Intraday Liquidity and Money Market Dislocations*

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Abstract

This paper proposes a new model of monetary policy implementation to account for two key developments: (i) the introduction of intraday liquidity requirements and (ii) the decreasing relevance of the federal funds market in favor of repurchase agreement (repo) markets with nonbank participants. Our paper demonstrates how liquidity requirements prevent banks from arbitraging between the fed funds and repo markets and generate large repo spikes. We propose a simple calibration for excess intraday reserves. Consistent with our theory, this metric turned negative in the summer of 2019, at the time US repo markets experienced a spike of 400 basis points.

Keywords: Repo, Money Markets, Reserves, Monetary Policy Implementation

JEL Classifications: E43, E44, E52, G12

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Over the last decade, the monetary policy frameworks of developed economies have transformed substantially, with a large increase in reserves following several rounds of quantitative easing, new banking regulations, and the decreasing relevance of unsecured interbank markets (such as the federal funds market) in favor of secured repurchase agreement markets (repo) featuring nonbank participants.[1] However, frequent disruptions in those repo markets—exemplified by the mid-September 2019 overnight surge in US dollar repo rates to 7%—are a source of concern about the sustainability of this new regime.

No study to date has proposed a consistent framework that accounts for these key innovations in monetary policy implementation and can be used to investigate the source of the observed disruptions. This article aims to fill this gap. We update the seminal model of monetary policy implementation by Poole (1968)[2] with two key new elements: a nonbank sector that does not have access to a central bank discount window and an intraday liquidity constraint on banks as mandated by Basel III and implemented by Regulation YY in the US. The main contributions of this paper are (i) to show that the interaction between these two new elements can explain the recent volatility in US repo markets and requires the Federal Reserve (Fed) to maintain a balance sheet larger than previously thought, and (ii) to propose a new quantitative measure for excess *intraday* reserves, the relevant metric in this new regime.

Our model features two agents—banks and shadow banks—that trade in two money markets: a pure interbank market called *fed funds* and a bank-to-shadow-bank market called *repo*. Only banks can hold reserves at the Fed and have access to the discount window, to which they resort when their end-of-day reserves balance is short of the overnight requirement. Moreover, banks are connected through a real-time gross settlement (RTGS) system, which clears banks' reserves accounts in real time. This RTGS system allows reserves to be instantaneously redistributed across banks following exogenous shocks driven by payment system activities. During the day, banks have the option to trade in both the fed funds and repo markets. Shadow banks use the repo market to roll over a portfolio of illiquid securities. This feature captures the increasing involvement of shadow banking institutions, such as hedge funds, in arbitrage trades of asset mispricing financed with high leverage in repos.[3] Our main departure from Poole (1968) is to consider explicitly

[1] As documented by Afonso, Entz and LeSueur (2013), the fed funds market has significantly reduced in size since 2007, from around \$200 bn to \$50 bn, while the remaining volumes are mostly driven by institutions not receiving interest on reserves.

[2] We note that Poole (1968) is referred to by most monetary economics textbooks as the seminal article on monetary policy implementation (see Bindseil, 2014; Walsh, 2017).

[3] Before 2008, securities dealers were not balance sheet constrained and, hence, largely active in

how requiring banks to hold a minimum level of reserves *at each point during the day*, as mandated by regulation YY, affects the stability of repo markets and the liquidity provision to shadow banks.

We first show that, in an economy in which intraday liquidity is freely available through Fed overdrafts, banks always act as intermediaries between the repo and fed funds markets and prevent the repo rates from rising above the discount window rate. Although this result is standard in the setting of Poole (1968), our framework highlights its implicit reliance on the flexible intraday liquidity provision by the Fed, which is key to resolving the temporal mismatch of banks' disbursing reserves within the day when lending while only accessing the discount window at the end of the day. Consequently, intraday reserve flows are completely inconsequential as long as intraday overdrafts are accessible to banks. This result holds even in an economy with active shadow banks and featuring low reserve balances.

We then explore the consequences of introducing a regulatory intraday liquidity limit on traditional banks in an economy featuring shadow banks. Once banks have reached that limit, they are unable to further lend in fed funds or repo markets. Consequently, the provision of repo supply is rationed, and its rate jumps up to the marginal cost of fire-sale portfolio liquidations for shadow banks, which cannot access the discount window. This mechanism formalizes the insight from Pozsar (2019) that an intraday liquidity constraint turns an elastic *credit system* into a fixed-supply *token system* and explains the sharp upward spike in repo rates of September 2019.

We conclude by proposing a simple formula to estimate the level of reserves in excess of intraday liquidity needs as the total quantity of excess reserves minus the portion of these reserves already mobilized in repo lending activities and in clearing flows occurring from ordinary payment system activities. Given that the latter item is unobserved, we use a linear extrapolation of the pre-2008 peak Fed overdrafts from Fedwire flows. We show that, unlike the overnight excess reserves, our intraday-adjusted metric turns negative around the summer of 2019. With regulatory intraday, our model suggests that this shortage of intraday liquidity could be responsible for the concomitant sharp increase in repo rates.[4]

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multiple arbitrage trades, which enforced the law-of-one-price across markets. Since the financial crisis and subsequent regulations, large deviations from the law-of-one-price have emerged on multiple markets (Siriwardane, Sunderam and Wallen, 2022), and relative-value hedge funds have become increasingly active in those arbitrage trades. For instance, as documented by Barth and Kahn (2023), several hedge funds trade on mispricing between Treasuries and Treasuries' futures contracts while being financed in repos. Those hedge funds eventually suffered large losses in both September 2019 and March 2020.

[4] This intraday liquidity-centric explanation also anecdotally corresponds to declarations of market

Related Literature This paper contributes to the literature on monetary policy implementation. Adapting Poole (1968) to a modern over-the-counter setting, Afonso and Lagos (2015) captures many elements of pre-2008 fed funds dynamics, including intraday liquidity movements. Many articles have studied how limits to arbitrage can push interbank and money market rates below the interest on reserves: Bech and Klee (2011) finds such a result in the fed funds market; Andersen, Duffie and Song (2019) and Duffie and Krishnamurthy (2016) show that leverage ratio regulation generates increased dispersion in various rates; and d'Avernas and Vandeweyer (forthcoming) shows that those regulations result in a segmentation of money markets in which the T-bill supply is the main determinant of rates. This paper contributes to this literature by modeling the driver of sporadic disruptions in repo rates *above* the discount window rate and by relating those spikes to the quantity of intraday liquidity available to banks.

