requiring the dealer bank to use the Discount Window. Historically, it has been argued that banks are reluctant to use the Discount Window because of concerns with stigma (Armantier, Ghysels, Sarkar and Shrader, 2015). The Federal Reserve has taken steps to reduce this stigma (see, for example, a March 15, 2020 press release by the Federal Reserve), but Covas and Nelson (2019) argue that stigma concerns remain and are the main reason that funding market stresses are not mitigated by the drawing of reserves from the Discount Window.

5 Liquidity stress and low Fed balances

In this section, we quantify key liquidity stresses associated with low levels of Fed balances. The simplest important natural relationships that we find in the data are summarized as follows[33].

1. In aggregate, banks send payments later in the day when their Fed balances are lower (Table 1, column 1). But this relationship differs across types of banks. In a multivariate regression of the half-received time of payments to dealer banks on (a) dealer bank balances and (b) other-large-bank balances, we find the anticipated negative loading on other-large-bank balances. But the estimated coefficient on dealer-bank balances is positive (Table 1, column 2). This may reflect the endogenous response

[33] Our findings are robust to considering subsamples of the data, in particular the subsample of days on which there is substantial Treasury issuance (i.e., Treasury bill issuance over 19 billion dollars), as well as the subsample of days on which there is not substantial Treasury issuance (i.e., Treasury bill issuance is less than 19 billion dollars and coupon issuance is less than 10 billion dollars).

of dealer banks to the risk of intraday liquidity stress, thus increasing their balances in anticipation. The incoming payment delays can be substantial. For example, a one-standard-deviation reduction in other-large-bank opening balances ($231 billion) predicts a 57 minute delay in the dealer-bank half-received payment time (Table 1, column 2). The R^2 for this relationship, after controlling for a quarter-end fixed effect, is 73%.

2. Dealer banks likely increase their Fed balances when anticipating incoming payment delays because they plan to continue to send payments without significant delay. This may place pressure on their intraday liquidity. This interaction effect is shown graphically in Figure 6, where the half-sent time ranges from -50 to 50 minutes, whereas the half-received time ranges from -100 to 150 minutes. This effect is captured more systematically in a series of regressions showing that the half-received time is more sensitive to changes in reserves and repo rates than is the half-sent time. (Compare columns 2-4 with columns 6-8 of Table 1). Further, we estimate that a one-minute delay in the half-received time predicts only a 0.18 minute delay in the half-sent time (Table 1, column 9). Finally, reflecting both the need to send payments earlier to the TGA on issuance days and also the dominant role played by dealer banks in Treasury markets, net Treasury issuance has a large, negative, and significant relationship with the half-sent time. This is not the case for the half-received time.

3. Each successive doubling of the difference between SOFR$-$IOR and its sample minimum predicts a delay in the half-received time of dealer banks of approximately 43 minutes, with an estimated standard error of 2 minutes (Table 1, column 3).[34]

4. Treasury repo rates rise further above efficient-market levels (IOR) when dealer banks receive their payments later in the day. A one-standard-deviation delay in the half-received time of dealer bank payments (58 minutes) predicts an elevation of SOFR$-$IOR

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

of 8.2 basis points, with a standard deviation of approximately 0.6 basis points, after controlling for quarter-end fixed effects (Table 2, column 3). The R^2 for this relationship is 36%.

5. Large spikes in repo rates are much more likely on days with large issuances of coupon Treasuries and on days with much longer than normal intraday delays in payments to the large repo-active dealer banks. For example, on September 17, 2019, SOFR−IOR spiked to 315 basis points and the half-received payment time for dealer banks was 151 minutes above its sample average, a record high to that point of our sample period. Half-sent payment times were only delayed by 6 minutes.[35] The estimated probit models shown in Table 3 and Appendix Table 5 indicate that a spike in repo rates is much more likely to occur on days that (a) have a significantly delayed half-received time of payment to the repo active dealer banks, (b) have large Treasury coupon security issuances, (c) have low dealer balances, (d) are quarter ends, and (e) have combinations of two or more of these effects.

6. Treasury issuance settlements result in cash transfers from banks' accounts at the Fed to the TGA account, and moreover these transfers must occur near the beginning of the day, as we have verified from multiple authoritative sources. Issuance settlements also add to demands for financing in the repo market (Fleming, Hrung and Keane, 2010), both of which elevate repo-rate distortions. For example, after controlling for other key factors (Table 2, column 7), a typical $50 billion issuance of coupon Treasuries predicts an increase of SOFR−IOR by 3.45 basis points (with a standard error of about 0.6 basis points). The analogous prediction for the interdealer market (GCF Repo−IOR) is 5 basis points (Appendix Table 7, column 7). This issuance effect was previously reflected in the results of Correa, Du and Liao (2020), whose Table A5 shows that the amount of repo "lending" (reverse repurchases) conducted by U.S. globally systemically important banks (GSIBs) has risen significantly with increases in

[35] Note that this outlier scatter dot is not displayed in Figure 6.

