Frictions in the Interbank Market and the Demand for Reserves: Lessons from the Financial Crisis

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Abstract

Many central banks around the world have adopted a framework for implementing monetary policy that involves targeting a value for the overnight rate on unsecured loans of reserves between banks. The financial crisis wrecked havoc in this market and central banks responded, in part, by flooding the system with reserves, driving rates lower. We extend the canonical model of implementation of monetary policy within a corridor system to include credit risk and transactions cost. We empirically test how well this model can describe the demand for reserves dynamics during the crisis and find that both frictions played important roles.

JEL classification: E43, E52 and E58

Keywords: Reserves, Corridor System, Monetary Policy, Financial Crisis

1 Introduction

Unconventional has been the buzzword in the realm of monetary policy lately. The policy debate in the United States has focused on the implementation of large scale asset purchases and its effects on longer term interest rates. A consequence of these purchases has been a very large Federal Reserve balance sheet and a high level of reserve balances. Yet, most observers believe that current state of affairs – an expanded balance sheet and near zero overnight rates – is temporary.

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A natural question is then how the Federal Reserve will implement monetary policy in the future. One new innovation is already in place: On October 1, 2008, the Federal Reserve received authority to pay interest on balances held by depository institutions at Federal Reserve Banks, and it began to use that authority immediately. At the January 2010 Federal Open Market Committee meeting "most policymakers saw benefits in continuing to use the federal funds rate as the operating target for implementing monetary policy." Moreover, "[m]any, thought that an approach in which the primary credit rate was set above the Committee's target for the federal funds rate and the [interest on excess reserves] rate was set below that target–a corridor system–would be beneficial."[1]

As corridor systems have been a long-standing practice at many central banks around the world it seems prudent to learn from their experiences during the financial crisis.[2] In particular, it interesting to see how monetary policy implementation theory compared to practice during the crisis.

A key component for most monetary policy implementation frameworks is the demand for central bank liabilities, and specificallly,reserve balances. The estimation of the demand curve for reserve balances has been an important task for central banks and the focus of academic research. Since Hamilton (1997), studies have shown that there exists a price response to changes in the level of reserve balances, otherwise known as the *liquidity effect*. Liquidity effects have been documented in other operating environments as well; for example, Hayashi (2001), Moschitz (2004), and Angelini (2008).

However, most of these studies were undertaken in an environment with a relatively constant level of reserve balances. The large expansion of central bank balance sheets during the recent financial crisis and the concomitant increases in reserve balances provide a natural experiment to estimate the demand for reserve balances in different regions of the demand curve than what was possible previously.

Unfortunately, for U.S. policy makers, several idiosyncrasies in the implementation of interest on reserves as well as the timing at the height of the financial crisis (see Bech and Klee (2011)), renders

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[1] Minutes of the Federal Open Market Committee, January 26-27, 2010, available for download at http://www.federalreserve.gov/monetarypolicy/files/fomcminutes20100127.pdf.

[2] Refer to Bowman, Gagnon and Leahy (2010), for example.

the U.S. experience less suitable for independent analysis. Consequently, we turn our attention to the experience of the European Central Bank to help guide the analysis.

Using data for the overnight rate and reserves in the Eurozone, we are able to trace out the demand curve for reserve balances. Importantly, our results highlight two frictions affecting the demand for reserve balances that have received relatively little attention in previous work. First, we show both theoretically and empirically that transaction costs materially affect the demand for reserves. The proportional effect of transaction costs is more pronounced in environments with lower levels of reserve balances than in the current large-balance sheet environment, representing a larger share of the deviation of fundamentals for demand. Second, we show that the credit risk of institutions also present a friction in the demand for reserves.

The paper is organized as follows. Section 2 provides background information on the framework for implementing monetary policy in the Euro-area. Section 3 presents the theoretical model. Section 4 describes the empirical framework and discusses the results. Section 5 concludes.

2 Background on monetary policy implementation

This section describes the ECB's tools for monetary policy implementation, highlighting the tools used in the crisis as well as the behavior of the rates indicating the monetary policy stance. The information presented here will inform the modeling choices made later in the paper, both theoretical and empirical.

2.1 The corridor system and policy stance

Since its inception in 1999, the European Central Bank (ECB) has used a corridor system for monetary policy implementation. The European Central Bank (ECB) guides short-term market rates through open market operations and its two standing overnight facilities: the marginal lending facility and the deposit facility. At the marginal lending facility banks can obtain overnight funds against eligible collateral and as such it creates a ceiling for the overnight market interest rate. At the deposit facility banks can place funds with the central bank. The interest rate paid here provides a floor for the overnight market interest rate. As in the United States, banks are subject to minimum reserve requirements. Before January 2012, banks were required to hold reserves in an amount of 2 percent of selected liabilities at the central bank; since then, the reserve coefficient has been 1 percent.[3] In addition, banks hold excess reserves over and above reserve requirements.

Prior to the financial crisis, the Eurosystem supplied reserves to banks via weekly so-called main refinancing operations (MROs) and three-month so-called long-term refinancing operations (LTROs). However, during the financial crisis, the latter type of operations were expanded to include one month, six months, one year, and finally operations with duration of up to three years. In fact, longer term operations have become the "main" provider of reserves to the Euro-area banking system. The operations are conducted as auctions and are either variable or fixed-rate tenders (some with full-allotment). The minimum bid rates on these open market operations constitute the main indication of the monetary policy stance.

Like other central banks, the ECB changed its policy rates as well as the details of open market operations multiple times during the financial crisis as discussed in e.g. ECB (2010b) and ECB (2011a). Table 1 provides an overview of these changes from June 2007 through September 2012. The ECB reduced its policy target from $4\frac{1}{4}$ percent to 1 percent over a period of just seven months from October 2008 to May 2009. In April 2011, the ECB changed tack and increased the target twice by 25 basis points. However, this reversal was not to last and since late 2011 the ECB has eased three times to 75 basis points.

In addition, the ECB changed the width of the standing facilities corridor three times. In October 2008 the width was reduced from 200 to 100 basis points in order to ease monetary conditions. This decision was reversed in January 2009 when the corridor was widened to 200 basis points again. However, when the policy rate was cut to 1 percent later in May, the width of the corridor was reduced to 150 basis points - allegedly to avoid reducing the deposit facility rate to zero. Nevertheless, eventually this proved unavoidable in July 2012 (see Table 1).

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[3] Refer to http://www.ecb.int/mopo/implement/mr/html/calc.en.html#ded.

Date	Deposit Facility	Main Refinancing Operations	Marginal Lending Facility	Other Changes
		Percent		
2007				
Jun. 13	3.00	4.00	5.00	
2008				
Jul. 9	3.25	4.25	5.25	
Oct. 8	2.75	-	4.75	
Oct. 9	3.25	-	4.25	Corridor 100 bps
Oct. 15	3.25	3.75	4.25	Fixed rate tender, full allotment
Nov. 12	2.75	3.25	3.75	
Dec. 10	2.00	2.50	3.00	
2009				
Jan. 21	1.00	2.00	3.00	Corridor 200 bps
Mar. 11	0.50	1.50	2.50	
Apr. 8	0.25	1.25	2.25	
May 13	0.25	1.00	1.75	Corridor 150 bps
Jun. 25	-	-	-	1 year LTRO (€442B)
Oct. 1	-	-	-	1 year LTRO (€75B)
Dec. 12	-	-	-	1 year LTRO (€97B)
2011				
Apr. 13	0.50	1.25	2.00	
Jul. 13	0.75	1.50	2.25	
Oct. 27	-	-	-	1 year LTRO (€57B)
Nov. 9	0.50	1.25	2.00	
Dec. 14	0.25	1.00	1.75	
Dec. 22	-	-	-	3 year LTRO (€489B)
2012				
Mar. 1	-	-	-	3 year LTRO (€530B)
Jul. 5	0.00	0.75	1.50	
Aug. 2	-	-	-	OMT announced
Sep. 6	-	-	-	SMP terminated

Note: Bps = basis points, B = Billion, Rate changes reported by effective date and LTROs reported by settlement date, OMT = Outright Monetary Transactions, SMP = Securities Market Program.

