Do bank reserves affect interest rates when reserves are abundant?*

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Abstract

An important concern for central banks is how to control short-term interest rates, with the ultimate goal of stabilizing the economy and maintaining price stability. Prior to 2008, the Federal Reserve achieved this by changing the supply of bank reserves in the interbank market. When reserves increased from billions to trillions during and after the global financial crisis, the Federal Reserve changed how it implements monetary policy and now uses administered interest rates, notably the interest paid on reserves. In this new policy environment, is there still an impact on short-term rates from changes in reserve supply? And if so, what is the nature of this relationship, and does the impact change over time?

I estimate the effect of changes in bank reserves on the federal funds rate spread (a measure of the price of liquidity in the banking system) between 2009 to 2020 while also controlling for changes in the Fed's policy rates. I test whether the impact of reserve changes depends on overall banking sector liquidity by using threshold models that distinguish between periods of high or low reserve balances. I demonstrate that both changes in reserves and changes in policy rates determine short-term interest rates after 2008, with three key findings. First, for reserves there is a nonlinear relationship: changes in reserves only affect the federal funds spread at lower (though still ample) levels of reserves, but not when they are very high, in line with having differently sloped sections on the reserve demand curve. Second, I find the critical threshold to be time-varying. Third, I find that reserve changes have a stronger effect after the Fed started monetary tightening in 2015. My results show that there is feedback between the Fed's interest rate and reserve policies, which has important implications for the formulation of current monetary policy.

Keywords: reserve balances, monetary policy implementation, threshold model, interest on reserves, federal funds rate

JEL Classification: C24, E43, E52, E58

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1 Introduction

The impact of changes to the Federal Reserve's (Fed) balance sheet, both in size and composition, has recently gained renewed public and academic interest, in particular since the Fed began reducing its balance sheet through quantitative tightening (QT) and has been raising interest rates at a faster pace than at any time since the 1990s. While policymakers acknowledge the need to reduce the balance sheet, they also intend to "maintain securities holdings in amounts needed to implement monetary policy efficiently and effectively in its ample reserves regime."[1] This raises questions about the role of the abundant deposits that banks keep in accounts at the Fed (bank reserves) for implementing and transmitting monetary policy through interest rates in money markets.

Bank reserves ("reserves" from here on) are used to settle payments and are therefore essential for banks to manage their liquidity needs. Prior to the global financial crisis, the relationship between reserves and interest rates was well established: more reserves led to a decrease in rates, and vice versa. Banks minimized their reserve holdings since they did not earn interest, so there was no financial incentive to hold more than necessary to fulfill legal requirements.[2] If a bank faced unexpectedly large payment outflows, it could borrow reserves from other banks in the interbank market, paying the federal funds rate (fed funds rate). The Fed only supplied enough reserves to meet overall bank demand, using open market operations as its primary tool to keep the fed funds rate at the desired target level. As overall reserves were relatively scarce, when the Fed added or removed reserves from the market, the fed funds rate would adjust.[3]

In contrast, the mechanism through which reserve balances impact monetary policy implementation and transmission after 2008 is not fully understood. In response to the crisis, the Fed fundamentally changed the way it implements monetary policy, which included balance sheet policies such as large-scale asset purchases and lending programs. This increased reserves to levels far exceeding daily bank demand, which made open-market operations ineffective. As a result, the Fed now adjusts two policy rates (administered rates) to control its target interest rate, the effective federal funds rate. In particular, banks receive interest on reserves (IOR)[4]. This payment provides an incentive to hold what used to be considered excess reserves on their balance sheets, and also introduces an opportunity cost for lending to other banks.

This new policy environment of abundant reserves raises the question that I investigate in this paper: is there still an impact on short-term interest rates from changes in reserve supply? And if so, does the impact change over time? Understanding the answer to this question is important for

[1] https://www.federalreserve.gov/newsevents/pressreleases/monetary20220126c.htm

[2] Reserve requirements were officially set to zero in March 2020 (https://www.federalreserve.gov/monetarypolicy/reservereq.htm)

[3] On the individual bank level, inflows or outflows on commercial bank balance sheets can increase or drain reserves. In contrast, the aggregate level of reserves is fixed by the Fed and can only fluctuate with changes in autonomous factors such as the Treasury's account at the Fed.

[4] The current official designation is interest rate on reserve balances (IORB), which replaced the interest rate on excess reserves (IOER) in July 2021. I refer to the merged series as IOR for simplicity. See Section 2.5 for details.

policymakers as they shrink the Fed's balance sheet through quantitative tightening, which withdraws reserves from the financial system. If changes in the amount of reserves matter independently of other policy tools for keeping the fed funds rate at the desired target, reserve supply could be considered an additional policy tool in its own right. This would have important implications for current and future design of monetary policy operating procedures.

One common view of reserve demand when reserves earn interest suggests that the demand curve becomes flat at a certain saturation point. Above this level, changes in reserve supply no longer affect the funds rate, which is then solely determined by arbitrage with the Fed's policy rates. This implies that changes in the Fed's balance sheet (and therefore reserves) would be "divorced" (Keister, Martin and McAndrews, 2008) from changes in the target interest rate. However, the significant stress observed in U.S. money markets in September 2019 seemed to suggest otherwise, and recent research rejects the idea that reserves themselves have no impact on short-term interest rates (Afonso et al., 2023*a*; Smith and Valcarcel, 2023; Lopez-Salido and Vissing-Jorgensen, 2023).

In this paper, I analyze the role of reserves in determining short-term interest rates with a reduced-form model of the spread between the fed funds rate and the IOR (fed funds spread) as a function of changes in reserve balances. This spread is chosen to capture the cost of liquidity in the wholesale banking market as it represents the marginal benefit of lending reserves compared to being paid the IOR by the Fed. I specify the model first as a linear model and then test it against a nonlinear threshold autoregressive (TAR) model, in which the interest rate response depends on a measure of how abundant overall liquidity in the financial system is. The baseline estimation period starts in 2009 and ends before the start of the pandemic in 2020.[5] In addition, I separately examine the two time periods before and after the Fed began raising interest rates from effectively zero in December 2015 (referred to as interest rate "liftoff"). This approach takes into account that a structural break in the monetary transmission mechanism might have occurred when quantitative easing (QE) and the zero-lower-bound ended and balance sheet unwinding and interest rate increases started. In addition, the linear models are also estimated as rolling window regressions in order to capture slower-moving structural changes and time-varying effects.

This paper extends the previous literature by analyzing whether the effect of reserve changes on the fed funds spread depends on the overall reserve environment, and whether any such dependency changes over time. To my knowledge, it is the first paper to formally estimate the threshold at which reserves become relatively "scarce" during different time periods with a nonlinear threshold model.

First, my results show that reserve changes have a negative impact on the fed funds spread in the post-crisis period, even though overall reserves are abundant. That is, additional liquidity in the form of a higher supply of reserves lowers the price of obtaining funds in the interbank market, which is also known as a "liquidity effect". This finding is consistent with related work such as

[5]For robustness, I also estimate a longer sample including the pandemic.

Smith (2019) and Afonso et al. (2023*a*). Second, I find evidence that a linear model is misspecified, as both reserve changes and changes in the Fed's administered rates affect the fed funds spread nonlinearly. When reserves drop below a critical threshold that signals a lack of overall available liquidity, increases in reserves decrease the fed funds spread. In contrast, there is little to no effect when reserves are above the threshold. As expected, the IOR plays a role in determining the funds rate for all periods. However, the pass-through of changes in the IOR to the fed funds rate is stronger when reserves are above the threshold. Given the estimated threshold level for the baseline period (a ratio of reserves to nominal GDP of 12 percent) the empirical results suggests that during the majority of the studied time period (61 percent), reserves and the IOR jointly determine the funds rate.

I also find changes over time in the relationship between reserves and the fed funds spread, but the rolling window regressions suggest that these changes are gradual. Therefore it is unclear whether this time-variation in the coefficients can be precisely attributed to certain policy changes such as the interest rate liftoff or quantitative tightening. The value of the threshold that separates periods of high and low liquidity itself is time-varying as well, fluctuating between a ratio of overall liquidity relative to GDP of 12% and 7%. This might be due to factors such as overall economic conditions or changes in banking sector regulation, which affect the need for banks to hold reserves as highly liquid assets.

My analysis builds on the growing literature on the role of reserves in the current monetary policy implementation framework. Theoretical work by Goodfriend (2002) and later Ireland (2014) suggests that in such a system, there would be no relationship between changes in reserves and short-term interest rates. The Fed could then independently manage short-term interest rates and bank reserves, as long as abundant reserves satisfy banks' demand for daily liquidity and banks are compensated for holding them with the IOR.

There are several properties in the market for reserves in the U.S., however, that do not match the assumptions of those models. For example, segmentation and heterogeneity in U.S. money markets prevent frictionless and costless arbitrage for funds (Lagos and Navarro, 2023). There were also structural changes in the banking sector after the financial crisis that might have permanently increased overall demand for reserves and made them more convenient to hold compared to other types of assets. This would then affect the relative interest rates between reserves and these assets (Lopez-Salido and Vissing-Jorgensen, 2023; Afonso et al., 2023*a*). Thus, recent models such as Afonso et al. (2023*b*) and Williamson (2023) allow for reserves to matter in the determination of short-term interest rates.

Consistent with these models, empirical studies have shown that increases in reserves during the post-2008 period lower short-term interest rates. In linear estimation, Bräuning (2018), Smith (2019) and Smith and Valcarcel (2022) find evidence of a significant unconditional effect of reserves on the fed funds spread in the post-crisis environment. In time-varying analysis, Smith and Valcarcel

(2023) also document a strengthening of the liquidity effect after 2017, once the Fed started to let assets from its balance sheet run-off. In related work, Afonso et al. (2023*a*) estimate a time-varying demand curve for reserves that is identified with an instrumental variable approach. They plot the estimated demand curves and find a weaker liquidity effect between 2012-2017, and a stronger effect before and after. Lopez-Salido and Vissing-Jorgensen (2023) argue that bank deposits are an essential variable in a reserve demand equation and that any apparent time-varying effects in the response in reserve demand can be attributed to deposits being an omitted variable in that equation. They also account for the increasing role of the Fed's overnight reverse repo facility (ON RRP) by estimating their model with adjusted reserves (reserves + ON RRP volume) as a regressor.

My work extends these papers with threshold-switching analysis that explicitly models the liquidity effect as dependent both on time and the overall level of available reserves. In addition, I use the measure of adjusted reserves proposed in Lopez-Salido and Vissing-Jorgensen (2023) in order to account for potential endogeneity of reserves to changes in the Fed's balance sheet composition as well as treasury supply and overall money market conditions.

The rest of the paper is structured as follows. I present the overall framework used in the paper in Section 2. In particular, I explain how the changes in the Fed's overall operating procedures inform my modeling choices in Section 2.3 and I present the data in Section 2.5. In Section 3 I analyze and discuss the results. Section 4 concludes. Tables and graphs are shown in Section 5.

2 Empirical Framework

2.1 Monetary policy implementation in the U.S. after 2008

Like other central banks, the Fed fundamentally changed the way it conducts and implements monetary policy in response to the 2007/2008 global financial crisis. One of the new tools it used were multiple rounds of large scale purchases of assets such as longer-term treasuries and mortgage-backed securities from the private sector, commonly known as quantitative easing (QE). The Fed paid for asset purchases mostly by creating reserves, which belong to the liability side of its balance sheet (see Table 1 for a representation of the Fed's balance sheet). Correspondingly, when the seller receives the reserve balances, they are added as an asset on their balance sheet. The Fed's purchase of a security therefore mechanically "lengthens" the size of the Fed's balance sheet as an equal dollar amount is added to both Fed assets (representing the value of the newly acquired security) and Fed liabilities (representing the newly created reserves). The result is an overall expansion of reserve supply (Acharya et al., 2023; Sablik, 2022).

