Drain, Baby, Drain: Term Deposits, Reserves and Interbank Rates

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Abstract

Prior to the financial crisis, term deposits were a rarely used part of the central bank tool box. However, both during and in the aftermath of the turmoil, term deposits have become in vogue among central banks. They have been used by Reserve Bank of Australia, the European Central Bank and the Bank of Korea. Moreover, the Federal Reserve's new term deposits facility is one of the tools it may employ to drain reserves when policy makers decide to remove the current accommodative stance of monetary policy. We review the recent use of term deposits across central banks. Furthermore, we extend the standard theoretical model of reserve demand within a corridor system of Woodford (2001) and Whitesell (2006) to include term deposits (and credit risk). We find that the (minimum) rate that banks will require to place funds with a term deposits facility increases in the amount of reserves the central bank seeks to drain, decreases if the counterparty concerns are elevated and increases with the duration of the deposits. We also explore whether a central bank will want to restrict permissible bids. Finally, we test empirically how our model stacks up against the results from the Reserve Bank of Australia's term deposit auctions.

JEL classification:

Keywords: Reserves, Corridor System, Monetary Policy, Term Deposits

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1 Introduction

A term deposit is a money deposit with a banking institution that cannot be withdrawn for a certain period of time unless penalties are paid. Such deposits are a key feature of commercial banking but they have been less prevalent in central banking.[1] A 2004 survey by the International Monetary Fund (Buzeneca and Maino (2007)) found that while central bank use of overnight deposits facilities had been increasing over time, longer term deposits were used only by a limited number of central banks in emerging or developing economies. Recently, however, term deposits have become in vogue among central banks in the developed world as interventions to stem the impact of the financial crisis required additional tools to control the liquidity position of the banking system.

For example, on September 24, 2008 the Reserve Bank of Australia introduced a term deposits facility (TDF) to "further enhance the flexibility of domestic liquidity management operations" (RBA (2008)). The following year on December 28, the Federal Reserve Board announced its intention to amend Regulation D to allow Reserve Banks to offer term deposits. In a similar vein, on May 18, 2010 the European Central Bank (ECB) exercised its existing authority and began to tender one week deposits with a view to re-absorb the liquidity injected through its Securities Markets Program.[2] Furthermore, on August 31, 2010, the Bank of Korea introduced a term deposit facility - the so-called market-friendly monetary stabilization accounts - in order to be able to absorb excess liquidity (Bank of Korea (2010)).[3]

In sum, term deposits are part of the tool box of central banks and their use have increased lately. However, very little formal research has been conducted on central bank term deposits facilities and their implications for the practical implementation of monetary policy. This paper is a first attempt to try and fill this gap. We are interested in trying to understand how the availability of a term deposit facility will affect the demand for reserves and consequently the overnight interbank

[1] Large time deposits have averaged about 11% of the liabilities of domestically chartered commercial banks in the United States over the last decade.

[2] On May 10, 2010 the Governing Council of the ECB decided to conduct interventions in the euro area public and private debt securities markets (Securities Markets Programme) to ensure depth and liquidity in those market segments which were dysfunctional. The objective of this program was to address the malfunctioning of securities markets and restore an appropriate monetary policy transmission mechanism (ECB (2010a)).

[3] In addition, many central banks have for years used short term central bank securities as part of their operational frameworks. Unlike, term deposits such securities are in principle negotiable. But to the extent that there is not an active market in these securities they are economically equivalent to term deposits.

rate. This is important as central banks tend to target the overnight rate and – in the case of the Federal Reserve – the new term deposits facility is one of several tools that may be employed to drain reserves when policy makers judge that it is appropriate to begin to normalize both the stance and conduct of monetary policy.

We begin by documenting the key features of the term deposits facilities implemented by the central banks listed above and we present the results of term deposit auctions held so far. We then turn to our theoretical model. First, we review the standard reserve demand framework within a corridor system of Woodford (2001) and Whitesell (2006). In these models the demand for reserves is primarily driven by unpredictable payment shocks which give rise to a downward sloping demand curve for reserves. However, the basic version of this framework ignores credit risk, which we explicitly introduce with a view to better match the money market dynamics observed during the financial crisis. In the appendix we show that the model fits quite well the experiences of Denmark in the early 1990s as well as the ECB since October, 2008. Within the extended framework, we then add a term deposit facility and derive the minimum rate of return that banks require to hold term deposits with the central bank. We find that the bids, that banks will submit, are increasing in the amount of reserves, the central bank wishes to absorb while decreasing in both the amount of credit risk and the size of the central bank balance sheet. Furthermore, we discuss the extent to which the central bank may wish to limit the permissible bids or introduce a standing term deposit facility.

In the last part of the paper, we seek to assess empirically how reasonable the model is. We show that the bidding behavior predicted by the model can in part explain the observed outcomes of the RBAs term deposit auctions. Finally, we conclude with some observations on the implications of our analysis for the Federal Reserve's eventual exit from the current accommodative monetary policy stance.

2 Term Deposit Facilities

Central banks face many choices in designing term deposits facilities. In the following, we review the key characteristics (as well as the auction results) of the four term deposit facilities (TDF) implemented by the RBA, Federal Reserve, ECB and BoK. We seek to highlight many of the practical challenges and choices that face central banks in designing and operating TDFs. A comparative overview is provided in Table 1. As we shall abstract from some of these important design issues later on in the theoretical part of the paper, it is helpful to keep the issues highlighted in this section in mind when evaluating the results we present.

2.1 Reserve Bank of Australia[4]

On September 28, 2008, the Reserve Bank of Australia (RBA) announced the introduction of a domestic term deposit facility to further enhance the flexibility of domestic liquidity management operations. At the time, the RBA sought to alleviate term funding pressures by offering repo transactions at longer maturities. However, to expand its repo operations at these longer terms, the RBA had to increase the supply of settlement balances, i.e., reserves, which had the potential to put downward pressure on the overnight cash rate. To relieve this tension the RBA introduced the term deposit facility. The RBA stopped offering term deposit again in Marts 2009 but the facility can obviously be reactivated on short notice. The amounts of term deposits collected and their maturity over the six month period are shown in Figure 1. The RBA offered term deposits ranging from 4 to 26 days with the majority being 7 or 14 days. The total value across maturities allotted was less than 4.5 billion Australian Dollar (AUD) on any given day. However, the total amount of term deposits outstanding peaked at 18 billion AUD and exceeded the amount of settlement balances held by banks for most of the period (see Figure 2).

The following rules apply to the RBA's TDF. Eligible counterparties are any institution holding a settlement account with the RBA or any authorized deposit-taking institution that is a member of the Australian real time gross settlement system, RITS. All bids are submitted in multiples of 1 million AUD with the minimum bid size being 20 million AUD. Other than the size of the

[4] The material in this section is based on www.rba.gov.au/mkt-operations/tech-notes/term-deposits.html

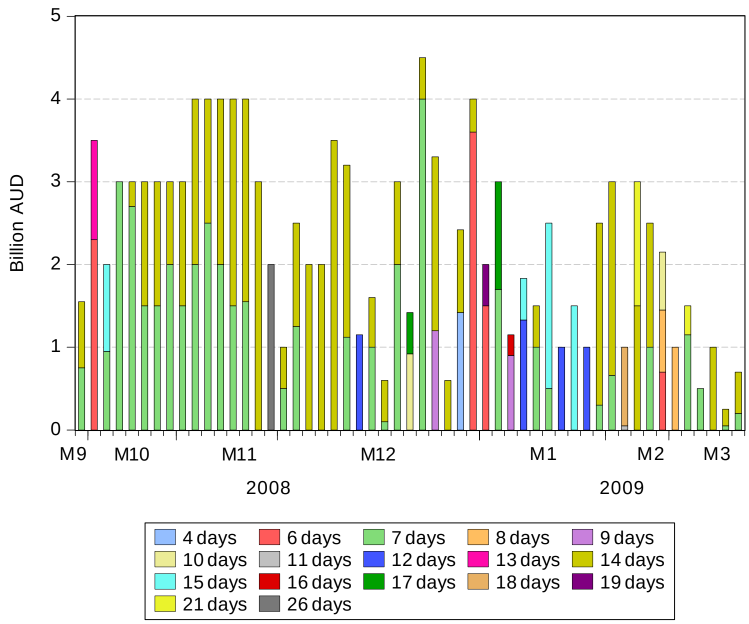


Figure 1: Term Deposits Collected by the RBA Sep. 2008 - Mar. 2009

tender, there is no limit on the size of individual bids, nor on the number of bids that a participant can make. Consequently, the maximum aggregate value of bids from a single counterparty is the tender amount.