In contemporaneous work, Copeland, Duffie and Yang (2022) come to a similar conclusion that the supply of reserves is scarcer than previously believed due to a shortage of intraday liquidity by analyzing the timing of intraday Fedwire flows. Afonso et al. (2022) estimate the slope of the reserves demand in the fed funds market; and Lopez-Salido and Vissing-Jorgensen (2023) stress the importance of bank deposits for its level. Building on earlier literature on intraday payment dynamics (Bech and Garratt, 2003; McAndrews and Rajan, 2000), Yang (2020) proposes a microeconomic model in which repo spikes appear as a consequence of strategic complementarity in intraday payment timing among banks. Afonso et al. (2020); Correa, Du and Liao (2021); and Avalos, Ehlers and Eren (2019) explore potential explanations for the September 2019 repo rate spike and point to the role of large global dealer-banks with balance sheet constraints. Kahn et al. (2023) finds that a confluence of factors caused the 2019 spike, exacerbated by a lack of price transparency along repo market segments.

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participants such as that of JPMorgan Chase CEO Jamie Dimon during a call report on Oct. 13, 2020: *"[W]e 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? That will be up to regulators to decide, but right now, we have to meet those rules, and we don't want to violate what we told them we are going to do."*

I Environment

Our model's economic setup consists of two types of financial institutions: traditional and shadow banks. Traditional banks hold reserve accounts with the central bank, the Fed, and are granted access to the Fed's overnight discount window lending. They are also subject to specific liquidity regulations. All interbank transactions among them are settled instantaneously in reserves. In contrast, shadow banks operate without access to Fed reserves or the discount window, and their activities consist of financing a securities portfolio by borrowing from traditional banks via repos.

Timing Figure 1 summarizes the timing of the model. Traditional banks are exposed to two deposit shocks: one in the morning and one at the close of business. The two shocks feature both an aggregate and an idiosyncratic part. After the first shock, the fed funds, repo, and securities markets are open for trading. Following the second shock, banks borrow at the discount window and receive interest payments on their reserves balance. The subscript - denotes variables set before the morning shock, and the subscript + denotes variables set after the close of business. The variable m accounts for traditional banks' reserves; d is their deposits; and p and f are the repo and fed funds they lend during the trading period, respectively. Let the unit mass of traditional banks be denoted by $j \in [0, 1]$ and the unit mass of shadow banks be denoted by $s \in [0, 1]$. For ease of notation, we write x instead of $x(j)$ or $x(s)$ when the indexation is not necessary.

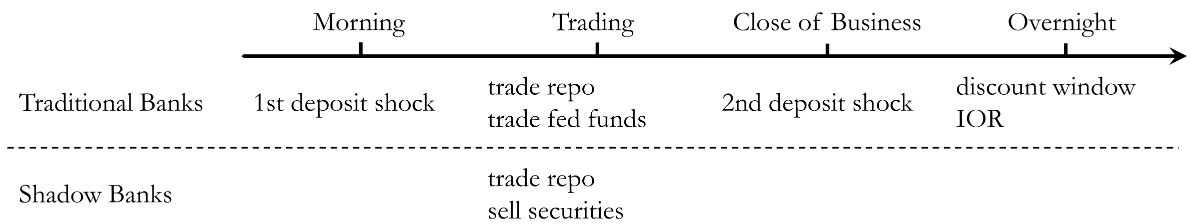

Figure 1: Model Timeline

Morning Shock At the beginning of the day, traditional banks are subject to a deposit aggregate shock $d_{-}\varepsilon^a_{-}$ and a deposit idiosyncratic shock $d_{-}\varepsilon^i_{-}$ that shift deposits and corresponding reserves to other banks. These shocks are meant to capture the various intraday movements of reserves driven by firm and household payments. Although reserves do not leave the traditional banking sector, the aggregate shock represents reserves encumbered by payment delays (the velocity of reserves is finite) or transferred to banks not active in the repo and fed funds lending markets. Thus, the quantity of reserves after the morning shock is given by $m_- + d_-(\varepsilon^a_- + \varepsilon^i_-)$. To derive our results analytically, we only need to define bounds on these shocks: $\varepsilon^a_- \in [-\sigma^a, \sigma^a]$ and $\varepsilon^i_- \in [-\sigma^i, \sigma^i]$. Furthermore, ε^i_- is such that $\int_0^1 d_-(j)\varepsilon^i_-(j)dj = 0$.

Close of Business Shocks After the closing of the trading period, traditional banks are subject to a second deposit shock that results in reserve transfers. This shock also features two parts: the aggregate part, $d_-\varepsilon^a_+ = -d_-\varepsilon^a_-$, which fully reverses the morning outflow, and the idiosyncratic part, $d_-\varepsilon^i_+$, which further reshuffles reserves across banks. Traditional banks that end the day with fewer reserves than stipulated by reserve requirements (RR) have to borrow the difference at the discount window facility on which they pay the discount window rate $r^m + r^w$. This feature generates a motive for traditional banks to hold reserves as a buffer against deposit shocks. Gross intraday deposit flows Δd are defined as

$$\Delta d = d_-(\varepsilon^a_- + \varepsilon^i_-) + d_-(\varepsilon^a_+ + \varepsilon^i_+) = d_-(\varepsilon^i_- + \varepsilon^i_+). \tag{1}$$

We denote by $\mathcal{F}(\varepsilon; j)$ the conditional distribution of the idiosyncratic shock $\varepsilon^i_+(j)$ for traditional bank j, also constrained on $[-\sigma^i, \sigma^i]$, such that $\int_0^1 d_-(j)\varepsilon^i_+(j)dj = 0$. For ease of notation, we define $\varepsilon_- \equiv \varepsilon^a_- + \varepsilon^i_-$ and $\varepsilon_+ \equiv \varepsilon^a_+ + \varepsilon^i_+$.

Intraday Flows In the trading period, traditional banks have the option to lend (reverse) repo to shadow banks and fed funds to other traditional banks. Lending triggers an instantaneous outflow of reserves. Hence, for traditional banks, lending in money markets amounts to swapping a quantity $p + f$ of reserves into repos and fed funds.

The intraday law of motion for deposits d_+ and reserves m_+ is given by

$$d_+ = d_- + \Delta d \quad \text{and} \quad m_+ = m_- + \Delta d - p - f. \tag{2}$$

Thus, lending in repo or fed funds encumbers reserves until the next day. Finally, daylight overdrafts at the Fed are created by banks carrying a negative balance on their reserves account during the day, with volume given by $o = \max\{0, p + f - m_- - d_-\varepsilon_-\}$. For simplicity, we assume that the interest rate on these intraday loans by the Fed is 0.

