Overnight Interest Rates and Reserve Balances: Econometric Modeling of Exit Strategies

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ABSTRACT

This paper models overnight funding markets to assess the effect of a reversal of the Federal Reserve's large-scale asset purchases and other tools for monetary easing on overnight interest rates. Our approach involves the estimation of a system of four equations modeling the federal funds rate, the repo rate, the Eurodollar rate, and reserve balances held by depository institutions in terms of three policy rates and the Federal Reserve's securities holdings in its System Open Market Account (SOMA). The two differentiating features of our work is the treatment of the Federal Reserve's asset purchases as the policy tool and the reliance on full-information methods for parameter estimation, recognizing the interdependencies among the three overnight funding rates and reserve balances. We find that the Federal Reserve needs to reduce its securities holdings from about $2.6 trillion to about $1.5 trillion to raise the federal funds rate from 10 basis points to 25 basis points. Moreover, the short-run transition of the federal funds rate in response to a shock is quick; the federal funds rate reaches a new steady state in five months. Finally, while the steady state is invariant to the order of policy changes, the profile of changes of the federal funds rate is not invariant to alternative sequencing.

JEL classification: E43, E47, E52, E65, G01, G17

Keywords: Reserve Balances, Federal Funds Rate, Repo Rate, Eurodollar Rate, Interest Rate on Excess Reserves, Exit Strategy, FIML

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I. Introduction

The financial crisis of 2008 translated into an unprecedented decline in the overnight federal funds rate and equally unprecedented increases in reserve balances and assets on the Federal Reserve's balance sheet, as illustrated in Figure 1. The forces behind these changes are well known (see, e.g., Afonso, Kovner, and Schoar (Afonso et al.) and Bech et al. (2010)). Very little is known, however, about the effect of the process of a normalization of the Federal Reserve's balance sheet on the functioning of overnight funding markets in general and on overnight rates in particular. In addition to addressing the obvious uncertainties from the aftermath of a dramatic event, it is unknown how the introduction of new tools for monetary policy, such as paying interest on excess reserves, will affect the functioning of short-term funding markets. This paper reports interim results of a project we have undertaken to quantify these effects.

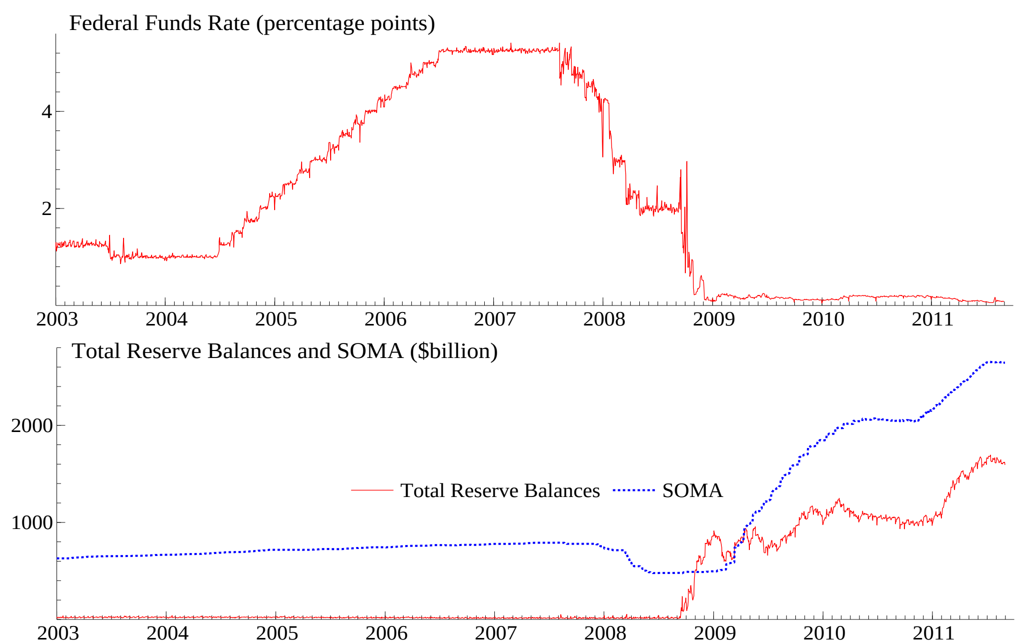

Figure 1: Federal Funds Rate, Reserve Balances of Depository Institutions, and Securities Held by the Federal Reserve

The purpose of this paper is the econometric modeling of overnight funding markets. Our approach involves the estimation of systems of four equations modeling the federal funds rate, the repo rate, the Eurodollar rate, and reserve balances held by depository institutions (DIs) in terms of three policy rates and securities holdings in the Federal Reserve's System Open Market Account (SOMA).[1] For each of these models, we assess the interactions among these rates and evaluate the effect of a reversal of the large-scale asset purchases by the Federal Reserve and other tools for monetary easing on overnight interest rates.

Since the work of Hamilton (1996) and Hamilton (1997), the relation between the federal funds rate and reserve balances—or, more specifically, the "liquidity effect"—has been extensively studied at both daily and longer-term frequencies.[2] The previous literature, however, has several limitations that need to be addressed to answer the question of interest. First, with the exception of Bech et al. (2010), the previous literature on the liquidity effect estimates the effect of monetary policy changes on the federal funds rate but does not account for interdependencies among short-term interest rates. Our framework recognizes that a reduction in reserve balances raises the federal funds rate and simultaneously affects the repo rate and the Eurodollar rate that, in turn, feed back to the federal funds rate. Instead of imposing that relationship, in this framework, we estimate it. Second, previous work does not model reserve balances explicitly. In contrast, we model reserve balances as an endogenous variable by including a "supply" equation for reserve balances in the estimated system of equations. Currently, we treat the Federal Reserve as adjusting the supply of reserve balances in the presence of a spread between the (expected) federal funds rate and its target and/or when the Federal Reserve conducts asset purchases to change its monetary policy stance. Third, it is unknown how the introduction of new tools for monetary policy, such as paying interest on excess reserves, will affect the functioning of short-term funding markets. Indeed, to the best of our knowledge, there is no empirical evidence available on the role of the interest rate paid on excess reserves (IOER rate) on funding markets. We treat this rate as an additional exogenous variable that is controlled by the Federal Reserve. Doing so allows us to investigate the IOER rate's efficacy for monetary tightening. Fourth, previous studies focus on

[1] Throughout the paper we use the generic term *bank* and depository institutions interchangeably when referring to institutions holding accounts at the Federal Reserve, i.e., commercial banks, credit unions, and thrift institutions.

[2] See, for instance, Carpenter and Demiralp (2006), Carpenter and Demiralp (2008), Judson and Klee (2010), Bech et al. (2010), and Kopchak (2011).

short-term dynamics of changes to reserve balances on changes in short-term interest rates.[3] The models we develop handle short-run dynamics and yield an empirical characterization of the steady state. Fifth, we investigate to what extent the order of policy decisions in an exit strategy matters for the response of the federal funds rate, i.e., whether changing policy rates and then draining reserve balances, or the reverse, leads to the same outcome with respect to short-term interest rates.

The results indicate that a fair amount of drainage is needed to just raise the federal funds rate to the current level of the interest rate on excess reserves—25 basis points.[4] Indeed, the Federal Reserve needs to reduce its SOMA holdings from $2.6 trillion to about $1.5 trillion to raise the federal funds rate to 25 basis points. Furthermore, the transition from short-run responses to steady states is quick. The estimated dynamic responses predict that, in response to an increase in the interest rate on excess reserves, the federal funds rate reaches a new steady state in 2 1/2 months. Finally, the sequencing of changes in policies matters for the profile of the response of the federal funds rate; its steady state, however, is invariant to the sequencing of policy changes.

The remainder of the paper proceeds as follows: Section II provides some background on overnight funding markets over the sample period and summarizes the data. Section III describes the econometric framework used to model the relationship between overnight interest rates and reserve balances and presents the estimation results. Section IV shows the findings of simulation exercises to quantify the effect of different drainage scenarios on the federal funds rate. Section V presents the results of a sensitivity analysis. Section VI concludes.

[3] See Hamilton (1997), Carpenter and Demiralp (2006), Carpenter and Demiralp (2008), Judson and Klee (2010), and Bech et al. (2010).

[4] Likely reasons for the IOER rate providing only an imperfect floor for the federal funds rate are discussed in Bech and Klee (2010). Foremost, government-sponsored enterprises' ineligibility to receive interest payments on their reserve balances at the Federal Reserve may explain the willingness to lend at a rate below the IOER rate.

II. Background and Data Description

The data set used in this study consists of daily observations from January 10, 2003 to July 29, 2011. The overnight wholesale funding rates are the federal funds rate, the overnight Treasury general collateral (GC) repo rate, and the Eurodollar rate. The effective federal funds rate, which is published in the Federal Reserve's H.15 release, is calculated as the weighted average rate on brokered overnight federal funds transactions, which are a form of uncollateralized borrowing by DIs, typically overnight.[5] Repo transactions are collateralized borrowing. In this market, borrowers typically are financing the specific asset pledged as collateral in the trade. The Treasury GC repo rate is calculated as a weighted average rate paid by dealers and their customers on overnight repurchase agreements collateralized with U.S. Treasury securities.[6] The repo data is collected by the Federal Reserve Bank of New York (FRBNY) as part of a daily survey of the primary dealers. Uncollateralized borrowing by DIs may also be booked through offshore affiliates. These borrowings are classified as Eurodollar deposits and are brokered through the same brokers that serve the federal funds market.[7] The series for the Eurodollar rate is obtained from Bloomberg.

Figure 2 plots the overnight interest rates that are modeled as the endogenous variables as well as the federal funds target rate. Throughout the sample, the federal funds, the repo, and the Eurodollar rates are closely linked, with little deviation from the intended target rate set by the Federal Open Market Committee (FOMC). In the fall of 2008, the federal funds rate drops to near zero as the various liquidity facilities dramatically increase and reserve balances of depository institutions increase from about $20 billion to more than $1,000 billion soon after. On October 9, 2008, the Federal Reserve began to pay interest on banks' required and excess reserve balances, serving as an additional monetary policy tool for the Federal Reserve. Data on the interest rate paid on excess reserves and the federal funds target rate

[5] An exemption in Regulation D allows borrowing from a specific set of lenders—other depository institutions, broker dealers, and the GSEs—to be classified as federal funds instead of deposits.

[6] See, for instance, Stigum and Crescenzi (2007) and Bech et al. (2010) for more institutional details on the repo market.

[7] See Stigum and Crescenzi (2007) for an overview of the Eurodollar market.

are available from the web pages of the FRBNY and the Federal Reserve Board, respectively.