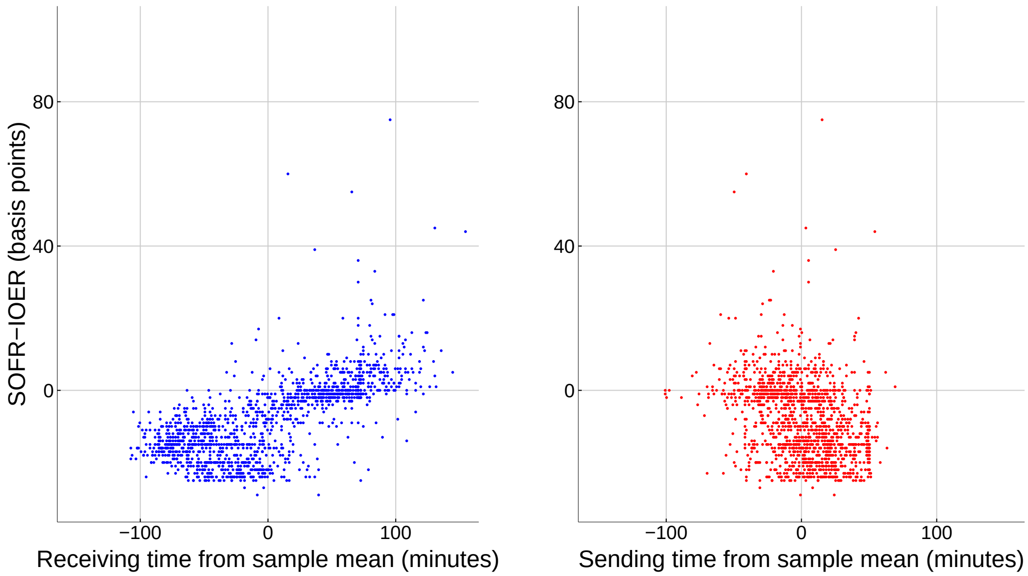

Figure 6: Repo rates and dealer-bank payment timing

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. Sources: Fedwire Funds Service and FRBNY.

net Treasury issuance. Our sample is not restricted to U.S. dealer banks, and we focus on the role of new Treasury issuances, not issuances net of maturing securities, given the distinct role of new issuances on the repo market.[36]

The results in Tables 2 and 5 are not estimates of causal sensitivities to reserve balances because of the endogneity of opening-of-day reserve balances to anticipated stresses during the day to intraday balances and funding market opportunities. The coefficients associated with dealer bank balances in our basic regression models in Table 2, although large economically and highly statistically significant, are likely to underestimate the causal dependence of SOFR−IOR on the supply of dealer bank opening balances.

In an attempt to account for this endogeneity, we take an instrumental-variables (IV) approach. We begin with a focus the dealer-bank balances and repo rates. In a first-stage

[36]Somewhat surprisingly, Correa, Du and Liao (2020) find that U.S. 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.

Table 1: Estimated coefficients of a linear model of dealer banks' median receive and send times

	median receive time				median send time				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
100 large banks	−120.***				18.5***				
	(3.43)				(2.22)				
dealer opening balances		95.5***	101.***	101.***		−27.8***	−15.4**	−14.6**	−32.8***
		(7.87)	(6.27)	(7.24)		(6.62)	(6.33)	(6.59)	(8.41)
other large bank balances		−248.***	−216.***	−221.***		45.9***	31.9***	35.5***	75.4***
		(4.00)	(3.70)	(9.55)		(3.90)	(3.92)	(5.13)	(7.42)
log (normalized SOFR-IOR)			28.7***				−9.00***		
			(1.71)				(1.42)		
SOFR - IOER SOFR_IOER				0.964**				−0.228	−0.402
				(0.380)				(0.148)	(0.245)
net Treasury issuance			−73.9*	−22.4			−248.***	−272.***	−268.***
			(41.5)	(58.9)			(36.0)	(39.0)	(42.2)
median time of receives									0.180***
									(0.0416)
Constant	221.***	220.***	95.4***	194.***	−33.9***	−33.7***	2.48	−30.4***	−65.3***
	(5.85)	(4.28)	(8.50)	(9.48)	(4.06)	(3.84)	(7.26)	(5.13)	(6.77)
Observations	1,464	1,464	1,450	1,450	1,464	1,464	1,450	1,450	1,450
R^2	0.515	0.728	0.809	0.789	0.0498	0.090	0.159	0.144	0.173
Adjusted R^2	0.515	0.728	0.808	0.789	0.0492	0.0888	0.157	0.141	0.17
Residual Std. Error	40.4	30.2	25.0	26.3	27.9	27.3	25.4	25.7	25.2

Note: Payments 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 October 30, 2020. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

regression shown in Appendix Table 12, we use intraday payment timing variables on day $t-1$ and corporate tax payments[37] on day t, along with the exogenous variables related to Treasury issuance, to predict dealer-bank opening balances on day t. In a second-stage regression shown in Table 4, we examine the linear relationship between SOFR−IOR and the dealer-bank opening balances predicted by the first-stage model.

The intraday payment timing measures used in the first-stage IV are the times on day $t-1$ when dealer-banks have received 25%, 50%, and 75% of the value of all payments sent to them by banks that are not dealer-banks (nor the bank that clears and settles the majority of trades involving Treasury securities).[38] With this approach, we aim to account for

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

[38]The half-received time statistics used previously (e.g., Table 1) considered all payments received by a

Table 2: Estimated coefficients of a linear model of repo rate spread (SOFR−IOR)

	Dependent variable: SOFR - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-32.2^{***}	-32.1^{***}		-13.3^{***}	-50.6^{***}	-33.9^{***}	-34.6^{***}
	(3.53)	(3.52)		(1.92)	(3.51)	(2.15)	(2.07)
median time of receives			0.141^{***}	0.128^{***}		0.0642^{***}	0.0644^{***}
			(0.0102)	(0.00888)		(0.0156)	(0.0153)
quarter-end fixed effect		13.6^{***}	13.3^{***}	13.3^{***}	13.9^{***}	13.9^{***}	9.72^{**}
		(4.12)	(4.09)	(3.90)	(3.96)	(3.95)	(4.00)
Tbills outstanding					9.04^{***}	5.50^{***}	5.19^{***}
					(0.352)	(0.645)	(0.667)
Treasuries redemption							-38.9^{***}
							(10.3)
Bill issuance							44.4^{***}
							(9.02)
Coupon issuance							69.0^{***}
							(11.0)
Observations	1,452	1,452	1,454	1,451	1,450	1,449	1,448
R^2	0.122	0.136	0.360	0.378	0.392	0.414	0.424
Adjusted R^2	0.121	0.135	0.360	0.377	0.391	0.412	0.421
Residual Std. Error	12.9	12.8	11.0	10.9	10.8	10.6	10.5

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. 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 October 30, 2020. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

endogenous changes to dealer-bank balances that are based on aggregate reserves and other factors unrelated to repo market shocks. The identifying assumption is that the timing of other banks' payments to the dealer-banks on date $t-1$ is unrelated to repo market activity on date t. This assumption is supported by the fact that these other banks play at best minor roles in the repo market. We also include the total value of corporate taxes received by the Treasury on date t as an instrument because this variable is independent of repo rates and shocks the total reserve balances of banks. (On its own, however, this tax variable turns out to be a weak instrument.)

dealer-bank, including payments sent among dealer banks. This measure considers the subset of payments received by a dealer bank which are sent by banks that are *not* dealer banks.