Regulation Traditional banks face two regulatory constraints. First, as in Poole (1968), they are subject to a traditional reserves requirement (RR)

$$m_+ \geq \chi^m d_+, \tag{RR}$$

where χ^m is the regulatory reserve ratio set by the regulator. If necessary to satisfy the RR, a traditional bank must borrow reserves at the discount window rate $r^m + r^w$, a premium r^w over the interest paid on reserves r^m.[5]

Second, traditional banks are subject to an intraday liquidity constraint (IC)

$$p + f \leq \theta(m_- + d_- \varepsilon_-), \tag{IC}$$

where $m_- + d_-\varepsilon_-$ represents reserves after the morning shock before the trading period opens. Therefore, traditional bank lending is constrained by their buffer of reserves during the trading period. This constraint is meant to capture new intraday liquidity requirements as specified by Basel III and implemented in Regulation YY through various liquidity stress tests known as RLEN and RLAP that require banks to have enough reserves to meet day-one outflows.[6]

Traditional Banks The problem faced by traditional banks is given by

$$\max_{p,f} \left\{ \mathbb{E}\Big[m_+ r^m - (\chi^m d_+ - m_+) \mathbb{1}\{m_+ < \chi^m d_+\} r^w \Big] + p r^p + f r^f \right\} \tag{3}$$

$$\text{s.t.} \quad p + f \leq \theta(m_- + d_- \varepsilon_-). \tag{IC}$$

[5]Since March 2020, the reserves requirement has been lifted in the US. This case corresponds in our model to setting $\chi = 0$ or, equivalently, to impose a non-negativity constraint on m. Our qualitative results still hold in this case, given that close-of-business deposit shocks can still push banks to violate this non-negativity constraint and borrow at the discount window.

[6]Although no public account gives precise details of the implementation of these pieces of regulation by the regulators, converging evidence points to an emphasis on central bank reserves being necessary to meet these newly established requirements. Consistent with this interpretation, the Fed vice-chairman responsible for banking supervision stated the following in January 2020: "However, it may be difficult to liquidate a large stock of Treasury securities to meet large "day one" outflows. [...] The LCR does not capture these on-the-ground realities. But supervision does. Under Regulation YY's enhanced prudential standards, large firms are required to conduct internal liquidity stress tests. Supervisors expect firms to estimate day-one outflows and to ensure that their liquidity buffers can cover those outflows without reliance on the Federal Reserve. For firms with large day-one outflows, reserves can meet this need most clearly." We further refer to Pozsar (2019) and Nelson and Waxman (2021) for information about the new regulatory regime relative to intraday liquidity and its emphasis on reserves. In particular, Nelson and Waxman (2021) report that "[t]he size of the liquidity requirements imposed by RLAP and RLEN are treated as confidential supervisory information; however, many large banks have reported that resolution liquidity requirements are the most binding constraint."

The exogenous variables r^p, r^f, and r^m are interest rates on repos, federal funds, and reserves, respectively. Banks maximize their expected profits subject to the intraday constraint (IC), deciding on trading-period lending volumes in repos p and fed funds f. In scenarios in which the bank reserve stock does not meet the required reserve ratio (RR) at the end of the day, banks have to compensate for this shortfall by paying the penalty associated with the discount window, r^w.

Shadow Banks We use the grapheme tilde ($\sim$) to denote shadow bank variables. Shadow banks borrow in repo to roll over a pre-existing portfolio of securities $\tilde{b}$:

$$\min_{0\leq\tilde{p}\leq\tilde{b}} \left\{\tilde{p}r^p + (\tilde{b} - \tilde{p})\lambda\right\}. \tag{4}$$

This problem boils down to selecting the least expensive method to finance $\tilde{b}$. Without the ability to borrow repos from traditional banks, shadow banks' only option is to fire-sell securities at a loss rate of λ per unit.

Equilibrium All agents solve their respective problem, and the following market-clearing conditions are satisfied: $\int_0^1 p(j)dj = \int_0^1 \tilde{p}(s)ds$ for repos, $\int_0^1 f(j)dj = 0$ for fed funds, and $B = \int_0^1 \tilde{b}(s)ds$ for shadow banks securities. The state of the economy in the trading period is given by the aggregate shock ε_-^a, the joint distribution of $\{d_-(j), m_-(j), \varepsilon_-^i(j)\}$ for $j \in [0,1]$, and the distribution of $\tilde{b}(s)$ for $s \in [0,1]$.

II Analysis

In this section, we derive the theoretical implications of introducing an intraday constraint in a standard model of monetary policy with shadow banks. As a benchmark, we first derive the implications of the model for an economy in which the only piece of liquidity regulation is the reserve requirement, highlighting the banks' dependence on intraday overdrafts at the Fed. We then study the impact of the intraday constraint. Below, we make three assumptions to simplify our analysis.

Assumption 1. *The bounds of the deposit shocks satisfy* $\sigma^a + \sigma^i < 1$ *and* $\sigma^i < 0.5$ *such that deposits are never negative at any time during the day.*

Assumption 2. *The fire-sale cost satisfies* $\lambda > r^w + r^m$ *such that shadow banks face* *higher liquidity risk than traditional banks.*[7]

Assumption 3. *Traditional banks never lend repo to other traditional banks, so they only trade with each other through the fed funds market.*[8]

A First Order Conditions

The first-order conditions of traditional banks with regard to p or f is given by

$$r^f = r^p = r^m + r^w \mathbb{P}\{m_+ < \chi^m d_+\} + \mu, \tag{5}$$

where μ is the Lagrangian multiplier for the intraday liquidity constraint (IC) and $\mathbb{P}\{m_+ < \chi^m d_+\}$ is the probability of having to borrow at the discount window conditionally on available information for the second deposit shock.[9] The first-order condition of shadow banks with regard to $\tilde{p}$ is given by

$$\tilde{p} = \begin{cases} \tilde{b} & \text{if} \quad r^p < \lambda, \\ (0, \tilde{b}) & \text{if} \quad r^p = \lambda, \\ 0 & \text{if} \quad r^p > \lambda. \end{cases} \tag{6}$$

When the repo rate r^p is below the fire-sale cost λ, shadow banks will finance their entire portfolio with repos. When the repo rate is above λ, their repo demand falls to zero. In an in-between edge case in which the repo rate is precisely equal to λ, shadow banks are indifferent between repo funding and fire sales.

B Benchmark without the Intraday Constraint

We first examine a benchmark case without the intraday liquidity constraint. This case corresponds to the setting studied in Poole (1968), extended to include a bank-to-shadow-bank repo market. We study how the repo market and the fed funds market interact with each other and find that traditional banks act as unconstrained arbitrageurs between these two market segments, ensuring that the two rates remain equal at all times. Proposition

[7] Note that if spikes are short-lived, even a relatively small transaction cost associated with trading Treasuries is large when compared to paying an annualized interest rate spread of around 7%, as with the September spike, for just a couple of days.

[8] Although, in reality, banks may trade in repo markets because of their preference for collateralized lending, this assumption stems from our interpretation of the repo market as a bank-to-shadow-bank market.

[9] See Appendix A for derivations.

1 characterizes the main properties of such an economy without an intraday liquidity constraint.