To stabilize the economy and maintain price stability, the Fed's goal both before and after 2008 has been to control short-term interest rates, notably the federal funds rate (funds rate), which is determined by market participants in the market for reserves (federal funds). As in other markets, when supply exceeds demand, the price of the good falls, barring any frictions. Before the crisis, the Fed used this relationship to adjust the funds rate by conducting asset purchases and sales. Averaging around $6 billion per day between 2002 and 2008, these open market operations would lead to small changes in reserve supply and thereby in the funds rate.

In contrast, after 2008, the large volume of asset purchases lead to an equally large increase in total reserve supply, as described above. Thus daily demand for reserves by depository institutions, both to protect against unexpected payment flows as well as to meet reserve requirements was more than satisfied (see Section 2.2 for a discussion of relevant models). As a result, the funds rate fell, and the incentive to trade reserves disappeared.[6] Small changes in reserve supply could therefore no longer sufficiently affect the funds rate, and the Fed switched to directly setting two administered policy rates (explained below), in order to control the funds rate via arbitrage.

In October 2008 the Fed started to offer banks interest on their reserve balances (IOR). For depository institutions this means that they have no incentive to lend in the federal funds market at a rate lower than IOR since they can obtain that rate by lending to the Fed. Therefore the IOR was meant to provide a "floor" for the federal funds rate. However, this did not work as intended due to differences in market participants in the market for reserves. Among market participants who are eligible to hold reserves at the Fed, government-sponsored enterprises (GSE) such as Fannie Mae and Freddie Mac and the Federal Home Loan Banks (FHLB) can trade their reserve balances but they cannot earn IOR. Due to this market segmentation, GSEs continued to have an incentive to lend funds at rates below IOR (Swanson, 2022), which was termed the "leaky floor" problem (Hamilton, 2020). In addition, the over-the-counter nature of the market means that counterparties can exert a certain degree of market power (Armenter and Lester, 2017).

In September 2013 the Fed therefore introduced an additional facility, the overnight reverse repurchase agreement (ON RRP) facility through which it borrows funds at the ON RRP rate. This allows a wider range of market participants who are not eligible to obtain IOR, notably money-market funds (MMF), to be compensated for their excess liquidity. The Fed sets this rate lower than IOR such that it provides a floor for the funds rate (Afonso, Cipriani and La Spada, 2022).

The Fed's key tool for implementing monetary policy in the new "ample reserves" regime is therefore to adjust the ON RRP and IOR while maintaining a sufficiently large amount of reserves.[7] As stated by the Federal Open Market Committee (FOMC), "with an ample supply of reserves, control over the level of the federal funds rate and other short-term interest rates is exercised primarily through the setting of the Federal Reserve's administered rates" (Federal Reserve Board, 2020). As indicated by the word "primarily", this suggests that determinants other than administered rates impact short-term interest rates. In this paper, I focus on one such potential factor: whether and to which extent reserves affect short-term interest rates.

[6] Today's trading volume is substantially below what it was before 2008. Kim, Martin and Nosal (2020) and Swanson (2022) provide an overview and discussion.

[7] See Ihrig, Senyuz and Weinbach (2020) for a more detailed description of the framework.

2.2 Models of the reserve market

The new approach for implementing monetary policy under ample reserves described in Section 2.1 has only been in effect for a relatively short period of time, as the Fed adopted it in response to events during and after the 2007/2008 financial crisis. As a result, while there is a growing literature on monetary policy implementation and transmission after 2008, there is currently no agreed-upon benchmark model of the overall regime. Regarding the role of reserves for determining short-term interest rates, there is a theoretical divide on whether they matter, which motivates the empirical analysis in this paper.

As described in Section 1 and Section 2.1, prior to 2008 the Fed used adjustments in the supply of reserves via open market operations to influence the fed funds rate. The seminal work by Poole (1968) analyzes the mechanism behind this tool from the bank's perspective. In the model, a bank optimizes its liquid balances in the form of reserves to meet regulatory requirements (including formal reserve requirements) and manage payment inflows and outflows. Prior to 2008, when reserve balances were scarce and did not earn interest, holding excess reserves meant forgoing potential returns from other asset types. However, payment flows occur later in the day when the interbank market is closed, making it uncertain for the bank to determine the optimal amount of reserves ex-ante. Consequently, the bank faces a trade-off between minimizing the opportunity cost of excessive reserve holdings and safeguarding against unexpected payment flows by trading in the interbank market. Based on each bank's reserve demand, the aggregate reserve demand curve slopes downward because a lower fed funds rate affects the opportunity costs for both borrowers and lenders. For borrowers, the cost of borrowing decreases, while for lenders, the benefit of lending decreases. As a result, all banks are generally willing to hold more reserves than they did previously (Ireland, 2014).

Based on the Poole (1968) view of the interbank market, authors such as Goodfriend (2002); Keister, Martin and McAndrews (2008); Ireland (2014) argue that when there is a large supply of reserves and interest payments on reserves, the link between reserves and the funds rate breaks down. Graphically, this results in a demand curve with a kink point, as shown in Figure 1a. Once the total supply of reserves exceeds a saturation point at which bank demand is fully satisfied, the demand curve for reserves becomes flat. Beyond this point, the funds rate is equal to the interest rate paid on reserves, and banks are indifferent between different amounts of reserve supply, as shown in the graph. Based on such a demand curve, short-term rates thus become "divorced" (Keister, Martin and McAndrews, 2008) from reserve balances when the Fed supplies high levels of reserves.[8]

The stylized view of Figure 1a is incomplete, however, because the original Poole (1968) model does not consider several types of frictions in post-2008 U.S. money markets and the banking system in

[8] As discussed in Section 2.1, segmentation in U.S. money markets meant that the IOR did not provide a floor for the funds rate, and this led to the introduction of the overnight reverse repurchase facility. Figure 1b shows the reserve market with the ON RRP as the floor instead of IOR.

general. One constraint for banks' arbitrage and trading of reserves is the over-the-counter nature of the fed funds market, where market participants can vary significantly in their characteristics and bargaining power (Bianchi and Bigio, 2022; Lagos and Navarro, 2023). Another important factor for post-crisis reserve demand are new regulations for bank liquidity management. These regulations introduce various additional trade-offs for banks when engaging in lending and borrowing. For instance, both the Basel III supplemental leverage ratio (SLR) and the Federal Deposit Insurance Corporation (FDIC) assessment fee penalize banks for having a larger balance sheet. This creates a wedge for arbitrage opportunities; for instance, a borrower in the funds market will only be willing to pay $(IOR - \kappa)$ such as to account for the balance sheet cost κ incurred by the transaction (Afonso et al., 2023*a*).

In addition, ongoing research has focused on the Liquidity Coverage Ratio (LCR) (Bech and Keister, 2017; Keister, 2017). The LCR requires banks to hold sufficient levels of high-quality liquid assets to cover a month's worth of net outflows (House, Sablik and Walter, 2016). While reserves are just one option of "Level 1" assets that can meet these requirements, banks and bank examiners prefer reserves for additional internal stress testing because they are more liquid and immediately accessible compared to other assets like treasuries (Nelson, 2022). The LCR also discourages banks from relying on unsecured overnight funding, such as in the federal funds market. It is likely that these regulations have permanently increased aggregate demand for reserves compared to before the financial crisis.

When taking into account this new regulatory environment and market micro-structures, theory allows for changes in reserves to impact the determination of short-term rates at a level of overall reserves that is still somewhat ample. Building on the Poole (1968) model, Afonso et al. (2023*b*) illustrate the reserve demand curve predicted by their model, which is separated into three zones (see Figure 1c). At the lower end, there is a steep region with "scarce" reserves, followed by an intermediate, flatter section with "ample" reserves, and a completely flat section with "abundant" reserves. The transition between ample and abundant reserves represents the point of satiation for the banking sector. If overall reserves fall below this level, short-term interest rates are jointly determined by reserves and policy rates, with the slope of the reserve demand curve steepening as reserves become scarcer. If overall reserves are above the satiation point, short-term interest rates are solely determined by the Fed's policy rates. This suggests that the relationship between reserves and interest rates is nonlinear, and strengthens as overall reserves drop.

2.3 Empirical model and estimation

The institutional background of monetary policy implementation after 2008 described in Section 2.1 as well as the theoretical work described in Section 2.2 provide the structure for an empirical model of the relationship between reserves and short-term interest rates.

The model starts from the perspective of an individual bank that solves a liquidity management problem which is based upon interest rates in different markets such as those for interbank and repo lending. The opportunity cost of choosing one option over the other is therefore represented by the relevant interest rate spread. If additional reserve balances decrease this opportunity cost directly, given market conditions, regulatory restrictions and other bank-specific aspects, these reserves are said to have a liquidity effect on interest rates. Monetary policy also enters the model through the Fed's administered rates and their arbitrage relationship with other interest rates.

At the aggregate level, the banking sector's choice of liquidity provision as a function of reserve balances can therefore be modeled in a single-equation specification capturing these two potential channels of monetary policy, with the relevant money market spread s_t, as follows:

$$s_t = c + \alpha \Delta ln(q_t) + \beta x_t + \gamma d_t + \sum_{j=1}^{p} \theta_j s_{t-j} + u_t \tag{1}$$

The commonly used spread in this context is the difference between the effective federal funds rate and interest on reserves ("fed funds spread" from here on). It captures the benefit of lending reserves on the interbank market at the funds rate minus the opportunity cost of not earning the IOR, and therefore represents bank choices about their balance sheet in the wholesale sector.

q_t is the main regressor that represents reserve balances. The parameter α therefore measures the impact of changes in reserves on money market rates, also referred to as liquidity effect. The regressor is included in log-differenced form due to non-stationarity. I discuss below how the data input series is constructed to avoid endogeneity in the regression.

I also include an appropriately chosen number (p) of lags of the dependent variable, a constant and two controls. x_t designates the spread between the treasury General Collateral Finance (GCF) repo index rate and IOR ("repo spread" from here on). Following Correa, Du and Liao (2022), this variable is used to represent the lending rate of banks in the reverse repo market as well as control for changes in the Fed's ON RRP rate, which is closely correlated with private repo rates. Based on post-crisis regulations that discourage unsecured lending, the repo market is an important part of banks' liquidity management, as they face a trade-off between lending on the wholesale market versus lending in the reverse repo market. It is therefore crucial to include a proxy for rates of this market in the model.

d_t is a dummy variable that indicates whether time t corresponds to the last trading day of the month. Such a variable is necessary since there is substantial evidence for month-end regularities in short-term rates that have to do with banks' window dressing of their Basel III liquidity coverage ratio (LCR), leverage ratio and other regulatory requirements (Correa, Du and Liao, 2022).

As discussed in Section 2.2, one way to look at the relationship between reserves and the fed funds spread after 2008 is through the lens of a kinked reserve demand curve with a satiation point (Afonso et al., 2023*b*). This framework offers several testable implications for the reduced-form relationship between the fed funds spread and changes in reserves. Does a satiation point of reserves exist? If yes, how strongly do reserve changes affect the fed funds spread above or below it? That is, how much does the effect depend on the overall liquidity environment?