Bids are expressed as a margin to the overnight target rate (the so-called cash rate). This implies that there is no issue of monetary policy expectations affecting the bid if the deposit were to span a RBA board meeting (Debelle (2008)). Moreover, bids are expressed in whole basis points and can be negative or positive (for example a successful bid of -5 basis point in relation to a cash rate target of 7.00 per cent implies that the bidder will receive an interest rate of 6.95 per cent on the deposit). The weighted average spreads from the auctions are shown in Figure 3. With one exception, the spread was less than the target cash rate for that day.

While not expected to be a regular occurrence, funds placed in term deposits may be called at any time. The proceeds paid on the called portion of a term deposit is adjusted down by 25 basis points. A term deposit need not be called in full but a called term deposit may not be re-lodged for the remaining maturity – that is, the term deposit facility is not available as an intraday lending

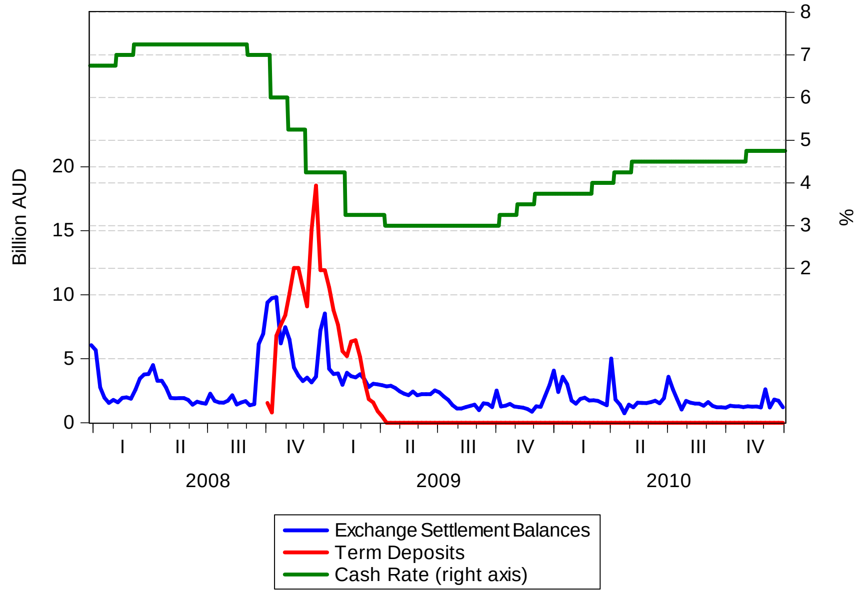


Figure 2: RBA - Settlement Balances, Term deposits and Overnight Rate

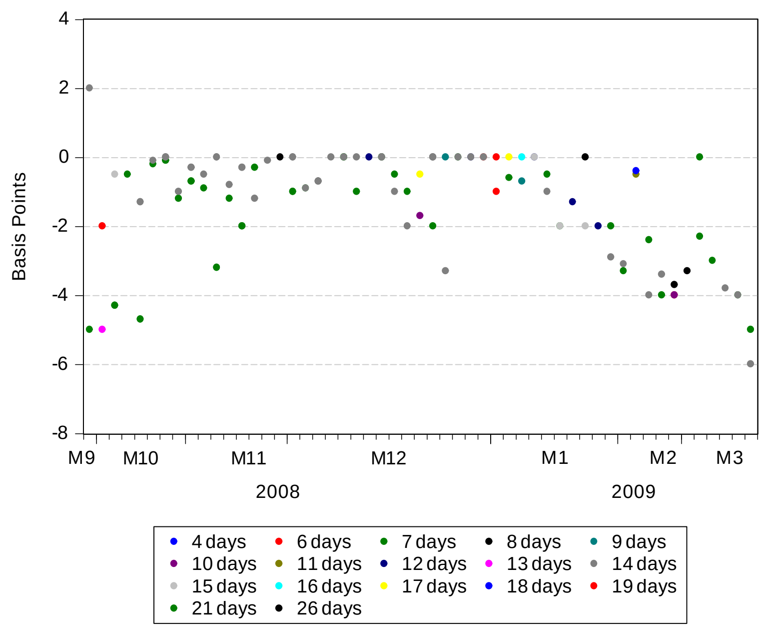


Figure 3: RBA Term Deposits - Weighted Average Spread to Cash Rate

facility. Term deposits will normally settle on a $T+1$ basis but same-day settlement is technically feasible.

	RBA	Federal Reserve	ECB	Bank of Korea
Announcement	Sep. 24, 2008	Dec. 28 2009	May 17, 2010	Aug. 31, 2010
Operational	Sep. 29, 2008	Jun. 14, 2010	May 18, 2010	Oct. 11, 2010
Auction Type	Multiple price	Single price	Multiple price	Single price
Bid procedure	Margin to target	Rate	Rate	Rate
Max. bid rate	Discretion	Primary Credit rate	MRO rate	Discretion
Non competitive bids	No	Yes	No	No
Max amount per bank	100%	25%	100%	Discretion
Duration	$\leq$ 26 days	$\leq$ 84 days	1 week	$\leq$ 28 days
Amount	$\leq$5.5B AUD	$\leq$ \$5B	Equal to SMP	$\leq$\$1.5T KRW
Settlement	$T+1$	$T+3$	$T+1$	$T+0$
Intraday credit	No	Yes	Yes	No
Callable	Penalty	No	No	Discretion

Notes: Based on observations as of March 7, 2010, SMP = Securities Market Program
MRO = Marginal Refinancing Operations

Table 1: Key Features of Selected Central Bank Term Deposits Facilities

2.2 Federal Reserve[5]

On December 28, 2009 the Federal Reserve Board proposed amendments to Regulation D (Reserve Requirements of Depository Institutions) that would enable the establishment of a term deposit facility. Under the proposal, the Federal Reserve Banks would offer interest-bearing term deposits to eligible institutions through an auction mechanism. Term deposits would be one of several tools that the Federal Reserve could employ to drain reserves to support the effective implementation of monetary policy.

After a public comment period, the amendments were approved on April 30, 2010 and on May 10, the Board authorized a series of small-value offerings under the Term Deposit Facility. These small-value offerings are designed to ensure the effectiveness of TDF operations and to provide eligible institutions with an opportunity to gain familiarity with term deposit procedures. The first auction for \$1 billion of 14-day term deposits was conducted on June 14 with standard settlement 3 days later. Since then, the Federal Reserve has continued to conduct small-value offerings of \$5

[5] For futher information please see www.frbservices.org/centralbank/term_deposit_facility.html.

billion or less and with maturities up to 84 days. The results from the auctions are shown in Table 2.[6]

Auction Date	Term	Competitive. Amount Offered	Non-Comp. Amount Awarded	Bid to Cover	Stop Out Rate
2010	Days	$Billions	$Millions	Ratio	%
Jun. 14	14	1	152	6.14	0.270
Jun. 28	28	2	121	5.57	0.270
Jul. 12	84	2	199	3.70	0.310
Oct. 4	28	5	113	2.72	0.269
Nov. 29	28	5	113	2.93	0.260
2011					
Feb. 7	28	5	70	2.52	0.260
Apr. 4	28	5	81	2.20	0.260
May 31	28	5	87	2.17	0.259
Jul. 25	28	5	88	1.26	0.280
Sep. 19	28	5	77	2.41	0.265
Nov. 14	28	5	55	2.22	0.263

Source: Federal Reserve

Table 2: Federal Reserve Term Deposit Test Auctions

The term deposits has been offered through a combination of competitive single-price auctions and a noncompetitive bidding option to ensure access to term deposits for smaller institutions. The maximum award to any individual bidder has been set at 25 percent of the amount offered and the maximum rate at the auction has been set at the Primary Credit Rate[7].

Eligible institutions are those that are permitted by statute to receive interest on balances maintained at the Reserve Banks. Hence, eligible institutions include banks, savings associations, savings institutions, credit unions, trust companies, Edge and agreement corporations, and U.S. agencies and branches of foreign banks but, importantly, exclude government sponsored enterprises such as Fannie Mae, Freddie Mac and the Federal Home Loan Banks.[8]

Term deposits with Reserve Banks cannot be used to satisfy reserve balance requirements,

[6] On September 8, 2010 the Federal Reserve Board on announced that it had authorized ongoing small-value offerings of term deposits under the (TDF).

[7] The rate at which the Discount Window extends very short term (usually overnight) loans to depository institutions in generally sound financial condition.

[8] As of February 2011, more than 500 depository institutions have registered for the term deposit facility. Those firms, in aggregate, held nearly $600 billion of the reserve balances that were in the financial system Sack (2011).

meet a contractual clearing balance, or clear payments. Term deposits cannot reduce daylight or overnight overdrafts and must be held to maturity but can be used as collateral for discount window advances and for Payment System Risk purposes.