Proposition 1. *In an economy in which there is no intraday constraint:*

- *The repo rate is always equal to the fed funds rate, and both of these rates are bounded by the interest on reserves below and the discount window rate above,*

$$r^m \leq r^f = r^p \leq r^m + r^w; \tag{7}$$

- *The volume of intraday Fed overdrafts is given by*

$$O = \int_0^1 \max\left\{\left[(1-\chi^m)\mathcal{F}^{-1}\left(\frac{r^p - r^m}{r^w}; j\right) - \chi^m - \chi^m \varepsilon^i_-(j) - \varepsilon^a_-\right] d_-(j), 0\right\} dj \tag{8}$$

when $r^m < r^f = r^p < r^m + r^w$*; and*

- *The volume of transactions in the fed funds market is given by*

$$F = \int_0^1 \max\left\{m_-(j) + \left[(1-\chi^m)\left(\mathcal{F}^{-1}\left(\frac{r^p - r^m}{r^w}; j\right) + \varepsilon^i_-(j)\right) - \chi^m\right] d_-(j), 0\right\} dj - B \tag{9}$$

when $r^m < r^f = r^p < r^m + r^w$.

As in Poole (1968), banks trade off the interest revenues in interbank markets (marginal benefits) and the probability of having to borrow at the discount window (marginal cost). As this probability is bounded between 0 and 1, the two rates are contained within the boundaries of the interest rate on reserve r^m and the discount window rate $r^m + r^w$. The novelty of this setting resides in the additional option for banks to lend to shadow banks in repos. Because the marginal cost of lending in the repo market is the same as lending in the fed funds market, traditional banks' arbitrage repos and fed funds rates. In other words, by acting as arbitrageurs, traditional banks intermediate liquidity from the market for reserves into the broader repo market.

The second part of Proposition1 highlights the key role played by Fed overdrafts in allowing banks to always arbitrage between the two markets. As seen in equation (8), the volume of intraday overdrafts is given by the integral of individual overdrafts over the unit mass of banks, which depends on banks' shock history and the aggregate market conditions. In particular, a higher repo rate r^p or larger morning outflows, $-\varepsilon^i_-$ and $-\varepsilon^a_-$, lead to more overdrafts. As indicated by Jamie Dimon (see footnote 4) and observed in Fed Board data for total intraday peak overdrafts and reserves in 2007, overdrafts would typically peak at around \$150 bn, whereas bank reserves would only be a third of this figure, around \$50 bn.

Finally, the third part of Proposition 1 characterizes the trading volume in the fed funds market. As in Poole (1968), equation (9) implies that interbank lending depends on the intensity of the deposit shocks. The novelty of our setting is that a larger aggregate repo demand B decreases transactions in the fed funds market because reserves lent in repos cannot be simultaneously lent in fed funds.

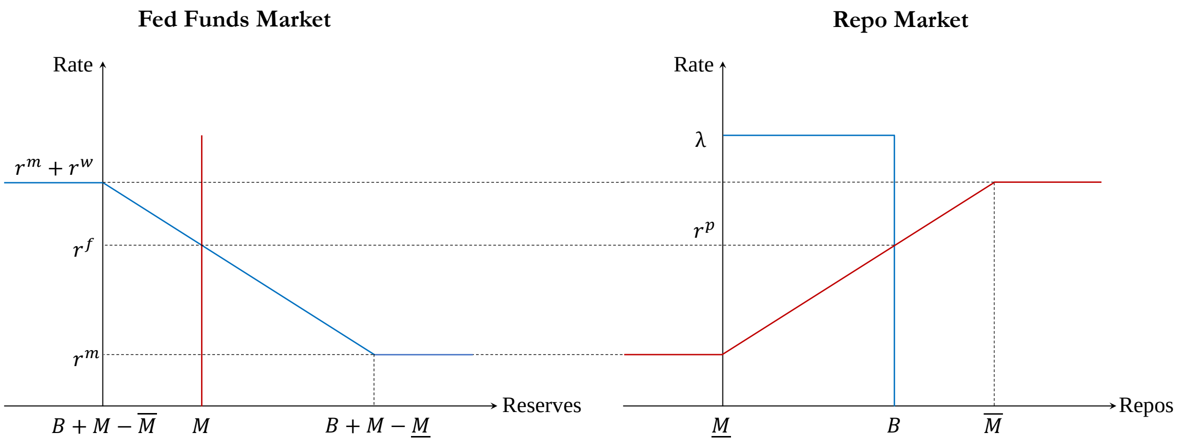

Figure 2: Enonomy without an Intraday Constraint: Benchmark

Note. The figure shows the fed funds and repo markets in an economy without an intraday constraint, where $M \equiv \int_0^1 m_-(j)dj$ is the aggregate quantity of reserves, $D_- \equiv \int_0^1 d_-(j)dj$ is the aggregate quantity of deposits in the morning, $\underline{M}$ is defined as $M - \chi^m D_- - (1-\chi^m)\sigma^i D_-$, and $\overline{M}$ is defined as $M - \chi^m D_- + (1-\chi^m)\sigma^i D_-$. Detailed derivations are provided in Appendix B. For this illustration, we set $d_-(j)$ and $m_-(j)$ identical across all banks and ε^i_-, and ε^i_+ are uniformly distributed on $[-\sigma^i, \sigma^i]$.

C Economy with an Intraday Constraint

In this subsection, we characterize an economy with traditional banks subject to the intraday liquidity constraint. We find that this constraint prevents the use of overdrafts and limits traditional banks' ability to intermediate liquidity to shadow banks, resulting in large equilibrium repo spreads.

Define $\overline{P}$ as the maximum aggregate quantity of repos that could be supplied by traditional banks before hitting the intraday liquidity constraint, that is, $\overline{P} \equiv \theta(M + D_{-}\varepsilon^{a}_{-})$. When $B < \overline{P}$, at least some traditional banks do not hit the intraday constraint. If none of the traditional banks are constrained by (IC), the economy is equivalent to the benchmark case. If only a subset of traditional banks is constrained, equilibrium interest rates still remain within the monetary policy corridor as $r^f = r^p = r^m + r^w \mathbb{P}\{m_{+} < \chi^m d_{+}\}$ must hold given the first-order conditions of unconstrained banks. Nonetheless, because some banks are constrained, the supply curve becomes steeper, and repo and fed funds rates are higher when compared to the economy without an intraday liquidity constraint. The left panel of Figure 3 illustrates the repo market under this scenario.

In Proposition 2, we describe an economy in which all traditional banks reach the intraday liquidity constraint (IC) and the demand for funds by shadow banks cannot be fully intermediated by traditional banks, that is, $B > \overline{P}$.[10]

Proposition 2. *In an economy in which the demand for repo funds cannot be fully fulfilled by traditional banks, that is, $B > \overline{P}$:*

- *The repo rate is above the discount window rate: $r^p = \lambda > r^m + r^w$, and*
- *Transactions in the fed funds market are given by:*

$$\int_0^1 \max\{-\theta(m_{-}(j) + d_{-}(j)\varepsilon_{-}(j)), 0\} dj. \tag{10}$$

Thus, if all banks begin the trading period with a positive quantity of reserves, that is, $m_{-}(j) + d_{-}(j)\varepsilon_{-}(j) \geq 0$ for all j, there are no transactions in the fed funds market.