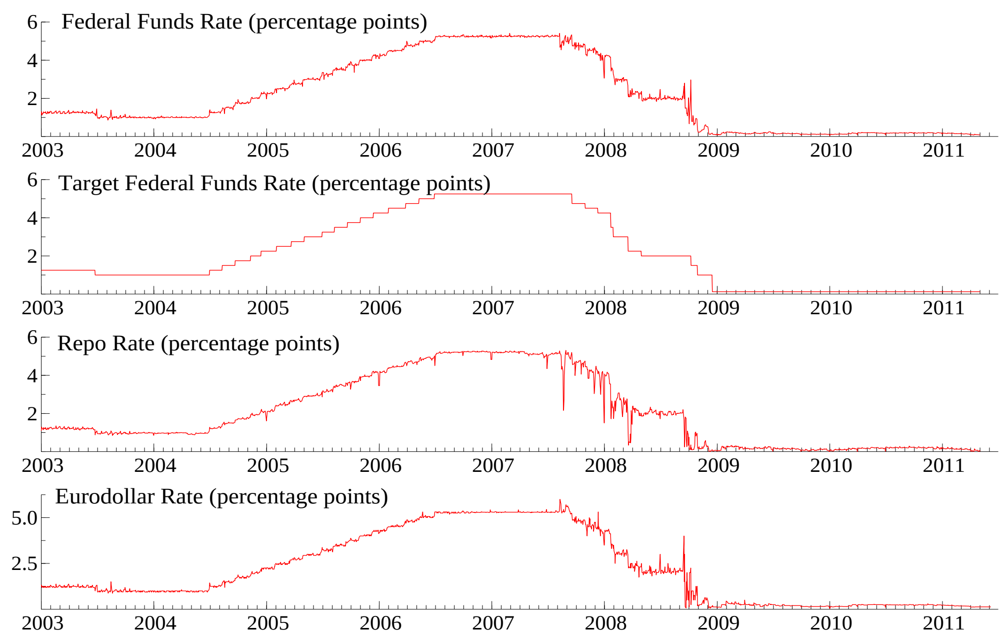

Figure 2: Overnight Interest Rates and the Federal Funds Target Rate

Interdependencies among wholesale funding markets is one reason for the co-movements in these rates. These interdependencies are explained in large part by the overlap of participants and the active arbitrage across markets. As noted in the top row of Table I, DIs borrow in all three markets. DIs generally rely on federal funds and Eurodollars as marginal sources of borrowing to meet general funding needs. In addition, since the advent of payment of interest on reserves, DIs have also borrowed in these markets to arbitrage the market rates against the higher IOER rate. In contrast, institutions borrowing in the triparty repo market—which include DIs, broker-dealers, and others—are typically financing the specific assets pledged as collateral in the trade. On the lending side of the markets, as shown in the bottom row of the table, there is more segmentation in participation across the markets. Depository institutions, broker dealers, and government-sponsored enterprises (GSEs) are the lenders in the federal funds market.[8] Even though GSEs could lend Eurodollars as well, they tend, in practice,

[8] If any other lenders were to extend funds like this to DIs, under Regulation D, the funds would be classified as deposits rather than federal funds.

to be less active in this market. They are, however, active participants in the repo market. Money market mutual funds are active lenders in the Eurodollar market and the repo market.

Table I: Major Market Participants

	(1) **Federal Funds Market**	(2) **Eurodollar Market**	(3) **Repo Market**
Borrowers	Depository Institutions	Depository Institutions	Depository Institutions Broker Dealers
Lenders	Depository Institutions Broker Dealers GSEs	Money Market Funds Financial and Nonfinancial Lenders	Money Market Funds Securities Lenders GSEs

The table lists the major participants in the federal funds (column (1)), the Eurodollar (column (2)), and the triparty repo (column (3)) markets.

The relationship between reserve balances and the federal funds rate is illustrated in Figure 3 based on a sample from October 1, 2008 to July 29, 2011. The data suggest that there is generally a negative, convex relationship between reserve balances and the federal funds rate. As reserve balances moved above $600 billion, the relationship appears to have become extremely flat. In addition, the federal funds rate eventually fell below the IOER rate, currently 25 basis points. That said, even at current very elevated levels of reserves, the demand curve still remains negatively sloped.

In addition, we obtained data on the securities holdings in SOMA from the FRBNY, which contains dollar-denominated assets purchased through open market operations (Figure 1).[9]

III. Empirical Analysis

A. Framework

Following Hamilton (1997), we propose a system of four equations to explain the simultaneous interactions among four endogenous variables: the federal funds rate (i^{fed}), the repo rate

[9] This series is an item of the Federal Reserve's balance sheet that is described in the Federal Reserve's statistical release H.4.1. Throughout the paper, we refer to this balance sheet item as SOMA.

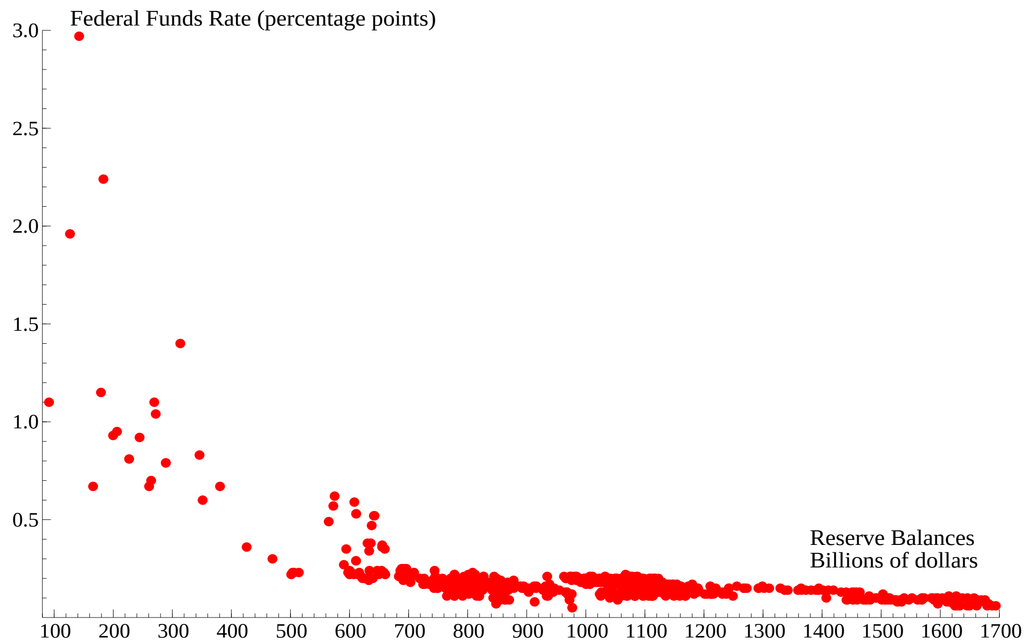

Figure 3: Scatterplot of Reserve Balances and the Federal Funds Rate over the Period October 1, 2008 to July 29, 2011

(i^{repo}), the Eurodollar rate (i^{eurdol}), and the aggregate level of reserve balances (R).[10] As exogenous variables, we use SOMA holdings (S), the federal funds target rate (i^{fed^*}), the interest rate on excess reserves (i^{er}), and the discount rate (i^{disc}). In compact form, our model is

$$i^{fed} = f^{fed}(\underset{+}{i^{repo}}, \underset{+}{i^{eurdol}}, \underset{-}{R}, \underset{+}{i^{er}}, \underset{+}{i^{disc}}), \quad (1)$$

$$i^{repo} = f^{repo}(\underset{+}{i^{fed}}, \underset{+}{i^{eurdol}}), \quad (2)$$

$$i^{eurdol} = f^{eurdol}(\underset{+}{i^{fed}}, \underset{+}{i^{repo}}), \quad (3)$$

$$R = f^{R}(\underset{+}{S}, \underbrace{i^{fed} - i^{fed^*}}_{+}), \quad (4)$$

where the sign underneath the variable indicates its a-priori effect on the dependent variable,

[10]Unlike previous studies, such as Hamilton (1997) and Bech et al. (2010), we account for the endogeneity between the federal funds rate and reserve balances by estimating simultaneously a system of equations that not only contains a "demand" equation for reserve balances but also a "supply" equation. CITE HANDBOOK.

all else unchanged.[11]

We treat equation (1) as the demand equation for reserve balances. Indeed, if borrowing rates go up in the repo/discount market or the Eurodollar market, then the demand for funding will switch to the federal funds market which, in turn, will raise the federal funds rate given the supply of reserve balances. Increases in reserve balances lower the federal funds rate, all else unchanged. The inclusion of the IOER rate recognizes the relevant opportunity cost of lending out funds. Moreover, since the ability to pay interest on excess reserves provides the Federal Reserve with an alternative tool to change its monetary policy stance (see, e.g., Bech and Klee (2010) for a detailed discussion), its inclusion in the empirical framework allows us to assess its efficacy in an exit strategy.[12]

Equation (4), represents the supply equation for reserve balances. We assume that the Federal Reserve changes the amount of reserve balances for two reasons. First, the equation allows for the Federal Reserve to change the amount of reserve balances through asset purchases as a means to change its policy stance, as increases in SOMA (S) are paid with an increase in reserve balances. This modeling is appealing when studying exit strategies because reducing the size of the balance sheet via decrease in SOMA is a likely action the Federal Reserve will consider as it decides to tighten monetary policy. Second, in the spirit of Taylor (1997), we assume that the Federal Reserve increases reserve balances whenever the effective federal funds rate exceeds its target, and vice versa.[13] The sensitivity of reserves to this interest-rate differential has been studied extensively but no consensus exists on the

[11]Table A in Appendix A reports the results from the tests of non-stationarity in the data using the Augmented Dickey-Fuller test, Panel A, and the Phillips-Perron test, Panel B. Specifically, we test for a unit root in the logarithms of the federal funds rate, the repo rate, the Eurodollar rate, and reserve balances, using various lag lengths and including a drift term. Both the Augmented Dickey-Fuller and Phillips-Perron tests generally reject the null hypothesis of non-stationarity although there are a few exceptions depending on the number of lags.

[12]In the spirit of Bech and Klee (2010) in their analysis of bargaining power in the federal funds market, we also experimented with the Gini coefficient as a distributional measure for reserve balances among depository institutions in our empirical analysis, but found no substantial benefit of incorporating it.

[13]Similarly, Sarno et al. (2005) use the deviation of the federal funds rate from its target as a predictor of changes in the federal funds rate. The channel in our study is through repo operations.

best estimation strategy; the most important source of disagreement is on the information set. Specifically, Taylor (1997) proposes a backward looking formulation

$$R_t = f^R(i_{t-1}^{fed} - i_{t-1}^{fed*}), \tag{5}$$

whereas Friedman and Kuttner (2010), as an alternative, propose a forward looking version:

$$R_t = f^R(E_{t-1}i_t^{fed} - i_t^{fed*}). \tag{6}$$

Unfortunately, these studies provide no evidence in support of their views and hence, at this point, we proceed by using the contemporaneous value of these two rates to capture the potential simultaneity between the demand and supply of reserve balances.

B. Model Specification

We use a double-log formulation to specify the relations and in doing so, we depart from a more traditional approach where the level of interest rates is employed.[14] Nevertheless, using logarithms allows us to capture non-linear relations among the variables, to ensure that the ranges of the dependent variables are consistent with the ranges of the disturbances and to prevent negative predictions of the overnight rates. We specify equations (1)-(4) as

$$\begin{aligned}
\ln i_t^{fed} - i_t^{er} &= \alpha_0 + \alpha_1 \ln i_t^{repo} + \alpha_2 \ln i_t^{eurdol} + \alpha_3 \ln R_t + \alpha_4(\ln i_{t-1}^{fed} - i_{t-1}^{er}) + \alpha_5 \ln i_t^{disc} \\
&\quad + u_t^{fed}, &(7)\\
\ln i_t^{repo} &= \beta_0 + \beta_1 \ln i_t^{fed} + \beta_2 \ln i_{t-1}^{repo} + \beta_3 \ln i_t^{eurdol} + u_t^{repo}, &(8)\\
\ln i_t^{eurdol} &= \delta_0 + \delta_1 \ln i_t^{fed} + \delta_2 \ln i_t^{repo} + \delta_3 \ln i_{t-1}^{eurdol} + u_t^{eurdol}, &(9)\\
\ln R_t &= \gamma_0 + \gamma_1 \ln S_t + \gamma_2 \ln S_{t-1} + \gamma_3(\ln i_t^{fed} - \ln i_t^{fed*}) + \gamma_4 \ln R_{t-1} + u_t^R, &(10)\\
\mathbf{u}_t &= (u_t^{fed}, u_t^{repo}, u_t^{eurdol}, u_t^R)' \sim N(0, \mathbf{\Omega}).
\end{aligned}$$

Note that the interest rate on excess reserves in equation (7) is not expressed in logarithm. This asymmetric treatment of interest rates owes to our setting the interest rate on excess

[14] Friedman and Kuttner (2010) use logarithms of interest rates in their estimations for excess reserve demand for Japan.

reserves, i_t^{er}, equal to zero prior to early October 2008 when paying interest on excess reserves was not allowed. This assumption is strong and the implications of relaxing it are reviewed in Section V.