2.3 European Central Bank

Term deposits have since the ECB's inception – in principle – been part of the operational framework. The general documentation on monetary policy instruments and procedures states:

> "The Eurosystem may invite counterparties to place remunerated fixed-term deposits with the national central bank in the Member State in which the counterparty is established. The collection of fixed-term deposits is envisaged only for fine-tuning purposes in order to absorb liquidity in the market" ECB (2008b).

Nevertheless, the ECB operated for more than a decade without using this tool. That changed on May 10, 2010. In connection with the announcement of its Securities Market Program (see footnote 1), the ECB also stated that it would re-absorb (sterilize) the liquidity injected as a result of the interventions in order to ensure that the monetary policy stance would not be affected (ECB (2010a)) For this purpose the ECB decided to collect one-week fixed-term deposits. The first such operation was conducted on May 18, 2010 and the amount offered has grown in lock step with the SMP to €211 billion as of December 19, 2011. The operations are carried out as variable rate quick tenders with a maximum bid rate equal to the rate at the ECB's main refinancing operations (MROs).[9] Quick tenders generally imply that the operations are conducted only with a subset of the institutions eligible at the MROs. Fixed term deposits held with the Eurosystem settle $T+1$ and are eligible as collateral for the Eurosystem's credit operations (including intraday credit for payments purposes).

The results of the ECB's term deposit auctions are shown in Figure 4. The operations have all been oversubscribed with the exception of six. The weighted average rate of bids accepted in the auction has tracked the overnight night rate (Eonia) and has on most occasions been below.

[9] As the ECB, at the time of writing, provides full allotment at its MROs, setting the maximum rate equal to the MRO rate eliminates a risk-free arbitrage opportunity for banks.

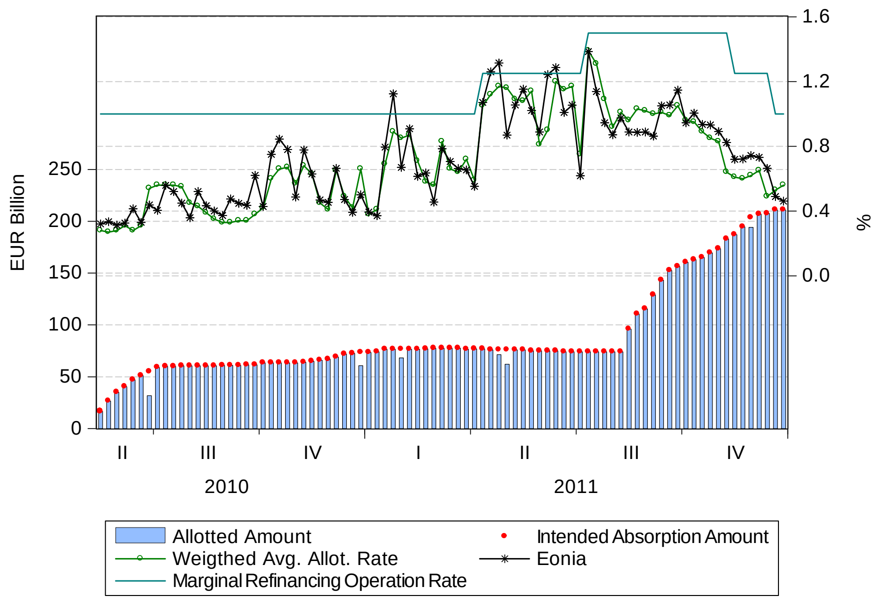


Figure 4: ECB: Results of Term Deposit Auctions

2.4 Bank of Korea[10]

On August 31, 2010, the Bank of Korea (BoK) announced the introduction of the so-called Market-Friendly Monetary Stabilization Accounts (MSA). This term deposit facility was introduced to absorb liquidity from capital inflows due to "non-residents' increased investment in domestic securities". It was created to supplement the Monetary Stabilization Bonds (MSB) that the Bank of Korea for years have used to absorb liquidity from the banking system.[11] However, in a environment of increasing interest rates financial institutions may be reluctant to buy "longer term" MSBs. Moreover, foreign investors had been attracted to the MSBs due to their yields and hence adding to the capital inflows (**?**).

The first operation was conducted on October 11, 2010. The deposits are offered through competitive tenders using a single price auction format. Eligible institutions are restricted to

[10] This section is based on Bank of Korea (2010). We also thank Sung Jun Kim from the Bank of Korea for his patience in terms of answering our clarifying questions.

[11] MSBs, which are issued only by the Bank of Korea are used for structural adjustments of market liquidity. In terms of maturity, they range from 14 days to two years (the majority of issuance). A ceiling on the issuance of MSBs is set by the Monetary Policy Committee every three months in consideration of market liquidity conditions.

banks that are entitled to participate in the reverse repo transactions with the BoK but other institution may participate indirectly via the eligible institutions. The BoK may set individual limits on the maximum amount for each participants. The maximum bid that the BoK will accept is set ahead of the action but is not publicly announced even apriori. It varies from auction to auction and is set by BoK staff taking into account several factors such as recent movements in money markets. The auctions are settled same day. In its initial press release, the BoK stated that the maturity of the MSAs would be up to 91 days but so far the modal term has been 28 days.[12] Redemption prior to maturity is not allowed but the BoK states that it may make an exception in case of "a severe imbalance between funds supply and demand in the financial market". MSAs cannot be used to satisfy reserve requirements nor be used as collateral vis-à-vis the Bank of Korea. The results of the first 44 MSA auctions are shown in Figure 5. The intended size of the first four operations were $1 trillion Korean won (KRW); followed by two auctions of half that size. Since then auction sizes have varied – reaching up to $5 trillion KRW ($4.8 billion). In two auctions, the allotted amount was less than the amount offered by the BoK. In the first instance on October 25, 2010, the amount of bids exceed the amount offered. Hence, the BoK exercised its discretion to reject bids seen as too high rather than allocate the entire amount planned. In contrast, on April 25, 2011 the amount of bids were insufficient to match the amount offered. The stop out rates in all auctions have been above the corresponding overnight cash rate. The average spread has been 12 basis points with some evidence of spreads rising ahead of subsequent hikes in the policy rate.

3 The Demand for Reserves

In this section, we present a simple model for thinking about the interaction between the demand reserves and credit risk. This model forms the basis for our theoretical modelling of term deposit facilities in the following section. We start by reviewing the standard model of monetary policy implementation within a corridor system of Woodford (2001) and Whitesell (2006). As overnight interbank loans often are unsecured, we extend the standard model by explicitly including credit

[12] The auction on April 11, 2011 was for 20 days deposits and the auction on April 25, 2011 was for14 day deposits. The rest have been for 28 days.

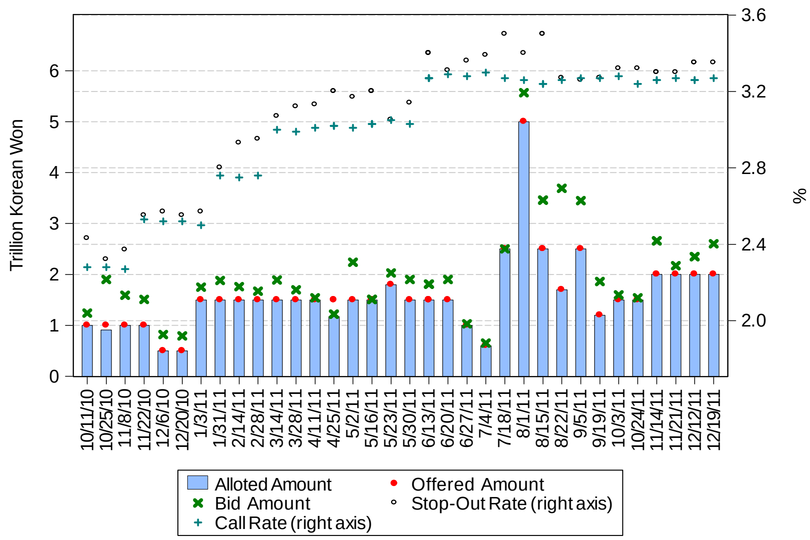


Figure 5: Bank of Korea: Results of Term Deposit Auctions

risk.

3.1 Standard model

The demand for reserves by banks normally stems from either reserve requirements or from a need for excess reserves (or working balances) or from a combination of both. Reserve requirements are set by the central bank according to some formula based on the liability side of depository institutions balance sheet. On the other hand, demand for excess reserves requires that banks face some uncertainties related to their payment flows (Bindseil (2004)). As many central banks do not impose reserve requirements (as well as simplicity) we abstract from them here.