When $B > \overline{P}$, shadow banks are able to finance only a subset of their portfolio in repos and have to fire-sell some of their securities. In that case, the cost for shadow banks of not accessing overnight liquidity is not bounded by the discount window rate $r^m + r^w$—which they cannot access—and jumps to the fire-sale cost λ. This case is illustrated in the right panel of Figure 3.

The second part of Proposition 2 characterizes the trading volume in the fed funds market. Since traditional banks have access to both repo and fed funds markets, the fed funds rate should be equal to the repo rate in equilibrium. However, no bank is willing to borrow fed funds at a rate higher than the discount window rate unless they are forced to borrow to satisfy the intraday liquidity constraint (IC) because having to

[10] See Appendix D for the case $B = \overline{P}$.

borrow at the discount window rate is their worst-case scenario. This result corresponds to the empirical observation of sharp drops in fed funds volume on days with large repo spikes, such as September 16-17, 2019.[11] When no traditional banks violate the intraday liquidity constraint after the morning shock, transactions in the fed funds market drop to zero.

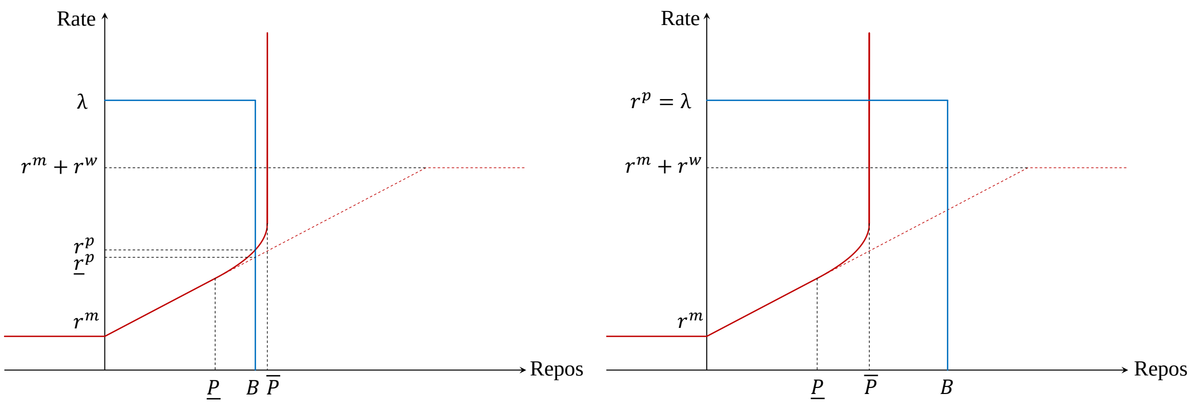

Figure 3: Economy with an Intraday Constraint

Note. In the figure, solid red lines present the repo supply with an intraday constraint, and dashed red lines are the repo supply in the benchmark case without an intraday constraint. The left panel shows an economy in which only a subset of banks are constrained by (IC), that is, $\underline{P} < B < \overline{P}$, where $\underline{P}$ is defined as the threshold at which at least some banks are constrained. We denote by $\underline{r}^p$ the corresponding repo rate for the economy without an intraday liquidity constraint. The right panel shows an economy in which the repo demand is unfulfilled due to the restricted intraday constraint, that is, $B > \overline{P}$. The derivation of $\underline{P}$ is shown in Appendix C. For this illustration, we set $d_{-}(j)$ and $m_{-}(j)$ identical across all banks, and ε^i_{-} and ε^i_{+} are uniformly distributed on $[-\sigma^i, \sigma^i]$.

In this economy, we can also compute the probability of observing the repo rate spiking above the discount window rate as

$$\mathbb{P}\{\overline{P} < B\} = \mathbb{P}\left\{\theta\left(M + D_{-}\varepsilon^a_{-}\right) < B\right\} = \mathbb{P}\left\{\varepsilon^a_{-} < \frac{B}{\theta D_{-}} - \frac{M}{D_{-}}\right\}. \quad (11)$$

This equation shows that a less restrictive intraday liquidity constraint (larger θ), lower demand for repos by shadow banks B, or a larger quantity of reserves M decreases the probability of a repo spike. This result is intuitive as our model illustrates that conditions in repo markets depend on the demand for repo from shadow banks relative to a supply from banks, which is limited by the quantity of reserves through the intraday constraint.

[11] See series EFFRVOL from the Federal Reserve Bank of New York, available at https://fred.stlouisfed.org/series/EFFRVOL.

In sum, we explore the implications of implementing an intraday liquidity constraint for money markets. The constraint alters money market rates by preventing banks from intermediating liquidity from reserves markets to repo markets, causing spikes in repo rates. When shadow banks are short of funds, the repo rate jumps above the discount window rate up to the cost of fire sales, λ.

III Estimating Intraday Excess Reserves

In this section, we propose a simple formula to estimate the supply of reserves in excess of intraday liquidity needs. According to the model, in an economy with an intraday liquidity constraint, a low quantity of excess reserves should be indicative of a high likelihood of observing a repo rate spike above the discount window. We write the formula for intraday excess reserves (IER) as

$$\text{IER}_t \equiv \text{Excess Reserves}_t - \text{Bank Repos}_t - \text{Bank Fed Funds}_t - \text{Peak Intraday Flows}_t. \tag{12}$$

We compute this measure by making use of call reports and data from the Federal Reserve Bank System.[12] Unfortunately, there is no direct measure for the peak intraday liquidity needs as generated by payment flows post-2008, as the large reserves supply following several rounds of quantitative easing have made intraday overdrafts unnecessary for banks. Consequently, to proxy for the peak intraday liquidity needs from the payment system, we propose to use a simple linear extrapolation from the pre-2008 peak intraday overdrafts. For reference, this figure is around \$80 bn in 2000 and \$150 in 2007, yielding an extrapolated value of around \$450 bn in 2019.

We plot the time series for IER in Figure 4. A first observation is that this series shifted from negative to positive around 2009 as a consequence of the rounds of quantitative easing following the global financial crisis. The IER then peaks around 2015 at \$2 tr and steadily decreases between 2015 and 2019 as the Fed reduced the size of its balance sheet. Interestingly, the IER falls to close to zero in the summer of 2019 following a

[12] More precisely, EXCSRESNS from FRED is used for Bank Excess Reserves until it was discontinued in September 2020. After that, TOTRESNS is applied because the reserve requirement was lifted in March 2020, equalizing EXCSRESNS and TOTRESNS thereafter. For banks' repo and fed funds lending, we apply RCFDB989 and RCFDB987 from call reports from the Bank Regulatory dataset at WRDS, respectively. These two RCFD series were discontinued in March 2020, and we use the B3092NCBDM series from FRB Data H.8 after this point. To infer peak intraday flows, we use the series Total Intraday Peak Overdraft from the Federal Reserves Board.

combination of additional reductions in central bank reserves and increases in bank repo lending. This time corresponds to the large repo spike that took place on September 17, 2019. After the Fed reacted by injecting reserves back into money markets through open market operations, the IER drifts back into positive territory and keeps increasing after March 2020 as a consequence of the new pandemic programs. As of 2023, the IER remains largely in positive territory at around \$2 tr.