Source: www.ecb.int

Table 1: ECB Policy Rate Changes - June 2007 - September 2012

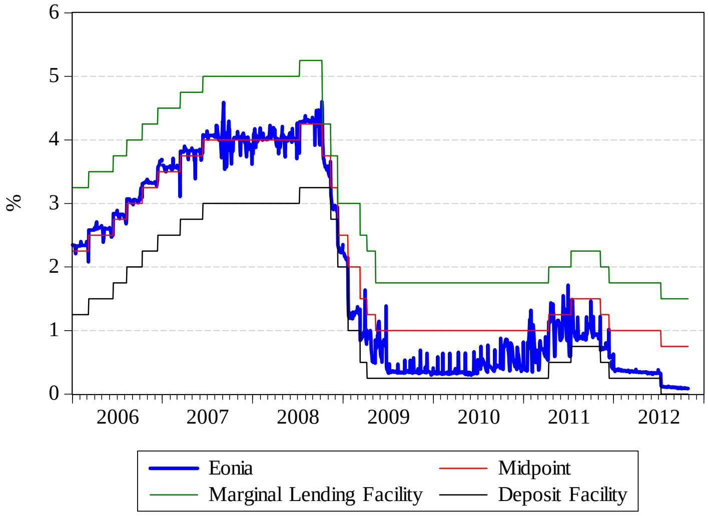

Figure 1: Eonia

2.2 Eonia

The Euro OverNight Index Average (Eonia®) rate is the effective overnight reference rate for the euro. It is computed as a weighted average of all overnight unsecured lending transactions initiated by a panel of banks active in the euro area interbank money market.[4] As shown in Figure 1, the Eonia tracked the policy rate, with some volatility, up to October 2008. Thereafter, the Eonia fell below the midpoint of the corridor spanned by the rates at the deposit and the marginal lending facility. In fact, from mid-2009 to mid-2010, the Eonia was very close the deposit rate. After mid-2010 the Eonia move of the floor but mostly stayed below the midpoint. From late 2011, the Eonia has once again been close to the floor.

2.3 Reserves

The reason the Eonia moved to the bottom of the corridor is that the amount of excess reserves increased substantially from late 2008 to the present. In order to understand how this increase came about, it is helpful to review the ECB's balance sheet. A simplified version of the ECB's balance sheet is presented in Table 2.

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[4] The banks contributing to Eonia are the same banks as the panel banks quoting for Euribor®.

The asset side shows factors supplying reserves and the liability side shows the uses of reserves. The asset side consists of two components: open market operations and loans to bank extended via the marginal lending facility. In addition, to the refinancing operations, open market operations include two components of the Eurosystem's non-standard monetary policy measures: the covered bonds purchase programs (CBPP) and the reserves-absorbing operations that are carried out to sterilize the reserves provided through the Securities Market Program (SMP).[5]

Assets (Supply of reserve funds)	Liabilities (Uses of reserve funds)
Open market operations	Current accounts
Refinancing operations	Deposit facility
Covered bond purchase program	Net reserves effect from autonomous factors
Term deposits	*Securities market program*
Marginal lending facility	*Emergency Liquidity Assistance*

Table 2: Simplified Eurosystem Balance Sheet

As shown in Figure 2, the amount of outstanding open market operations increased substantially from late 2008 to early 2010, and then declined through 2010 and 2011 before climbing again in late 2011.

The liability side comprises three components. Two of these represent balances held by banks in the Eurosystem. They are balances in the current account of the bank where they earn no interest and balances placed at the deposit facility where they do earn interest.[6] The third component is the net reserves effect from a wide range of other balance sheet components over which the ECB has little or no control. These so-called autonomous factors include - as it is standard among central banks - items such as government accounts, currency in circulation, FX reserves and investment portfolios. But the autonomous factors also include the reserves add by the SMP and Emergency Liquidity Assistance provided by national central banks to banks in their jurisdictions.

As a result of the non-standard policy measures employed by the ECB, excess reserves held by banks, defined as the sum of current account deposits and deposit facility funds in excess of

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[5] The Euro-system has purchases euro-denominated covered bonds under the its Covered Bond Purchase Program (CBPP) and the its has purchased euro area debt securities under its Securitiies Markets Programme. To ensure that conditions in the market for reserves were not affected, all purchases under the latter program were fully sterilised by conducting reserve-absorbing operations.

[6] Our term "banks" corresponds to the ECB's more precise term "credit institutions."

reserve requirements, ballooned during the financial crisis.[7] As shown in Figure 3, the amount of excess reserves were generally low through the fall of 2008. The ECB's liquidity provision measures increased excess reserves substantially through the fall of 2008, and moderated through the spring of 2009. In the second half of 2009 with the €442 billion LTRO, excess reserves climbed again, and stayed elevated until the LTRO matured in June 2010. As strains in European markets reappeared and the ECB embarked on a new round of the CBPP program, as well as performed more LTROs, excess reserves increased again, and reached unprecedented high levels at the end of the sample following the two 3 year LTROs.

Somewhat surprisingly, despite the significant run-up in excess liquidity, the Eonia has stayed somewhat above the floor of the corridor during the entire period and unlikely the United States never hits (or goes below) the rate of the deposit facility. In fact, the difference between the Eonia and the deposits rate on a monthly average basis is 8 basis points or more despite the high level of excess reserves. The model below suggests reasons why this is the case.

3 Model

In this section, we extend the standard framework for understanding banks' demand for reserves by introducing frictions in the interbank markets such as transaction costs and default Our analysis build on that of e.g. Poole (1968), Woodford (2001), Whitesell (2006) and Ennis and Keister (2008).

3.1 The standard framework

We follow Whitesell (2006) and envision an economy where risk neutral banks seek to manage their end-of-day reserve position during the day by trading central bank balances (interbank loans) with other banks at the market rate, i. This task is made difficult as payments flows between banks, auxiliary payments systems and the central bank redistributes the reserves in the system throughout the day. Some of these payment flows are predictable but others are not. Unexpected

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[7] Note that this is not the exact definition of excess reserves, but closer to the "due to" the financial sector concept outlined in Bindseil (2004). This definition is slightly more appealing for our purposes, as this represents total central bank liquidity held by banks.