The model below is based on Poole (1968), Woodford (2001), Whitesell (2006) and Ennis and Keister (2008). Envision an economy with n risk neutral banks and a central bank. Banks settle payments amongst each other over accounts at the central bank. That is during the day, the bank receive payments from other banks as well as request to make payments on behalf of customers. While doing so, banks seek to manage their end-of-day position by trading central bank balances overnight with other banks. This task is made difficult as some of the payment flows are not perfectly predictable. With a view to fulfill its monetary policy mandate, the central bank targets a certain level of the overnight interbank rate using a combination of open market operations and standing facilities. The central bank operates a corridor system and provides both a standing deposit facility as well as a marginal lending facility. If a bank has a positive account position at the end-of-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} In order to fix ideas we adopt the following time line from Bartolini and Pratti (2003).

- At 9:00 am the central bank conduct open market operations if such are need. That is the supply of reserves from the central bank is R^{CB}.

- At 10:00 am a random shock, v (autonomous factors) hits the reserves position of banks from the non-bank sector. The supply of reserves is now $R^S = R^{CB} + v$

- At noon the a frictionless interbank market opens, banks trade at the market rate ρ to get to their desired level of (non-borrowed) reserves R_i

- At 3:00 p.m.: After the interbank market has cleared payments continue to flow in and out of the bank's account. The cumulative effect of these flows is $\varepsilon_i \sim F_i$ which we denote the payment shock.

Consequently, a bank can only determine its end-of-day position within a margin of error given by a stochastic term, ε_i. In other words, while during the day a bank targets a reserve position of R_i, its end-of-day position is ongoing to be $B_i = R_i + \varepsilon_i$. Absent uncertainty banks would chose $R_i = -\varepsilon_i$. We assume that F_i is symmetric and $E[\varepsilon_i] = 0$.

A bank's overnight profit on holding R_i is given by

$$\Pi_i(R_i) = r_{ior} B_i 1_{B_i > 0} + r_{dw} B_i 1_{B_i < 0} - \rho R_i \tag{1}$$

where 1_x is the indicator function taking on the value one if true and zero otherwise. The expected profit, which banks seek to maximize by choosing R_i, is

$$E[\Pi_i(R_i)] = (r_{ior} - \rho)P[B_i > 0]E[B_i|B_i > 0] + (r_{dw} - \rho)P[B_i < 0]E[B_i|B_i < 0] \tag{2}$$

As discussed by Whitesell (2006), without knowing ε_i, a bank chooses R_i to minimize two types of costs: the opportunity cost of holding a positive end-of-day balance in its account at the central bank, relative to lending fund in the market given by $r_{ior} - \rho$, and the loss in case of an overdrafts, on borrowing from the central bank rather than from the market, given by $r_{dw} - \rho$. Unpacking the expectation operators yields

$$\begin{aligned} E[\Pi_i(R_i)] &= r_{ior}(1 - F_i(-R_i)) \int_{-R_i}^{\infty} (R_i + \varepsilon_i) \frac{dF_i(\varepsilon_i)}{1 - F_i(-R_i)} \\ &\quad + r_{dw} F_i(-R_i) \int_{-\infty}^{-R_i} (R_i + \varepsilon_i) \frac{dF_i(\varepsilon_i)}{F_i(-R_i)} - \rho R_i \\ &= r_{ior} \int_{-R_i}^{\infty} (R_i + \varepsilon_i) dF_i(\varepsilon_i) + r_{dw} \int_{-\infty}^{-R_i} (R_i + \varepsilon_i) dF_i(\varepsilon_i) - \rho R_i \end{aligned} \tag{3}$$

The first-order condition may be written as[13]

$$r_{ior} \int_{-R_i}^{\infty} dF_i(\varepsilon_i) + r_{dw} \int_{-\infty}^{-R_i} dF_i(\varepsilon_i) r_{ior} = r_{dw} F_i(-R_i) + r_{ior}(1 - F_i(-R_i)) = \rho \tag{4}$$

The overnight rate is a weighted average of the interest paid on overnight reserves and the rate charged at the marginal lending facility, where the weights are the probability of having a positive

[13] Recall Leibniz integral rule for differentiation of a definite integral whose limits are functions of the diffential variable.

$$\frac{d}{dz} \int_{a(z)}^{b(z)} g(x, z) dx = \int_{a(z)}^{b(z)} \frac{\partial g}{\partial z} dx + g(b(z), z) \frac{\partial b}{\partial z} - g(a(z), z) \frac{\partial a}{\partial z}$$

For example, we have

$$\begin{aligned} \frac{\partial}{\partial R} \int_{-\infty}^{-R} (R + \varepsilon) f(\varepsilon) d\varepsilon &= \int_{-\infty}^{-R} f(\varepsilon) d\varepsilon + (R - R) f(-R)(-1) - (R - \infty) f(-\infty) 0 \\ &= \int_{-\infty}^{-R} f(\varepsilon) d\varepsilon = F(-R) \end{aligned}$$

and negative balances, respectively. Rearranging the terms, we get

$$\tilde{\rho} = \frac{\rho - r_{ior}}{r_{dw} - r_{ior}} = F(-R_i^*) \tag{5}$$

where $\tilde{\rho}$ is the relative position of the overnight rate within the corridor spanned by r_{ior} and r_{dw}. Basically, Eq. (5) is the (inverse) demand curve for reserves with the price measured as the relative position of the overnight rate. Conversely, the desired amount of reserves is given by

$$R_i^* = -F_i^{-1}(\tilde{\rho}) \tag{6}$$

As F_i is symmetric, the demand for excess reserves will be zero when the market rate is at the midpoint of the corridor, i.e., $\tilde{\rho} = \frac{1}{2}$. In the words of Woodford (2001), we have the following result

Proposition 1 (Demand for Reserves) *"the demand for [excess reserves is] 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".*

Assumptions regarding the distribution of the payment shock are required in order to derive the demand schedule for reserves. Ennis and Keister (2008) use the uniform distribution whereas Whitesell (2006) uses the normal distribution. The resulting demand curves in terms of the relative corridor position are shown in Figure 6 for low and high variance of the underlying payment shock, respectively. As noted by Poole (1968) the inverse demand curve for reserves flattens as the uncertainty increase (i.e. the variance of the underlying payment shock) increases.

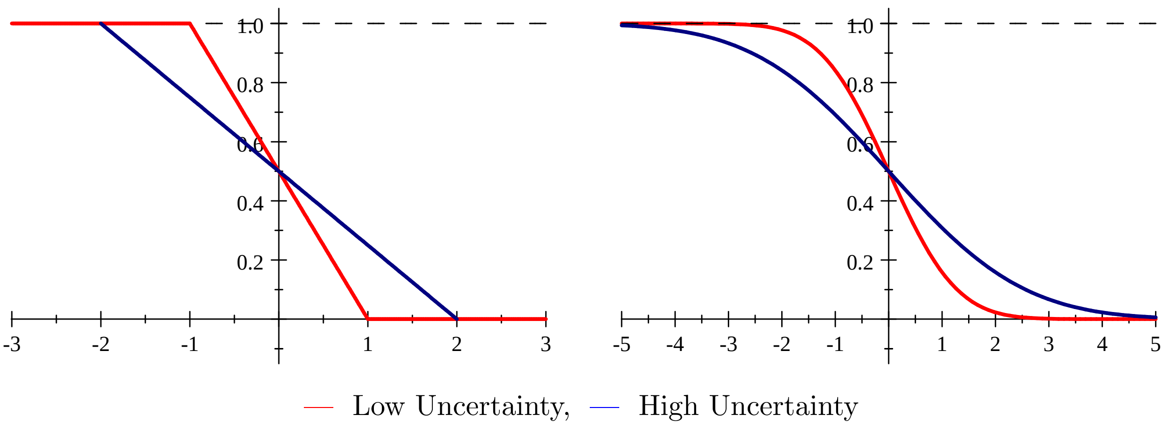


Figure 6: Individual Bank Demand for Excess Reserves, Uniform and Gaussian Payment Shock

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

$$R^{AD} = \sum R_i^* = \sum F_i^{-1}(\theta_\rho) \tag{7}$$

The market-clearing overnight interest rate ρ is then the rate that results in the aggregate demand being equal to the central bank's supply of reserves, R^S.[14] If banks are identical, we have that in equilibrium $R^S = R^{AD} \Rightarrow R^S = nR_i^*$. We have

$$\frac{R^S}{n} = -F^{-1}(\tilde{\rho}^*) \Rightarrow \tilde{\rho}^*(R^S) = F\left(\frac{-R^S}{n}\right) \tag{8}$$

The overnight rate is pinned down by the per bank supply of reserves by the central bank.[15] In appendix A, we show that the model provides a nice framework for describing the Danish experience with a corridor system in the early 1990s.