To account for the presence of such nonlinearities in the relationship between the fed funds spread and reserves, a threshold autoregressive (TAR) model is estimated. Such a model allows estimated coefficients to formally depend on a chosen state variable Z_t and distinguishes between two different states. It is therefore a fitting method to test the hypothesis that a nonlinear relationship between the fed funds spread and reserves is driven by the overall level of available reserves (and therefore liquidity).

In the TAR, the spread s_t is modeled in two different states, depending on whether overall reserves are "high" (above λ) or "low" (below or equal to λ) as follows:

$$s_t = \begin{cases} c_2 + \alpha_2 \Delta ln(q_t) + \beta_2 x_t + \gamma_2 d_t + \sum_{j=1}^{p} \theta_{2,j} s_{t-j} + u_t & \text{if } Z_t < \lambda \\ c_1 + \alpha_1 \Delta ln(q_t) + \beta_1 x_t + \gamma_1 d_t + \sum_{j=1}^{p} \theta_{1,j} s_{t-j} + u_t & \text{if } Z_t \geq \lambda \end{cases} \tag{2}$$

The threshold λ used in Equation 2 is estimated via a grid search procedure based on a threshold variable that measures the overall liquidity environment (defined below). From all possible threshold options, the optimal threshold $\hat{\lambda}$ is then selected based on which model has the lowest Akaike Information Criterion (AIC).

The third part of the analysis is time varying. It builds on Equation 1 and uses rolling window estimation, where the equation is estimated for the linear model with updated estimation periods over time. The amount, or step, by which the samples move forward is chosen such that every subperiod, or estimation window, contains 350 observations. I then plot the estimated coefficients and standard error bands for each estimation window.

2.4 Identification

While the model in Equation 1 does not represent a demand function for reserves, it can be interpreted through that conceptual framework (see Figure 1c). In particular, to analyze the impact of reserve changes on short-term interest rates, we are interested in the sensitivity of reserve demand to changes in supply, which is the slope of the demand curve.

The slope parameter is closely related to the liquidity effect α in the reduced-form models of Equation 1 and Equation 2. But in order to correctly estimate α , a key condition must be satisfied: q_t needs to be uncorrelated with reserve demand shocks included in the error term u_t. In other words, the variable needs to capture changes in reserve balances that are not a consequence of money market conditions or other factors that themselves affect short-term interest rates.

Is this condition met when using data on total reserve balances held at the Fed? To determine any potential endogeneity, consider two different changes in the amount of reserves on the Fed balance sheet in Table 1. If the Fed increases or decreases the length of its balance sheet through open market operations, large-scale asset purchases or sales, reserves are added to or removed from the banking sector. If there is an increase in the volume of "autonomous" factors (reverse repo, treasury account, currency and others), however, there is simply a corresponding decrease in reserve balances. While fluctuations in autonomous factors change the composition of Fed liabilities, they do not affect the length of its balance sheet. An example is a household who sends a tax payment to the government. This transaction decreases the reserve balances of the depository institution that the household banks with, and increases the TGA by the same amount.

Before the crisis, the Fed used daily open market operations to adjust the supply of reserves and thereby changed the length of its balance sheet. Given that this occurred in reaction to reserve demand shocks that moved the fed funds rate off target, observed fluctuations in reserve balances were endogenous with respect to short-term interest rates. Since the current operational framework uses interest on reserves and the overnight reverse repo rate as policy tools to control the funds rate, the Fed has ended daily open market operations. Even though changes in the Fed's asset holdings through quantitative easing/quantitative tightening change the length of the balance sheet and thereby reserves, they are not used as a policy tool to target short-term interest rates. Therefore, changes in the Fed's total assets can be assumed to be exogenous with respect to the fed funds spread.

In contrast, changes in the composition of the liability side through fluctuations in the autonomous factors are likely correlated with demand shocks in u_t. But Lopez-Salido and Vissing-Jorgensen (2023) show that it is possible to construct an adjusted reserves measure without endogenous components. Based on the balance sheet in Table 1, the sum of reserve balances and the overnight reverse repo facility equals total Fed assets minus autonomous factors:

$$\underline{\text{Adjusted Reserves}} \coloneqq (\text{Reserves} + \text{ON RRP}) = (\text{Assets - Autonomous Factors}) \tag{3}$$

Since the measure of adjusted reserves corresponds directly to the exogenous portion of Fed assets, it is a suitable variable for estimating the liquidity effect in Equation 1 and Equation 2. Adjusted reserves are also used to calculate the threshold variable for the TAR estimation, where the reserve ratio is equal to adjusted reserves divided by nominal GDP, in percent.

The removal of any effects from autonomous factors from asset changes is especially needed such that there is no omitted variable bias due to the overall supply of treasuries. When a treasury bill is sold to a depository institution or money market fund, there will be a decrease in the reserve balances of the buyer, and a matching increase in the TGA balance as the government is paid for the sale. Similarly, money market funds can finance purchases of newly issued treasuries by reducing their investment in the Fed's overnight repo facility (Cipriani et al., 2022). At the same time, treasury issuance has an impact on repo rates such as the GCF repo rate because treasuries are used as collateral in these markets. As the TGA balance is included in the autonomous factors, these fluctuations are already excluded from the adjusted reserves measure in Equation 3. In addition, Smith (2019) provides institutional details on the timing of treasury auction settlement that exclude a simultaneous effect on both reserves and repo rates when using Wednesday-ending weekly data as in this paper.[9]

2.5 Data

Weekly time series data on the Fed's balance sheet are released in the Board of Governors' H.4.1. statistical release "Factors affecting reserve balances". The release is published each Thursday and contains the data from the previous day, which makes the data Wednesday-ending. To match the frequency and timing of this balance sheet data for the analysis, daily data are transformed into weekly by retaining their Wednesday value, and quarterly data are assumed to repeat their value each week of the quarter.

All spreads and interest rates are measured in basis points. The daily interest rate index for General Collateral Finance (GCF) repurchase contracts on U.S. Treasuries is obtained from the Depository Trust and Clearing Corporation (DTCC).[10] Its historical data is published with a one-year delay and therefore available until the end of 2022 at the time of writing. The other interest rates are downloaded from Federal Reserve Economic Data, FRED (with website identifier listed in brackets): the daily effective federal funds rate ("DFF"), and the interest on excess reserves ("IOER") (until 07/28/2021) and interest on reserve balances ("IORB") (from 07/29/2021). The latter two series are merged to form one continuous series that I refer to as IOR in the paper for simplicity. Two separate series exist because initially the Fed distinguished between interest on required reserves (IORR) and interest on excess reserves (IOER). Given the large increase in overall reserves and the switch to the ample reserves regime, reserve requirements did not play a significant role, as opposed to during pre-crisis monetary policy implementation under scarce reserves. Required reserves were officially set to zero in March 2020, which ended the need to distinguish between IORR and IOER, and the Fed introduced a new series.

Reserves in this paper correspond to the balance sheet item "Reserve Balances with Federal Reserve Banks" in the H.4.1. release, which is also available from FRED ("WRBWFRBL"). The overall volume of overnight reverse repurchase agreements (ON RRP) is the balance sheet item "Liabilities and Capital: Liabilities: Reverse Repurchase Agreements: Others", which excludes foreign official and international accounts ("WLRRAOL"). Seasonally adjusted nominal GDP is obtained at quarterly frequency ("GDP").

[9] When a treasury auction with details of the offering such as maturity and amount is announced before a given Wednesday, traders have all the information needed to trade and price the new securities before they are issued. Thus the effect of treasury supply on money market rates such as the repo rate is immediate. In contrast, the settlement of the payment only occurs after Wednesday, up to one week after.

[10] https://www.dtcc.com/-/media/Files/Downloads/Clearing-Services/FICC/GCF-Index-Graph.xlsx

As argued previously, the introduction of IOR in October 2008 represented a profound change in the Fed's monetary policy implementation framework. To eliminate any potential confounding effects during the initial transition period, the first observation of the sample is January 7, 2009. To investigate any potential time shifts in the spread-reserves relationship, I estimate models over four different subperiods: baseline (before the pandemic), including the pandemic, pre-liftoff and post-liftoff (without pandemic).

The pre-pandemic subperiod ends in February 26, 2020 given that the Fed cut the target range for the fed funds in an emergency measure on March 3, 2020. For estimation including the pandemic, the data ends on December 28, 2022. To capture only pre-pandemic policy tightening, the first observation of the post-liftoff subperiod is set to December 23, 2015, which is the first Wednesday after an increase in the fed funds target range was announced by the Federal Open Market Committee (FOMC) on December 16, 2015.

3 Results

3.1 Linear model and rolling-window regression

To provide a starting point for the analysis, I first estimate the linear model in Equation 1. The dependent variable is the spread between the effective federal funds rate over interest on reserves (fed funds spread), and adjusted reserves (Equation 3) as well as the spread of the GCF repo rate over interest on reserves (repo spread) are the main regressors of interest. Table 2 shows the results of this estimation.

For both the baseline period between 2009 and 2020, as well as for the subperiods, changes in adjusted reserves have a negative effect on the fed funds spread. The coefficient is statistically significant at the 5% level or lower for all four estimation periods. Since the model controls for policy changes in the Fed's administered policy rates, this result indicates that reserves independently contribute to the determination of the funds spread. When interpreting the results from the perspective of reserve demand by the banking sector (as seen in Figure 1b), the negative sign of the coefficient is consistent with a point on the negatively-sloped part of the reserve demand curve. As discussed in Section 2.2, increases in overall reserves reduce the cost of obtaining and holding additional liquidity, which in turn lowers the fed funds spread.

During the baseline period, the average week-to-week change in the funds spread is relatively low, at 0.015 basis points. Based on the linear model, when the growth rate of adjusted reserves decreases by one percentage point, the fed funds spread increases by about 0.08 basis points. This is a relatively large decrease in reserves, however. To increase the funds spread by its average of 0.015 basis points with only a change in reserves (holding policy rates constant), the model indicates that the growth rate of reserves only needs to decrease by 0.16 percentage points.

In addition, I find that the repo spread has an equally important effect on the fed funds spread as reserves, as shown in Table 2. The estimated coefficients are positive for all four estimation periods and statistically significant at the 5% or 1% level. In absolute size, the impact of the repo spread on the fed funds spread is similar to the effect of changes in adjusted reserves. For the baseline estimation, an increase in the repo spread by one basis point increases the fed funds spread by 0.09 basis points.

The strength of this relationship provides evidence that the ON RRP facility is an important element of monetary policy implementation, as private repo rates like the GCF rate in the repo spread are closely related to the Fed's ON RRP rate. Recall that a much larger number of counterparties than those eligible for IOR can earn a return on their excess funds at the ON RRP facility. Given the outside option of investing in the ON RRP, they have bargaining power to demand higher rates for other transactions. Afonso et al. (2023*c*) show that both rates are needed to maintain control over the fed funds rate in its target range, as each administered rate affects a different part of the distribution of fed funds rates paid in the market.