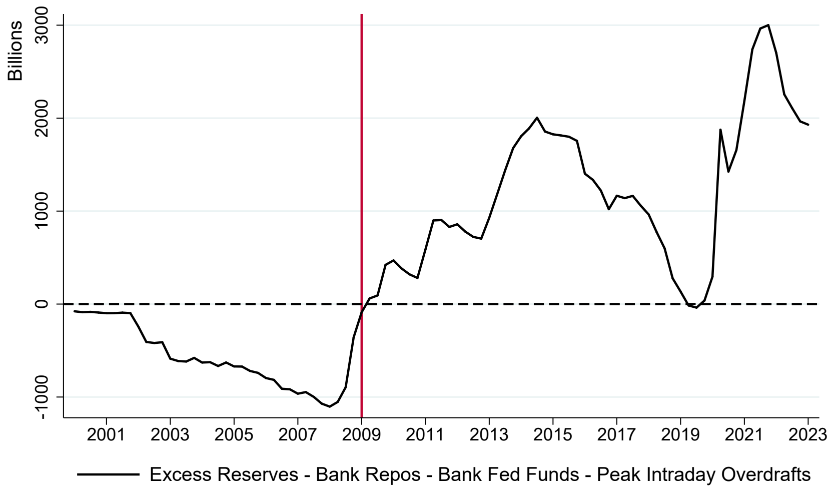

Figure 4: Time Series of Intraday Excess Reserves

Note. The figure shows the time series $\text{IER}_t \equiv \text{Excess Reserves}_t - \text{Bank Repos}_t - \text{Bank Fed Funds}_t - \text{Peak Intraday Flows}_t$ from 2000Q1 to 2023Q1 on a quarterly basis.

IV Conclusion

This article proposes a framework to study the interplay between intraday and overnight liquidity and how this interaction can lead to spikes in money market rates. The analysis reveals that regulatory requirements for banks to pre-fund intraday outflows with reserves limit the supply of repurchase agreements (repos) to shadow banks. This finding implies that a lack of intraday liquidity for banks can result in an overnight liquidity shortage for shadow banks, causing repo rates to potentially spike significantly. This possibility is particularly concerning as shadow banks, which hold significant Treasury debt, lack access to the central bank's emergency lending facilities. Sudden spikes in repo rates may then trigger fire sales and generate some Treasury inconvenience yield, as documented by He, Nagel and Song (2022). Numerous questions linking Treasury markets to repo markets and intraday limits remain to be investigated in future research.

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Appendices

A First-order Conditions for Traditional Banks

As in the main text, for ease of notation, we write x instead of $x(j)$ and $x(s)$ when the indexation is not necessary. The traditional banks' problem is given by

$$\max_{p,f}\left\{\mathbb{E}\Big[m_{+}r^{m}-(\chi^{m}d_{+}-m_{+})\mathbb{1}\{m_{+}<\chi^{m}d_{+}\}r^{w}\Big]+pr^{p}+fr^{f}\right\} \tag{13}$$

$$\text{s.t.}\quad p+f\leq\theta(m_{-}+d_{-}\varepsilon_{-}), \tag{IC}$$

where $d_{+}=d_{-}+\Delta d$, $m_{+}=m_{-}+\Delta d-p-f$, and $\Delta d=d_{-}(\varepsilon_{-}^{i}+\varepsilon_{+}^{i})$. The Lagrangian multiplier μ on (IC) is given by

$$\mathcal{L}=\mathbb{E}\Big[m_{+}r^{m}-(\chi^{m}d_{+}-m_{+})\mathbb{1}\{m_{+}<\chi^{m}d_{+}\}r^{w}\Big]+pr^{p}+fr^{f}-\mu(p+f-\theta(m_{-}+d_{-}\varepsilon_{-})). \tag{14}$$

Denote $\omega\equiv p+f$, then we have $m_{+}=m_{-}+\Delta d-\omega$. Let us further define $\phi(\omega)=(\chi^{m}d_{-}-m_{-}+\omega)/\left[(1-\chi^{m})d_{-}\right]-\varepsilon_{-}^{i}$, which is the value of ε_{+}^{i} given d_{-} that satisfies $m_{+}=\chi^{m}d_{+}$. Given the definition of $\mathcal{F}(\varepsilon;j)$, we have

$$\mathbb{P}\{m_{+}<\chi^{m}d_{+}\}=\begin{cases}0 & \text{if}\quad \omega\leq\underline{m}\\ \mathcal{F}(\phi(\omega);j) & \text{if}\quad \omega\in(\underline{m},\overline{m})\\ 1 & \text{if}\quad \omega\geq\overline{m}\end{cases}, \tag{15}$$

where $\underline{m}\equiv m_{-}-\chi^{m}d_{-}+(1-\chi^{m})d_{-}(\varepsilon_{-}^{i}-\sigma^{i})$ and $\overline{m}\equiv m_{-}-\chi^{m}d_{-}+(1-\chi^{m})d_{-}(\varepsilon_{-}^{i}+\sigma^{i})$. The first-order conditions for p or f is given by $r^{p}=r^{f}=r^{m}+r^{w}\mathbb{P}\{m_{+}<\chi^{m}d_{+}\}+\mu$.

B Proof of Proposition 1

First, we define the total quantity of reserves as $M\equiv\int_0^1 m_{-}(j)dj$, the total quantity of shadow bank securities as $B\equiv\int_0^1 b(s)ds$, and the total quantity of deposits in the morning as $D_{-}\equiv\int_0^1 d_{-}(j)dj$, $\underline{M}\equiv\int_0^1\underline{m}(j)dj$, and $\overline{M}\equiv\int_0^1\overline{m}(j)dj$.

When there is no intraday constraint or the constraint is not binding, $\mu=0$, and $r^{p}-r^{m}=\mathbb{P}\{m_{+}<\chi^{m}d_{+}\}r^{w}$. Thus, $r^{m}\leq r^{f}=r^{p}\leq r^{m}+r^{w}$ and $\tilde{p}=\tilde{b}$.

Whenever traditional banks lend more repo and fed funds than reserves they hold—

that is, $m_- + d_-\varepsilon_- < \omega$—they borrow with intraday Fed overdrafts. The total volume of overdrafts is given by $O = \int_0^1 \max\{\omega(j) - m_-(j) - d_-(j)\varepsilon_-(j), 0\}dj$. Given Assumption 3, the trading volume in the fed funds market is $F = \int_0^1 \max\{\omega(j), 0\}dj - B$.