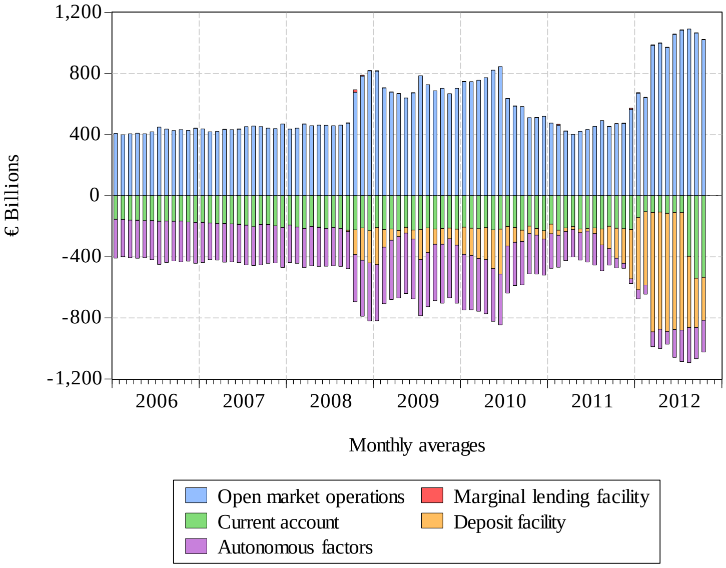

Figure 2: ECB Simplified balance sheet

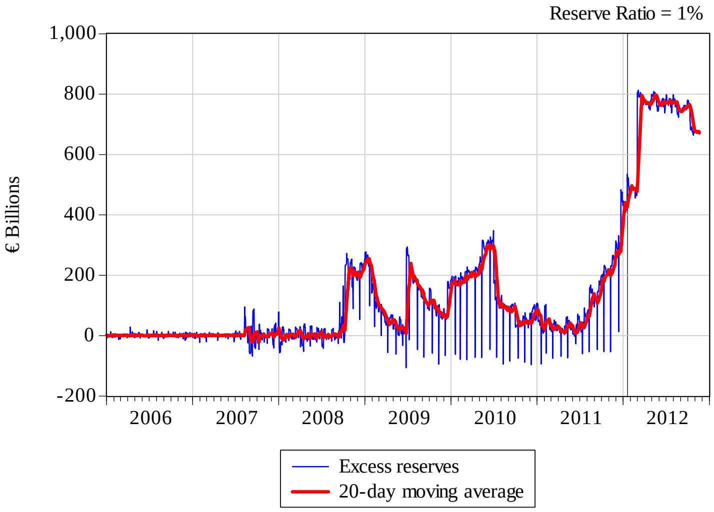

Figure 3: ECB excess reserves

(or delayed) incoming payments or payment requests from either customers or the banks' own operations may occur up to the close of the payment system. While trading of overnight funds is in principle possible up to the close of business, execution risk implies that a bank can only determine its end-of-day position within a margin of error. We model this by a stochastic term, ε (the payment shock). Let F denote the cumulative distribution function of the shock and assume that $E[\varepsilon] = 0$.

For simplicity, we ignore reserve requirements in the model and hence excess reserves and reserves are equivalent.[8] During the day, a bank targets a reserve position of R, but its end-of-day position is $R + \varepsilon$. The central bank operates both a deposit and a lending facility. Hence, if the bank has a positive account position at the end of the day then the central bank will remunerate the balances at the rate r_{ior} whereas if the bank has a negative account position the bank will have to turn to the lending facility to cover the overdraft and pay the rate r_{dw}. As noted by Whitesell (2006), without knowing ε, the bank chooses R to minimize two types of expected costs: the opportunity cost of holding positive reserves with the central bank, relative to lending the funds in the market, and the loss, in the case of deficiencies, on borrowing from the central bank rather than from the market. Formally, the bank's problem is:

$$\min_{R}(i - r_{ior}) \int_{-R}^{\infty} (R + \varepsilon) dF(\varepsilon) - (r_{dw} - i) \int_{-\infty}^{-R} (R + \varepsilon) dF(\varepsilon) \tag{1}$$

The first-order condition is

$$(i - r_{ior}) \int_{-R}^{\infty} dF(\varepsilon) - (r_{dw} - i) \int_{-\infty}^{-R} dF(\varepsilon) = 0 \tag{2}$$

and rearranging the terms yields

$$i = r_{ior} + (r_{dw} - r_{ior}) F(-R) \tag{3}$$

That is, the marginal cost of borrowing an additional unit of reserves, i.e. the overnight rate, is equal to the marginal benefit. The marginal benefit is is equal to the rate the central bank pays

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[8] That is reserves holdings beyond any requirements imposed by the central bank

on overnight deposits plus the expected savings in terms of not having to go to the lending facility, i.e., the width of the corridor times the probability of an deficiency. Alternatively, we can write overnight rate in terms of its (relative) position with within the corridor spanned by r_{ior} and r_{dw}.

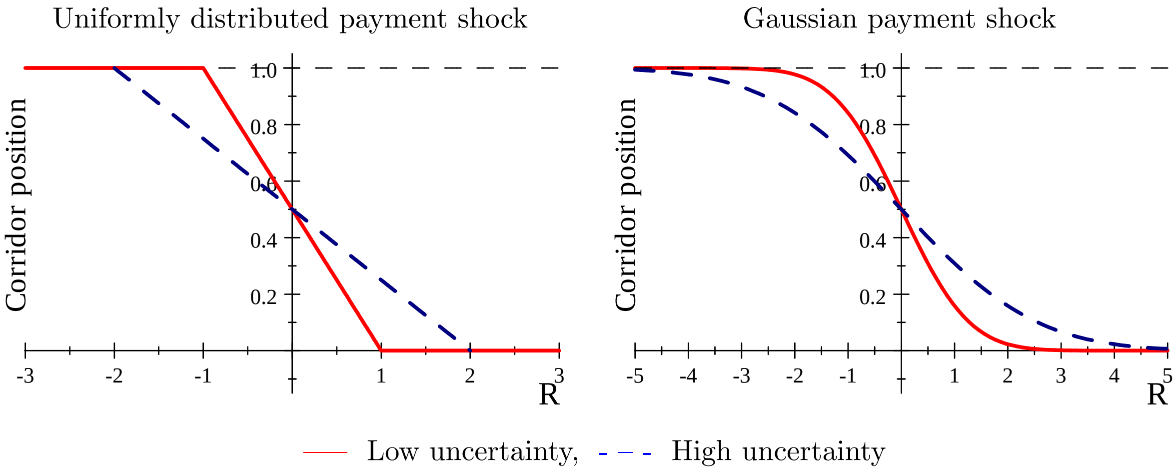
$$\theta \equiv \frac{i - r_{ior}}{r_{dw} - r_{ior}} = \frac{i - r_{ior}}{c} = F(-R) \tag{4}$$

The rate sensitivity with respect to reserves (i.e. the liquidity effect) is

$$\frac{\partial \theta}{\partial R} = f(-R) \tag{5}$$

where f is the density function of the payment shock.

Four insights follow, see Figure 4. First, the shape of the demand schedule for reserves is determined by the distribution of the payment shock, Second, if F is symmetric then the demand for reserves will be zero when the market rate is at the midpoint of the corridor. Third, as noted by Woodford (2001), "the demand for [reserves] should be a function of the location of the overnight rate relative to the [central bank] lending rate and [central bank] deposit rate, but independent of the absolute level of any of these interest rates." From an empirical perspective this implies that as long as the interbank market can be assumed to be reasonably frictionless, then demand for reserves can be estimated by transforming the overnight rate into its relative position of the corridor and pooling observations across different regimes, even if the level of the policy rate and the corridor width differ.Fourth, the demand curve flattens as uncertainty increases (Poole (1968)).