[14] Woodford (2001) lets the supply of reserves be composed of the targeted supply by the central bank R_{CB} and a random term ν reflecting variation due to forecast errors in currency demand and payments to and from the government account. That is $R^S = R_{CB} + \nu$.

[15] If the payment shocks are Gaussian, we have

$$\theta_\rho^* = \Phi\left(\frac{-R^S}{\sum \sigma_i}\right) = \Phi\left(\frac{-R^S}{n\sigma}\right)$$

where $\Phi(\cdot)$ denotes the standard normal cumulative distribution function and the last equality only holds if banks are also identical. Here, the overnight rate is pinned down by the uncertainty adjusted amount of reserves (per bank).

3.2 Credit Risk

The financial crisis highlighted the fact that credit risk plays an important role in money markets as many loans are unsecured. 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 [exchange settlement (ES)] balances, reinforced by the fact that ES balances are a risk-free asset. The effect was the demand curve for ES balances shifted out.

In this section, we introduce the possibility of default into the decision process of banks. For simplicity, we take all banks to be identical. Moreover, we assume that when evaluating the interest income from an overnight loan the lender include a spread for expected credit losses or roll-over risk, δ. That is $\rho^l = \rho - \delta$. The bank's problem is now

$$\max_R \ (r_{ior} - \rho^l)P[B_i > 0]E[B_i|B_i > 0] + (r_{dw} - \rho)P[B_i < 0]E[B_i|B_i < 0] \tag{9}$$

The first-order condition may be written as

$$(r_{ior} - \rho^l)\int_{-R}^{\infty} dF(\varepsilon_i) + (r_{dw} - \rho)\int_{-\infty}^{-R} dF(\varepsilon_i) = 0 \tag{10}$$

Rearranging the terms yields

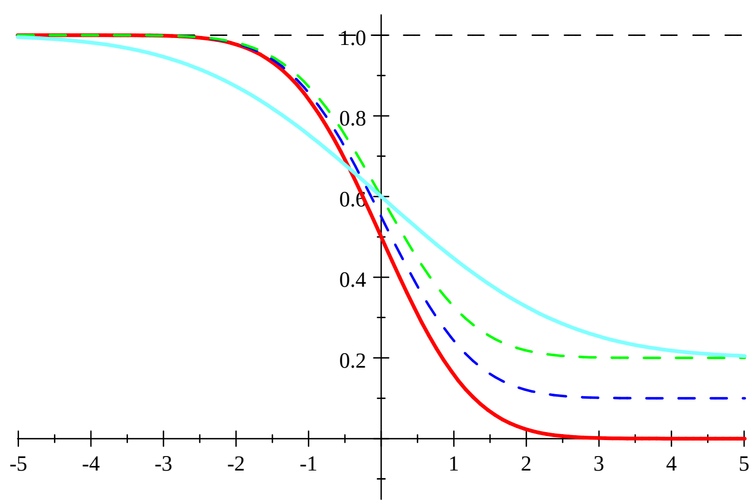
$$\tilde{\rho}^*(\delta, c, R^S) = \frac{\rho - r_{ior}}{c} = (1 - \frac{\delta}{c})F(-\frac{R^S}{n}) + \frac{\delta}{c} \tag{11}$$

where $c = r_{dw} - r_{ior}$ denotes the width of the corridor. Importantly, the demand for reserves is no longer independent of the width of the corridor even though it remains independent of the absolute level of interest rates. The spread between the overnight rate with and without credit risk is given by

$$\tilde{\rho}^*(\delta, \cdot) - \tilde{\rho}^*(0, \cdot) = \frac{\delta}{c}(1 - F(-\frac{R^S}{n})) > 0 \tag{12}$$

The spread is positive and increasing in the amount of risk while decreasing in the width of the corridor. The overnight rate no longer converges to rate paid on overnight deposits (r_{ior}) as the amount of reserves increases. Rather, it converges to $r_{ior} + \delta$, i.e., the rate at which a bank is indifferent between lending in the market relative to leaving funds with the central bank.

Example 1 *Assume that the payment shocks are Gaussian with zero mean. The overnight interbank rate is shown for different levels of credit risk and payment shock uncertainty below. Note that it is no longer the case that the demand for excess reserves is zero when the market rate is at the midpoint of the corridor when credit risk is a concern. As observed by Debelle (2008), the effect of increased credit risk is that the demand curve for reserves shifts out. For positive levels of excess reserves increased payment uncertainty amplifies the shift.*



— $\tilde{\rho}(\delta = 0, \sigma = 1, \cdot)$, — $\tilde{\rho}(\delta = .1c.\sigma = 1, \cdot)$, — $\tilde{\rho}(\delta = .2c, \sigma = 1, \cdot)$, — $\tilde{\rho}(\delta = .2c, \sigma = 2, \cdot)$,

Figure 7: Demand for Excess Reserves with Credit Risk

We summarize our results as follows

Proposition 2 (Credit Risk) *Credit Risk or roll over risk shifts out the demand curve for reserves. Increased payment shock uncertainty amplifies the shift if the demand for reserves is positive.*

In appendix B we show how the demand for reserves in the Eurozone shifted during the financial crisis both as a result of counterparty concerns but also due to changes in the width of the corridor spanned by the ECB's overnight deposit facility and the marginal lending facility. With these components in hand, we then turn to term deposits and add an auction based facility to our model. We start with a simple one day facility but subsequently allow for terms of multiple days. In addition, we also investigate how a standing term deposit facility would work. With these components in hand, we then turn to term deposits and add an auction based facility to our model.

4 Term Deposit Facility

Envision now, that the central bank has an expanded balance sheet and that the central bank no longer conduct open market operations. Each bank holds an amount of central bank liabilities, $\bar{Q}_i > 0$ and to begin with all liabilities are held in the form of reserves, i.e., $R_i = \bar{Q}_i$.[16] Now, however, assume that the central bank decides to offer a fixed amount of term deposits, $D < \bar{Q} = \Sigma\bar{Q}_i$. via an auction facility. We assume that the central bank is interested in draining the amount D at the least cost and by "term" we initially mean intraday plus overnight (we deal with multiple day facilities later). This implies that funds placed at the term deposit facility are locked up in the morning and not available to the bank until the following morning. Hence, such funds cannot be used for payments purposes and to square settlement accounts at the close of business. In other words, the supply of reserves is the residual amount of central bank liabilities that have not been committed to the term deposit facility., i.e., $R^S = \bar{Q} - D$.

In a typical auction, the auctioneer is the seller of the object and the bidders are the buyers. However, in a term deposit auction the roles are reversed. The object being auctioned is the right

[16] For simplicity, we ignore the random shock at 10:00 am to the reserves position of banks from the non-bank sector

to "supply" funds to central bank and hence the central bank, i.e., the auctioneer, is the buyer and the banks, i.e., the bidders are the sellers. This type of auction is commonly referred to as a *reverse* auction. Moreover, in a term deposit auction the object is divisible in that more banks may combine to supply the central bank with the desired amount. In particular, if $D < \max Q_i$ then at least two banks will have to provide funds to the term deposit facility for the central bank to drain the desired amount.[17] Furthermore, we assume that the auctions are conducted and settled by 9:00 am, individual banks are capacity constrained. That is banks are constrained in the amount of funds they can supply to the central bank. As the money market is not open at bank can not supply more than its endowment, Q_i. so are individual banks.

In the following, we are interested in how banks will bid for term deposits, whether a standing facility might be a desirable option and the extent to which the central bank will want to restrict permissible bids.

4.1 Minimum Auction Rate

Our first question is what rate of return banks will require to place funds with the term deposit facility? Providing funds to the TDF is costly as the funds supplied can not be used to offset payment shocks. On the other hand, the central seeks to minimize that cost of draining D. That is

$$\begin{aligned} &\min_{a_i} \Sigma_i a_i D_i \\ &\text{s.t. } \Sigma_i D_i = D \end{aligned} \tag{13}$$

where a_i is the rate paid on the term deposit to bank i. Following Iyengar and Kumar (200x) we assume that banks submit complete cost schedules, $C(D_i)$, that lay out their cost of providing $D_i \in [0, \bar{Q}_i]$. The marginal cost of providing funds for a bank is non-decreasing, i.e., $C'(D_i) > 0$.