Based on the theoretical framework of reserve demand discussed in Section 2.2, the linear results suggest model misspecification. The issue arises from the fact that the model consistently shows a negative and significant relationship between reserve changes and the fed funds spread, regardless of the estimation period. However, this contradicts what would be expected in a regime of monetary policy implementation with ample reserves. Due to the substantial variation in total liquidity in the form of reserves and the ON RRP over the estimation period (see Figure 2a), it is unlikely that the relationship is constant, and always negative. The fact that the Fed has maintained control over the funds rate without substantial interventions in the form of open market operations suggests the existence of a point of saturation for liquidity, as illustrated in Figure 1c. The time variation for the estimated coefficients between the estimation periods in Table 2 also suggests a changing relationship over time. For instance, during the pre-liftoff period (Column (3)), a one percentage point increase in the growth rate of adjusted reserves is estimated to decrease the fed funds spread by 0.05 basis points. In contrast, during the post-liftoff period (Column (4)), the effect nearly doubles and the spread decreases by 0.09 basis points.

The results of rolling window regressions of the linear model in Figure 5 provide further evidence of a time-varying relationship between reserves and the fed funds spread. The graphs display the estimated coefficients for adjusted reserves and the repo spread for each estimated sample window, along with their error bands. The baseline rolling window regression for adjusted reserves suggests a stable and consistently negative relationship that gradually changes over time. Initially the estimated coefficient becomes smaller in absolute value but there is a relatively steep increase in absolute value once the model is estimated for data between 2010 and 2016 (Figures 5a and 5c). For the repo spread, I find a different pattern of large, yet gradual decline in its value (Figures 5b and 5d). At the beginning of the estimation period, a one basis point increase is estimated to increase the fed funds spread by 0.16 basis points. However, over time, the effect weakens steadily and eventually approaches zero. This suggests that the trade-off between lending rates in the reverse repo market and lending rates in the wholesale market has become less important for banks over time. In addition, considering the correlation between private repo rates and the Fed's ON RRP rate, it also indicates a change in the pass-through of ON RRP rate changes to the fed funds spread. Similar results are obtained when including the pandemic period.

Taken together, the subperiod estimation of the linear model as well as the rolling window regressions provide further evidence for time-varying coefficients on both variables. The strengthening of the impact of adjusted reserves on the funds spread in the later part of the estimation period is consistent with the time-varying estimation in Smith and Valcarcel (2023). They find that reserves affect the fed funds spread more strongly during the Fed's pre-pandemic periods of balance sheet unwinding than during the earlier balance sheet expansion. This could be due to the different operational nature of these two periods. For example, the FOMC made a deliberate effort to separate expectations of future rate increases from balance sheet unwinding during the post-liftoff period after 2015, aiming to communicate balance sheet changes as a separate policy tool.Regulatory changes, such as reforms in the tri-party repo market and changes in capital requirements, may also contribute to the time variation. The finalization of the supplemental leverage ratio (SLR) in September 2014 is particularly important, as it could have permanently increased banks' demand for reserves for regulatory reasons. This makes the fed funds spread more sensitive to fluctuations in adjusted reserves after that date.

While these factors may contribute to changes in the relationship between reserves and the funds spread over time, I am primarily interested in whether this relationship depends nonlinearly on the overall level of adjusted reserves, or available liquidity. Figure 2a shows the substantial fluctuations in the levels of reserves and the ON RRP, and Figure 2c illustrates the resulting reserve ratio of adjusted reserves as a percentage of nominal GDP. It reached a maximum level before the pandemic of almost 17% in 2014 before quantitative tightening led to a decline below 7% in 2019. The ratio then increased again due to monetary policy interventions during the pandemic. I use the variation in this variable for the estimation of the threshold model presented in Section 3.2.

3.2 Threshold model

To determine whether the relationship between the funds spread and reserve changes as well as the repo spread is time-varying, regime-dependent on overall liquidity, or both, I estimate threshold autoregressive (TAR) models. The models condition on adjusted reserves scaled by nominal GDP as state variable that triggers the switch between regimes (Equation 2). They are estimated for the same time periods as the linear model so that both time variation and the effect of varying liquidity conditions are controlled for. As described in Section 2.3, for each subperiod the threshold of the reserve ratio at which the overall reserves environment transitions from relatively scarce to more ample is estimated via grid search based on AIC.

The results for these estimations are presented in Table 3 for the baseline estimation and the robustness check with the pandemic, and in Table 4 for the subperiods before and after interest rate liftoff. While the model is a reduced-form estimation, it provides empirical evidence related to the shape of the reserve demand function, as discussed in Section 2.2. In particular, interpreted through the lens of such a model, the estimated threshold suggests a potential value for the satiation point of reserves (that is, the kink point in the demand function of Figure 1b and Figure 1c)

I find that as for the linear model, adjusted reserves have a negative effect on the fed funds spread during the four estimation periods. However, the nonlinear estimation reveals that this is mainly the case when the reserve ratio drops below the estimated threshold, but not when it is above. This is therefore in line with the idea of a demand curve with a satiation point. In the baseline estimation, the estimated threshold is a reserve ratio of 12% . Below the threshold, a one percentage point increase in the growth rate of adjusted reserves is estimated to decrease the fed funds spread by 0.09 basis points, whereas above the threshold, the effect of adjusted reserves on the funds spread is statistically insignificant. Similarly, the repo spread increases the funds spread by 0.11 basis points in the low regime, and by 0.04 in the high regime. An informal test of parameter stability also rejects the null hypothesis that either the impact of reserves or the repo spread is equal in the two regimes. Figure 3a shows the distribution between the two regimes over time. Given the number of time periods where the ratio is below 12%, reserve changes contribute to the determination of the funds spread 61% of the time.

In Table 4, I present the results of estimating a separate TAR model for the period before the interest rate liftoff in 2015, and for the period after liftoff until the pandemic, respectively. This allows to simultaneously check whether the relationship between reserves and the funds spread is time-varying, as well as whether the threshold (satiation point) itself changes over time.

The results confirm the previous finding that adjusted reserves have a larger impact on the fed funds spread after the interest rate liftoff than before. Before liftoff, a one percentage point increase in the growth rate of adjusted reserves decreases the funds spread by 0.06 basis points when reserves are low, and has no significant effect when reserves are high. Even though these coefficients are different in the two regimes, the informal Wald test cannot reject the null hypothesis that there is no difference between low and high reserve ratio periods. In contrast, after liftoff, when reserves are low, a one percentage point increase in the growth rate of adjusted reserves decreases the funds spread by -0.66 basis points. Adjusted reserves still do not significantly affect the funds spread when reserves are high, but for this time period, the null hypothesis that adjusted reserves affect the fed funds spread equally in both regimes is rejected at the 5% significance level. Similarly, the results for the model estimated on data including the pandemic (Table 3) suggest that during this time period the relationship between adjusted reserves and the fed funds spread might not be dependent on overall reserves (though that is not the case for the repo spread).

The results also suggest a time-varying satiation point of reserves. During the pre-pandemic period, reserves become relatively scarce when the reserve ratio falls below 12%. When this time period is split up into pre- and post-liftoff, the threshold is higher before liftoff (9%) than after (7%). Similarly, the threshold is also 7% when the pandemic is included. A potential issue with this threshold value is that only a limited number of observations are included in the low reserves regime, and those fall mostly within the time period around the severe stress in U.S. money markets in September 2019. Given that threshold model selection can be sensitive to outliers, it is therefore advisable to use judgement and compare the first-best selection of the model with the second-best selection. These threshold values are shown in Figures 3 and 4. Figure 4a shows that the second-best choice for the post-liftoff threshold is at 11% instead of 7%, which is closer to the baseline estimate of 12%. There is also evidence that this threshold is more appropriate to describe the satiation point during the post-2015 period, based on the evolution of the ON RRP facility. The time period during which the reserve ratio is below 11% (Figure 4b) coincides with the time during which the volume at the ON RRP was drawing down substantially. As the ON RRP is often described as an outlet for "excessive" liquidity, this suggests that a decrease in balances deposited there indicated the beginning of a regime with less ample reserves.

Given that the banking sector's liquidity needs likely evolve over time, a time-varying threshold seems plausible. From the bank side, this could be determined by factors such as regulatory requirements, non-performing loan rates and competition on deposits and deposit rates. Therefore, what is considered an "ample" amount of overall reserves at one point in time might be insufficient at another time. As the informal Wald tests for the TAR models illustrate, the threshold is probably not always binding.

The results also add additional insight to the findings in Afonso et al. (2023*a*). They identify 2010-2011 and 2018-2019 as time periods where their estimated reserve demand curve has a steeper slope. Both time periods overlap with the reserve ratio falling below the estimated threshold for the pre-and post-liftoff models, or alternatively, the model without the pandemic (see Figure 2c). Under these conditions the TAR estimations capture larger effects of adjusted reserve changes on the fed funds spread than above the thresholds. This suggests that the larger slope (in absolute value) in Afonso et al. (2023*a*) during 2010-2011 and 2018-2019 is driven by the state-dependent relationship between adjusted reserves and the fed funds spread based on the overall level of reserves. In comparison, the rolling regression in Figure 5 shows that the coefficient on adjusted reserves in the linear (unconditional) fed funds spread regression is largely stable over time, even though there are some fluctuations in its absolute value. Thus it seems that the common properties of the liquidity effect during the 2010-2011 and 2018-2019 time periods only arise when accounting for the overall amount of reserves. My results therefore show that the effect of adjusted reserves on the funds spread does not only change during periods of balance sheet expansion or contraction, but that even within these periods, there are differences between relatively high and low reserves regimes.

Overall the TAR estimation provides evidence that the reduced-form relationship between the fed funds spread and adjusted reserves as well as the repo spread depends on the overall reserves environment, in addition to being time-varying. The results also suggest that this state-dependency might disappear, as can be seen for the estimation period before interest-rate liftoff, or when data including the pandemic is included. The latter might suffer from various structural breaks due to the overall negative economic impacts of the pandemic, however, and should be interpreted with caution.[11]

To further check the robustness of TAR models, I compare whether the threshold selection via grid search changes the results (see Figure 6 - Figure 9). For each of the possible threshold values of the adjusted reserve ratio, the TAR is estimated and the coefficient values as well as the standard errors for both the low and high regime are plotted. For the baseline period, the graphs in Figure 6 show that the results are not substantially affected by choosing the optimal threshold at 12% (from Table 3). When the reserve ratio is low, an increase in adjusted reserves consistently has a negative and statistically significant effect of similar size on the fed funds spread. Similarly, when overall reserves are high, the effect is statistically insignificant for all but the lowest threshold value choices. For the repo spread various threshold choices also do not materially change either the quantitative or qualitative conclusions.

3.3 Counterfactual analysis

So far, the results have been presented in terms of changes in the growth rate of adjusted reserves, in line with the formulation of the econometric model. To provide a clearer understanding of how policymakers might consider the role of the overall reserves environment in controlling short-term interest rates, I present the impact of a counterfactual policy intervention in Table 5. This intervention involves increasing adjusted reserves by \$100 billion at date T during each of the four estimation periods. All other interest rates and control variables are assumed to remain constant. The resulting change in the fed funds spread (in basis points) is referred to as the "liquidity effect".

I consider two scenarios for the simulation: in the first scenario, even with the additional reserves, the overall reserves environment stays "low". The liquidity effect is therefore calculated using the estimated coefficients for the low regime from the TAR models (from Table 3 and Table 4). If, however, the additional reserves lead to a switch into the "high" regime, the liquidity effect is calculated with the high regime coefficients. Date T, which provides the starting level of adjusted reserves, is specifically chosen such that the reserve ratio for that week is just below the estimated threshold for the respective model. This choice of the starting level for adjusted reserves can therefore illustrate nonlinear effects right at the transition between a scarcer and more abundant reserves environment, as defined by the results of the TAR estimation. For reference, the liquidity

[11] In particular, between 2020 and 2021 the Fed temporarily excluded U.S. Treasury securities and reserves from the calculation of the SLR requirement. As a result, any previously binding constraint for banks with regard to reserve holdings might have been removed, which would lead to a weaker effect of adjusted reserve changes on the funds spread. The decrease of the estimated threshold from 12% pre-pandemic to 7% when the pandemic is included could also be interpreted as a consequence of this temporary policy change.

effect is also calculated using the estimated coefficients of the linear model (from Table 2).