Table 3: Estimated probabilities of a repo rate spike

spike probability	median receive time	dealer opening balances	coupon issuance	quarter end
0.00962	−0.375	686.	10.2	0
0.0201	57.6	686.	10.2	0
0.019	−0.375	536.	10.2	0
0.0371	57.6	536.	10.2	0
0.112	57.6	536.	91.1	0
0.0383	−0.375	686.	91.1	0
0.112	57.6	536.	91.1	0
0.373	−0.375	686.	10.2	1
0.486	57.6	686.	10.2	1
0.477	−0.375	536.	10.2	1
0.597	−0.375	686.	91.1	1

Note: Spike probabilities are estimates from the probit model (column (7) of Table 5) at various levels of the explanatory variables. Explanatory variables which are not displayed are set at their sample mean. Continuous explanatory variables on display are set at the sample mean plus or minus one sample standard deviation. The units of the explanatory variables are minutes and billions of dollars.

Our IV regression results are shown in Table 4. The first column shows how SOFR−IOR is related to dealer bank balances and a host of exogenous variables related to Treasury issuance. The second column lists the estimated coefficients when replacing dealer balances with first-stage predicted balances. We find that instrumenting for dealer opening balances increases the magnitude of the negative coefficient on dealer opening reserve balances from 51.3 basis points per trillion dollars to 58.2 basis points. This is consistent with an endogenous response of opening balances to anticipated liquidity stress. Statistical significance remains high, and the coefficients on the Treasury issuance variables remain roughly the same.

A concern with our IV approach is the omission of the half-received payment time, a variable that we have shown is an important predictor of repo rates. In order to account for this payment timing variable, beyond its influence on dealer bank balances, we take a two-step approach. We first regress the half-received time on dealer bank balances and compute the residuals. We then include these residuals (denoted "residual median received time" in the IV regression), so as to account for variation in this incoming payment timing variable beyond its role in predicting dealer-bank balances. As shown in Table 4, column 3, the estimated coefficient on dealer bank balances changes from −58.2 basis points per trillion dollars of balances to −47.0 basis points.

Table 4: Estimated coefficients of an IV model of SOFR as a spread to IOR

	Dependent variable: SOFR - IOR		
	(1)	(2)	(3)
dealer opening balances	-51.3^{***}		
	(3.49)		
predicted dealer opening balances		-58.2^{***}	-47.3^{***}
		(5.25)	(3.06)
residual of median receive time on opening balances			0.0465^{***}
			(0.0173)
quarter-end fixed effect	9.89^{**}	9.53^{**}	9.58^{**}
	(4.02)	(4.34)	(4.32)
Tbills outstanding	8.72^{***}	9.07^{***}	6.19^{***}
	(0.307)	(0.403)	(0.854)
Treasuries redemption	-35.6^{***}	-47.5^{***}	-39.1^{***}
	(11.2)	(12.1)	(12.6)
Bill issuance	43.5^{***}	54.4^{***}	44.5^{***}
	(9.62)	(11.2)	(10.7)
Coupon issuance	65.1^{***}	77.7^{***}	72.5^{***}
	(12.2)	(12.6)	(12.9)
Constant	7.87^{***}	11.8^{***}	10.5^{***}
	(2.02)	(2.98)	(2.57)
Observations	1,449	1,394	1,393
R^2	0.402	0.336	0.343
Adjusted R^2	0.40	0.333	0.340
Residual Std. Error	10.7	11.2	11.1

Note: SOFR is the secured overnight financing rate and IOR is interest on reserves. SOFR-IOR is in basis points. Predicted dealer balances are those predicted from a first stage regression (see Table 12).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 October 30, 2020. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Evidence in favor of the validity of our instruments is that during the period of balance sheet normalization, the total reserve balances of large financial institutions other than the ten dealer banks was much less related to repo rates, as indicated in Appendix Table 10. Again, this is not to suggest that other bank balances are not causally important to the determination of repo rate distortions. As we have discussed, other large bank balances are highly predictive of delayed payments to the dealer banks, which are in turn highly predictive of repo rate distortions. In any case, the distribution of opening balances between the dealer banks and the other large banks seems to play an important role in repo rates, as one might expect from a lack of perfect-market competition and from imperfect mobility of reserve balances into the repo market.

6 The role of capital requirements

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

On quarter-end dates, we find that interdealer repo rates are substantially elevated, most likely because regulatory capital requirements on foreign bank holding companies cause them to reduce their provision of liquidity to interdealer markets, leaving the market to be intermediated mainly by U.S. dealer banks, which are subject to daily-average capital requirements rather than quarter-end requirements. Beyond the associated reduction in the supply of funding market liquidity on quarter ends, the quarter-end effect could be magnified by the associated reduction in the degree of competition facing U.S. dealer banks (Wallen, 2020; Eisenschmidt, Ma and Zhang, 2021). Correa, Du and Liao (2020) write that "on quarter-ends, we find that U.S. banks reduce their reserve balances by about \$60 billion, and increase their net reverse repo positions by \$40 billion and dollar lending in the FX swap market by $20 billion."