Here, we focus on the full information case where all banks submit their true cost schedules. In

[17] In case of the Federal Reserve's TDF, the minimum number of banks will be 4 as the maximum amount a bank may bid for is 25 percent of the offered amount as noted in Section 2.

other words, there is no private information that allow banks to shade their bids..[18] In this setting the surplus of each bank will be zero. Hence, we derive the rate that makes banks indifferent between holding the term deposits or not. The profit of a bank holding D_i in term deposits is

$$\begin{aligned} E[\Pi(R_i)] = a_i D_i + (r_{ior} - \rho^l(\cdot, \bar{Q} - D))P[B_i > 0]E[B_i | B_i > 0] \\ +(r_{dw} - \rho(\cdot, \bar{Q} - D))P[B_i < 0]E[B_i | B_i < 0] \end{aligned} \tag{14}$$

where a_i is the auction rate obtained by bank i. The difference in profits between holding zero and D_i in term deposits is (see Appendix C)

$$E[\Pi(D_i) - \Pi(0)] = (a_i - \rho^l(\cdot, \bar{Q} - D))D_i + (r_{dw} - r_{ior} - \delta) \int_{-\bar{Q}_i}^{D_i - \bar{Q}_i} \varepsilon_i dF(\varepsilon_i) \tag{15}$$

The first term is the pickup from placing D_i at the term deposit facility where $\rho^l(\delta, c, \bar{Q} - D)$ is the risk adjusted overnight lending rate that results from banks reducing reserve holdings from $\bar{Q}$ to $\bar{Q} - D$. The integral in the second term is the expected additional end-of-day overdraft and thus the second term reflects the expected opportunity cost of additional overdrafts due to lower reserves holdings.

Setting the difference in Eq. (15) equal to zero and solving for the minimum rate – in terms of relative corridor position – yields (Appendix C)

$$\begin{aligned} \tilde{a}_i^{\min}(\delta, c, \bar{Q} - D) &= \tilde{\rho}(\delta, c, \bar{Q} - D) - \frac{1 - \frac{\delta}{c}}{D_i} \int_{-\bar{Q}_i}^{D_i - \bar{Q}_i} \varepsilon_i dF(\varepsilon_i) - \frac{\delta}{c} \\ &= (1 - \frac{\delta}{c}) \left(F(\frac{D - \bar{Q}}{n}) - \frac{1}{D_i} \int_{-\bar{Q}_i}^{D_i - \bar{Q}_i} \varepsilon_i dF(\varepsilon_i) \right) \end{aligned} \tag{16}$$

In the special case, where there is no credit risk we have

$$\tilde{a}_i^{\min}(0, c, \bar{Q} - D) - \tilde{\rho}(0, c, \bar{Q} - D) = -\frac{1}{D_i} \int_{-\bar{Q}_i}^{D_i - \bar{Q}_i} \varepsilon_i dF(\varepsilon_i) > 0 \tag{17}$$

[18] In case of the Federal Reserve's TDF, the minimum number of banks will be 4 as the maximum amount a bank may bid for is 25 percent of the offered amount as noted in Section 2.

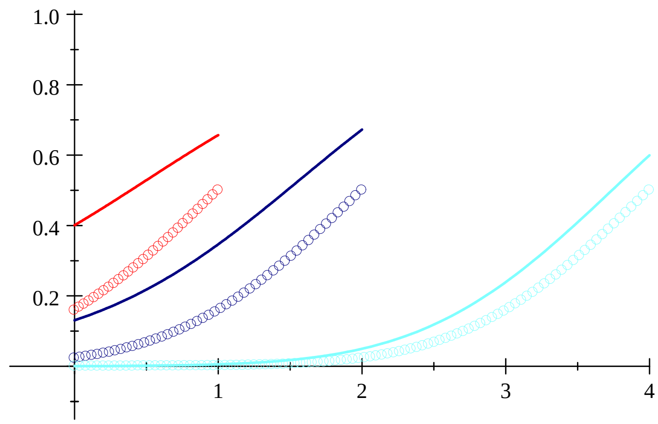
That is the spread (in terms of relative corridor position) is equal to the ratio of the expected additional overdraft to the amount of term deposit. We have the following results with regards to the minimum bid rate. In the case where banks have identical cost schedules, i.e., have the same payment shock distribution, the outcome of the auction will be to have each bank supply the same amount $\frac{1}{n}D$ (as long as $\bar{Q}_i \geq \frac{1}{n}D \; \forall \; i$) and hence each bank will be paid the same amount $\tilde{a}_i^{\min} = \tilde{a}^{\min}$. The outcome of an auction with private information is likely to be above the minimum rate. In particular, the outcome will depend critically on the competitiveness of the auction and the strategic interaction between banks. Important factors include the heterogeneity (which we ignore) across banks e.g. in terms of payment shocks and initial reserves holdings

Proposition 3 (Minimum auction rate) *For a given amount of central bank liabilities the minimum auction rate is ceteris paribus (i) increasing in the amount of term deposits, $\bar{D}$, (ii) decreasing in the level of credit risk, δ and increasing the variance of the payment shock.*

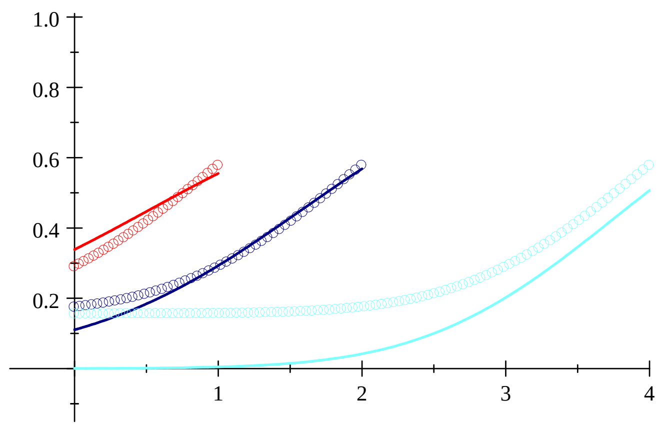
Proof. Appendix D ■

The minimum auction rate and the overnight rate as functions of the amount of term deposits collected are shown in Figure 8 below for different sizes of the central bank balance sheet and levels of credit risk. Both the minimum auction rate and the overnight rate are increasing in the amount of reserves drained. In the case without credit risk, the central bank can bring the overnight rate to the midpoint of the corridor by draining the entire amount of reserves (i.e., $D = \bar{Q}$). Introducing credit risk makes leaving funds with the central bank more attractive and hence reduces the minimum auction rate and increases the overnight rate (as shown in section 3.2). Hence, the spread between minimum auction rate and the overnight rate decreases and becomes negative for certain values of the level of credit and size of the central bank balance sheet.

No Credit Risk, $\delta = 0$



Credit Risk, $\delta = .155c$



$\tilde{b}_{\min} = -$ and $\tilde{\rho} = \circ$, Colors: $\bar{Q}$=1, $\bar{Q}$=2 and $\bar{Q}$=4

Figure 8: Term Deposits Minimum Bid Function and Overnight Rate

4.2 Multiple Period Term Deposit Facility [To be completed]

In the previous section, we looked at a one-day term deposit facility. But as described in Section 2, the four central banks discussed are offering term deposits at a wide variety of durations. Here, we extend the analysis to multiple days. We get the following intuitive result

Proposition 4 (Multi-day Term Deposits) *The minimum bid rate* $\tilde{b}^T_{\min}$ *(and the spread to the* *overnight rate) is increasing in the duration of the term deposits.*

Proof. See Appendix ■

4.3 Restricting Auction Bids

As shown in Table 1, the RBA, the Federal Reserve, the ECB and the BoK have taken different approaches to the highest bids that are permissible in their auctions. The Federal Reserve and the ECB have both chosen fixed rates set ex ante. In contrast, the RBA and the BoK retains some degree of discretion to reject bids if the rates offered are deemed too high. As higher bids reduce seigniorage, the central bank should be concerned about "overpaying" to drain reserves. Unfortunately, determining what constitutes "too much" is hard to pin down and – as discussed in Section 2 – involves subjective judgment on the part of the RBA and the BoK. Nonetheless, paying say close to upper bound of the corridor may be a sign of insufficient competition or even collusion in the auctions.

Here, we take the view that a central bank ought not pay a rate higher on a given amount of term deposits than the rate it would have to pay for banks to chose the same amount if the central bank offered term deposits *ad infinitum* at a predetermined rate. If that was the case, the central bank should simply replace its auctions with a standing facility.

Assume now that the central bank offers term deposits at a standing facility at rate, r_{tdf}. The problem of banks is thus to maximize profits by allocating central bank funds between overnight reserve holdings and the term deposits facility. Importantly, in this case, the supply of reserves is not determined directly by the central bank but rather by the allocation decisions of the individual banks. The market rate will now depend on the (sum of the) individual allocation decision of banks. For example, if banks collectively choose to place a large amount of funds at the term deposit facility then this will tend to drive up the federal funds rate. A higher level of the federal funds rate will make the term deposit facility less attractive compared to the market.