Uniformly distributed payment shock

Gaussian payment shock

Figure 4: Individual Bank Demand for Reserves, Uniform and Gaussian Payment Shock

The aggregate demand for reserves can be obtained by summing across banks

$$R^{AD} = \sum R_j^* = F_j^{-1}(\theta) \tag{6}$$

where j denotes individual banks. The market clearing overnight interest rate, i^* or θ^*, is the rate that results in aggregate demand being equal to the central bank's aggregate supply of reserves, R^S. If banks are identical, we have that in equilibrium $R^S = R^{AD} \Rightarrow R^S = nR_j^*$. We have $\frac{1}{n}R^S = -F^{-1}(\theta^*) \Rightarrow \theta^* = F^{-1}(\frac{1}{n}R^S)$. The overnight rate is pinned down by the central bank's per bank supply of reserves. For the ease of exposition, we treat - from this point on - banks as identical and use supply of excess reserves as shorthand for the *per bank* supply of reserves.

One final point is that the supply of reserves is not only determined by the central bank via open market operations but also by factors beyond its control. These so-called autonomous factors include shifts in currency demand and flows in and out of the government account at the central bank. While central banks seek to forecast the impact hereof errors occur and this introduces volatility in the overnight rate. The amount of the volatility depends on the size or the errors and on the steepness of the demand curve. Consequently most central banks do not impose reserve requirements on a day to day basis but rather use an average over a period. Reserve averaging flattens the demand curve, at least on days prior to the last day of the maintenance period (see e.g. Whitesell (2006) and Ennis and Keister (2008)). In our theoretical model we ignore the impact of reserve averaging for simplicity but do control for such effects in our empirical work.

3.2 Adding frictions

The standard framework assumes that the interbank market is "frictionless". That is, the effective cost (income) from borrowing (lending) from another bank is equal to the quoted market rate i. Here, we assume that the overnight market rate at which banks can effectively lend, potentially differs from the rate at which banks can borrow, i^b. That is, $i^l \leq i \leq i^b$. Formally, the bank's problem becomes

$$\min_R (i^l - r_{ior}) \int_{-R}^{\infty} (R+\varepsilon)dF(\varepsilon) - (r_{dw} - i^b) \int_{-\infty}^{-R} (R+\varepsilon)dF(\varepsilon) \tag{7}$$

Taking the derivative with respect to reserves and rearranging the terms as before, we get

$$F(-R) = \frac{i^l - r_{ior}}{(r_{dw} - r_{ior}) - (i^b - i^l)} = \frac{i^l - r_{ior}}{c - w} \tag{8}$$

where w is the wedge between the rates at which banks effectively borrow and lend.

For simplicity, assume that the effective lending and borrowing rates faced by a bank differ from the market by a fixed spread. That is, $i^l = i - w^l$ and $i^b = i + w^b$. Solving equation (8) in terms of the relative position of the market rate in the corridor yields the following inverse demand curve

$$\theta = \frac{i - r_{ior}}{c} = (1 - \frac{w}{c})F(-R) + \frac{w^l}{c} \tag{9}$$

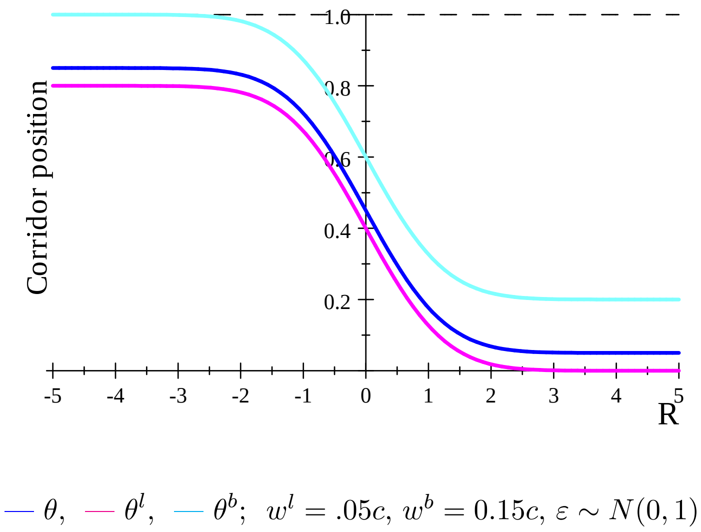
with rate sensitivity

$$\frac{\partial \theta}{\partial R} = -(1 - \frac{w}{c})f(-R) \tag{10}$$

where $w = w^l + w^b$. Moreover, while the relative position (inverse) demand curve in the standard model is independent of the corridor width this is no longer the case. We have

$$\frac{\partial \theta}{\partial c} = \frac{1}{c^2}(wF(-R) - w^l) \gtreqless 0 \text{ if } F(-R) \gtreqless \frac{w^l}{w} \tag{11}$$

Note, however, that the relative position within the corridor is still invariant to the level of interest rates (measure either by r_{ior} or r_{dw}) as long as the width of the corridor is constant.



— θ, — θ^l, — θ^b; $w^l = .05c$, $w^b = 0.15c$, $\varepsilon \sim N(0,1)$

Figure 5: Demand for reserves, fixed friction spread

The relevant rate for a seller of funds in the interbank market is

$$\theta^l = \frac{i^l - r_{ior}}{c} = \frac{i - w^l - r_{ior}}{c} = (1 - \frac{w}{c})F(-R) \tag{12}$$

whereas the relevant rate for a buyer of funds is

$$\theta^b = \frac{i^b - r_{ior}}{c} = \frac{i + w^b - r_{ior}}{c} = (1 - \frac{w}{c})F(-R) + \frac{w}{c}. \tag{13}$$

These two rates provides the effective boundaries of the corridor (see Figure 5). If θ^l is “zero” then a bank is indifferent between leaving funds at the central bank and lending it out in the interbank market even though the loan yields θ in interest. On the other hand, if θ^b is “one” then a bank indifferent between borrowing from other banks or the central bank.

3.2.1 Special cases

A couple of special cases highlight the setup presented above form the basis for the empirical analysis that follows.

Transaction costs Transaction costs in the interbank market may introduce a wedge between the cost of borrowing and lending. In the United States, anecdotal evidence suggest that federal funds brokers charge both the buyer and seller a brokerage fee of 50 cents per \$1 million of funds intermediated (Stigum and Credenzi (2007), p.514). In addition, there are the costs of maintaining a funds desk, search costs of finding a seller or buyer of funds, and back-office costs of clearing and settling the transactions. And finally, there are reserve-maintenance period induced transactions costs. There may be costs of fulfilling a reserve requirement towards the end of the maintenance period that does not exist in the weeks prior to the end of the maintenance period.

Let τ denote the (symmetric) transaction cost. We have that $i^l = i - \tau$ and $i^b = i + \tau$. From equation (9), it follows that

$$\theta_\tau = (1 - \frac{2\tau}{c})F(-R) + \frac{\tau}{c} \tag{14}$$

As shown in Figure 6, the demand for reserves is, as before, zero if the market rate is at the midpoint of the corridor. Moreover, the imposition of transaction costs narrows the potential range for the market rate within the corridor spanned by the policy rates. The market rate depends on the level of transactions costs as follows

$$\frac{\partial \theta_\tau}{\partial \tau} = -\frac{2}{c}F(-R) + \frac{1}{c} \gtreqless 0 \text{ if } F(-R) \lesseqgtr \frac{1}{2} \Leftrightarrow R \gtreqless 0 \tag{15}$$

As illustrated in Figure 6, higher transaction costs increases (lowers) the market rate when the demand for reserves is positive (negative).