Our predicted quarter-end increase in the spread between GCF Repo and IOR is 26 basis points, after controlling for other key factors. When estimating the quarter-end effect of regulatory capital requirements, it is particularly important to control (Appendix Table 7, column 7) for Treasury issuances, which somewhat frequently occur at quarter ends (Appendix Table 11). Our estimated quarter-end fixed effect on GCF Repo−IOR is substantially larger than that estimated by Correa, Du and Liao (2020). The predicted quarter-end effect on tri-party repo rates, after controlling for Treasury issuances, is not statistically significant (Appendix Table 8, column 7).

This difference between tri-party repo and interdealer repo is likely due in part to U.S. Supplementary Leverage Ratio (SLR) constraints. When a large dealer bank invests cash in an interdealer repo, it is subject to the SLR, but when the dealer bank sources funds in the tri-party repo market, it is not subject to SLR because tri-party repo financing shows up on the dealer bank's balance sheet as a liability.[39] Given our quarter-end fixed-effect estimates, it is likely that the dealer banks demanded higher rates to invest cash in repos as compensation for the associated increase in SLR-related costs to their shareholders. This represents an inefficient wedge in funding markets that reduces gains from trade, because balance-sheet costs are simply debt-overhang frictions (Andersen, Duffie and Song, 2019).

There is also a non-trivial upward impact of capital requirements on intra-quarter repo-IOR spreads, mainly because the U.S. SLR rule applies to the large U.S. dealer banks on a daily-averaging basis.[40] 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.

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

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

Capital requirements based on "GSIB scores" also impinge on balance sheet space for repo market intermediation (Covas and Nelson, 2019).

7 Other factors relevant to repo rate spreads

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

Because of the option of non-bank investors, especially government money market funds, to substitute between Treasury bills and Treasury repos, an increase in the outstanding supply of Treasury Bills is strongly associated with an increase in SOFR−IOR (Table 2, Columns 5-7). Depending on the regression model, the estimated effect is 4 to 9 basis points per trillion dollars of outstanding Treasury bills. From minimum to maximum during our sample period,[41] the quantity of Treasury bills outstanding varied by \$3.6 trillion, suggesting a large estimated effect on SOFR−IOR.

We next consider how the concentration of Fed balances among the 10 dealer banks affects repo rates. Figure 7 shows how, as the Fed balances of the dealer banks fluctuated over our sample period, the concentration of balances across these 10 firms varied. Concentration is measured with the Herfindahl-Hirschman index.[42] As shown, when dealer-bank Fed balances are higher, the concentration of balances among dealer banks tends to rise. Perhaps sharing

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

[42] 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 $2 \times 50^2 = 5000$.

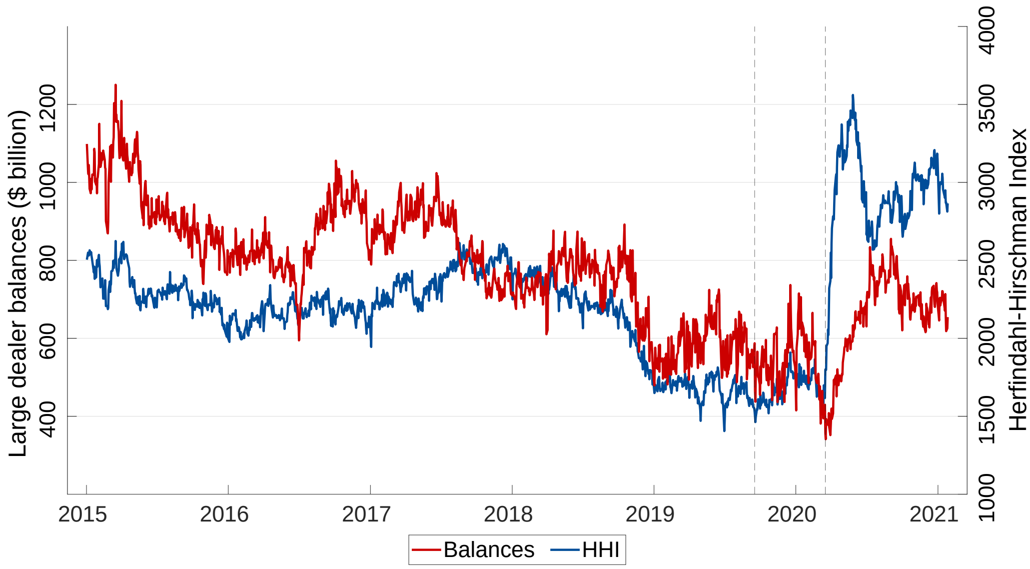

Figure 7: Concentration of dealer bank balances over time
Note: In blue is the total reserve balances of the dealer banks (left axis). In red is the Herfindahl-Hirschman index (HHI) of the concentration of dealer bank balances (right axis). The vertical black dashed lines corresponds to the dates of the repo rate spikes on September 17, 2019 and March 17, 2020.
Source: Fedwire Funds Service.

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

8 Concluding policy-related remarks

We show that only with a substantial amount of reserves do the large dealer banks avoid intraday liquidity stress and provide liquidity efficiently to wholesale funding markets. We also show that when aggregate reserve balances get sufficiently low, the share of reserves held by the large dealer BHCs is important to liquidity in funding markets. We document that as balance sheet normalization proceeded and the total quantity of reserves declined, there were adverse impacts on Treasury repo markets. This raises potential alternative policy approaches for the Fed, including the following.

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

2. Establish a standing repo facility, which would offer financing to a designated set of repo market participants at a rate slightly above IOR.[43] The facility rate could be set high enough that the Fed's balance sheet expands only as needed to address temporary liquidity crunches.

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

[43]See Andolfatto and Ihrig (2019); Pozsar (2019b); Gagnon and Sack (2020) for arguments in favor of the creation of such a facilty.

banks to use their liquidity buffers, and temporarily suspended restrictions and fees on the use of daylight overdrafts.

4. Offer greater incentives for banks to utilize the Discount Window for backstop funding. Alternatively, as mooted by Quarles (2020), the Fed could relax the amount of high quality liquid assets that banks must keep on their balance sheets under liquidity regulations by counting Discount Window access as a substitute for HQLA. Taking a related approach,[44] the Reserve Bank of Australia offers a Committed Liquidity Facility (CLF). Australian banks can access the CLF by paying a fee for a committed line of credit that counts toward their regulatory liquidity requirements.