For expository convenience and without loss of generality, we express equations (7)-(10) as

$$\mathbf{y}_t = f(\mathbf{y}_t, \mathbf{y}_{t-1}, \mathbf{x}_t, \mathbf{u}_t, \Theta), \tag{11}$$

where

$\mathbf{y}_t' = \begin{pmatrix} \ln i_t^{fed} & \ln i_t^{repo} & \ln R_t & \ln i_t^{eurdol} \end{pmatrix}$ is the vector of endogenous variables;

$\mathbf{x}_t' = \begin{pmatrix} 1 & \ln S_t & i_t^{er} & \ln i_t^{disc} & \ln i_t^{fed^*} \end{pmatrix}$ is the vector of exogenous variables;

$\Theta' = \begin{pmatrix} \alpha_0 & \cdots & \gamma_3 & \alpha_4 & \alpha_5 & \gamma_4 & \sigma_{11} & \cdots & \sigma_{44} \end{pmatrix}$ is the vector of unknown parameters.

The static reduced form model implied by equations (7)-(10) can be expressed as

$$\mathbf{y}_t = f(\mathbf{y}_t, \mathbf{y}_t, \mathbf{x}_t, \mathbf{u}_t = 0, \Theta), \tag{12}$$

and given that it is linear in the parameters, one may solve for $\mathbf{y}_t$ as

$$\mathbf{y}_t = \Pi \cdot \mathbf{x}_t, \tag{13}$$

where $\Pi = \|\pi_{ij}\|$ is the matrix of reduced-form coefficients. These coefficients are non-linear functions of the parameters in all of the equations and, hence, trying to attribute a-priori a sign to the entries ofΠ is difficult. As a substitute, we offer our ad-hoc a-priori beliefs about these signs:[15]

$$\Pi = \begin{pmatrix} \underset{\pm}{\pi_{11}} & \underset{-}{\pi_{12}} & \underset{+}{\pi_{13}} & \underset{+}{\pi_{14}} & \underset{+}{\pi_{15}} \\ \underset{\pm}{\pi_{21}} & \underset{-}{\pi_{22}} & \underset{+}{\pi_{23}} & \underset{+}{\pi_{24}} & \underset{+}{\pi_{25}} \\ \underset{\pm}{\pi_{31}} & \underset{+}{\pi_{32}} & \underset{+}{\pi_{33}} & \underset{+}{\pi_{34}} & \underset{-}{\pi_{35}} \\ \underset{\pm}{\pi_{41}} & \underset{-}{\pi_{42}} & \underset{+}{\pi_{43}} & \underset{+}{\pi_{44}} & \underset{+}{\pi_{45}} \end{pmatrix}.$$

[15] We emphasize that we first estimate the elements of Θ and then compute the entries of Π.

C. Parameter Estimation

Given the simultaneity among the endogenous variables, we use full-information maximum likelihood (FIML) to estimate the parameters of equations (7)-(10). The estimation sample consists of daily observations (business days) from January 10, 2003 to July 29, 2011. We focus on this sample and not a shorter sample (e.g., October 1, 2008 to June 8, 2011) for two reasons. First, from a practical standpoint, the variability of interest rates in the shorter sample is virtually absent (see Figure 2). Hence, the explanatory variables do not change much and are nearly collinear. Second, from a methodological standpoint, the estimated parameters should reflect the full range of potential values for the variables of interest, a especially relevant consideration for a simulation study that seeks to estimate reserves in a range outside the shorter sample.

To lighten up the exposition, we focus on the implications of the parameter estimates for the reduced form coefficients, which are reported in Table II.[16] According to these coefficients, an increase in SOMA lowers all overnight rates; the effect is less than proportional, similar across all overnight rates, and significant. Further, an increase in SOMA raises reserve balances and the effect is more than proportional and significant. An increase in the IOER rate raises all overnight rates and reserve balances; the effect is similar across rates. In addition, an increase in the target federal funds rate has negligible effects on all the endogenous variables. Finally, an increase in the discount rate raises all overnight rates.

An obvious question to ask is whether our estimates are unduly affected by potential structural changes induced by the financial crisis. Section D below compares these estimates to those based on a sample that starts in 2008 instead of 2003. The point estimates associated with the shorter sample decline in magnitude relative to estimates based on the full sample and are less precise which is why, at this point, we rely on the longer sample.

[16] The short-run coefficient estimates are available from the authors upon request.

Table II: Long-Run, Reduced-Form Parameter Estimates, FIML, January 10, 2003 to July 29, 2011

Variable	Equation			
	Federal Funds Rate	Repo Rate	Eurodollar Rate	Reserve Balances
Constant	4.2753	4.4066	4.0369	-9.9059
	[1.7063]	[1.8086]	[1.5827]	[4.0625]
SOMA	-0.7432	-0.7864	-0.6893	2.0288
	[0.26056]	[0.27627]	[0.2417]	[0.60247]
IOER	1.3360	1.4136	1.2391	0.6555
	[0.33984]	[0.36099]	[0.31541]	[0.22179]
Target Federal Funds Rate	0.1523	0.1612	0.1413	-0.4159
	[0.39448]	[0.41742]	[0.36587]	[1.0743]
Discount Rate	0.9185	0.9719	0.8519	0.4506
	[0.15308]	[0.16357]	[0.14224]	[0.12395]

The table presents the long-run, reduced-form coefficient estimates for the structural system. Standard errors in squared brackets. All variables, except IOER, are expressed in logarithms.

D. Model Evaluation

We use statistical and economic criteria to evaluate the usefulness of the model; specifically, we assess the in-sample fit, the properties of the residuals, the dynamic stability, the properties of the steady state, and the response of the steady state to policy shocks. Section V repeats this evaluation for three additional models: (1) Log-linear model with short sample (2008-01-01 to 2011-07-29), (2) linear model with long sample (2003-01-01 to 2011-07-29), and (3) linear model with short sample (2008-01-01 to 2011-07-29). We find that statistical criteria alone are not powerful enough to discriminate among models, as all models have comparable statistical properties and a steady state. However, these additional models give counterintuitive and implausible responses to policy shocks, all of which are documented in Section V. Of course, the meanings of "counterintuitive" and "implausible" are arbitrary and further data could change these considerations.[17]

D.1. In-Sample Properties of the Model

Figure 4 shows that the model described by equations (7)-(10) has a large degree of explanatory power (first column) but that the residuals are heteroskedastic (second column) and not

[17] The project began with the estimation of VAR models for the three interest rates, augmented with reserve balances as an exogenous variable; for estimation we used 2SLS. We switched to the model used here to avoid reserve balances having a dual role: endogenous for estimation but exogenous for analysis. The results from the VAR models are available upon request.

normally distributed (fourth column). However, the residuals are serially uncorrelated (third column). We are currently working on addressing these limitations and, hence, they need to be taken into account when judging the reliability of our conclusions.

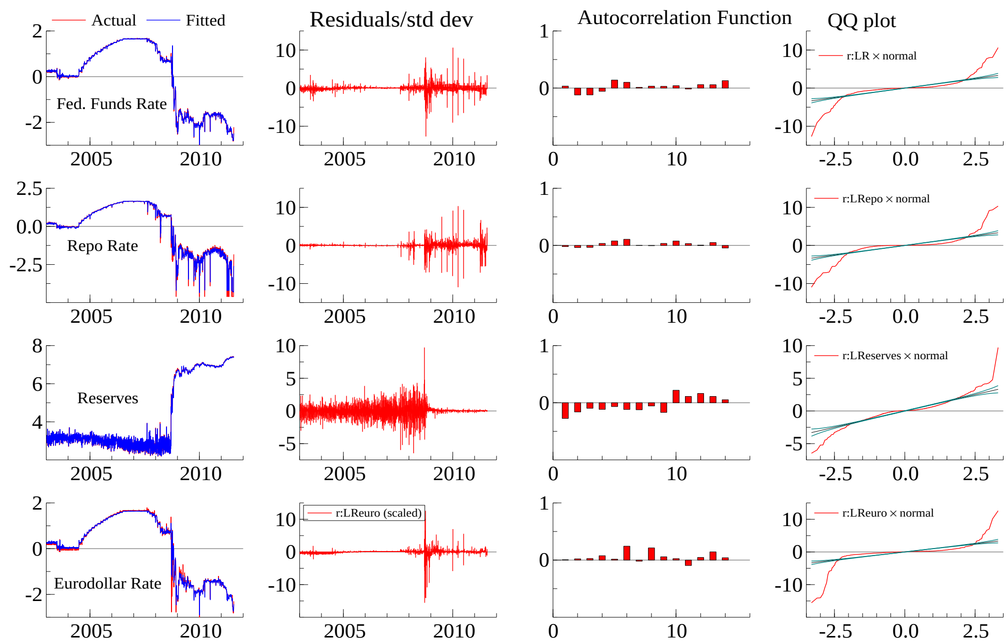

Figure 4: In-Sample Model Properties

D.2. Dynamic Stability

Figure 5 documents the dynamic properties of the model, showing the impulse response functions to unit shocks. The results suggest that the model is dynamically stable—that is, the impulse responses return to zero. The results also indicate that a positive unit shock to reserves lowers all three overnight rates by the same magnitude (third row). Further, a positive shock to an overnight interest rate triggers an increase in all overnight interest rates. These two findings corroborate the tight correlation among these three rates that can be seen in the raw data. Finally, overnight rates show a fair amount of persistence: it takes about 300 days for the effects of shocks to vanish.