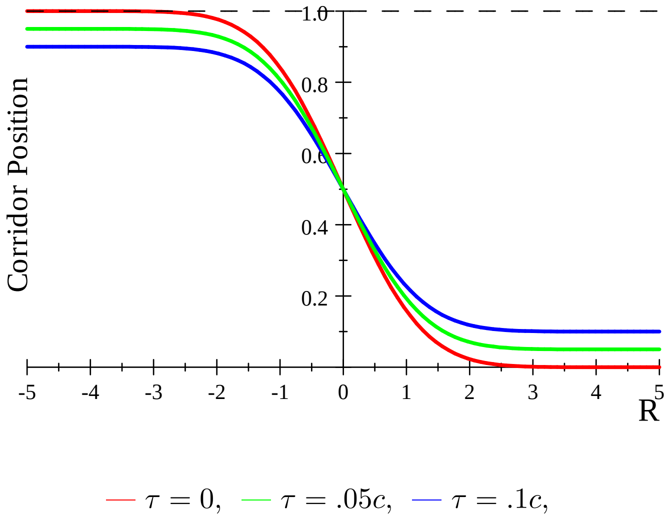


Figure 6: Demand for reserves, symmetric transaction costs

Moreover, we have

$$\frac{\partial \theta_\tau}{\partial c} = \frac{1}{c^2} \tau \left(2F - 1\right) \gtreqless 0 \text{ if } R \lesseqgtr 0 \tag{16}$$

We collect the results in the following proposition:

Proposition 1 *With symmetric interbank money market transaction costs, and if the distribution of the payment shock is also symmetric, then the market interest rate is at the midpoint of the corridor when the demand for reserves is zero. Moreover, the demand curve is flatter relative to the case without transaction costs. The relative position of the demand curve is not invariant to changes in the width of the corridor.*

Defaults The financial crisis highlighted the fact that credit risk plays an important role in money markets as many loans are unsecured. In this section, we introduce the possibility of default into the decision process of banks. Debelle (2008) describes the situation in the Australian money market at the outset of the financial turmoil as follows:

> "Beginning in August 2007, as banks became less certain of their own funding requirements and less confident of the credit profile of their counterparties, the inter-bank borrowing markets became quite tight. Banks were more inclined to hold onto cash,

> both because of an increased unwillingness to lend it, but also reflecting a concern about their ability to obtain funding themselves from the market in the future should they require it. This was most evident in term markets, where borrowing rates increased sharply. However, for similar reasons, there was an increased precautionary demand for [reserves] balances, reinforced by the fact that [reserves] are a risk-free asset. The effect was the demand curve for [reserves] shifted out."

We assume that when evaluating the expected interest income from a overnight loan, the lender includes a spread for expected credit losses, δ. For simplicity, assume that this spread does not depend on the overnight interest rate. We have that $i^l = i - \delta$, $\delta > 0$ but the interest cost of bank that borrows is $i^b = i$. The inverse demand curve from equation (9) becomes

$$\theta_\delta = (1 - \frac{\delta}{c})F(-R) + \frac{\delta}{c}. \tag{17}$$

As illustrated in Figure 7, increasing credit risk spread tilts the inverse demand curve up:

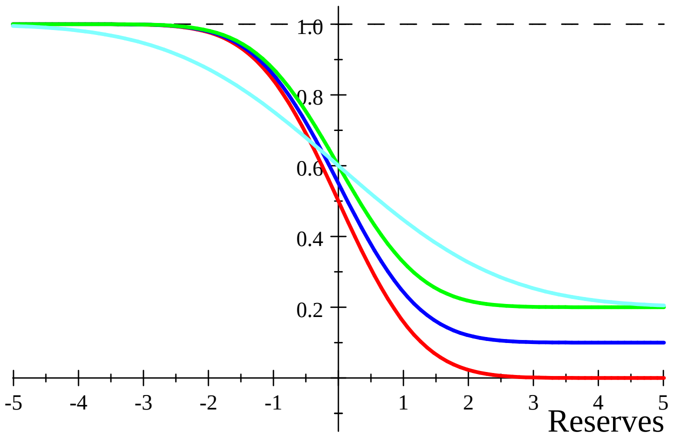
$$\frac{\partial \theta_\delta}{\partial \delta} = \frac{1}{c}(1 - F(-R)) \geq 0. \tag{18}$$

Note that it is no longer the case that the demand for reserves is zero when the market rate is at the midpoint of the corridor as we have $\theta_\delta(0) = (1 - \frac{\delta}{c})F(0) + \frac{\delta}{c} = \frac{1}{2} + \frac{1}{2}\frac{\delta}{c} = \frac{c+\delta}{2c} > \frac{1}{2}$. Moreover, we have

$$\frac{\partial \theta_\delta}{\partial c} = \frac{1}{c^2}\delta\,(F - 1) < 0 \tag{19}$$

We summarize the results in the following proposition:

Proposition 2 *Credit risk tilts out the demand curve for reserves. Increased payment shock uncertainty amplifies the shift if the demand for reserves is positive. Expanding the width of the corridor decreases the corridor position of the overnight rate.*



— $\delta = 0, \sigma = 1,$ — $\delta = .1c, \sigma = 1,$ — $\delta = .2c, \sigma = 1,$ — $\delta = .2c, \sigma = 2.$

Figure 7: Demand for reserves with defaults

4 Empirics

The simple framework outline above yields a number of testable implications:

- As the supply of reserves increases the market rate should move towards the bottom of the corridor.
- Transaction costs ensure that the market rate will never reach the bottom (or top) of the corridor.
- An increase in credit risk will lift the market rate for a given level of reserves.
- An increase in the width of the corridor should decrease the corridor position of the overnight rate if credit risk is an important friction.

This section develops an empirical model that can test these hypotheses.

4.1 Preliminaries

Our variable of interest is the position of the Eonia within the corridor spanned by the standing facilities as shown in Figure 8 . Prior to fall of 2008, it hovers around .5 before dropping towards zero.

It stays within the corridor for the entire period.[9] Around the end of the maintenance periods, the corridor position spikes up, as the ECB at times implements fine-tuning reserve-draining operations towards the in order to adjust outstanding reserves closer to reserve requirements. Moreover, as expected excess reserves are negatively correlated with the position of the overnight rate within the corridor as shown in Figures 9 and Figure 10. The latter shows a scatterplots of weekly average ECB excess reserves against the corridor position over the period of October 2008 through September 2012, i.e., the empirical analog of Figure 4. The left hand panel shows the entire sample. In contrast the right hand panel only shows observations for the periods where the width of the corridor was 150 basis and it includes a curve fitted using a nearest neighbor smoother. The curve is reminiscent of the demand schedules drawn for positive values of (excess) reserves in the theory section above.