The results of this counterfactual analysis in Table 5 again illustrate that reserve changes consistently have larger effects on the fed funds spread during low reserve periods than during high reserve periods. For all estimation periods, an increase in adjusted reserves corresponds to a decrease in the fed funds spread, whereas during high reserve periods, this change is much smaller or even positive (and statistically insignificant).

In addition, for the same starting value of adjusted reserves, the counterfactual liquidity effects in the low reserves environment calculated with the results of the linear model are smaller than if they are calculated based on results from the nonlinear model. Again, this suggests that linear estimation understates the liquidity effect because it averages out the effect of fluctuating overall reserve availability. For example, Bräuning (2018) finds a liquidity effect of around - 0.3 basis points for a $100 billion increase in reserves during the 2013 - 2017 time period with a linear model. In comparison, from the threshold estimation I find that the counterfactual liquidity effect for the pre-liftoff period in the low regime is - 0.47. It becomes even higher after liftoff, with a substantial liquidity effect of minus 4 basis points as a result of an increase in adjusted reserves by $100 billion (Column (d) in Table 5). As mentioned before, this strengthening of the liquidity effect is consistent with previous literature (Afonso et al., 2023*a*; Smith and Valcarcel, 2023).

As discussed in Section 3.2, for the post-liftoff period in particular, the optimal threshold of 7% leads to a low regime with only a small number of observations, which could be picking up outlier effects. Table 5 therefore also includes the simulation results for the second-best TAR specification choice according to AIC for the post-liftoff period, which has a threshold of 11%. This reduces the liquidity effect in the lower regime and makes it more comparable in size to the other subperiods. For this model, the counterfactual liquidity effect is -0.859 basis points in the low regime and 0.41 basis points in the high regime (though not statistically significant). Thus even with a higher threshold, the liquidity effect more than doubles in the low regime compared to the pre-liftoff period.

4 Summary and concluding remarks

The global financial crisis significantly altered the way monetary policy is carried out in the United States, leading to new policy procedures. Key changes include the creation of ample bank reserves, expansion of the Fed's balance sheet through large-scale asset purchases, the use of new liquidity management operations including interest on reserves, and enhanced banking sector regulation and supervision.

A key question for the successful implementation of monetary policy and consideration of a return to scarce reserves in the future is: how do ample bank reserves impact monetary policy implementation?

I address this question by focusing on the relationship between reserves and the fed funds spread (fed funds rate - IOR), which captures the price of liquidity in the banking system. I build on the prior literature in this area by using both linear and threshold-autoregressive (TAR) models and an adjusted measure of reserves to control for potential endogeneity.

I provide evidence that the relationship between adjusted reserves and the fed funds spread is both dependent on the overall amount of reserves as well as time-varying. When a linear model is estimated over various subperiods, the impact of adjusted reserves is statistically significant as well as relatively stable in magnitude. But this is because the linear model does not capture the state-dependence of the interest rate response. In contrast, the TAR estimations show a difference between periods with overall low and high reserves: in the low reserves environment, additional adjusted reserves lower the fed funds spread, whereas in the high reserves regime, the effect is either smaller, or insignificant. This state-dependency is likely due to the unique role of reserves in post-crisis liquidity management. Time variation between different subperiods in both the size of the liquidity effect as well as the threshold at which overall reserves become "scarce" also suggests that the constraints banks face with respect to wholesale lending and borrowing change over time.

One limitation of the analysis in this paper is that repo markets are not theoretically modeled, due to the reduced-form nature of the estimation. Yet the liquidity effect from reserve changes could be affected by simultaneous choices that banks and other market participants make on wholesale and retail lending, on the reserve volume held on their balance sheets, and on short-term repo financing. Repo markets have also undergone reforms over the post-crisis years that might have led to structural changes in arbitrage relationships. In addition, given that treasury securities form the basis for most of U.S. collateralized lending, repo markets and treasury markets are also closely linked. As interest rates continue to rise with QT, the collateral value of these assets on bank balance sheets will decline and thereby reduce the overall quantity of safe assets available in the economy as well as lead to unrealized losses for banks. A future extension of my work could therefore consist in a multi-equation estimation that explicitly models these markets, similar to the simultaneous estimation method in Smith and Valcarcel (2023).

The results in this paper could have important implications for future monetary policy goal setting and banking sector regulation. Currently the level of reserves is only monitored by the Fed indirectly in the context of what has been termed "minimally ample" reserves,[12] but has not taken the role of an official, additional target of monetary policy. Yet if the composition of the Fed's overall balance sheet interacts with banks' wholesale borrowing and lending, this could mean that its role requires more consideration, and the Fed could even consider a more explicit target as it continues quantitative tightening.

The more recent growth in usage of the ON RRP facility (see Figure 2a) also raises the question of whether current projections by the Federal Reserve Bank of New York for the path of reserves/GDP sufficiently measure overall liquidity from the perspective of the banking sector. My results as well

[12] https://www.reuters.com/business/finance/us-banks-face-trillion-dollar-reverse-repo-headache-2022-08-02/

as those in Lopez-Salido and Vissing-Jorgensen (2023) suggest that the sum of reserves and ON RRP might be an alternative measure to monitor, as upward pressure on the fed funds spread might appear at higher thresholds than the currently used reserves/GDP criterion predicts. Closely related is also the question of whether certain post-crisis rules for liquidity management have had undesirable effects on monetary policy transmission and should be modified accordingly.

5 Figures and Tables

Table 1: Federal Reserve Balance Sheet

Assets	**Liabilities**
U.S. Treasury securities	Reserve balances
Mortgage-backed securities (MBS)	Reverse repurchase agreements (ONRRP)
Other assets	Treasury General Account (TGA)
	Currency
	Other liabilities

Table 2: Linear model

	Dependent variable: Fed funds spread (bps)			
	(1)	(2)	(3)	(4)
Key regressors	Baseline	With pandemic	Pre-Liftoff	Post-Liftoff
Constant	-0.677***	-0.365***	-1.454***	-0.359
	(0.188)	(0.142)	(0.294)	(0.238)
Δln(Adjusted Reserves)	-8.466***	-8.628***	-5.778**	-9.775**
	(2.217)	(2.274)	(2.536)	(3.882)
Repo spread	0.086***	0.076***	0.151***	0.064**
	(0.022)	(0.019)	(0.023)	(0.028)
Observations	579	727	360	219
Regression R^2	0.94	0.93	0.89	0.94

The table shows the results of the linear estimation of the fed funds spread model (Equation 1) over different estimation periods (adjusted for lags): baseline (28 January 2009 - 26 February 2020), including the pandemic (28 January 2009 - 28 December 2022), pre-liftoff (28 January 2009 - 16 December 2015) and post-liftoff (23 December 2015 - 26 February 2020). The regressors are the week-to-week change in the natural logarithm of adjusted reserves, the repo spread (General Collateral Finance (GCF) repo rate - IOR), a constant and four lags of the dependent variable as well as a dummy for the last trading day of the month. Standard errors are adjusted for heteroskedasticity and autocorrelation using the Newey-West procedure. $***$, $**$, and $*$ indicate statistical significance at the 1 percent, 5 percent and 10 percent significance level, respectively.

Table 3: Threshold model: baseline (Jan 2009- Feb 2020) and with pandemic (Jan 2009 - Dec 2022)

	Dependent variable: Fed funds spread (bps)			
Key regressors	(1) Baseline		(2) With pandemic	
	Low ($Z_t < \hat{\lambda}$)	High ($Z_t \geq \hat{\lambda}$)	Low ($Z_t < \hat{\lambda}$)	High ($Z_t \geq \hat{\lambda}$)
Constant	-0.791***	-1.738***	-0.261	-0.419***
	(0.203)	(0.508)	(0.255)	(0.149)
Δln(Adjusted Reserves)	-9.807***	2.056	-8.901*	-8.096***
	(2.726)	(3.690)	(4.952)	(2.561)
Repo spread	0.111***	0.042***	0.127***	0.058***
	(0.031)	(0.013)	(0.009)	0.015)
Observations	356	223	83	644
Estimated threshold ($\hat{\lambda}$)	12%		7%	
Regression R^2	0.94		0.93	
Wald-Tests				
a) $H0$: fully linear model	p-value = 0.0029		p-value = 0.000	
b) $H0$: $\alpha_1 = \alpha_2$	p-value = 0.0167		p-value = 0.890	
c) $H0$: $\beta_1 = \beta_2$	p-value = 0.0145		p-value = 0.000	

The table shows results for the threshold-autoregressive estimation of the fed funds spread model (Equation 2) over two estimation periods (adjusted for lags): baseline (28 January 2009 - 26 February 2020) and including the pandemic (28 January 2009 - 28 December 2022). The regressors are the week-to-week change in the natural logarithm of adjusted reserves, the repo spread (General Collateral Finance (GCF) repo rate - IOR), a constant and four lags of the dependent variable as well as a dummy for the last trading day of the month. Standard errors are adjusted for heteroskedasticity and autocorrelation using the Newey-West procedure. $***$, $**$, and $*$ indicate statistical significance at the 1 percent, 5 percent and 10 percent significance level, respectively.

The threshold variable is the ratio of adjusted reserves over nominal GDP (in percent). The threshold $\hat{\lambda}$ is estimated via grid search across a range of thresholds based on the lowest Akaike Information Criterion (AIC). Wald-Tests of parameter stability are used to test null hypotheses that different subsets of the regression parameters are equal in the two regimes. Null hypothesis a) restricts the parameters for all three regressors to be equal. In null hypothesis b), only the parameters for Δln(Adjusted Reserves) are equal, and in null hypothesis c), only those for the repo spread.

Note that the Wald-Test p-values should only be interpreted informally since they are analytical results from standard χ^2 distributions. Since the threshold parameter λ is undefined when testing the null hypothesis of linearity, the test statistic distribution becomes nonstandard. For formal test results, bootstrap simulation is therefore needed to determine correct standard errors and critical values (Caner and Hansen, 2001).