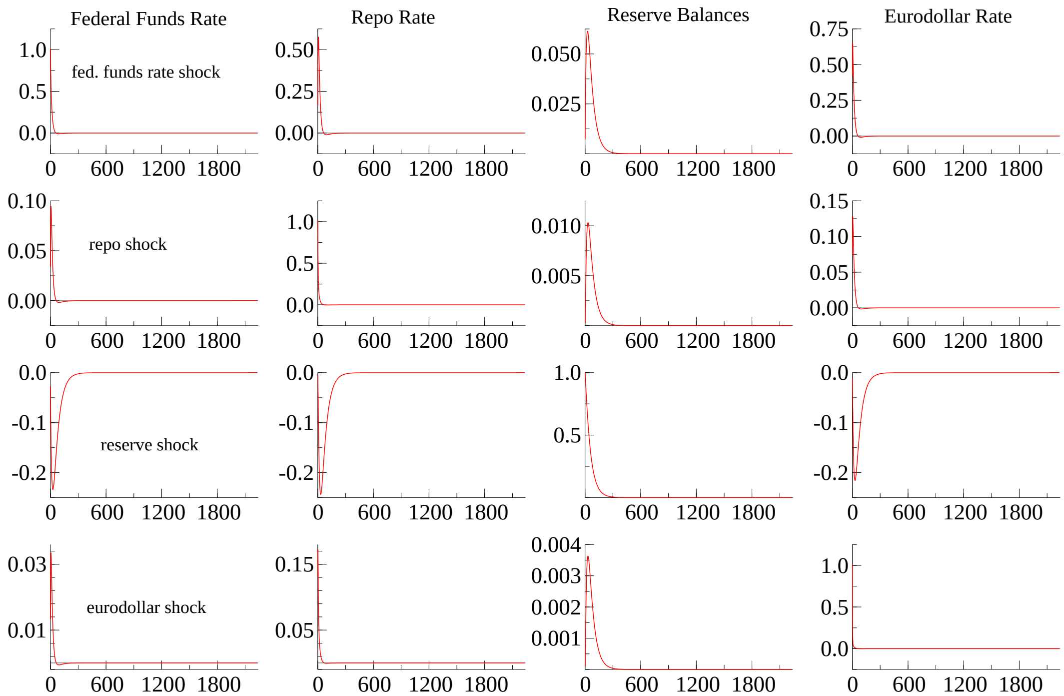

Figure 5: Impulse Response Functions

IV. Implications for Drainage of Reserve Balances

A. Long-Run Estimates

The impulse responses take as given the values of $\mathbf{x}_t$ and, hence, they are not informative about the effects of monetary policy changes on overnight rates. To that end, we rely on the estimates of π_{ij} to ask by how much should SOMA decline in order to raise the federal funds rate from its current level to 25 basis points in the long run. Specifically, relying on the static reduced form equation (13) above, we find that

$$\widehat{i}^{fed} = (S)^{\widehat{\pi}_{12}} \cdot exp\left[\widehat{\pi}_{11} + \widehat{\pi}_{13} i^{er} + \widehat{\pi}_{14} \ln i^{disc} + \widehat{\pi}_{15} \ln i^{fed^*}\right]. \tag{14}$$

The implications of changes in SOMA for the level of reserve balances are given by

$$\widehat{R} = (S)^{\widehat{\pi}_{32}} \cdot exp\left[\widehat{\pi}_{31} + \widehat{\pi}_{33} i^{er} + \widehat{\pi}_{34} \ln i^{disc} + \widehat{\pi}_{35} \ln i^{fed^*}\right]. \tag{15}$$

Figure 6 shows the hypothetical long-run values for SOMA and reserves needed to have a federal funds rate of 25 basis points, conditioned on the coefficient estimates and the current values of policy rates: $i^{er} = 0.25$, $i^{disc} = 0.75$, $i^{fed*} = 0.13$. According to these calculations, raising the federal funds rate to 25 basis imports involves reducing SOMA from \$2.6 trillion to about \$1.5 trillion; this decline in SOMA lowers reserves to \$300 billion.

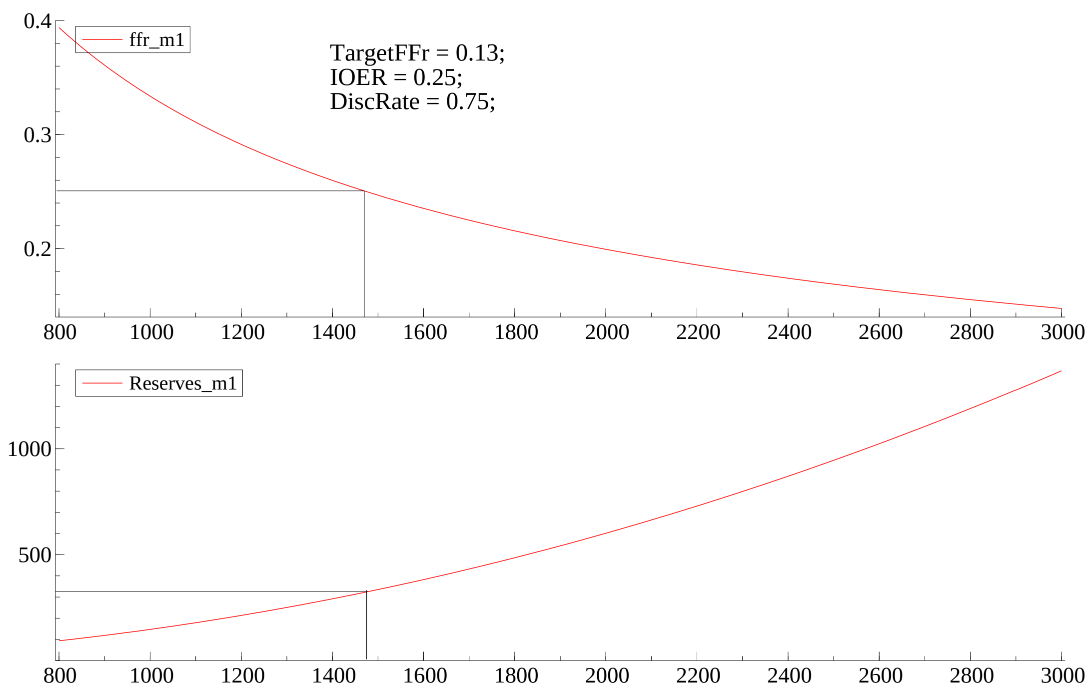

Figure 6: Long-Run Relation between SOMA and the Federal Funds Rate (top panel) and between SOMA and Reserve Balances (bottom panel)

B. Adjustment to the Steady State

The main disadvantage of relying solely on reduced-form coefficients is that they give us only comparative static results. One cannot get a sense of how long it would take to reach the target or what the character of the dynamic adjustment is. To address this issue, we implement dynamic simulations under alternative assumptions outline below:

- Baseline: The exogenous variables remain constant, through 2013-12-31, at their last historical value (July 29, 2011); the residuals are set to zero:

$$\widehat{\mathbf{y}}_t = f(\widehat{\mathbf{y}}_t, \widehat{\mathbf{y}}_{t-1}, \overline{\mathbf{x}}, \mathbf{u}_t = 0, \widehat{\Theta}), \tag{16}$$

where $\overline{\mathbf{x}}$ is the vector of exogenous variables with values fixed at their July 29, 2011 recordings;

- Scenario 1: A once and for all increase in the IOER rate of 10 basis points, all else unchanged;
- Scenario 2: A once and for all contraction of SOMA by 800 billion, all else unchanged;
- Scenario 3: Scenarios 1 and 2 combined.

For these three scenarios, and the ones considered later, we use

$$\widehat{\mathbf{y}}_t = f(\widehat{\mathbf{y}}_t, \widehat{\mathbf{y}}_{t-1}, \mathbf{x}', \mathbf{u}_t = 0, \widehat{\Theta}), \tag{17}$$

where $\mathbf{x}'$ is the vector of shocked exogenous variables. Note that these responses differ from the impulse responses because those do not change the policy variables.

Figure 7 shows that the model generates a meaningful steady state. Meaningful in the sense that the federal funds rate reaches 16 basis points, and not 20 percent points for example, and reserve balances $1,000 billion, instead of $10,000 billion. One could argue that the level of reserves dropping from $1600 billion in July 30, 2011 to $1000 billion by the end of 2012 is perhaps unrealistic. Recall, however, that the fourth quarter of 2008 witnessed an even bigger change in reserves: $800 billion.

In terms of the response to the shocks, the model is consistent with prior expectations: an increase in the IOER rate of 10 basis points, all else unchanged, raises the in the federal funds rate by four basis points; the adjustment takes two months. The increase in the IOER rate operates through demand and supply channels. The demand channel operates by raising the demand for reserves which, for a given level of reserve supply, raises the federal fund rate;

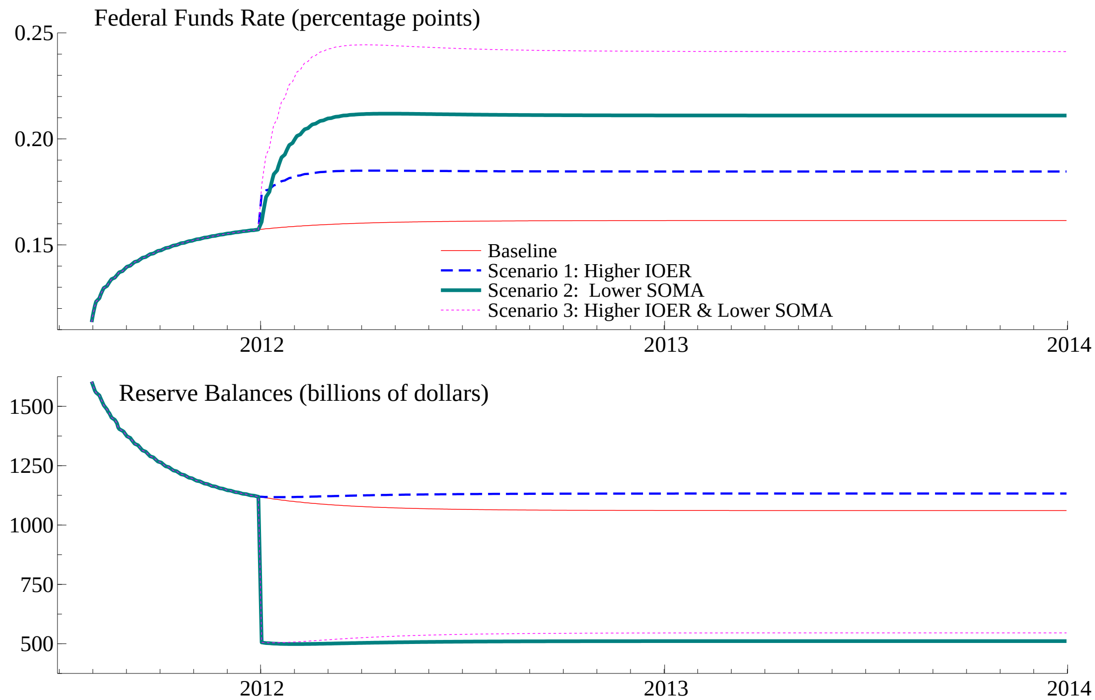

Figure 7: Adjustment to Steady States for the Federal Funds Rate (top panel) and Reserve Balances (bottom panel): Baseline and Scenarios 1-3

this effect is then transmitted to the repo and Eurodollar rates with a subsequent feedback to the federal funds rate. As for the supply of reserves, the increase in the federal funds rate raises the gap between the federal funds rate and its target. This change in the rate gap raises the supply of reserves, which then attenuates the demand-side effect. The results in the figure reflect these demand-supply interactions.

A decline in SOMA, all else unchanged, lowers reserves and raises the federal funds rate to 20 basis points after 2 1/2 months. Note that the $800 billion fails to raise the federal funds rate to 25 basis points.

A question of interest is whether these responses are non-linear. Specifically, if the model were linear, one would simply add the effects of Scenario 1 to those of Scenario 2 and would obtain the results of Scenario 3. Instead, we find that

$$(\widehat{i}_3^{fed} - \widehat{i}_{base}^{fed}) > (\widehat{i}_1^{fed} - \widehat{i}_{base}^{fed}) + (\widehat{i}_2^{fed} - \widehat{i}_{base}^{fed}). \tag{18}$$

In other words, the responsiveness of the federal funds rate to shocks in the policy rates depends on the level of SOMA.[18] This finding suggests that the timing of policy actions might affect the profile of the adjustment process. Indeed, policy makers and pundits have endorsed different sequencing of policy steps in an exit strategy. Harding (2011) argues that most policy makers endorse an exit strategy that involves to "first, scrap the promise of ultra-low rates for an "extended period," then drain reserves out of the banking system, raise short-term rates and only after that begin sales from the asset portfolio," while others argue that "tightening policy will happen via interest rates and shrinking the balance sheet can be kept separate" (Harding (2011), page 7).