- **Case 1:** $\exists j : \omega(j) \leq \underline{m}(j)$**.** Then $\mathbb{P}\{m_+ < \chi^m d_+\} = 0$, $r^f = r^p = r^m$,

$$B \leq \underline{M} \tag{16}$$

  and $\omega(j) \leq \underline{m}(j)$ for all j.

- **Case 2:** $\exists j : \omega(j) \geq \overline{m}(j)$**.** Then $\mathbb{P}\{m_+ < \chi^m d_+\} = 1$, $r^f = r^p = r^m + r^w$,

$$B \geq \overline{M} \tag{17}$$

  and $\omega(j) \geq \overline{m}(j)$ for all j.

- **Case 3:** $\underline{m}(j) < \omega(j) < \overline{m}(j)$ **for all** j**.** Then $\mathbb{P}\{m_+ < \chi^m d_+\} \in (0, 1)$ and $r^m < r^f = r^p < r^m + r^w$. Thus,

$$\omega(j) = \left(\mathcal{F}^{-1}\left(\frac{r^p - r^m}{r^w}; j\right) + \varepsilon_-^i(j)\right)(1 - \chi^m)d_-(j) + m_-(j) - \chi^m d_-(j). \tag{18}$$

  Integrating over (18), we get

$$B = M + \int_0^1 \left(\mathcal{F}^{-1}\left(\frac{r^p - r^m}{r^w}; j\right)(1 - \chi^m) - \chi^m\right) d_-(j)dj. \tag{19}$$

C Derivation of $\underline{P}$

We define $\underline{P}$ such that, if $B < \underline{P}$, then $\mu(j) = 0$ for all j, and if $B > \underline{P}$, then $\exists j$ such that $\mu(j) > 0$. Below, we derive the value of $\underline{P}$. We also define

$$\underline{\ell}(j) \equiv \min\{\theta(m_-(j) + d_-(j)\varepsilon_-(j)), \underline{m}(j)\} \tag{20}$$

$$\overline{\ell}(j) \equiv \min\{\theta(m_-(j) + d_-(j)\varepsilon_-(j)), \overline{m}(j)\}. \tag{21}$$

$\underline{L} \equiv \int_0^1 \underline{\ell}(j)dj$ and $\overline{L} \equiv \int_0^1 \overline{\ell}(j)dj$. It is direct to see that $\underline{L} \leq \underline{M} < \overline{M}$, and $\underline{L} \leq \overline{L} \leq \overline{M}$. Also note that $\int_0^1 \omega(j)dj = B$ when $B \leq \overline{P}$.

- **Case 1:** $\underline{L} < \underline{M}$**.**

Note that $\underline{L} < \underline{M}$ implies that $\exists j' : \underline{\ell}(j') < \underline{m}(j')$. Thus, $\theta(m_{\text{-}}(j') + d_{\text{-}}(j')\varepsilon_{\text{-}}(j')) < \underline{m}(j') < \overline{m}(j')$. Furthermore, $\overline{\ell}(j') < \overline{m}(j')$. Therefore, $\overline{L} < \overline{M}$ and we do not need to investigate what happens if $\underline{L} < \underline{M}$ and $\overline{L} = \overline{M}$.

- If $B < \underline{L}$, $\exists j' : \omega(j') < \underline{\ell}(j')$ and $r^m = r^p = r^f$. Thus, $\mu(j) = 0$ for all j.
- If $B > \underline{L}$, $\exists j' : \omega(j') > \underline{\ell}(j')$. Since $\omega(j') \leq \theta(m_{\text{-}}(j') + d_{\text{-}}(j')\varepsilon_{\text{-}}(j'))$, $\omega(j') > \underline{m}(j')$ and $r^p > r^m$.

  In addition, since $\underline{L} < \underline{M}$, $\exists j'' : \underline{\ell}(j'') < \underline{m}(j'')$. Thus, $\omega(j'') \leq \theta(m_{\text{-}}(j'') + d_{\text{-}}(j'')\varepsilon_{\text{-}}(j'')) < \underline{m}(j'')$, which implies $\mathbb{P}\{m_{+}(j'') < \chi^m d_{+}(j'')\} = 0$ from equation (15). So, $\mu(j'') > 0$.

Therefore, $\underline{P} = \underline{L}$.

- **Case 2:** $\underline{L} = \underline{M} \leq \overline{L} < \overline{M}$**.**

  - If $B < \underline{L} = \underline{M}$, $\exists j' : \omega(j') < \underline{\ell}(j')$ and $r^m = r^p = r^f$. Thus, $\mu(j) = 0$ for all j.
  - If $B > \overline{M} > \overline{L}$, $\exists j' : \omega(j') > \overline{m}(j')$, and $r^p \geq r^m + r^w$. In addition, since $\overline{L} < \overline{M}$, $\exists j'' : \overline{\ell}(j'') < \overline{m}(j'')$. Thus, $\omega(j'') \leq \theta(m_{\text{-}}(j'') + d_{\text{-}}(j'')\varepsilon_{\text{-}}(j'')) < \overline{m}(j'')$, which implies $\mathbb{P}\{m_{+}(j'') < \chi^m d_{+}(j'')\} < 1$ from equation (15). So, $\mu(j'') > 0$.

Thus, $\underline{M} \leq \underline{P} \leq \overline{M}$. Let us define $\underline{\mathcal{F}}$ as

$$\underline{\mathcal{F}} \equiv \min_{j \in [0,1]} \{\mathcal{F}(\varepsilon(j); j)\} \tag{22}$$

where $\varepsilon(j)$ is defined as

$$\varepsilon(j) \equiv \frac{\theta(m_{\text{-}}(j) + d_{\text{-}}(j)\varepsilon_{\text{-}}(j)) - m_{\text{-}}(j) + \chi^m d_{\text{-}}(j)}{(1-\chi^m)d_{\text{-}}(j)} - \varepsilon^i_{\text{-}}(j). \tag{23}$$

We now show that $\underline{P}$ is given by

$$\underline{P} = M + \int_0^1 \left(\mathcal{F}^{-1}\left(\underline{\mathcal{F}}; j\right)(1-\chi^m) - \chi^m\right) d_{\text{-}}(j)dj. \tag{24}$$

- If $\underline{M} < B < \underline{P}$, then $\exists j' : \omega(j') < (\mathcal{F}^{-1}(\underline{\mathcal{F}}; j') + \varepsilon^i_{\text{-}}(j'))\,(1-\chi^m)d_{\text{-}}(j') + m_{\text{-}}(j') - \chi^m d_{\text{-}}(j') \leq \theta(m_{\text{-}}(j') + \varepsilon_{\text{-}}(j'))$. Thus, $\mu(j') = 0$ and $(r^p - r^m)/r^w < \underline{\mathcal{F}}$.