Because of the huge pace of asset purchases by the Fed in response to the Covid pandemic, which continue,[45] the total amount of reserve balances is at an all-time high and continues to grow rapidly. Nevertheless, the Fed's past expressed preferences for balance sheet "normalization" may at some point in the future again raise tensions over an appropriate minimum aggregate level of reserves.

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

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

Appendix

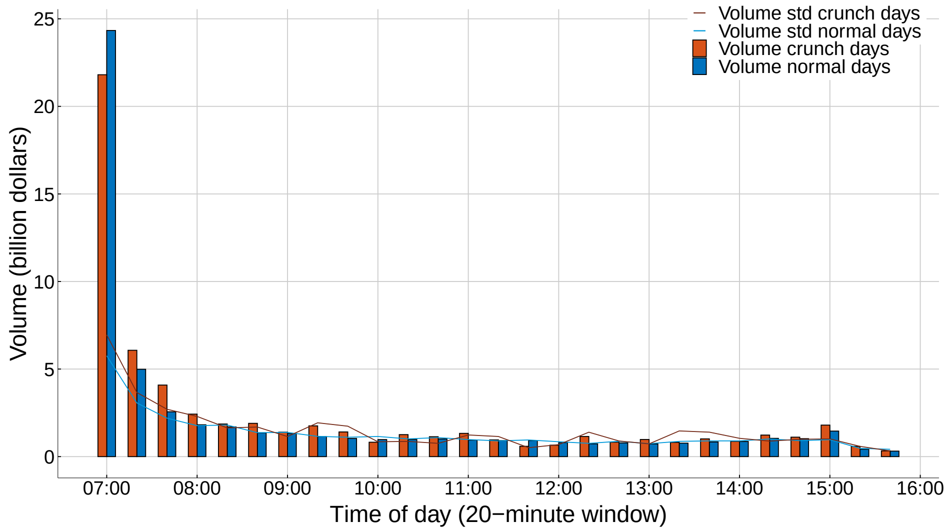

Figure 8: Average and standard deviation, across normal days and across crunch days, of total trading volume in each 20-minute time window. Source: Tradition.

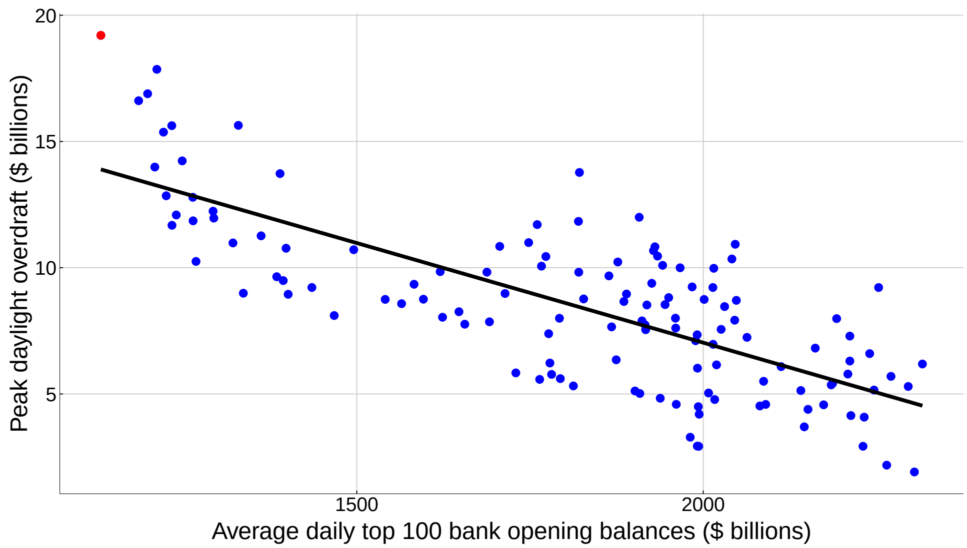

Figure 9: Peak intraday overdrafts and reserve balances

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 0.57. The slope coefficient, -0.0079, is estimated with a standard error of 0.00061. The red dot corresponds to the observation for the 2-week maintenance period ending September 25, 2019. Sources: Federal Reserve and Fedwire Funds Service.

Table 5: Estimated coefficients of a probit model of repo rate spikes

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
median time of receives	0.00569***		0.00342**		0.00628***	0.00372**	0.00499**
	(0.00126)		(0.00154)		(0.00144)	(0.00173)	(0.00199)
dealer opening balances		−2.52***	−1.47**			−1.62**	−1.78**
		(0.545)	(0.636)			(0.673)	(0.772)
Coupon issuance				10.1***	10.2***	10.6***	7.05***
				(1.37)	(1.41)	(1.44)	(1.71)
quarter-end fixed effect							2.02***
							(0.323)
Constant	−1.98***	−0.289	−1.0**	−2.13***	−2.25***	−1.18***	−1.19**
	(0.0782)	(0.336)	(0.419)	(0.0847)	(0.101)	(0.441)	(0.506)
Observations	1,418	1,417	1,416	1,415	1,414	1,412	1,412
Log Likelihood	-178.	-177.	-174.	-164.	-153.	-150.	-129.
Akaike Inf. Crit.	359.	358.	355.	332.	312.	307.	267.

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 11, 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 October 30, 2020. *p<0.1; **p<0.05; ***p<0.01.