To examine these possibilities, we consider three additional scenarios:

- Scenario 4: Start with a once and for all increase in all policy rates by 50 basis points, followed by a once and for all contraction in SOMA by \$800 billion;
- Scenario 5: Start with a once and for all contraction in SOMA by \$800 billion, followed by a once and for all increase in all policy rates by 50 basis points;
- Scenario 6: Implement a once and for all contraction in SOMA by \$800 billion with a simultaneous increase in all policy rates by 50 basis points.

Figure 8 below shows four findings of interest. First, the steady state of the model is invariant to the timing of the shock: these shocks raise the federal funds rate to about 80 basis points. Second, the delay in the federal funds rate reaching its steady state is quite sensitive to the timing of the shocks. Specifically, the implementation of Scenario 6 yields an adjustment delay of four months whereas the delay from the implementation of Scenario 5 is about nine months. Third, and not surprisingly, the effect of a contraction on SOMA on the federal

[18]Formally, assume a simplified version of the equation for the federal funds rate (equation (7)): $\ln i_t^{fed} = \alpha_1 \ln i_t^{repo} + \alpha_2 \ln R_t$. Differentiating yields $\partial i_t^{fed}/\partial R_t = \alpha_2 \cdot i_t^{fed}/R_t$ which indicates that the effect of a change in reserves depends upon the level of reserve balances.

funds rate is larger the lower is the level of reserve balances. Specifically, implementing a contraction of SOMA when reserve balances exceed $1 trillion raises interest rates by a bit less than 10 basis points (Scenario 5). However, implementing the same contraction in SOMA after a decrease in reserves more than doubles the effect on the federal funds rate (Scenario 4).

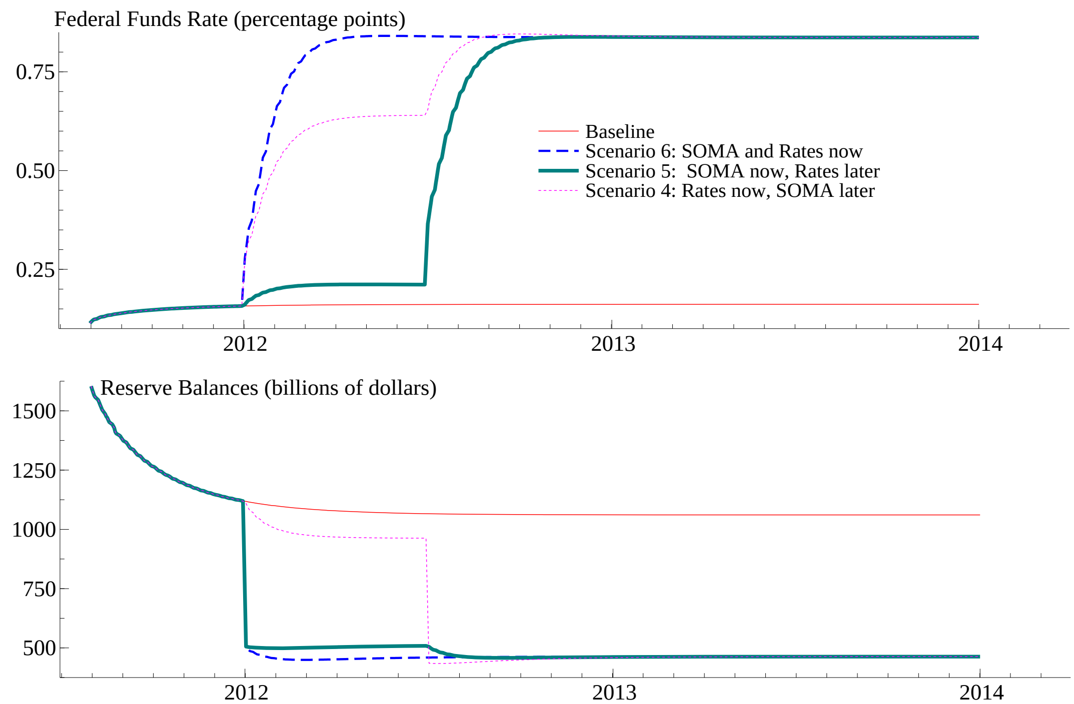

Figure 8: Steady States for the Federal Funds Rate (top panel) and Reserve Balances (bottom panel): Baseline and Scenarios 4-6

Policy makers need not be indifferent to the adjustment profile of interest rates, even if the steady state is invariant to the order of policy adjustments. To examine this possibility, we compute the present discounted value of the absolute value of the change in interest rates for Scenarios 4-6. The expression that we use is

$$\Upsilon_{s,\delta} = \sum_{t=2012-01-02}^{2014-01-24} \frac{|\widehat{i}^{fed}_{s,j} - \widehat{i}^{fed}_{s,j-1}|}{(1+\frac{\delta}{260})^j}, \tag{19}$$

where $\widehat{i}^{fed}_{s,j}$ is the predicted daily federal funds rate for scenario s at time j, and δ is the annual discount rate. Figure 9 presents the findings for $\Upsilon_{s,\delta}$ for Scenarios 4-6 using different values of the discount factor:

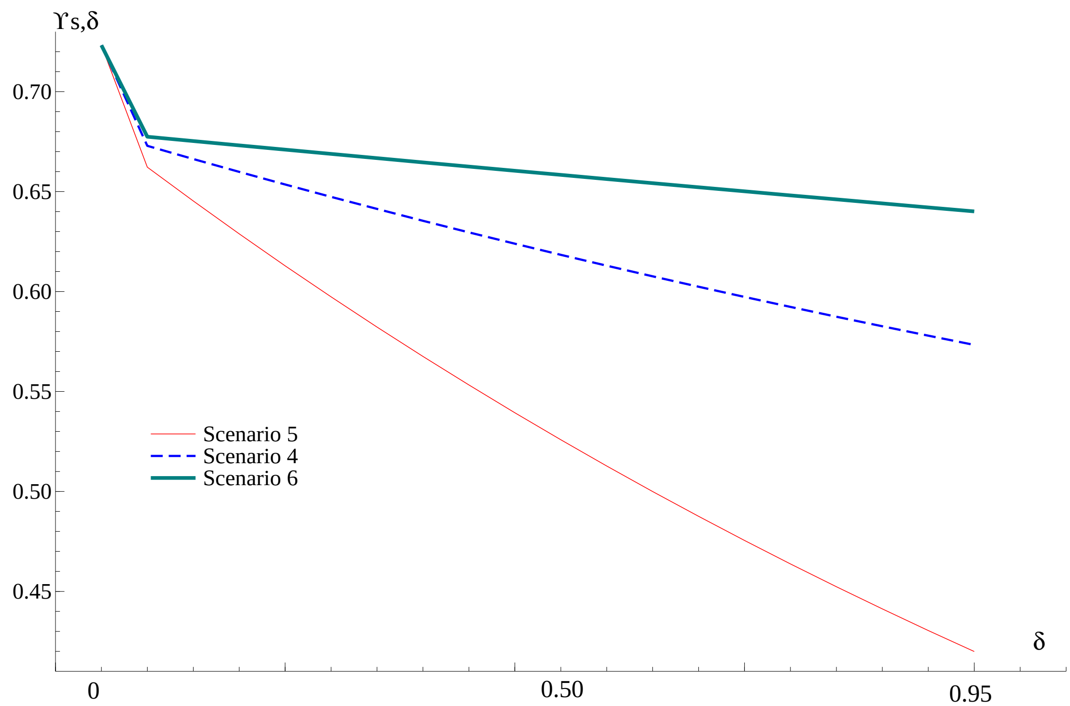

Figure 9: Evaluation of Scenarios 4-6

The calculations reveal that $\Upsilon_{5,\delta} < \Upsilon_{4,\delta} < \Upsilon_{6,\delta}$ for $\delta > 0$, and $\Upsilon_{5,\delta} = \Upsilon_{4,\delta} = \Upsilon_{6,\delta}$ for $\delta = 0$. In words, if policymakers emphasize a gradual adjustment, i.e., small daily changes in the federal funds rate, then the sequencing that begins with draining reserves followed by increases in policy rates yields the lowest value of Υ for every discount factor. Intuitively, this result owes to the timing of interest rate changes: small changes early in the adjustment period followed by large changes that are more heavily discounted because they occur in the distant future. If policymakers are keen on reaching the steady state sooner rather than later, then a sequencing that begins by raising the policy rates followed by a drainage of reserve balances (Scenario 4) yields a lower value of Υ for every discount factor than changing both SOMA and the policy rates now (Scenario 6).

C. Hypothetical Drainage Scenario

An important question in designing the exit strategy is the horizon over which it is implemented. Plosser (2011) reports calculations for a one-year exit strategy which combines increases in both the target for the federal funds rate and the IOER rate, along with declines in the Federal Reserve's holdings of U.S. Treasury securities and MBS. His reduction in SOMA is assumed to reduce reserve balances of DIs on a dollar-for-dollar basis. After one year, the strategy envisions a federal funds rate of 2.5 percent, an interest rate on excess reserves of 2.5 percent, and reserve balances of $50 billion. However, Plosser (2011) does not offer a framework that allows one to assess whether the changes in interest rates and SOMA holdings are mutually consistent. Thus, we ask whether combining our framework with his assumption about asset sales yields comparable results.

To that end, we implement two additional scenarios:

- Scenario 7: Implement a gradual reduction in SOMA in the middle of 2013 while keeping all policy rates at their current level. We reduce the size of the balance sheet to its 2008 level and keep it constant at that level thereafter. Specifically, we assume that SOMA declines about $4 billion per day, which is about the pace of the purchases of U.S. Treasury securities during the Federal Reserve's second large-scale asset purchase program (top right panel of Figure 10);
- Scenario 8: Combine Scenario 7 with an increase in the target federal funds rate to the level of the IOER when the federal funds rate reaches 25 basis points.

Implementing a gradual reduction of SOMA, all else unchanged, induces a gradual decline in reserves to $100 billion after 20 months (bottom left panel of Figure 10) and increases in both the federal funds rate (top left panel) and the repo rate (bottom right panel) reach 40 basis points and 15 basis points, respectively. Thus, in this scenario, our value for reserve balances is very close to that of Plosser but our estimate of the federal funds rate is far below his. Combining the contraction in SOMA with the increase in the target federal funds rate to

25 basis points accentuates the reduction in reserve balances and the increase in the federal funds rate, which still increases to only 45 basis points, well below Plosser's value.