Using equations (18) and (22), we get

$$\left(\mathcal{F}^{-1}\left(\frac{r^p - r^m}{r^w}; j\right) + \varepsilon^i_-(j)\right)(1-\chi^m)d_-(j) + m_-(j) - \chi^m d_-(j) \\ < \theta(m_-(j) + d_-(j)\varepsilon_-(j)) \tag{25}$$

for all j. Thus, $\mu(j) = 0$ for all j.

- If $\underline{P} < B < \overline{M}$, it is impossible that $\mu(j) = 0$ for all j. Otherwise, $(r^p - r^m)/r^w > \underline{\mathcal{F}}$, and there exists j'' such that

  $$\omega(j'') \leq \theta(m_-(j'') + d_-(j'')\varepsilon_-(j'')) \\ < \left(\mathcal{F}^{-1}\left(\frac{r^p - r^m}{r^w}; j''\right) + \varepsilon^i_-(j'')\right)(1-\chi^m)d_-(j'') + m_-(j'') - \chi^m d_-(j''). \tag{26}$$

  Thus, $\mu(j'') > 0$.

Therefore, $\underline{P}$ is given by equation (24).

- **Case 3.** If $\overline{L} = \overline{M}$:

  This implies $\overline{m}(j) \leq \theta(m_-(j) + d_-(j)\varepsilon_-(j))$ for all j. Thus, $\overline{L} = \overline{M} \leq \overline{P}$.

  - If $B < \overline{L} = \overline{M}$, then $\exists j' : \omega(j') < \overline{m}(j') \leq \theta(m_-(j') + d_-(j')\varepsilon_-(j'))$. Thus, $\mu(j') = 0$. Furthermore, $\mathbb{P}\{m_+(j') < \chi^m d_+(j')\} < 1$ by the definition of $\overline{m}(j')$. Therefore, $r^p < r^m + r^w$. Thus, $\mathbb{P}\{m_+(j) < \chi^m d_+(j)\} < 1$ and $\omega(j) < \overline{m}(j)$ for all j. Thus, $\mu(j) = 0$ for all j.
  - If $\overline{M} \leq B < \overline{P}$, then $\exists j' : \omega(j') \geq \overline{m}(j')$. Thus, $\mathbb{P}\{m_+(j') < \chi^m d_+(j')\} = 1$ by the definition of $\overline{m}(j')$. Therefore, $r^p \geq r^m + r^w$.

    In addition, $B < \overline{P}$ implies that $\exists j'' : \omega(j'') < \theta(m_-(j'') + d_-(j'')\varepsilon_-(j''))$ and $\mu(j'') = 0$. Therefore, $r^p \leq r^m + r^w$.

    Thus, $r^p = r^m + r^w$.

    Finally, if $\exists j''' : \mathbb{P}\{m_+(j''') < \chi^m d_+(j''')\} < 1$, then $\omega(j''') < \overline{m}(j''')$ and $\mu(j''') > 0$. This is not possible given that $\overline{m}(j''') \leq \theta(m_-(j''') + d_-(j''')\varepsilon_-(j'''))$. Thus, $\mathbb{P}\{m_+(j) < \chi^m d_+(j)\} = 1$ for all j. Thus, $\mu(j) = 0$ for all j.
  - If $B > \overline{P}$, we show in the proof of Proposition 2 in the main text that $r^p = \lambda > r^m + r^w$. Thus, $\mu(j) > 0$ for all j.

Therefore, $\underline{P} = \overline{P}$.

Overall, we have

$$\underline{P} = \begin{cases} \underline{L} & \text{if } \underline{L} < \underline{M}, \\ M + \int_0^1 \left(\mathcal{F}^{-1}\left(\underline{\mathcal{F}}; j\right)(1-\chi^m) - \chi^m\right) d_-(j)dj & \text{if } \underline{L} = \underline{M} \le \overline{L} < \overline{M}, \\ \overline{P} & \text{if } \overline{L} = \overline{M}, \end{cases} \tag{27}$$

where $\underline{\mathcal{F}}$ is defined as in equation (22). Note that the proof of Proposition 2 in the main text implies that $r^p = \lambda > r^m + r^w$ when $B > \overline{P}$. Thus, $\mu(j) > 0$ for all j when $B > \overline{P}$. Therefore, $\underline{P} \le \overline{P}$ by the definition of $\underline{P}$.

D Economy with an Intraday Constraint and $B = \overline{P}$

In this appendix, we characterize the case in which the demand for repo funds is just at the limit of the intraday constraint, $B = \overline{P}$.

First, we show that for *every* shadow bank, $\tilde{p} = \tilde{b}$. If $\exists s' : \tilde{p}(s') < \tilde{b}(s')$, then $r^p = \lambda$ given the maximization problem of shadow banks and $\int_0^1 \omega(j)dj = \int_0^1 \tilde{p}(s)ds < B = \overline{P} = \int_0^1 \theta(m_-(j) + d_-(j)\varepsilon_-(j))dj$. Thus, $\exists j' : \omega(j') < \theta(m_-(j') + d_-(j')\varepsilon_-(j'))$ and $\mu(j') = 0$, which implies that $r^p \le r^m + r^w$, a contradiction with $\lambda > r^m + r^w$. Therefore, $\tilde{p}(s) = \tilde{b}(s)$ for all s. In addition, $\int_0^1 \omega(j)dj = \int_0^1 \tilde{p}(s)ds = B = \overline{P}$ implies that $\omega(j) = \theta(m_-(j) + d_-(j)\varepsilon_-(j))$ for all j.

Given that $\tilde{p}(s) = \tilde{b}(s)$ for all s, $r^p \le \lambda$ given the maximization problem of shadow banks. In this edge case, there are multiple equilibria, and the rates, r^p and r^f, can land in the monetary policy corridor between r^m and $r^m + r^w$ or jump above the discount window rate, $r^m + r^w$. Below, we characterize the two types of equilibria.

- **Type 1:** $\mu(j) = 0$ **for all** j**.**

  This implies that $r^p \le r^m + r^w$. The equilibrium is equivalent to the benchmark case in Proposition 1.

- **Type 2:** $\exists j' : \mu(j') > 0$**.**

  The rates r^p and r^f are higher compared to those in the benchmark case.

Turning to the volume of transactions in the fed funds market, in both types of equilibria, we have $F = \int_0^1 \max\{-\theta(m_-(j) + d_-(j)\varepsilon_-(j)), 0\}dj$, as in Proposition 2. Given $\underline{P} \le \overline{P} = B$, we have two cases.

- **Case 1:** $\underline{P} = \overline{P} = B$**.**

  Both types of equilibria exist in this case.

- **Case 2:** $\underline{P} < \overline{P} = B$**.**

  Only equilibrium type 2 exists in this case. It is impossible to have $\mu(j) = 0$ for all j, because by the definition of $\underline{P}$, when $B > \underline{P}$, then $\exists j' : \mu(j') > 0$.