The profit of a bank is

$$\Pi(D_i) = (r_{tdf} - \rho^l(\cdot))D_i + (r_{ior} - \rho^l(\cdot))B_i 1_{B_i>0} + (r_{dw} - \rho(\cdot))B_i 1_{B_i<0} \tag{18}$$

The expected value is

$$
\begin{aligned}
E[\Pi(D)] &= r_{tdf} D_i + r_{ior} \int_{D_i - \bar{Q}_i}^{\infty} (\bar{Q}_i - D_i + \varepsilon_i) dF_i(\varepsilon_i) \\
&+ (r_{dw} - \delta) \int_{-\infty}^{D - \bar{Q}} (\bar{Q}_i - D_i + \varepsilon_i) dF_i(\varepsilon_i) - \rho^l(\cdot, \bar{Q}_i - D_i)\bar{Q}_i
\end{aligned} \tag{19}
$$

Maximizing Eq. (19) with respect to D_i yields the following first order condition:

$$
r_{tdf} - r_{ior}(1 - F(D_i - \bar{Q}_i)) - (r_{dw} - \delta)F(D_i - \bar{Q}_i)) - \frac{\partial \rho^l(R)}{\partial R}\frac{\partial R}{\partial D} Q = 0 \tag{20}
$$

Rearranging the terms, ignoring credit risk and using the fact from Eq. (5) that $\frac{\partial \tilde{\rho}^l(R)}{\partial R} = \frac{\partial \tilde{\rho}(R)}{\partial R} = f(-R)$ yields

$$
\tilde{r}_{tdf} - \tilde{\rho}(\bar{Q} - \bar{D}) = f(\bar{D} - \bar{Q})\bar{Q} \tag{21}
$$

Hence, the spread between the term deposit facility and the market rate required for a bank to allocate $\bar{Q}$ into D and R is positive. Moreover, the first order condition implies that the extra pick up from placing a dollar at the term deposit facility, $\tilde{r}_{tdf} - \tilde{\rho}(\cdot)$, has to compensate the bank for the increase in the opportunity cost of holding $\bar{Q}$ of central bank liabilities as a result of the increase in the overnight rate.

Let $\tilde{r}_{tdf}(\delta, c, \bar{D})$ denote the rate required to attract $\bar{D}$ to a standing term deposit facility. Substituting in Eq. (5) into Eq. (21) delivers

$$
\tilde{r}_{tdf}(D_i) = F((D_i - Q_i) + f(\bar{D}_i - Q_i)Q_i \tag{22}
$$

Furthermore, the maximum spread in rates between a standing and auction based term deposit facility (that drains the same amount of reserves, $\bar{D}$) is given by

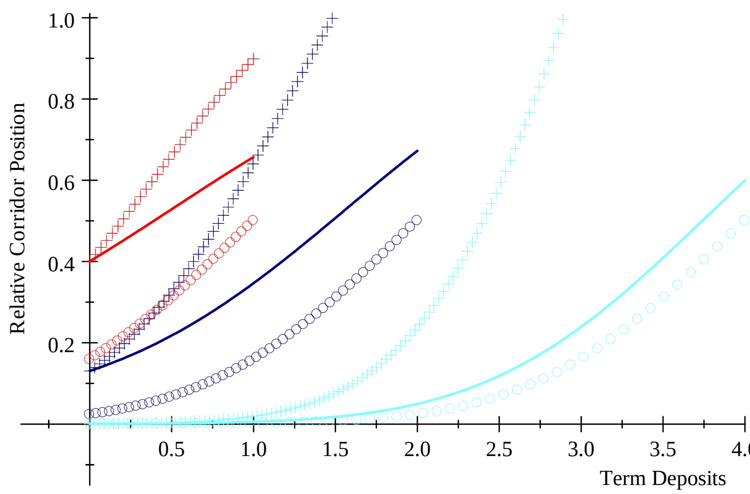
$$
\tilde{r}_{tdf}(D_i) - \tilde{a}^{\min}(D_i) = f(D - \bar{Q}_i)\bar{Q}_i - \frac{1}{\bar{D}_i}\int_{-\bar{Q}_i}^{\bar{D} - \bar{Q}_i} \varepsilon_i dF(\varepsilon_i) \tag{23}
$$

We have the following general results

Proposition 5 (Standing Facility) *The spread between the rate at the required at a standing term deposit facility and the minimum auction rate for a given amount of term deposits* $\tilde{r}_{tdf}(D) - \tilde{a}^{\min}(D)$ *is (i) positive and (ii) increasing in the amount of term deposits as long as* $\tilde{r}_{tdf}(D) \leq 1$.

Proof. The first part follows from Eq. (23) and the second part from $\frac{\partial(\tilde{r}_{tdf}(\bar{D}) - \tilde{b}_{\min}(\cdot,\bar{D}))}{\partial \bar{D}} = (1 - \frac{\delta}{c})\left(f'(\bar{D} - \bar{Q})\bar{Q} - \frac{1}{\bar{D}^2}\int_{-\bar{Q}}^{\bar{D}-\bar{Q}} \varepsilon dF(\varepsilon) - \frac{1}{\bar{D}}(\bar{D} - \bar{Q})f(\bar{D} - Q)\right) > 0$ see appendix E. ■

A figure is helpful in terms of fixing ideas. Figure 9 shows Figure 8 with the addition of $\tilde{r}_{tdf}(D)$. As shown above the rate required to drain D reserves via a standing facility is above the minimum bid rate and the spread between the two increase as the amount D increases. In this framework, the central bank should not accepts bid that are above $\tilde{r}_{tdf}(\bar{D})$. In other words, the wedge (or spread) between the two rates is the range or permissible rates. However, for large balances sheet $\tilde{r}_{tdf}(D)$ reaches the upper limit of the corridor before the central bank has drained all the reserves and in that case the standing facility comparison does not give the central bank any additional guidance. As noted in Prop. 5 credit risk reduces the rate required to attract a certain amount of reserves to a standing facility.



$\tilde{a}_{\min} = -$, $\tilde{\rho} = \circ$, and $D^{*^{-1}}(\tilde{r}_{tdf}) = \times$ Colors: $\bar{Q}$=1, $\bar{Q}$=2 and $\bar{Q}$=4

Figure 9: Term Deposits Minimum Bid Function, Overnight Rate and Standing Facility

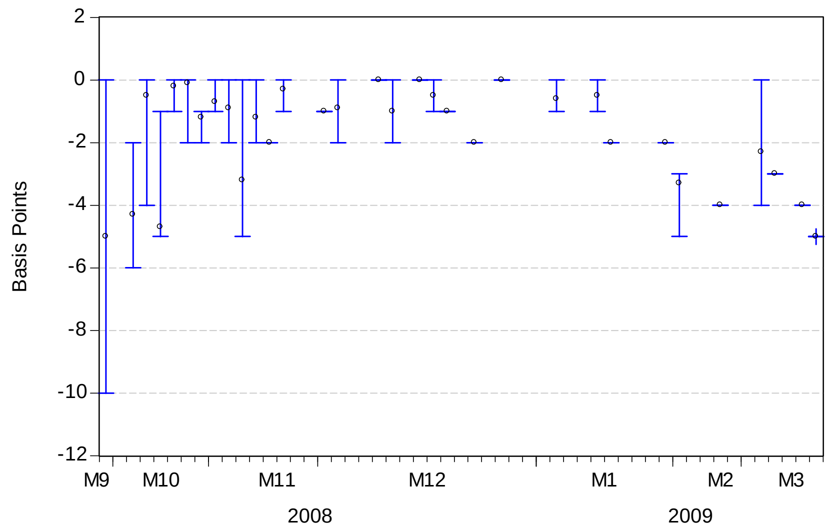


Figure 10: High, Low and Weighted Average Spread to Cash Rate Target - 7 day Term Deposits

5 Case Study: RBA Term Deposit Auction

A natural question is how well the term deposit model presented stack up against the results from the actually auctions held by central banks. Unfortunately, the data currently available is limited due to the small number of auctions conducted in all jurisdictions but Australia. Consequently in what follows, we focus exclusively on the results from the RBA auctions. To test the implications of the model laid out above, we run simple regressions of the following type:

$$\begin{aligned} \text{Spread to Cash Rate Target}_j \;&=\; \beta_0 + \beta_1 \times \text{Duration}_j + \beta_2 \times \text{Credit Risk Proxy}_{d(j)} \\ &\quad + \beta_3 \times \text{TDF Outstanding}_{w(j)} + \varepsilon_j \qquad (24) \end{aligned}$$

where j denotes the auction id, $d(j)$ denotes the day of the auction and $w(j)$ denotes the week of the auction. By propositions 3 and 4, we would expect to find that $\hat{\beta}_1 > 0$, $\hat{\beta}_2 < 0$ and $\hat{\beta}_3 > 0$.