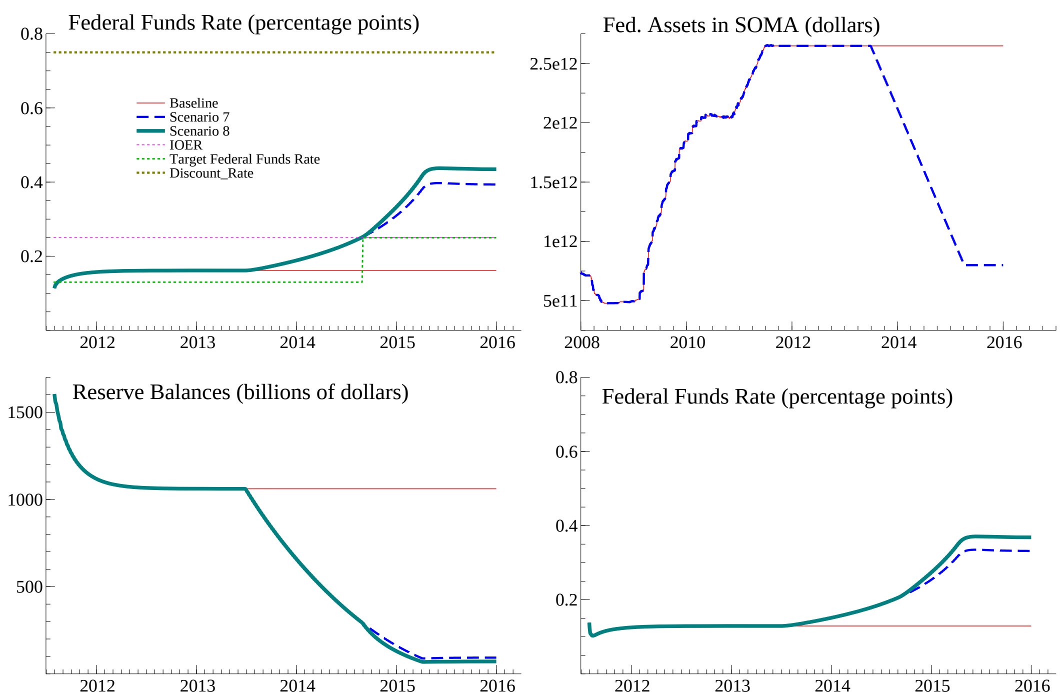

Figure 10: Hypothetical Drainage Scenarios

V. Sensitivity Analysis

As an alternative to equations (7)-(10), we use a formulation where the overnight rates are expressed in percentage points instead of the associated logarithms. Formally,

$$\begin{aligned}
i_t^{fed} - i_t^{er} &= \alpha_0 + \alpha_1 i_t^{repo} + \alpha_2 i_t^{eurdol} + \alpha_3 \ln R_t + \alpha_4 (i_{t-1}^{fed} - i_{t-1}^{er}) \\
&\quad + \alpha_5 i_t^{disc} + u_t^{fed}, && (20) \\
i_t^{repo} &= \beta_0 + \beta_1 i_t^{fed} + \beta_2 i_{t-1}^{repo} + \beta_3 i_t^{eurdol} + u_t^{repo}, && (21) \\
i_t^{eurdol} &= \beta_0 + \beta_1 i_t^{fed} + \beta_2 i_t^{repo} + \beta_3 i_{t-1}^{eurdol} + u_t^{eurdol}, && (22) \\
\ln R_t &= \gamma_0 + \gamma_1 \ln S_t + \gamma_2 \ln S_{t-1} + \gamma_3 (i_t^{fed} - i_t^{fed*}) + \gamma_4 \ln R_{t-1} + u_t^R, && (23) \\
u_t &= (u_t^{fed}, u_t^{repo}, u_t^{eurdol}, u_t^R)' \sim N(0, \mathbf{\Omega}).
\end{aligned}$$

We also consider the effects of using a shorter sample that begins in 2008-01-01. Combining the alternative model with two sample periods leaves us with three additional models:

- Model m2: Log-linear model with short sample (2008-01-01 to 2011-07-29);
- Model m3: Linear model with long sample (2003-01-01 to 2011-07-29);
- Model m4: Linear model with short sample (2008-01-01 to 2011-07-29).

We use statistical and economic criteria to evaluate the usefulness of the models; specifically, we rely on the coefficient estimates, the in-sample fit, the properties of the residuals, the dynamic stability, the properties of the steady state, and the response of the steady state to policy shocks.

Coefficient Estimates

Table III presents the long-run, reduced-form coefficient estimates for the various models. The effect of SOMA is not significant for models m2, m3, and m4. Lack of significance is not a criterion, however, to exclude a model. Yet the idea that an exit strategy based on reducing SOMA without an effect on rates is a stretch, in particular, since both quantitative easing (QE) plans relied on SOMA.

In-Sample Properties of Alternative Models

In-sample properties of the alternative models are shown in Figures 14-16 in Appendix Appendix B. While all three models offer a good fit of the data and serially uncorrelated residuals, their residuals also show heteroskedasticity and non-normality. Thus, these properties are not helpful for model selection.

Dynamic Stability

Impulse responses of the alternative models are shown in Figures 17-19 in Appendix C. All three models show stability as the impulse response values return to zero. A positive unit shock to reserves lowers all three overnight rates; the responses of interest rates are similar for a given model. The models differ in how fast the responses dissipate, but, in the absence

Table III: Long-Run, Reduced-Form Parameter Estimates, FIML

	Federal Funds Rate	Repo Rate	Eurodollar Rate	Reserve Balances
Panel 1: Logarithms with sample from 2003-1-09-2011-07-29 (m1)				
Constant	4.2753	4.4066	4.0369	-9.9059
	[1.7063]	[1.8086]	[1.5827]	[4.0625]
SOMA	-0.7432	-0.7864	-0.6893	2.0288
	[0.26056]	[0.27627]	[0.2417]	[0.60247]
IOER	1.3360	1.4136	1.2391	0.6555
	[0.33984]	[0.36099]	[0.31541]	[0.22179]
Target Federal Funds Rate	0.1523	0.1612	0.1413	-0.4159
	[0.39448]	[0.41742]	[0.36587]	[1.0743]
Discount Rate	0.9185	0.9719	0.8519	0.4506
	[0.15308]	[0.16357]	[0.14224]	[0.12395]
Panel 2: Logarithms with sample from 2008-01-01-2011-07-29 (m2)				
Constant	2.8864	2.6710	2.6309	-2.6467
	[2.4849]	[2.5139]	[2.2304]	[4.9303]
SOMA	-0.6007	-0.6038	-0.5390	1.2162
	[0.3583]	[0.36228]	[0.32157]	[0.69495]
IOER	0.8277	0.8320	0.7427	0.0934
	[0.26985]	[0.27624]	[0.2425]	[0.044914]
Target Federal Funds Rate	0.0528	0.0530	0.0473	-0.1068
	[0.52763]	[0.5304]	[0.47346]	[1.0684]
Discount Rate	0.6215	0.6248	0.5577	0.0701
	[0.12836]	[0.13548]	[0.11584]	[0.028286]
Panel 3: Levels with sample from 2003-1-09-2011-07-29 (m3)				
Constant	0.2961	0.2578	0.3098	-3.9145
	[0.43997]	[0.43004]	[0.44292]	[3.7708]
SOMA	-0.0933	-0.0910	-0.0939	0.7828
	[0.068451]	[0.066771]	[0.068893]	[0.58178]
IOER	0.7745	0.7554	0.7794	6.7457
	[0.21832]	[0.21311]	[0.21983]	[1.8897]
Target Federal Funds Rate	0.5094	0.4969	0.5127	-4.2730
	[0.24087]	[0.23499]	[0.24237]	[2.051]
Discount Rate	0.4504	0.4393	0.4532	3.9226
	[0.10557]	[0.10309]	[0.10633]	[0.89842]
Panel 4: Levels with sample from 2008-01-01-2011-07-29 (m4)				
Constant	0.6415	0.5550	0.6789	-0.0512
	[0.5716]	[0.48662]	[0.5674]	[4.7947]
SOMA	-0.1020	-0.0866	-0.1012	0.8495
	[0.080129]	[0.068158]	[0.079533]	[0.67122]
IOER	-0.4236	-0.3599	-0.4204	-1.2242
	[0.058216]	[0.051206]	[0.058108]	[0.38253]
Target Federal Funds Rate	0.2576	0.2188	0.2557	-2.1457
	[0.27999]	[0.23804]	[0.27787]	[2.312]
Discount Rate	0.5673	0.4819	0.5630	1.6395
	[0.080595]	[0.070731]	[0.08042]	[0.51844]

The table presents the long-run, reduced-form coefficient estimates for the alternative models. Standard errors in squared brackets.

of strong priors on the speed of adjustment, this observation is not helpful for model selection.

Thus, statistical criteria alone are not powerful enough to discriminate among models; they all have comparable statistical properties and are dynamically stable. Thus, we now examine whether one can use economic criteria to discriminate among these models.

Adjustment to the Steady State

Figure 11 shows that regardless of the choice of the model specification and the sample period, the parameter estimates generate a steady state for the different models. Though, the steady states and the associated adjustment paths differ greatly across models. For example, the level of reserves for model m3 drops from $1,600 billion on July 30, 2011 to $600 billion by the end of 2011 which is larger than the change that took place in the fourth quarter of 2008. Hence, on this basis, we exclude model m3 as it embodies unrealistic behavior.

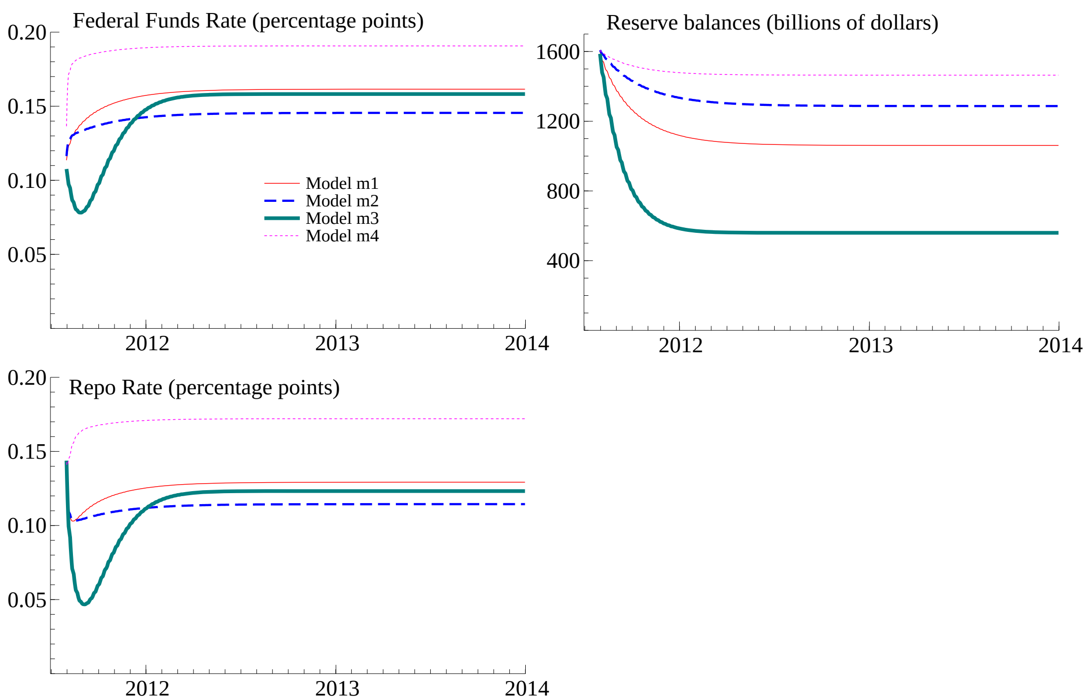

Figure 11: Steady States for the Federal Funds Rate, Reserve Balances, and the Repo Rate for Alternative Models

Response to Changes in Policy Settings

We now examine how the various models respond to changes in policy settings. We consider the same Scenarios 1 and 2 examined earlier:

- Scenario 1: An increase in the IOER rate of 10 basis points, all else unchanged;

- Scenario 2: A contraction of SOMA by 800 billion, all else unchanged.