Table 4: Threshold model: before and after interest rate liftoff on December 16, 2015

	Dependent variable: Fed funds spread (bps)			
Key regressors	(1) Pre-Liftoff		(2) Post-Liftoff	
	Low ($Z_t < \hat{\lambda}$)	High ($Z_t \geq \hat{\lambda}$)	Low ($Z_t < \hat{\lambda}$)	High ($Z_t \geq \hat{\lambda}$)
Constant	-1.610***	-3.462***	-1.599**	-0.326*
	(0.342)	(0.494)	(0.792)	(0.182)
Δln(Adjusted Reserves)	-6.151**	-0.958	-66.858**	-4.928
	(3.263)	(2.463)	(26.945)	(3.451)
Repo spread	0.224***	0.152***	0.135***	0.024**
	(0.029)	(0.021)	(0.014)	(0.010)
Observations	117	243	12	207
Estimated threshold ($\hat{\lambda}$)	9%		7%	
Regression R^2	0.91		0.96	
Wald-Tests				
a) $H0$: fully linear model	p-value = 0.000		p-value = 0.000	
b) $H0$: $\alpha_1 = \alpha_2$	p-value = 0.227		p-value = 0.018	
c) $H0$: $\beta_1 = \beta_2$	p-value = 0.004		p-value = 0.000	

The table shows results for the threshold-autoregressive estimation of the fed funds spread model (Equation 2) over two estimation periods (adjusted for lags): pre-liftoff (28 January 2009 - 16 December 2015) and post-liftoff (23 December 2015 - 26 February 2020). The regressors are the week-to-week change in the natural logarithm of adjusted reserves, the repo spread (General Collateral Finance (GCF) repo rate - IOR), a constant and four lags of the dependent variable as well as a dummy for the last trading day of the month. Standard errors are adjusted for heteroskedasticity and autocorrelation using the Newey-West procedure. $***$, $**$, and $*$ indicate statistical significance at the 1 percent, 5 percent and 10 percent significance level, respectively.
The threshold variable is the ratio of adjusted reserves over nominal GDP (in percent). The threshold $\hat{\lambda}$ is estimated via grid search across a range of thresholds based on the lowest Akaike Information Criterion (AIC). Wald-Tests of parameter stability are used to test null hypotheses that different subsets of the regression parameters are equal in the two regimes. Null hypothesis a) restricts the parameters for all three regressors to be equal. In null hypothesis b), only the parameters for Δln(Adjusted Reserves) are equal, and in null hypothesis c), only those for the repo spread.
Note that the Wald-Test p-values should only be interpreted informally since they are analytical results from standard χ^2 distributions. Since the threshold parameter λ is undefined when testing the null hypothesis of linearity, the test statistic distribution becomes nonstandard. For formal test results, bootstrap simulation is therefore needed to determine correct standard errors and critical values (Caner and Hansen, 2001).

Table 5: Counterfactual analysis: Liquidity effect in different reserve environments

	Model specification				
	(a) Baseline	(b) With pandemic	(c) Pre-Liftoff	(d) Post-Liftoff	(e) Post-Liftoff (Second-best)
Estimated threshold	12%	7%	9%	7%	11 %
Baseline at T					
Date	May 22, 2013	Oct 07, 2009	March 16, 2011	May 1, 2019	Jan 31, 2018
Adjusted reserves (R_T) ($millions)	1,975,178	963,186	1,334,289	1,460,037	2208173
Liquidity effect at T (in basis points)					
Low regime	- 0.507	- 0.957	- 0.471	- 4.429	- 0.859
High regime	0.097	- 0.787	- 0.049	- 0.326	0.410
Linear	- 0.441	- 0.881	- 0.441	-0.648	-0.433

The table shows the estimated change in the fed funds spread (in basis points) if there was an increase in adjusted reserves by $100 billion at date T while holding all other variables constant. The date is chosen for each estimation period such that the reserve ratio at that time lies just below the estimated threshold for the model. The total amount of adjusted reserves at date T is given in millions.

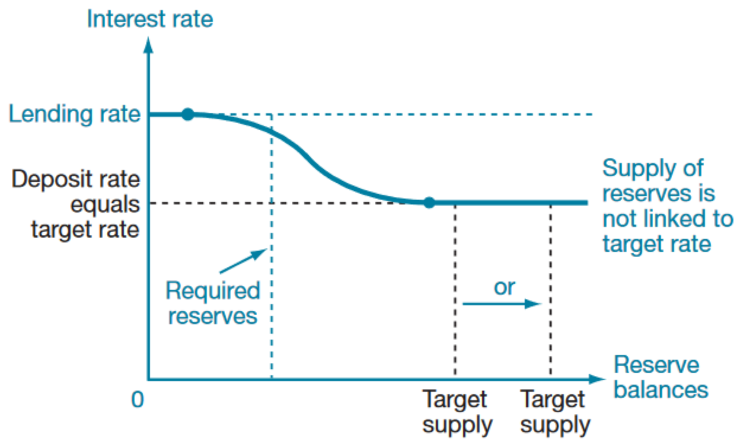
The counterfactual liquidity effect is then calculated as follows:

$$\text{Counterfactual LE} = \alpha * ln\left(\frac{R_T + 100,000}{R_T}\right) \tag{4}$$

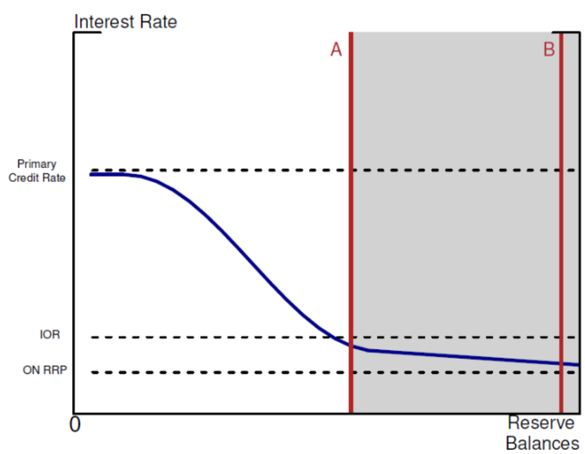
where R_T is the amount of adjusted reserves at T and α is the estimated regression coefficient for adjusted reserves from either the low or high regime of the TAR model (see Table 3 and 4), or from the linear model in Table 2.

Figure 1: Reserve market equilibrium with ample reserves

(a) No frictions: Interest on reserves as the floor (Keister, Martin and McAndrews, 2008)



(b) ON RRP as the true floor (Ihrig, Senyuz and Weinbach, 2020)



(c) Three zones of reserves demand curve (Afonso et al., 2023*a*)

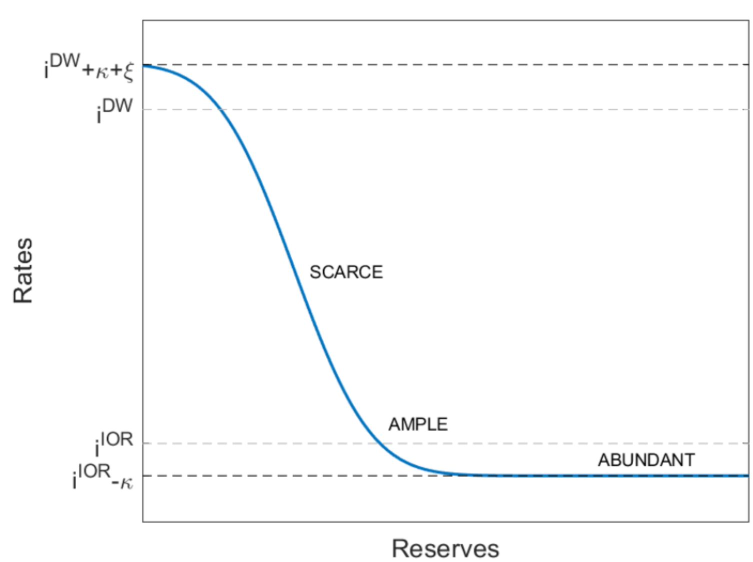
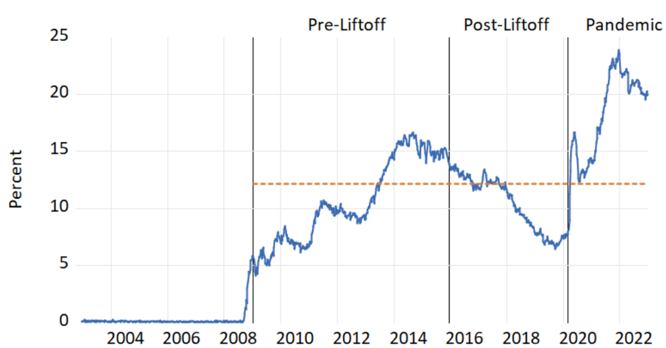


Figure 2: Reserve measures (Weekly data)

(a) Reserve balances and the and the Overnight Reverse Repurchase Facility (ON RRP)

(b) Adjusted reserves (Reserves + ON RRP)

(c) Reserve Ratio (Adjusted reserves/Nominal GDP)

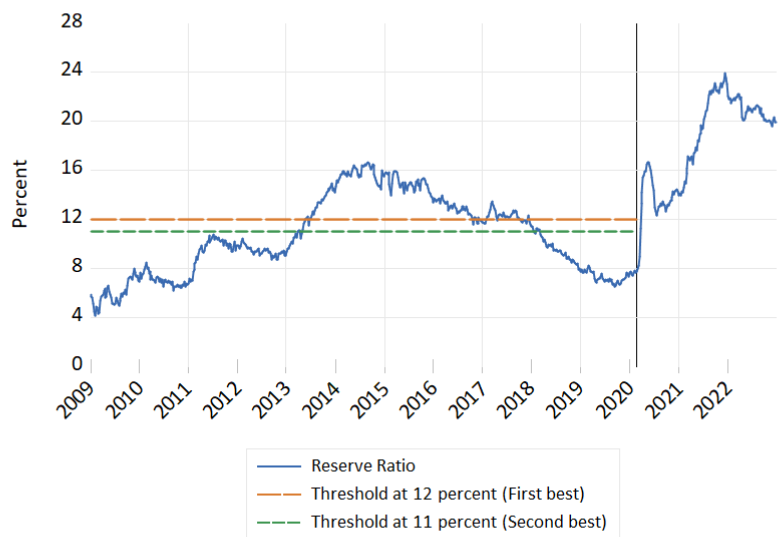


The vertical lines indicate (from left to right) the start of the estimation period in January 2009, the interest rate liftoff in December 2015, and the start of the pandemic in March 2020. The dotted line indicates the median of the reserve ratio between 2009 and 2022 (12.14 percent). Between 2009 and before the pandemic the median is 10.3 percent. The median is 9.9 percent for the period between 2009 and before the interest rate liftoff on December 23, 2015 and 10.4 percent after liftoff and before the pandemic.

Figure 3: Estimated thresholds for baseline threshold model and with pandemic

The graphs show the estimated value of the overall liquidity threshold in the threshold-autoregressive model. The threshold variable is the ratio of adjusted reserves (reserves + ON RRP) to nominal GDP (in percent). Intuitively, the estimated threshold can be interpreted as a point where liquidity reaches saturation, dividing the sample into two parts. Below the estimated threshold, liquidity in the form of reserves and the overnight reverse repo facility is relatively low, while above the threshold, liquidity is relatively high. The threshold estimate is obtained through a grid search across a range of thresholds, selecting the model with the lowest Akaike Information Criterion (AIC). The corresponding threshold value of that model is considered the best estimate. As a robustness check the graphs also show the second-best threshold estimate (from the model with the second lowest AIC). The vertical line indicates the beginning of the pandemic (March 2020).