Table 6: Summary statistics

Variable	N	Mean	St. Dev.	Min	$Q(0.25)$	$Q(0.75)$	Max
dealer opening balances ($ billions)	1,465	686.	150.	362.	619.	759.	1,224.
other large bank balances ($ billions)	1,465	1,153.	231.	652.	960.	1,335.	1,632.
Tbills outstanding ($ billions)	1,522	2,137.	841.	1,233.	1,557.	2,312.	4,802.
Bill issuance ($ billions)	1,463	33.	56.8	−0.017	0	75.	273.
Coupon issuance ($ billions)	1,463	10.2	31.8	−0.011	0	0	218.
TBills position ($ billions)	1,507	24.	20.5	−2.10	13.5	26.1	106.
Treasuries redemption ($ billions)	1,463	37.9	56.8	0	0	84.7	259.
net Treasuries inventory ($ billions)	1,507	138.	77.3	9.26	82.4	224.	295.
median time of receives (minutes)	1,467	−0.375	58.	−172.	−49.4	49.6	155.
median time of receives from non-dealer banks	1,467	−0.129	53.	−115.	−40.1	34.9	161.
median time of sends (minutes)	1,467	0.14	28.6	−155.	−18.7	20.3	69.3
SOFR - IOR (basis points)	1,455	−7.84	13.8	−29	−16	−1	315
GCF Repo - IOR (basis points)	1,421	−0.724	17.4	−30.2	−9	5.3	391.
TGCR - IOR (basis points)	1,455	−11.1	13.8	−26	−20	−3	315
Treasuries issuance ($ billions)	1,463	43.2	64.3	−0.017	0	87.	365.
quarter-end fixed effect	1,524	0.0164	0.127	0	0	0	1
corporate tax paid to US treasury ($ billions)	1,467	0.00117	0.00516	−6e-05	5e-05	0.00028	0.0595
Note issuance ($ billions)	1,463	9.27	29.5	−0.011	0	0	199.
log (normalized SOFR-IOR)	1,455	2.95	0.563	0	2.64	3.37	5.84

Table 7: Basic regression models for interdealer Treasury repo (GCF Repo) as a spread to IOR. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: GCF - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-38.6^{***}	-38.4^{***}		-18.3^{***}	-50.5^{***}	-31.7^{***}	-30.2^{***}
	(4.60)	(4.51)		(2.87)	(4.66)	(4.76)	(4.40)
median time of receives			0.137^{***}	0.117^{***}		0.0731^{***}	0.0728^{***}
			(0.0132)	(0.0116)		(0.0216)	(0.0246)
quarter-end fixed effect		31.0^{**}	30.8^{**}	30.7^{**}	32.5^{**}	32.4^{**}	26.1^{**}
		(12.5)	(12.8)	(12.6)	(12.9)	(13.0)	(12.8)
Tbills outstanding					8.26^{***}	4.06^{***}	2.69^{***}
					(0.514)	(1.10)	(0.926)
net Treasuries inventory							8.53
							(17.0)
Treasuries redemption							-46.3^{**}
							(18.2)
Bill issuance							54.6^{***}
							(18.8)
Coupon issuance							$100.^{***}$
							(18.1)
Observations	1,419	1,419	1,420	1,418	1,417	1,416	1,413
R^2	0.105	0.151	0.251	0.270	0.266	0.283	0.298
Adjusted R^2	0.104	0.150	0.250	0.268	0.264	0.281	0.294
Residual Std. Error	16.5	16.0	15.1	14.9	14.9	14.8	14.6

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

Table 8: Basic regression models for triparty (TGCR) Treasury repo spreads over IOR. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: TGCR - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-31.5^{***}	-31.5^{***}		-10.6^{***}	-52.0^{***}	-33.1^{***}	-34.2^{***}
	(3.66)	(3.66)		(1.96)	(3.56)	(2.10)	(1.99)
median time of receives			0.153^{***}	0.143^{***}		0.0726^{***}	0.0728^{***}
			(0.0102)	(0.00886)		(0.0156)	(0.0151)
quarter-end fixed effect		9.26^{**}	8.88^{**}	8.88^{**}	9.39^{***}	9.39^{***}	5.87
		(4.10)	(3.88)	(3.73)	(3.57)	(3.63)	(3.67)
Tbills outstanding					10.0^{***}	6.01^{***}	5.71^{***}
					(0.359)	(0.636)	(0.655)
Treasuries redemption							-57.0^{***}
							(9.45)
Bill issuance							59.8^{***}
							(8.27)
Coupon issuance							72.5^{***}
							(10.2)
Observations	1,452	1,452	1,454	1,451	1,450	1,449	1,448
R^2	0.116	0.123	0.408	0.419	0.433	0.460	0.469
Adjusted R^2	0.115	0.121	0.407	0.418	0.432	0.459	0.467
Residual Std. Error	13.0	13.0	10.6	10.6	10.4	10.2	10.1

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

Table 9: Regression models for interdealer (GCF) Treasury repo spread over triparty (TGCR) Treasury repo. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: GCF - TGCR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	−2.80	−2.65		−6.81***	0.892	1.91	2.20
	(1.83)	(1.72)		(1.67)	(1.91)	(3.62)	(3.45)
median time of receives			−0.0166***	−0.0241***		0.00396	0.00426
			(0.00382)	(0.00366)		(0.00962)	(0.00951)
quarter-end fixed effect		21.7**	21.8**	21.8**	22.5**	22.5**	19.5*
		(10.0)	(10.1)	(10.0)	(10.5)	(10.5)	(10.2)
Tbills outstanding					−2.36***	−2.58***	−2.80***
					(0.236)	(0.673)	(0.695)
Treasuries redemption							5.36
							(12.3)
Bill issuance							0.390
							(11.8)
Coupon issuance							30.9**
							(13.7)
Observations	1,418	1,418	1,419	1,417	1,416	1,415	1,415
R^2	0.0023	0.0972	0.107	0.118	0.138	0.138	0.154
Adjusted R^2	0.0016	0.0959	0.106	0.116	0.136	0.135	0.149
Residual Std. Error	8.51	8.10	8.05	8.01	7.92	7.93	7.86