For the federal funds rate, the results from models m1, m2, and m3 indicate that either a contraction of SOMA or an increase in the IOER rate induces an increase in the federal funds rate, consistent with our prior views. For model m4, however, the results indicate that an increase in the interest rate on reserves lowers the federal funds rate, which is counterintuitive

(Figure 12). For this reason, we deem model m4 as not suitable for analysis.

For the level of reserve balances, the results from model m2 indicate that an increase in the IOER rate has no effect on reserve balances, which is counterintuitive (Figure 13). For this reason, we deem model m2 as not suitable for analysis.

In summary, model m2 is not helpful because the effect of a change in the IOER rate on reserves is zero, which is counterintuitive. For model m3, the adjustment of the level of reserves to their steady state involves a huge swing in reserves that has not been observed in reality. Finally, for model m4, an increase in the IOER rate lowers the federal funds rate and reserves which is counterintuitive.

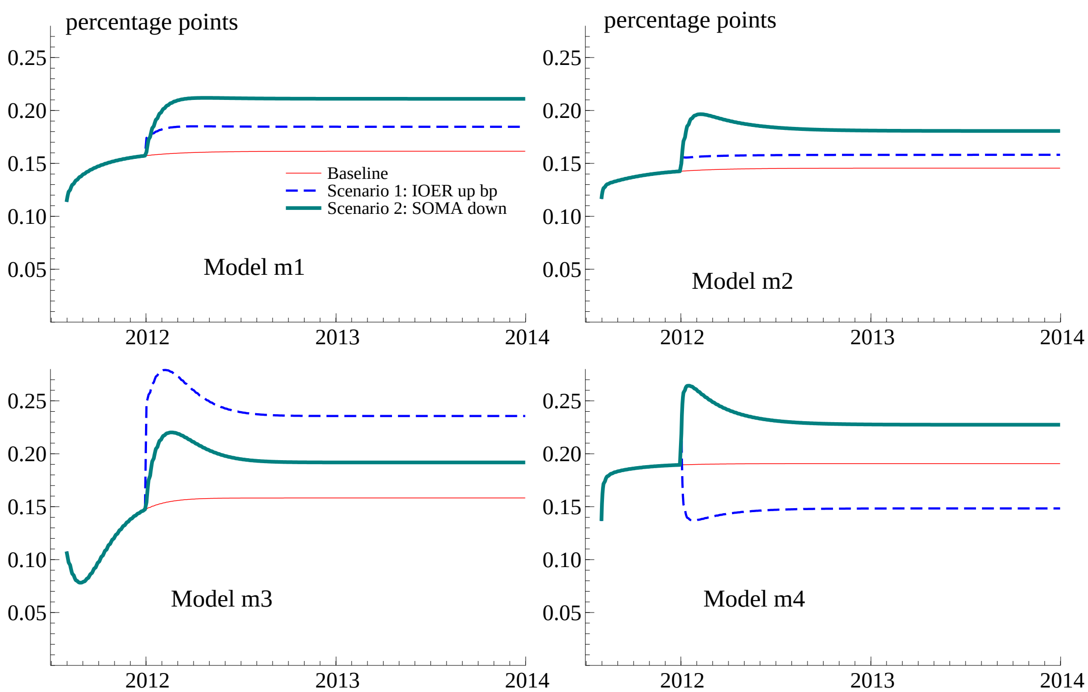

Figure 12: Adjustment to Steady States for the Federal Funds Rate: Models m1-m4

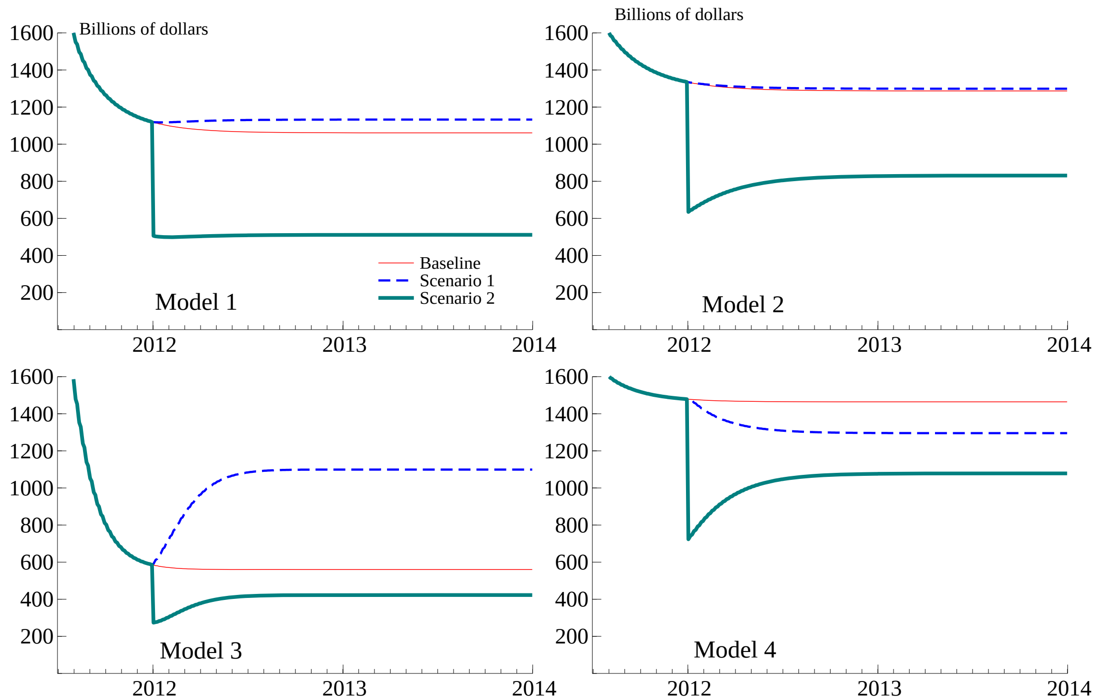

Figure 13: Adjustment to Steady States for Reserve Balances: Models m1-m4

VI. Conclusion

In this study, we model the relation between reserve balances and overnight interest rates to assess the effect of a reversal of the Federal Reserve's large-scale asset purchases on overnight interest rates and other tools for monetary tightening. In particular, we estimate a system of four equations modeling the federal funds rate, the repo rate, the Eurodollar rate, and reserve balances held by depository institutions in terms of three policy rates and the Federal Reserve's SOMA holdings.

Unlike previous studies, we treat the Federal Reserve's asset purchases as a policy tool and we rely on full-information methods for parameter estimation, recognizing the interdependencies among the overnight funding rates and reserve balances. According to our results, the Federal Reserve needs to reduce its asset holdings by about $1 trillion to raise the federal funds rate to 25 basis points. Moreover, we find that the short-run transition of the federal funds rate via short-run responses to the steady state is quick, i.e., in response to a shock, the federal funds rate reaches a new steady state in two months. Further, while the steady state is invariant to the order of policy changes, the sequencing of different policy measures in an exit strategy matters for the profile of the response of the federal funds rate. Finally, these conclusions rest on strong assumptions, which our project seeks to relax. Future work may change the empirical support for the specific findings we report here. Hence, our results have an undeniable tentative nature.

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Appendix

Appendix A. Stationarity Test Results

Table IV: Unit Root Test Results

Panel A: Aug. Dickey-Fuller	No Lags		10 Lags		20 Lags		30 Lags	
	Const.	No Const.	Const.	No Const.	Const.	No Const.	Const.	No Const.
Fed. Funds Rate	-1.286	-1.517	0.487	-0.642	0.763	-0.576	0.442	-0.641
Repo Rate	-4.254***	-3.727***	-1.245	-1.526	-0.209	-0.916	-0.465	-1.052
Eurodollar	-3.375**	-2.931***	-0.171	-0.986	0.739	-0.682	0.397	-0.745
Reserve Bal.	-4.855***	-1.461	0.838	1.671	1.256	2.011**	0.299	1.283

Panel B: Phillips-Perron	No Lags		10 Lags		20 Lags		30 Lags	
	Const.	No Const.	Const.	No Const.	Const.	No Const.	Const.	No Const.
Fed. Funds Rate	-5.447	-5.100	0.046	-1.632	0.641	-1.253	0.720	-1.200
Repo Rate	-39.148***	-28.259***	-12.360*	-9.709**	-8.450	-6.708*	-9.385	-6.922*
Eurodollar	-25.273***	-16.874***	-4.781	-4.586	-2.774	-3.236	-3.088	-3.260
Reserve Bal.	-50.849***	-5.417	-7.369	0.363	-7.126	0.697	-9.428	0.708

This table reports the results of the Augmented Dickey-Fuller and Phillips-Perron tests for the logarithms of the Federal Funds rate, the repo rate, the Eurodollar rate, and reserve balances for various specifications regarding the lag length and the inclusion/exclusion of a constant. *, **, *** denotes significance at the 10%, 5%, and 1%, respectively.

Appendix B. In-Sample Properties of Alternative Models

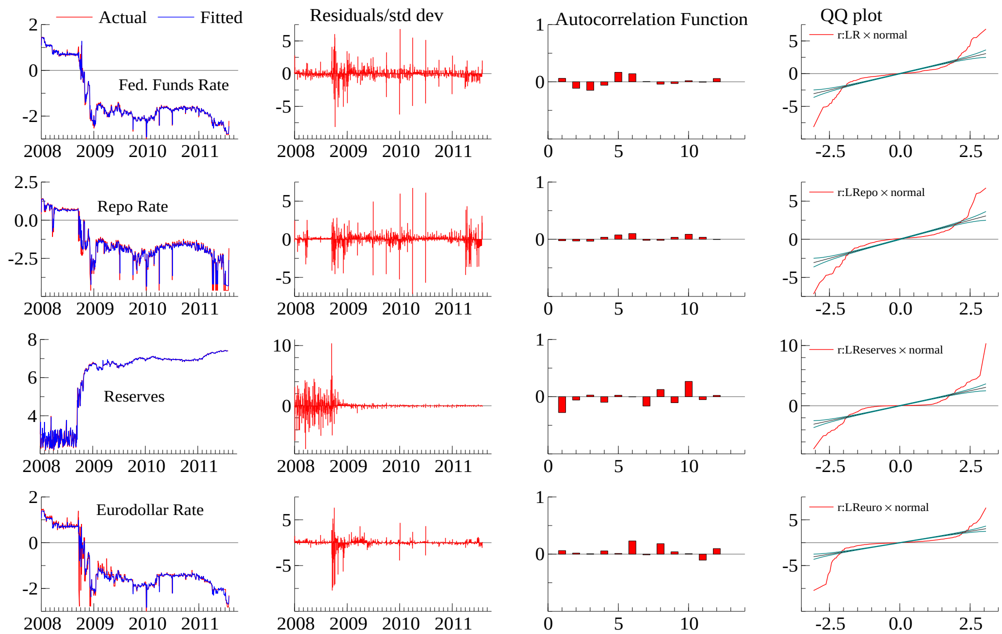

Figure 14: In-Sample Model Properties: Log-linear model with short sample (2008-01-01 to 2011-07-29)