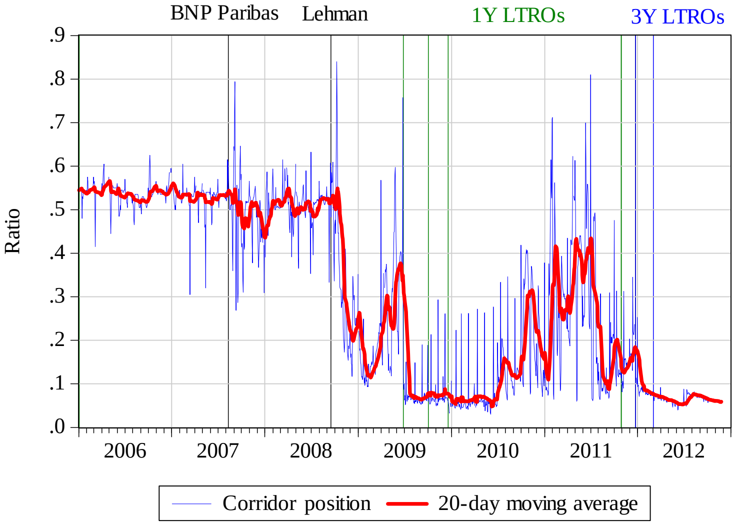


Figure 8: Eonia corridor position

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[9] This is in contrast to the U.S., where the federal funds rate traded below the corridor for many months. For details, refer to Bech and Klee (2011).

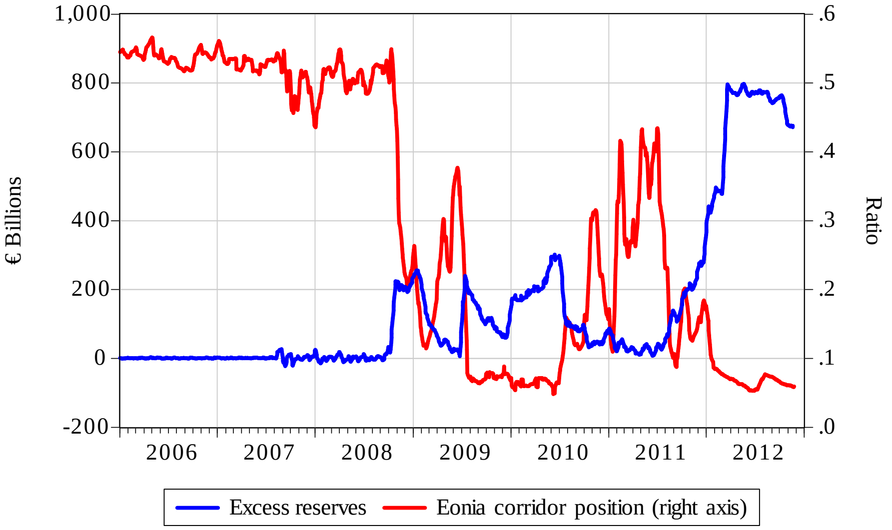
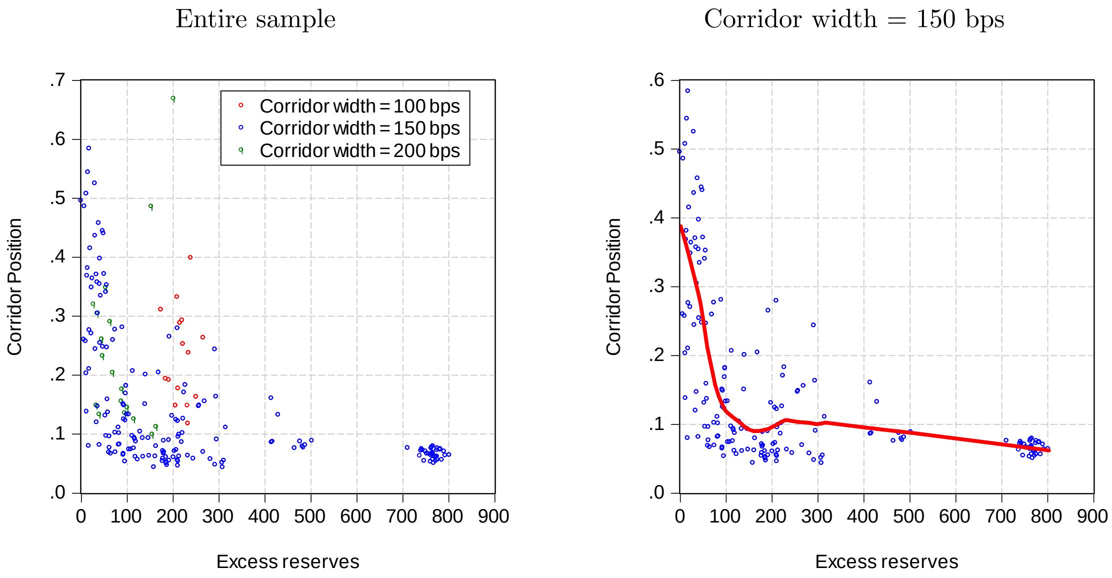


Figure 9: Excess reserves and corridor position


Entire sample

Corridor width = 150 bps

Figure 10: Excess reserves vs corridor position

We need to account for these facts in our estimation procedure and a nonlinear empirical model is likely more appropriate than a standard regression model. In particular, we specify the relationship between the corridor position and other factors as

$$\theta_t = 1 - e^{-e^{x_t \beta}} \tag{20}$$

where the right hand side of Equation (20) is the functional form for the minimum extreme value distribution. We use this functional form for three reasons. First, the long tail at the upper end of the support of the distribution fit our data well. Second, our variable of interest is bounded between zero and one, and estimating a probability model controls for this factor. And third, it is relatively computationally efficient, which allows us to estimate the model fairly easily.

With the functional form in hand, we now need to specify x_t, the factors that affect the daily corridor position, θ_t. Our specification is

$$\begin{aligned} x_t \beta &= \beta_0 + \beta_1 excess_t + \beta_2 transaction_t + \beta_3 credit_t + \\ &\quad \beta_4 policy_t + \beta_5 corridor_t + \beta_6 calendar_t + \varepsilon_t \end{aligned} \tag{21}$$

where $excess_t$ is the level of excess liquidity on day t, $transaction_t$ are the transaction costs on date t, $credit_t$ is a measure of credit risk, $calendar_t$ is a vector of calendar effects, and ε_t is the residual.

The terms are defined as follows. Excess liquidity is as defined above, that is, the level of balances held at the deposit facility plus those in current accounts, less reserve requirements.[10] Unlike in the U.S., decisions regarding excess liquidity in the Euro area can be reasonably assumed to be predetermined with respect to the overnight rate. In general, Governing Council decisions regarding changes in monetary policy are implemented about one week later, and reserve maintenance periods coincide with these changes in policy. Consequently, policy, as indicated by the corridor rates and the rate on main refinancing operations, is generally held constant for the length of the reserve maintenance period.[11] Therefore, as in Angelini (2008), we exploit the fact that the Eonia

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[10] As mentioned above, this is a slight abuse of terminology, and can be better thought of as "due to the banking sector." Again, Bindseil (2004) suggests that this measure can be useful in describing funds available to banks in the Eurosystem.

[11] An exception to this was on October 8, 2008, when multiple central banks lowered rates in concert and the corridor rates changed during a maintenance period. However, this is outside of our estimation sample.

is largely independent of central bank monetary policy operations. Unlike the U.S., where the Desk conducted an open market operation almost daily in order to influence reserve conditions so that federal funds would trade near the target federal funds rate, the timing and quantities of the ECB's main refinancing operations and longer-term refinancing operations are pre-set and generally independent of the exact level of trading of the Eonia. As a result, we can use the level of excess liquidity as a control variable in our regression with less concern that it would be endogenously determined with the overnight rate.