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

Table 10: Estimated regressions of SOFR−IOR, restricted to the sample period ending September 19, 2019, including as a regressor the total of the opening reserve balances of those accounts other than those of the ten large repo-active banks. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: SOFR - IOR				
	(1)	(2)	(3)	(4)	(5)
dealer opening balances	-48.1^{***}	-51.1^{***}	-50.4^{***}	-61.1^{***}	-50.7^{***}
	(4.02)	(3.37)	(3.26)	(4.9)	(3.36)
other large bank balances	11.2^{***}	33.9^{***}	33.3^{***}	13.9^{**}	33.2^{***}
	(3.65)	(3.78)	(3.88)	(6.94)	(3.86)
median time of receives	0.127^{***}	0.118^{***}	0.118^{***}		0.116^{***}
	(0.0227)	(0.0245)	(0.0241)		(0.0245)
median time of sends				0.0439^{***}	0.00299
				(0.0115)	(0.00875)
Tbills outstanding		16.5^{***}	16.0^{***}	19.6^{***}	16.1^{***}
		(4.06)	(4.21)	(3.70)	(4.25)
Bill issuance			27.7^{*}	19.1	27.9^{*}
			(14.8)	(14.5)	(14.8)
Coupon issuance			64.1^{***}	62.5^{***}	64.7^{***}
			(14.1)	(15.0)	(14.5)
Treasuries redemption			−21.6	−10.4	−21.8
			(14.0)	(14.6)	(14.0)
quarter-end fixed effect	14.7^{***}	17.3^{***}	13.7^{***}	13.0^{***}	13.7^{***}
	(4.02)	(4.04)	(3.90)	(3.94)	(3.90)
Observations	1,179	1,177	1,177	1,177	1,177
R^2	0.386	0.411	0.419	0.393	0.419
Adjusted R^2	0.383	0.408	0.415	0.388	0.415
Residual Std. Error	11.3	11.1	11.0	11.3	11.0

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

Table 11: Days on which repo rates spiked. The table shows spreads, in basis points (bps) over IOR, of the Secured Overnight Financing Rate (SOFR), of the General Collateral Finance (GCF) repo rate, and the Tri-Party General Collateral Rate (TGCR), for all days in our sample on which at least one of these repo rate spreads was above its previous 14 days rolling average by at least 15 basis points. The table also includes days for which SOFR or TGCR spread is above 20 basis points and for which GCF spread is above 30 basis points. Also shown are three key covariates: issuance and redemption of Treasuries and total opening reserve balances of the sample of ten large repo-active dealer banks.
Source: Fedwire Funds Service, FRBNY, and Tradition.

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

Table 12: First Stage of IV regression: Prediction of dealer opening balances.

	Dependent variable: dealer opening balances
lag(Q1 time of receives from non-dealer banks)	-0.00126^{***}
	(0.00019)
lag(median time of receives from non-dealer banks)	-0.00193^{***}
	(0.00012)
lag(Q3 time of receives from non-dealer banks)	0.0005^{***}
	(0.00012)
corporate tax to US treasury	0.343
	(0.472)
Tbills outstanding	0.095^{***}
	(0.00363)
Treasuries redemption	-0.633^{***}
	(0.159)
Bill issuance	0.644^{***}
	(0.148)
Coupon issuance	0.291^{*}
	(0.150)
quarter-end fixed effect	0.0238
	(0.0209)
Constant	0.482^{***}
	(0.00799)
Observations	1,403
R^2	0.642
Adjusted R^2	0.640
Residual Std. Error	0.0898

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

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

	Dependent variable: GCF - IOR		
	(1)	(2)	(3)
dealer opening balances	-51.4^{***}		
	(4.60)		
predicted dealer opening balances		-61.5^{***}	-50.6^{***}
		(6.75)	(6.06)
residual of median receive time on opening balances			0.047^{*}
			(0.0258)
quarter-end fixed effect	26.4^{**}	26.3^{**}	26.2^{**}
	(12.5)	(12.7)	(12.8)
Tbills outstanding	7.66^{***}	8.18^{***}	5.21^{***}
	(0.472)	(0.552)	(1.56)
Treasuries redemption	-45.0^{***}	-61.4^{***}	-53.4^{***}
	(17.2)	(18.2)	(18.1)
Bill issuance	55.6^{***}	71.1^{***}	61.8^{***}
	(15.7)	(17.7)	(16.2)
Coupon issuance	97.9^{***}	$112.^{***}$	$107.^{***}$
	(19.8)	(20.4)	(20.7)
Constant	16.9^{***}	22.6^{***}	21.5^{***}
	(2.62)	(3.82)	(3.45)
Observations	1,417	1,364	1,363
R^2	0.28	0.248	0.253
Adjusted R^2	0.277	0.245	0.249
Residual Std. Error	14.8	15.2	15.1

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

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

	Dependent variable: TGCR - IOR		
	(1)	(2)	(3)
dealer opening balances	-53.1^{***}		
	(3.53)		
predicted dealer opening balances		-62.4^{***}	-50.7^{***}
		(5.28)	(2.96)
residual of median receive time on opening balances			0.0498^{***}
			(0.017)
quarter-end fixed effect	6.06^{*}	5.65	5.70
	(3.63)	(4.01)	(4.05)
Tbills outstanding	9.71^{***}	10.2^{***}	7.13^{***}
	(0.313)	(0.401)	(0.822)
Treasuries redemption	-53.3^{***}	-69.7^{***}	-60.6^{***}
	(10.6)	(11.4)	(11.8)
Bill issuance	58.8^{***}	73.7^{***}	63.1^{***}
	(9.15)	(10.7)	(9.93)
Coupon issuance	68.0^{***}	83.8^{***}	78.2^{***}
	(11.8)	(11.9)	(12.2)
Constant	3.94^{*}	9.21^{***}	7.82^{***}
	(2.05)	(3.0)	(2.58)
Observations	1,449	1,394	1,393
R^2	0.442	0.386	0.394
Adjusted R^2	0.440	0.383	0.391
Residual Std. Error	10.4	10.8	10.8

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

Table 15: Summary statistics for selected other variables. The Broad General Collateral Rate (BGCR) is a volume-weighted median of overnight Treasury general collateral tri-party repo data published by the New York Fed.