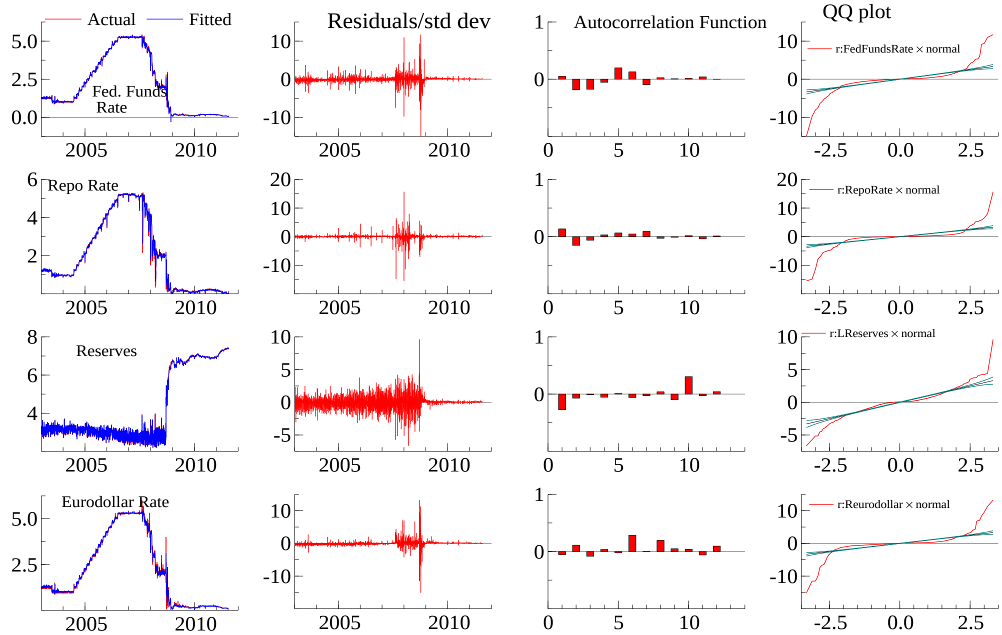

Figure 15: In-Sample Model Properties: Linear model with long sample (2003-01-01 to 2011-07-29)

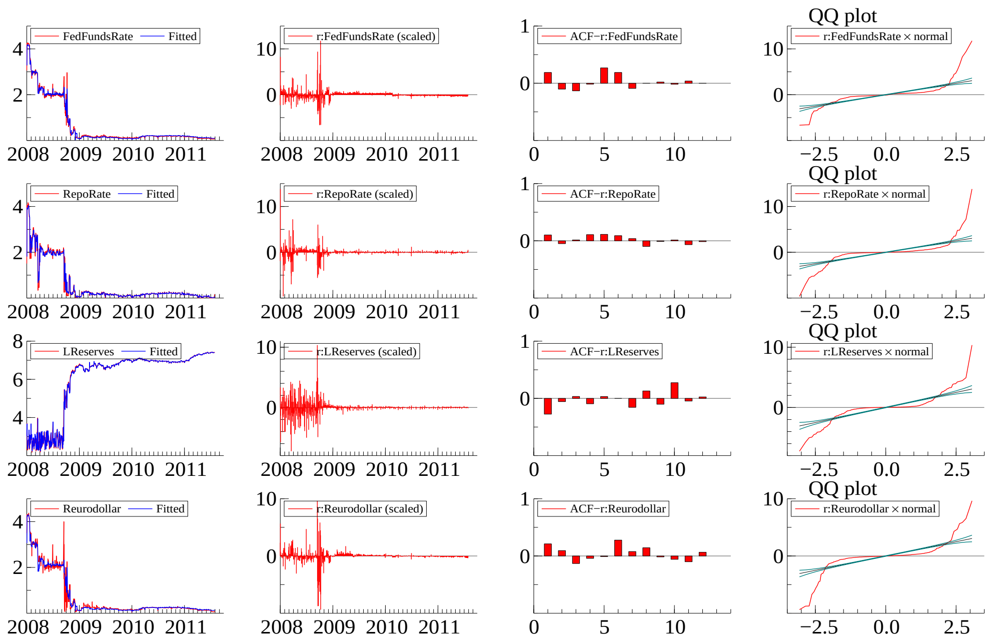

Figure 16: In-Sample Model Properties: Linear model with short sample (2008-01-01 to 2011-07-29)

Appendix C. Dynamic Stability

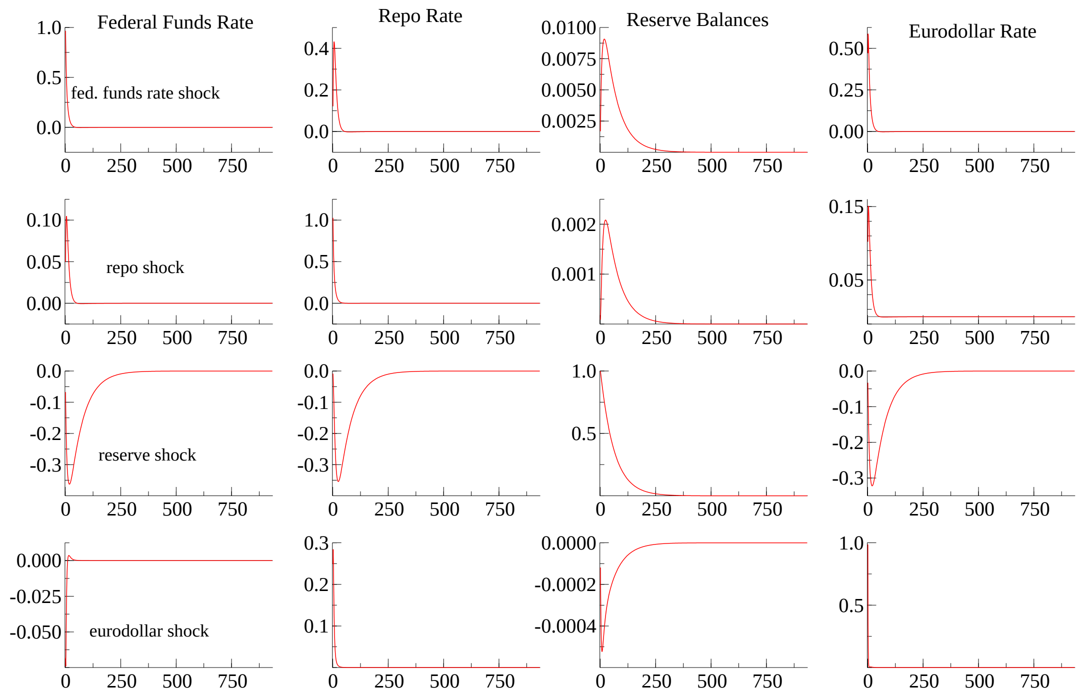

Figure 17: Impulse Response Functions: Log-Linear model with short sample (2008-01-01 to 2011-07-29)

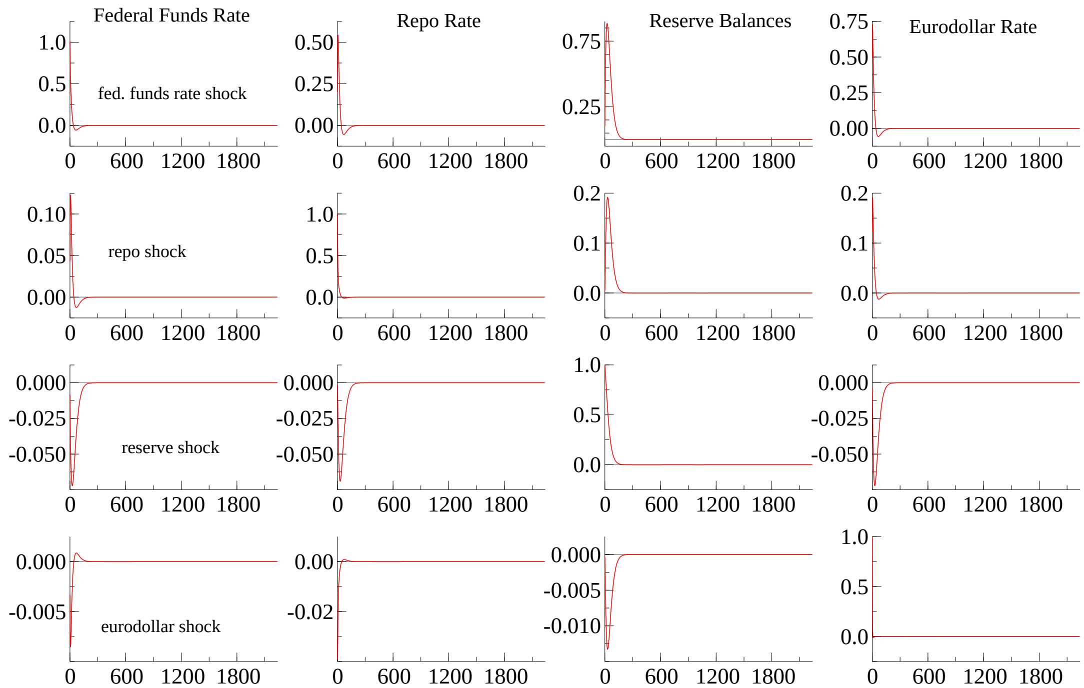

Figure 18: Impulse Response Functions: Linear model with long sample (2003-01-01 to 2011-07-29)

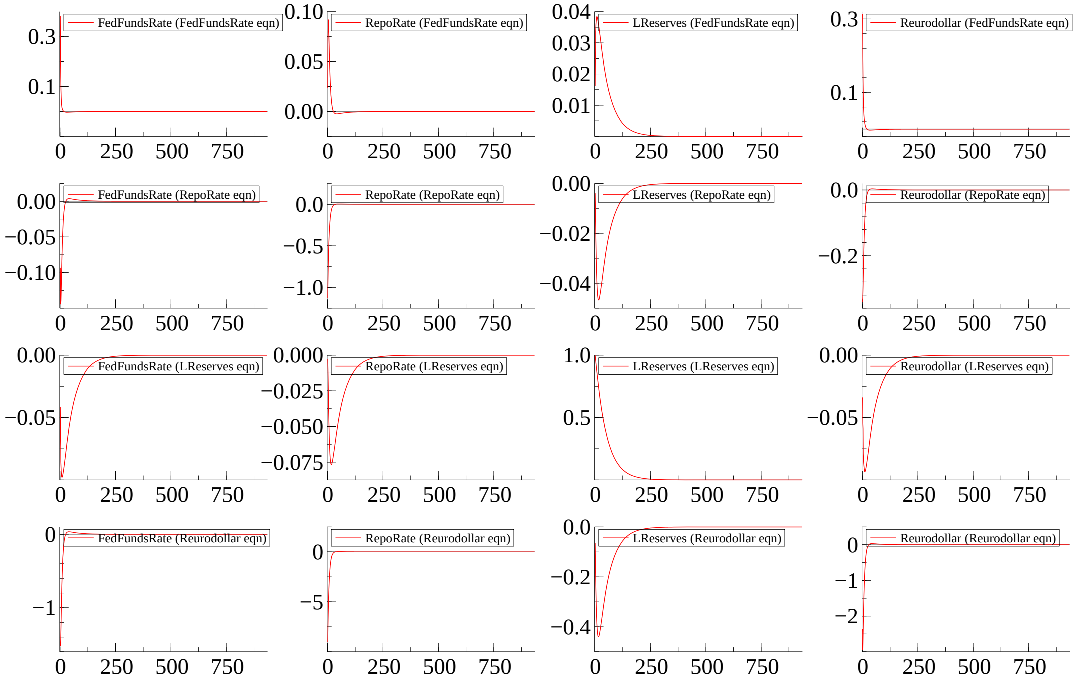

Figure 19: Impulse Response Functions: Linear model with short sample (2008-01-01 to 2011-07-29)