(a) Estimated thresholds for baseline period (January 2009 - February 2020)



(b) Estimated thresholds with pandemic (January 2009 - December 2022)

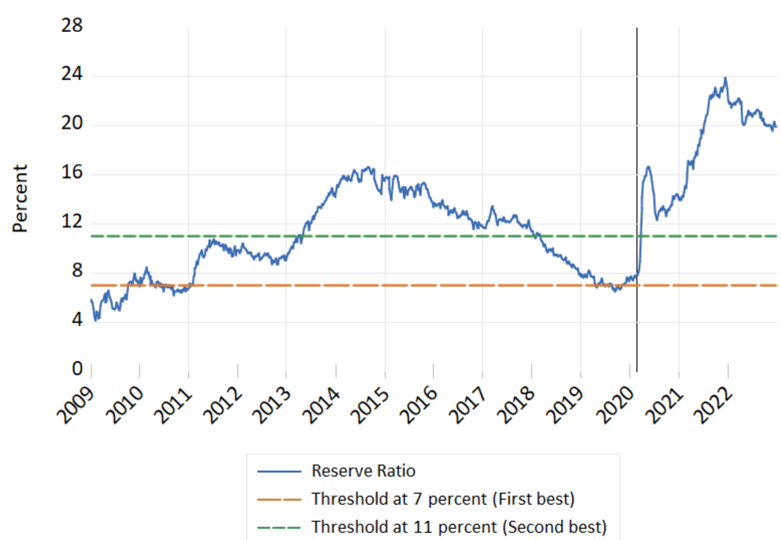
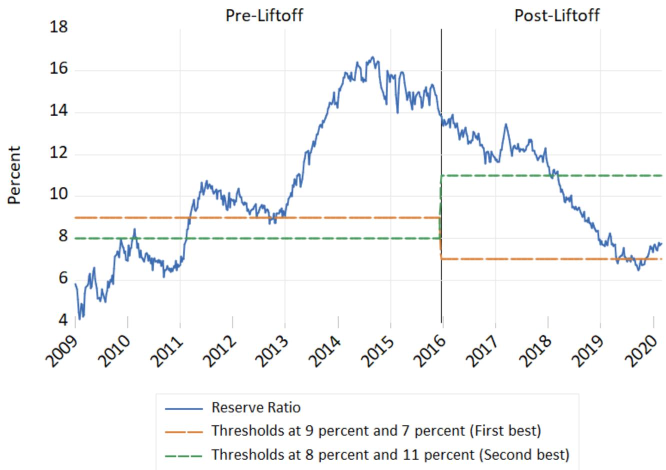


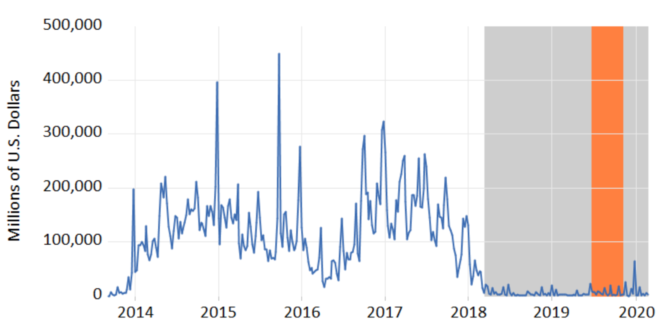
Figure 4: Estimated thresholds for subperiods and the role of the ON RRP facility

(a) Estimated thresholds for subperiods: before and after liftoff in December 2015 (vertical line)



The graph shows the estimated value of the overall liquidity threshold in the threshold-autoregressive model. The threshold variable is the ratio of adjusted reserves (reserves + ON RRP) to nominal GDP (in percent). Intuitively, the estimated threshold can be interpreted as a point where liquidity reaches saturation, dividing the sample into two parts. Below the estimated threshold, liquidity in the form of reserves and the overnight reverse repo facility is relatively low, while above the threshold, liquidity is relatively high. The threshold estimate is obtained through a grid search across a range of thresholds, selecting the model with the lowest Akaike Information Criterion (AIC). The corresponding threshold value of that model is considered the best estimate. As a robustness check the graphs also show the second-best threshold estimate (from the model with the second lowest AIC). The vertical line indicates when the Fed starting raising interest rates (December 2015).

(b) Overnight Reverse Repurchase Facility (ON RRP) after introduction of facility in September 2013.

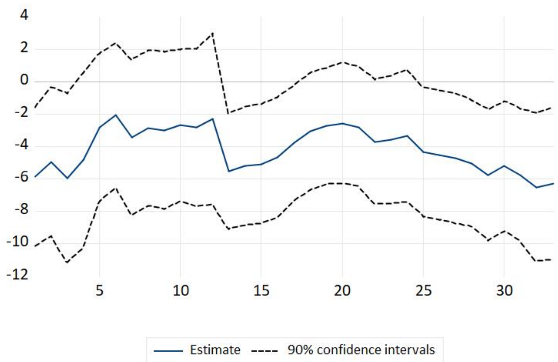


The graph compares the ON RRP with the high and low liquidity time periods found in the post-liftoff estimation shown above. The first best threshold value of that estimation is a reserve ratio of 7 percent. The time period during which the reserve ratio falls below that value is shaded dark/orange (June - November 2019). The second best threshold estimate is 11 percent. The time period during which the reserve ratio falls below that value is shaded grey/lighter-colored (March 2018 - March 2020).

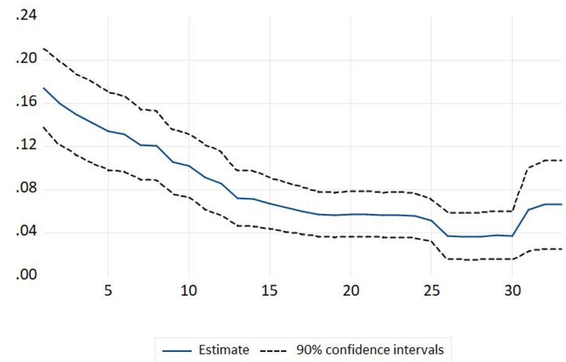
Figure 5: Linear rolling window estimation

Estimated coefficients: baseline

(a) Coefficient on $\Delta\ln$(Adjusted Reserves)

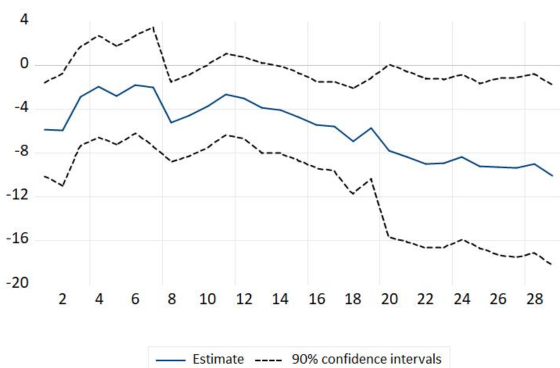


(b) Coefficient on the repo spread

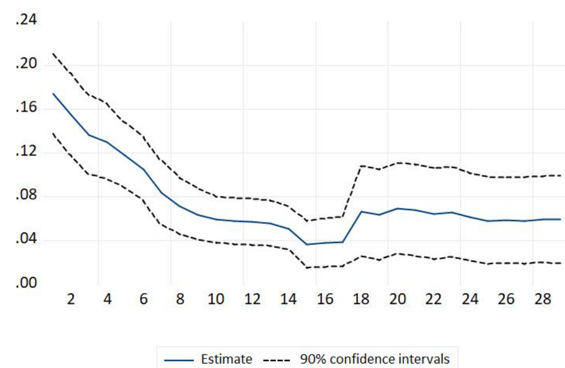


Estimated coefficients: with pandemic

(c) Coefficient on $\Delta\ln$(Adjusted Reserves)



(d) Coefficient on the repo spread

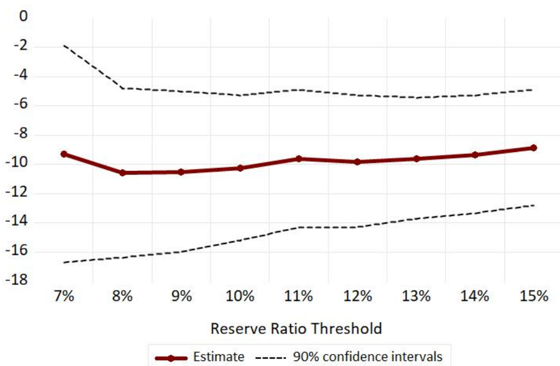


The graphs show the results of estimating Equation 1 for shifting (rolling) subperiods over time. Each observation on the graph represents the estimated coefficients of a separate regression. Each time, the graph plots the estimate as well as the 90 percent confidence interval. The amount, or step, by which the samples move forward is chosen such that every subperiod, or estimation window, contains 350 observations. When using data between January 2009 until before the pandemic in February 2020, the linear model is estimated 33 times on overlapping estimation windows. If data from the pandemic period is included (until December 2022), the linear model is estimated 29 times.

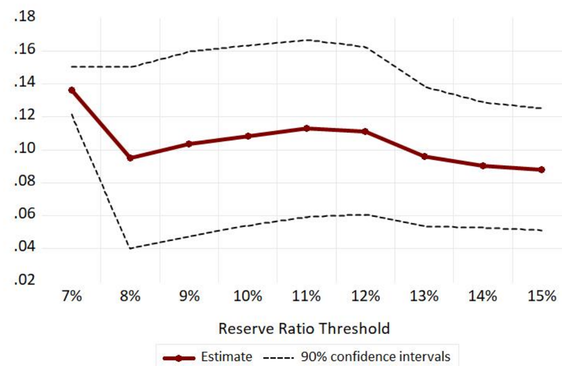
Figure 6: TAR model baseline - Robustness to threshold choice ($\hat{\lambda}$)

Estimated coefficients in low regime of TAR for given threshold

(a) Coefficient on Δln(Adjusted Reserves)

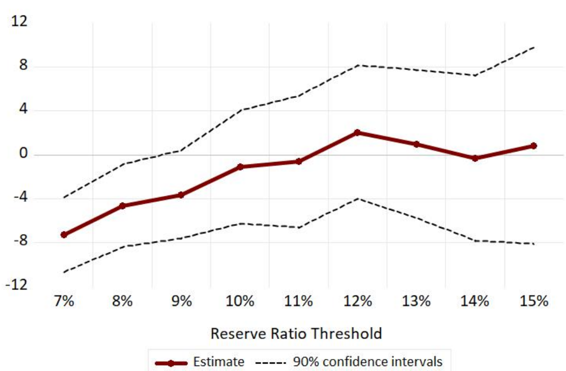


(b) Coefficient on the repo spread

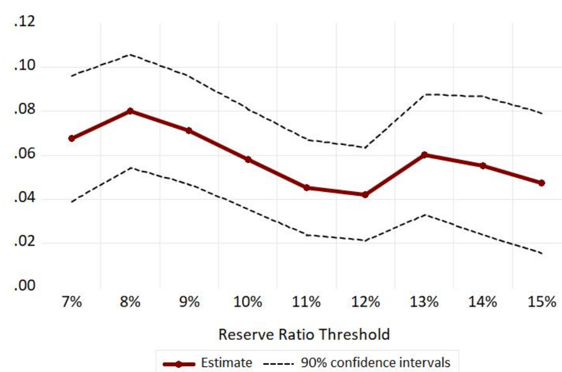


Estimated coefficients in high regime of TAR for given threshold

(c) Coefficient on Δln(Adjusted Reserves)



(d) Coefficient on the repo spread

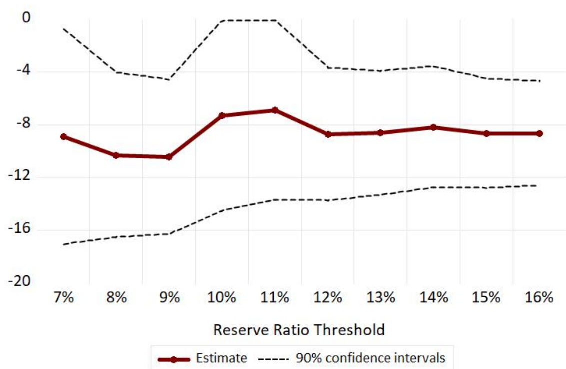


The graphs show the robustness of coefficient estimates to the threshold estimation via grid search for the baseline period (Jan 7, 2009 - February 26, 2020). The TAR in Equation 2 is estimated for values of λ ranging between 7% to 15% (based on trimming of the threshold variable following Caner and Hansen (2001)). Comparing across models, the one with the lowest Akaike Information Criterion (AIC) gives the optimal threshold $\hat{\lambda}$. For each model, the estimated coefficients both in the high and low regime, as well as their 90% confidence intervals are plotted. The optimal threshold is 12% (compare also Column (1) in Table 3).