The variable $transaction_t$ is proxied through the difference between the realized Eonia and the Eonia 7-day futures rate. Following analysis by Taylor (2001), Angelini (2008) and others, we assume that the one week futures rate predicts the monetary policy stance perfectly, and attribute any part of movements in the rate that is not associated with policy expectations is attributable to transaction costs. We can write

$$i_t = E_{t-7}(i_t) + \tau \tag{22}$$

where, as above, i_t represents the interest rate and τ represents transaction costs. However, transaction costs are unobserved. As a result, the futures rate we observe, E^*_{t-7} is

$$E^*_{t-7}(i_t) = E_{t-7}(i_t) + \tau \tag{23}$$

Our specification is in terms of the corridor position, so we can transform the observed futures rate as

$$\theta^*_{t-7} = \frac{E^*_{t-7}(i_t) - r_{ior}}{c} \tag{24}$$

If transaction costs are insignificant, then we would expect the coefficient on θ^*_{t-7} to be equal to one in a a regression with the corridor position as a dependent variable. However, if there are significant positive transaction costs, we would expect the coefficient to be different from zero . Over this period, anticipation of monetary policy was fairly accurate: The correlation of the Eonia with its expectation one week prior is about 0.997. Because rate changes were by-and-large well anticipated, we can therefore interpret "residual" movements in rates as indicating transaction costs. According to the theory, we would expect an increase in transaction costs to affect the mean in the demand for reserve balances; this movement can be summarized as the effect on the corridor position.

In addition to transaction costs, our model suggests that credit concerns could cause rates to trade above the corridor floor in an environment of ample liquidity. Our credit risk variable $credit_t$ is the iTraxx CDS index for European financial institutions. A positive correlation of this factor with the corridor position is consistent with risk premium pricing in the interbank market. We use both the level of this variable as well as its ratio to the corridor width (the relevant variable in our model discussion) in our specifications.

The remainder of the variables control for various other factors that apparently affect the corridor position in the market. These include the timing of policy meetings, the maintenance period construct, the width of the corridor, and calendar effects. Both here and in earlier research, these factors have been shown to have a significant impact on interbank market pricing.

We use several tests to arrive at our preferred specification. To start, an augmented Dickey-Fuller rejects the null hypothesis of a unit root in the corridor position series. However, we identified significant persistence in the data through the Ljung-Box Q-test, and selected the appropriate number of lags considering results from the Breusch-Godfrey serial correlation test. In most specifications, we find that five to seven lags of the dependent variable are necessary in order to control for autocorrelation in the residuals. In addition, a Breusch-Pagan-Godfrey test suggests the presence of heteroskedasticity in the residuals. Indeed, Figure 11 plots the residuals from estimating an ARMA(7,0) model on our baseline specification, which shows clear heteroskedasticity. Furthermore, because for much of our sample the corridor position is close to the floor, we allow for some asymmetry in the effect of shocks to the error process. Finally, visual inspection of the residuals suggest that there are systematic spikes in the residuals that occur around the time of the end of the maintenance period. This phenomenon was documented in the U.S. context by Hamilton (1997) and Carpenter and Demiralp (2006) in the ECB context by Bindseil (2004), and controlling for these will help improve the model fit.

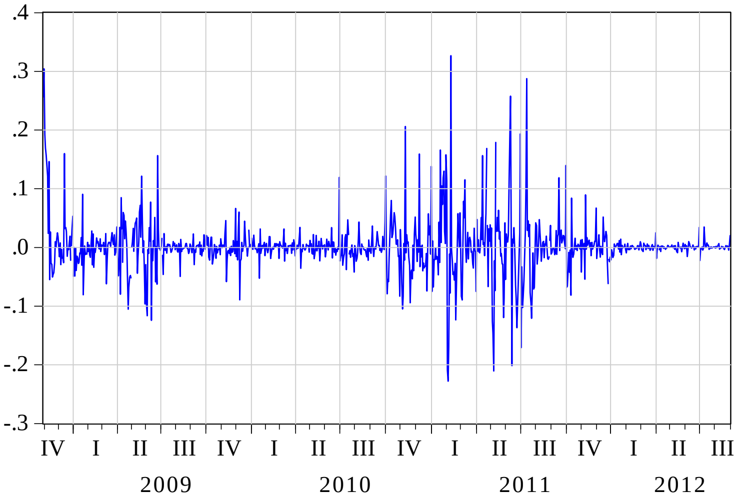

Figure 11: Residuals

Taking these together, in general, we use an power GARCH (1,1) specification for the error term,

$$\sigma_t^2 = \omega + \beta\sigma_{t-1}^{\delta} + \alpha\left(|\varepsilon_{t-1}| - \gamma\varepsilon_{t-1}\right)^{\delta} \tag{25}$$

where σ_t^2 is the conditional variance, ω is a constant, β, α,and γ are coefficients to be estimated, and δ is an exponent, also to be estimated. We assume a t-distribution for the error term in many cases in order to capture the fat tails of the distribution–tests for normality of the residuals are handily rejected.

4.2 Results

We estimate the model described above using daily data. We use four variations on the specification: a baseline specification using the minimum extreme value functional form (I); a specification that allows the transactions costs coefficient to vary by time period (II); and a specification that normalizes the credit risk variable by the width of the corridor, as predicted by the theory (III); and a specification with the same controls as the baseline, but with a logit functional form as a robustness check (IV). All models use a sample from the end of October 2008 to the end of August 2012, nearly four years of daily data. The "early" break in the sample is defined by the period before the first year-long refinancing operation, in late June 2009. A Bai-Perron breakpoint tests suggest a breakpoint in the corridor position series around that time. Table 3 displays the results.

	I		II		III		IV	
			Minimum extreme value				Logit	
Variable	Coeff	SE	Coeff	SE	Coeff	SE	Coeff	SE
Mean equation								
Excess reserves	–11.66**	0.43	-11.70**	0.35	-13.66**	0.41	-4.75**	0.07
$-$ × Week 4	-10.50**	1.60	-12.45**	1.45	-13.02**	1.34	0.07	0.05
iTraxx CDS	2.4**	0.16					0.39**	0.10
Corridor width	-0.61**	0.13	-1.32**	0.13			0.06	0.19
iTraxx/corridor					4.20**	0.26		
Transaction cost	-0.77**	0.19	-1.26**	0.14	-1.19**	0.15	1.10**	0.08
$-$ × Early			2.11**	0.29	2.25**	0.10		
2nd to last day of MP	-0.33**	0.14	-1.84**	0.64	-0.40**	0.15	-0.07**	0.01
End of MP	0.79**	0.15	0.43**	0.10	0.48**	0.11	0.21**	0.01
Week 2	-0.05	0.06	-0.14**	0.05	0.07	0.06	-0.07**	0.00
Week 3	-0.01	0.03	-0.16**	0.05	-0.06**	0.02	-0.19**	0.01
Week 4	-0.66**	0.11	-0.81**	0.09	-0.85**	0.10	-0.34**	0.02
Month end	1.07**	0.11	0.89**	0.07	0.85**	0.08	0.05**	0.01
Quarter end	1.14**	0.06	1.18**	0.05	1.37**	0.06	0.94**	0.01
Meeting	0.15*	0.08	-0.24**	0.12	0.10	0.08	0.05**	0.00
AR(1)	0.99**	0.02	0.95**	0.02	0.95**	0.02	0.86**	0.00
AR(2)	-0.01	0.03	0.02	0.02	0.02	0.03	-0.01	0.00
AR(3)	0.00	0.02	0.01	0.02	0.01	0.02	0.10**	0.01
AR(4)	0.00	0.01	0.00	0.02	0.01	0.02	-0.06**	0.01
AR(5)	-0.03	0.02	-0.03	0.02	-0.04*	0.02	0.09**	0.01
AR(6)	0.02	0.02	0.03**	0.02	0.02	0.02		
AR(7)	0.01	0.01			0.02	0.02		
Constant	-2.38	0.23	-0.98**	0.21	-3.10**	0.11	-0.11	0.30
Variance equation								
Constant (ω)	-2.73**	0.32	0.01*	0.00	0.00**	0.00	0.23**	0.03
ε_{t-1}	0.82**	0.06	0.55**	0.19	0.37**	0.14	0.30**	0.03
$\lvert\varepsilon_{t-1}\rvert$	0.08**	0.04	-0.23**	0.10	-0.18**	0.14	-0.14**	0.05
σ_{t-1}	0.61**	0.03	0.76**	0.02	0.84**	0.02	0.46**	0.03
Exponent (δ)	3.96**	0.26	0.55**	0.12	0.53**	0.14	0.17**	0.08
t-dist. dof	2.05	0.05	2.05	0.05	2.04	0.05		