Variable	N	Mean	St. Dev.	Min	$Q(0.25)$	$Q(0.75)$	Max
SOFR (basis points)	1,455	99.3	85.3	1	17	175	525
TGCR (basis points)	1,455	96.0	85.8	1	11	170	525
GCF (basis points)	1,421	109.	85.9	0.2	27.7	183	601.
IOER (basis points)	1,464	107.	78.8	10	25	175	240
BGCR (basis points)	1,455	96.1	85.7	1	11	170	525
BGCR−IOER (basis points)	1,455	−11	13.8	−27	−20	−3	315
Bond issuance ($ billions)	1,463	0.959	4.09	−0.005	0	0	41.5
Bill redemptions ($ billions)	1,463	30.6	51.9	0	0	75.0	207.
Bond redemptions ($ billions)	1,463	0.116	1.25	0	0	0	18.9
Note redemptions ($ billions)	1,463	7.20	24.7	0	0	0	155.
Coupon redemptions ($ billions)	1,463	7.32	25.1	0	0	0	155.
Bonds position ($ billions)	1,507	97.9	61.7	−7.38	54.8	158.	227.
Notes position ($ billions)	1,507	6.30	3.55	−0.729	3.75	8.09	20.3
TIPs position ($ billions)	1,507	9.35	3.74	−0.699	6.71	12.4	17.8
AGYMBS position ($ billions)	1,507	85.0	18.5	49.0	70.7	99.0	134.
net total inventory ($ billions)	1,507	223.	85.6	104.	158.	312.	428.
quarter end -1	1,523	0.0164	0.127	0	0	0	1
quarter end +1	1,524	0.0171	0.130	0	0	0	1
Q1 time of receives from non-dealer banks (minutes)	1,467	0.0221	21.8	−123.0	−14.6	14.4	59.4
Q3 time of receives from non-dealer banks (minutes)	1,467	−0.260	45.2	−166.	−27.6	33.4	116.
median time of receives and sends (minutes)	1,453	−3.36	30.2	−153.	−22.9	16.1	115.
Q1 time of receives and sends (minutes)	1,453	−2.89	17.2	−72.5	−13.5	7.48	102.
Q3 time of receives and sends (minutes)	1,453	0.576	13.5	−143.	−6.07	7.93	174.
median time of sends (minutes)	1,467	0.14	28.6	−155.	−18.7	20.3	69.3
Q1 time of sends (minutes)	1,467	0.257	26.1	−94.0	−21.0	20.0	86.0
Q3 time of sends (minutes)	1,467	−0.0211	12.0	−120.	−5.13	5.87	158.
Q1 time of receives (minutes)	1,467	−0.029	21.4	−111.	−17.1	13.9	79.9
Q3 time of receives (minutes)	1,467	−0.148	22.2	−225.	−14.6	16.4	177.
dealer opening balance - balance drop ($ billions)	1,464	0.552	0.152	0.174	0.479	0.638	1.04

Table 16: Basic regression models for market-wide (SOFR) Treasury repo spreads over IOR for the subsample without spike days. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: SOFR - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-24.7^{***}	-24.7^{***}		-9.03^{***}	-43.1^{***}	-33.0^{***}	-33.9^{***}
	(1.99)	(1.99)		(1.11)	(0.984)	(1.59)	(1.58)
median time of receives			0.123^{***}	0.114^{***}		0.0396^{***}	0.0406^{***}
			(0.00268)	(0.00276)		(0.00481)	(0.00484)
quarter-end fixed effect		5.09	2.14	2.49	1.30	1.51	-3.52
		(3.66)	(2.97)	(2.83)	(3.14)	(3.02)	(3.51)
Tbills outstanding					8.52^{***}	6.33^{***}	6.10^{***}
					(0.170)	(0.306)	(0.302)
Treasuries redemption							-47.0^{***}
							(8.46)
Bill issuance							46.6^{***}
							(7.40)
Coupon issuance							70.7^{***}
							(8.86)
Observations	1,410	1,410	1,412	1,409	1,408	1,407	1,406
R^2	0.147	0.149	0.528	0.544	0.622	0.639	0.655
Adjusted R^2	0.146	0.147	0.527	0.543	0.621	0.638	0.654
Residual Std. Error	8.84	8.83	6.58	6.47	5.89	5.76	5.63

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

Table 17: Basic regression models for interdealer (GCF) Treasury repo spreads over IOR for the subsample without spike days. The units of the explanatory variables are trillions of dollars and minutes.

	Dependent variable: GCF - IOR						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
dealer opening balances	-27.8^{***}	-27.8^{***}		-11.7^{***}	-39.6^{***}	-28.1^{***}	-29.3^{***}
	(1.94)	(1.94)		(1.22)	(1.06)	(1.87)	(1.87)
median time of receives			0.111^{***}	0.0983^{***}		0.0451^{***}	0.0466^{***}
			(0.00303)	(0.00323)		(0.00588)	(0.00586)
quarter-end fixed effect		4.71	2.37	2.61	2.31	2.25	−3.40
		(4.96)	(5.14)	(4.84)	(5.28)	(5.38)	(5.84)
Tbills outstanding					7.47^{***}	4.88^{***}	4.38^{***}
					(0.233)	(0.396)	(0.390)
Treasuries redemption							-52.8^{***}
							(10.0)
Bill issuance							57.1^{***}
							(8.79)
Coupon issuance							86.1^{***}
							(10.5)
Observations	1,377	1,377	1,378	1,376	1,375	1,374	1,374
R^2	0.171	0.172	0.415	0.440	0.467	0.488	0.514
Adjusted R^2	0.170	0.171	0.414	0.439	0.466	0.487	0.511
Residual Std. Error	8.88	8.87	7.46	7.31	7.12	6.99	6.82

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

9 Tradition repo transactions data

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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