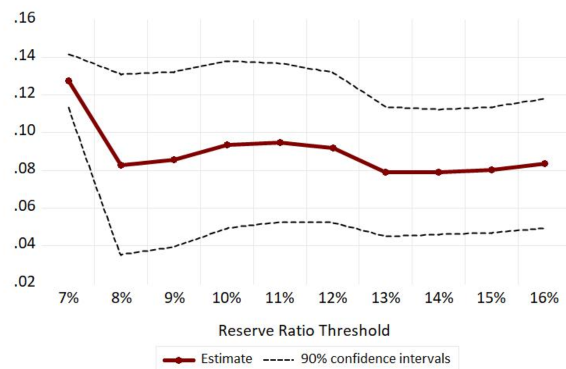
Figure 7: TAR model with pandemic - Robustness to threshold choice ($\hat{\lambda}$)

Estimated coefficients in low regime of TAR for given threshold

(a) Coefficient on Δln(Adjusted Reserves)

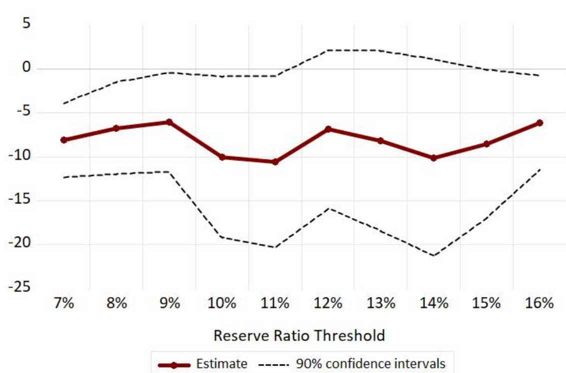


(b) Coefficient on the repo spread

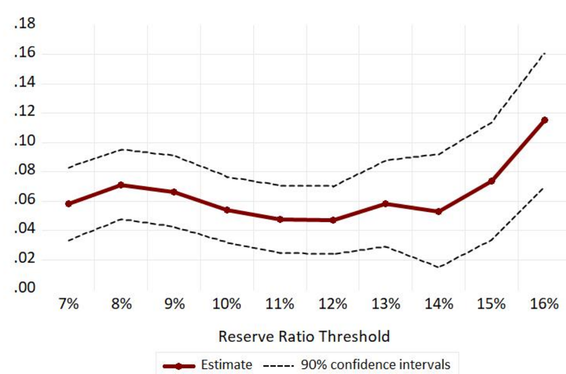


Estimated coefficients in high regime of TAR for given threshold

(c) Coefficient on Δln(Adjusted Reserves)



(d) Coefficient on the repo spread

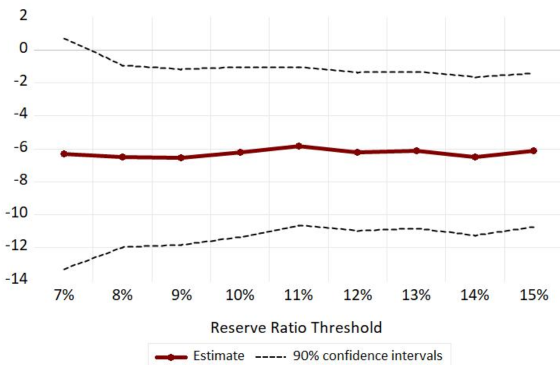


The graphs show the robustness of coefficient estimates to the threshold estimation via grid search for the estimation period including the pandemic (Jan 7, 2009 - December 28, 2022). The TAR in Equation 2 is estimated for values of λ ranging between 7% to 16% (based on trimming of the threshold variable following Caner and Hansen (2001)). Comparing across models, the one with the lowest Akaike Information Criterion (AIC) gives the optimal threshold $\hat{\lambda}$. For each model, the estimated coefficients both in the high and low regime, as well as their 90% confidence intervals are plotted. The optimal threshold is 7% (compare also Column (2) in Table 3).

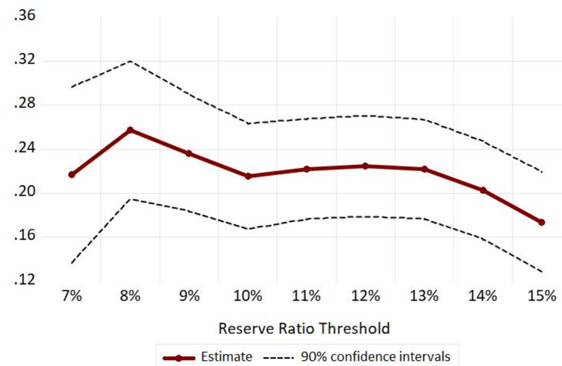
Figure 8: TAR model pre-liftoff - Robustness to threshold choice ($\hat{\lambda}$)

Estimated coefficients in low regime of TAR for given threshold

(a) Coefficient on Δln(Adjusted Reserves)

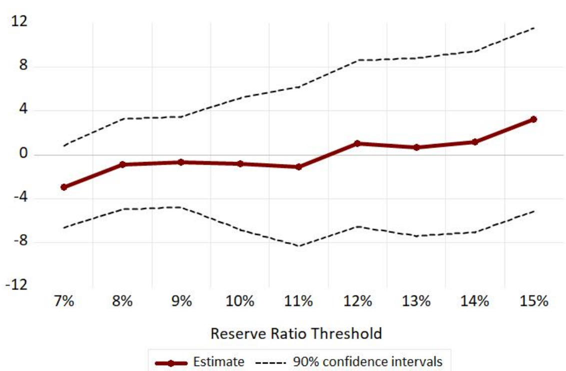


(b) Coefficient on the repo spread

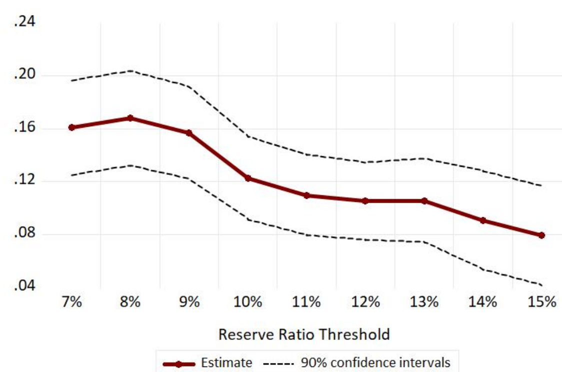


Estimated coefficients in high regime of TAR for given threshold

(c) Coefficient on Δln(Adjusted Reserves)



(d) Coefficient on the repo spread

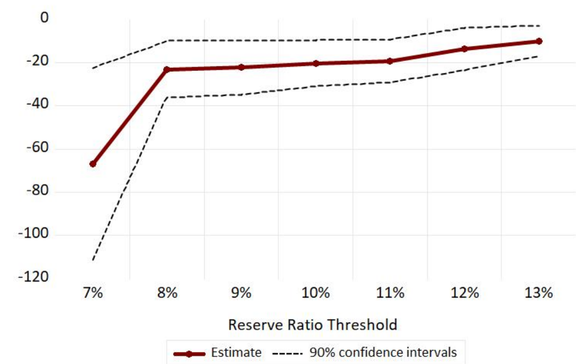


The graphs show the robustness of coefficient estimates to the threshold estimation via grid search for the estimation period before the Fed started raising interest rates (Jan 7, 2009 - Dec 16, 2015). The TAR in Equation 2 is estimated for values of λ ranging between 7% to 16% (based on trimming of the threshold variable following Caner and Hansen (2001)). Comparing across models, the one with the lowest Akaike Information Criterion (AIC) gives the optimal threshold $\hat{\lambda}$. For each model, the estimated coefficients both in the high and low regime, as well as their 90% confidence intervals are plotted. The optimal threshold is 9% (compare also Column (1) in Table 4).

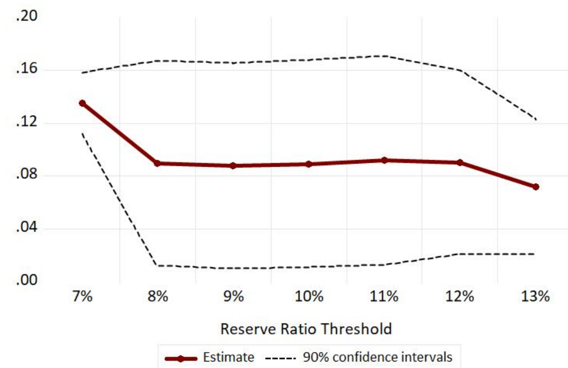
Figure 9: TAR model after liftoff - Robustness to threshold choice ($\hat{\lambda}$)

Estimated coefficients in low regime of TAR for given threshold

(a) Coefficient on Δln(Adjusted Reserves)

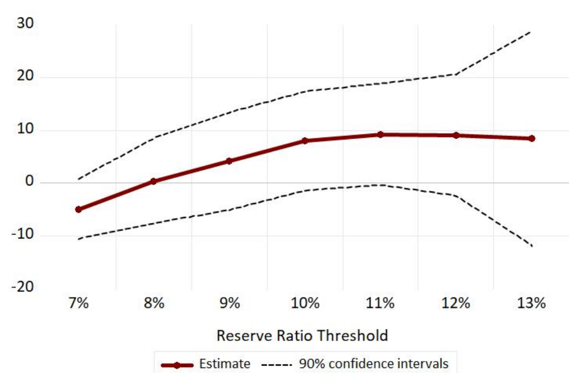


(b) Coefficient on the repo spread

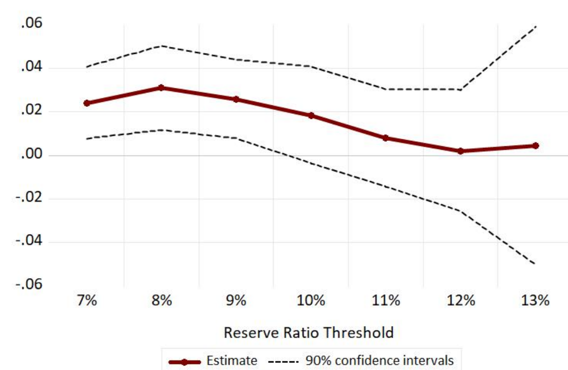


Estimated coefficients in high regime of TAR for given threshold

(c) Coefficient on Δln(Adjusted Reserves)



(d) Coefficient on the repo spread



The graphs show the robustness of coefficient estimates to the threshold estimation via grid search for the estimation period after the Fed started raising interest rates (Dec 23, 2015 - February 26, 2020). The TAR in Equation 2 is estimated for values of λ ranging between 7% to 16% (based on trimming of the threshold variable following Caner and Hansen (2001)). Comparing across models, the one with the lowest Akaike Information Criterion (AIC) gives the optimal threshold $\hat{\lambda}$. For each model, the estimated coefficients both in the high and low regime, as well as their 90% confidence intervals are plotted. The optimal threshold is 7% (compare also Column (2) in Table 4).

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