Notes: Sample10/30/2008 - 8/31/2012 (N = 979), MP = maintenance period, ** and * denotes significance at the 5% and 10% level,.

Table 3: Regression results

Overall, the coefficients are relatively consistent across specifications. Provision of reserve balances pushes down the corridor position of the Eonia, and in some specifications, the results suggest the effect is more pronounced towards the end of the maintenance period. A wider corridor is associated with a lower corridor position, calendar effects tend to boost the corridor position, and transaction costs are generally associated with a higher corridor position in the early part of the sample. The fit statistics suggest that the minimum extreme value functional form, with controls for differential effects of early and late transaction costs, provides the best fit of the data, as suggested by the AIC and SIC statistics (see Table 4). However, differences in the goodness-of-fit between the minimum extreme value specifications are generally not that large, and we can probably take signal from any of these without too much concern.

	I	II	III	IV
	Min.	extreme	value	Logit
R^2	0.85	0.87	0.89	0.90
Adj. R^2	0.85	0.87	0.89	0.90
SE of regession	0.05	0.05	0.05	0.29
Sum of squared resid	2.57	2.18	1.91	77.88
Log likelihood	2523	2528	2141	-6.02
Durbin-Watson stat.	1.98	1.82	1.37	1.74
Mean dependent var	0.16	0.16	0.16	-1.94
S.D. dependent var	0.13	0.13	0.13	0.90
Akaike info criterion	-5.10	-5.11	-4.35	0.06
Schwarz criterion	-4.97	-4.97	-4.22	0.18
Hannan-Quinn criterion	-5.05	-5.06	-4.30	0.11

Table 4: Goodness-of-fit statistics

Although it is possible to infer the direction of the effects from the raw coefficients, because the models are nonlinear, the marginal effect of any particular variable changes with the value of all of the independent variables, and furthermore, we need to transform the coefficients in order to evalute the sensitivity of the corridor position to various factors. Against this backdrop, as shown in Table 5, at the mean of the data, in the baseline specification, and scaling our corridor position from 0 to 100 percentage points, a €100 billion increase in the level of excess liquidity would cause the corridor position to drop by 5 percentage points in the baseline specification. The logit specification suggests a much stronger effect of 10 percentage points, but the specifications controlling for early transaction costs have responses closer to 3 percentage points. The difference in the tail behavior of the different functional forms may account for the differences in this elasticity estimate. Because the fit seems a little better for the minimum extreme value functional form, the truth is probably closer to 5 percentage points than to 10. There is some magnification of this effect towards the end of the maintenance period, when the ECB executed fine-tuning operations and the corridor position spiked as reserve requirements became binding.

Increases in credit risk as proxied by the iTraxx index translate almost one-to-one into changes in corridor position. When normalized by the width of the corridor, the effect is even greater, as a wider corridor will tend to push down the corridor position, but the effect of credit risk apparently outweighs this mitigating factor.

	I	II	III	IV
Variable	Minimum extreme value			Logit
		%-points		
Excess reserves (per €100B)	–4.78	-2.09	-2.91	-10.09
− × Week 4	–4.29	-2.16	0.03	0.16
iTraxx CDS	0.99	0.57		0.83
Corridor width	-2.52		-1.98	
iTraxx/corridor			2.07	
Transaction cost	-3.15	-2.01	4.03	23.31
− × Early		3.61	6.10	
End of MP	3.25	0.47	0.87	4.55
Week 2	-0.21	-0.20	-0.27	-1.56
Week 3	-0.04	-0.29	-1.79	-4.08
Week 4	-2.70	-1.42	-1.93	-7.26
Month end	4.39	1.06	1.27	0.56
Quarter end	4.68	4.54	2.14	19.99
Meeting	0.60	-0.52	0.78	1.11

Sample: 10/30/2008 - 8/31/2012 ($N = 979$)

Table 5: Marginal effects

Consistent with this, a wider corridor is associated with a lower corridor position, substantiating the theory that widening the corridor is one way to ease monetary policy. Again, consistent with the theory, transaction costs are associated with a higher level of the corridor position, particularly in the early part of the sample. Our estimates suggest that at the mean in the data, a one percentage point change in the expected corridor position from transaction costs likely leads to about a 3 percentage point change in the corridor position, but this effect approaches only 1 percentage point towards the end of the sample. The effect of transaction costs may be damped by the provision of excess liquidity, the change in the level of reserve requirements, or all of these things together.

The last few lines in the Table report results on the variance of the corridor position. As suggested by our preliminary analysis, there is significant persistence and heteroskedasticity in the error term for this specification. There appears to be some asymmetry in the effects, as evidenced by the coefficients on the absolute residual term. In particular, upside shocks to the corridor position are longer-lived than downside shocks. Part of this could be a result of the fact that the corridor position is bounded below at zero, and for most of the period, the position was closer to the floor of the corridor than to the ceiling.

5 Conclusion

This paper provides a view on banks' demand for reserves in the Euro area, and how that demand is affected by frictions in the interbank market The theoretical contribution of this paper is to extend a standard model of the demand for reserves to incorporate transaction costs and credit risk, both of which were important factors during diffferent periods of the financial crisis The theory suggests that these frictions will prevent rates from reaching the bottom of the corridor. The empirics confirm this observation, both within the context of simple summary statistics – despite unprecedented levels of reserves, the Eonia has not reached the bottom of the corridor – and with a more completely specified empirical model with controls for transaction costs and credit risk.

There are a few caveats to our results. In general, there is likely more and important differentiation between banks than what we model here either theoretically or empirically. Exploring how these costs affect rates paid at the bank level would shed light on price formation in the overnight unsecured market during the finanical crisis. Relatedly, our measures of transactions costs and credit risk are crude, and could be proxies for other factors affecting the markets. That said, our results are reasonably robust to functional form and specification. And finally, there could be important differences in the effect of the manner of the provision of reserves that could affect the corridor position. In particuar, even though different programs provide the same reserves, it could be the case that participation in some programs could increase or decrease either transactions costs or perceived credit risk.

In conclusion, within the confines of a straightforward theoretical model and relatively simple empirical specification, we show that frictions have had, and continue to have, important effects on money market rates, and therefore, likely on funding costs more generally. Tracing these costs over time should be helpful for understanding how best to implement monetary policy in the future.

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