The spread to the cash rate is either lowest accepted bid, the weighted average spread or the highest accepted bid from the auctions as published by the RBA (see Figure 10).[19] The lowest

[19] As the width of the RBA's corridor was unchanged at 2 percent over the sample period, the relative corridor position is just an afine transformation of the the spread to the target cash rate. For the ease of exposition we use

accepted bid was on average 2.2 basis points below the target cash rate whereas weighted average spread and highest accepted bid were averaging 1.4 and 0.8 basis points below, respectively. The duration variable is the term of the deposits measured in days. The credit risk proxy is the average of the 5 year credit default swap prices for senior debt for Australian New Zealand Bank (ANZ) or National Bank of Australia Ltd. (NAB) taken from Bloomberg. The data on term deposits outstanding comes from the weekly balance sheet statements of the RBA. The results are shown in Table 3. For all three measures of the auction pricing the duration of the term deposit increases the spread to the cash rate but for the high bid the effect is not significant. The effect is less than 0.1 basis points per day in all cases. According to the model above, one would expect increased credit risk to lower the rates at the term deposit auctions. Indeed, the estimated coefficients on the credit risk proxy are negative for all three price measures but only significantly different from zero for the weighted average and the highest accepted bid. Finally, the amount of term deposits outstanding is found to increase the bids at the auctions even though not significantly for the highest accepted bid.

While the bidding in the RBA term deposit auction is generally consistent with our model, the adjusted R^2 is less than 0.4 in all specifications leaving the majority of the variation in the bids unexplained. We suspect that further measures capturing the heterogeneity across banks would improve the fit.

the spread as our dependent variable.

	Spread to Cash Rate, bps		
	Lowest Accepted	Weighted Average	Highest Accepted
Constant	-4.702^{**}	-0.723	1.793^{**}
	(1.141)	(0.761)	(1.006)
Duration,	0.067^{*}	0.075^{**}	0.038
- days	(0.036)	(0.029)	(0.024)
Average ANZ and NAB CDS	-0.016^{**}	-0.023^{**}	-0.022^{**}
- basis points	(0.006)	(0.006)	(0.008)
TDs/(TDs+ES Balances)	6.795^{**}	2.821^{**}	0.329
	(1.030)	(0.814)	(1.532)
Observations	95	95	95
Adjusted R^2	0.41	0.25	0.13

Notes: Newey-West standard errors in parentheses,
** and * denotes significance at the 5% and 10% level, respectively
ANZ = Australian New Zealand Bank, NAB = National Bank of Australia,
CDS = Credit Default Swap, AUD = Australian Dollar, TD = Term Deposits
ES = Exchange Settlement

Table 3: RBA Term Deposit Auctions Pricing

6 Conclusion

The Federal Reserve has recently introduced a so-called term deposits facility. Together with e.g. the ability to pay interest on reserves and reverse repurchase agreement agreements, the new facility is one of several tools that may be employed to drain reserves when policy makers judge that it is appropriate to begin moving to a less accommodative stance of monetary policy. In this paper, we first reviewed the characteristics of the Federal Reserve's TDF as well as three facilities implemented by other central banks in the developed world. Relative to the term deposit facility currently being run in small-scale mode by the Federal Reserve, the review revealed a range of interesting differences. These included the callability, spread to target bidding, no limits in bid sizes, discretion in terms of bids accepted, lack of noncompetitive bids and same-day settlement. Moreover, the results from the auctions other central bank showed great variability in terms of pricing relative to the central bank's policy rate. The observed auction rates was generally below in the case of Australia, about the same for ECB and above for the Bank of Korea. Furthermore, the results documented that in certain situations a central bank may not be able to drain the desired amount of reserves.

In addition, we presented a simple theoretical framework for thinking about the interaction between the demand for reserves, the overnight rate and a term deposit facility. The model yielded a number of intuitive results. We found that the more a central bank wishes to drain the more the central bank will have to pay. Moreover, longer term deposits will be more expensive. Furthermore, our model highlighted that perceived credit risk of counterparties in the money market is important in terms of determining the rate of return that banks required to place funds with a term deposits facilities. Using data from the Reserve Bank Australia, we found the actual auction outcomes to be consistent with our model. We also argued that if the central bank suspect strategic bidding yielding auciton rates close to the upper bound of its corridor it might wish to implement a standing term deposits facility.

Yet, a relevant question is the extent to which these findings are relevant for the Federal Reserve's eventual exit for its current policy stance. In drawing lessons, it is important to remember that the facilities of other central banks are different in both scale and scope. For example, the size Federal Reserve's operations may be of different orders of magnitude and ECB's term deposit facility in narrowly focused on draining the exact amount of reserves injected via its Securities Markets Program rather than seeking to facilitate a certain level of short term interest rates. Moreover, the model does account for the important role that certain non-banks play in the U.S. money markets.

7 Appendix

A Denmark

In the early 1990s, the Danish central bank (Danmarks Nationalbank) offered both a deposit and an overdrafts facility for banks.[20] The central bank did not conduct open market operations with a view to fixing the overnight interbank rate at a certain point within the corridor. Rather open market operations (primarily foreign exchange interventions) were focused on keeping a fixed exchange rate (within bounds) vis-à-vis Germany. The buying and selling of foreign currency as

[20] The framework for implementing monetary policy was radically changed in April 1992.

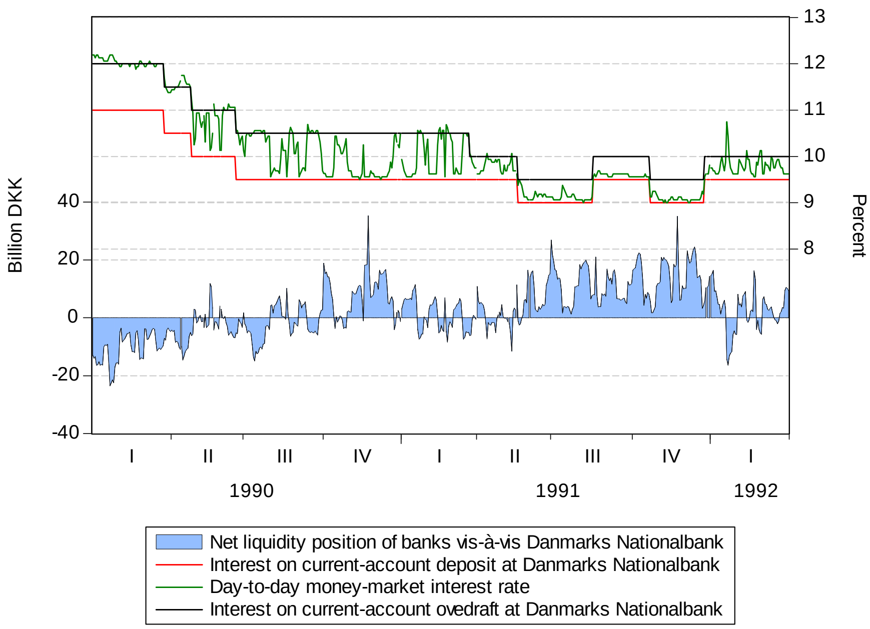


Figure 11: Net Positions and the Overnight Interbank Rate, Denmark 1990 - March 1992

well as in and outflows of the government account meant that the net liquidity position of banks (i.e. borrowings minus deposits at the central bank) varied considerably. Moreover, as banks were not subject to reserve requirements, the net position could be negative as well as positive. This is illustrated in the lower part of Figure 11 which shows the net position as a time series and Figure **??** which presents a histogram of the net positions over the period overlaid with a normal distribution with the same empirical mean and standard deviation ($\hat{\mu} = 2.6$ Billion DKK and $\hat{\sigma} = 9.4$ Billion DKK). In fact, based on this sample, one cannot reject the hypothesis that the net liquidity position is normally distributed using a standard Jarque Bera test ($p - value = 0.29$). But the hypothesis that the mean is zero is clearly rejected ($p - value = 0.00$).

Consistent with the model presented above the level of the overnight interbank rate was mostly within the corridor spanned by the deposit and overdraft rate (see Figure 11). The fact that a number of observations of the market rate are above the overdrafts rate likely can - in addition to the collateralization required in connection with overdrafts - be explained by the fact that individual banks were subject to limits on how much they could borrow at the central bank.

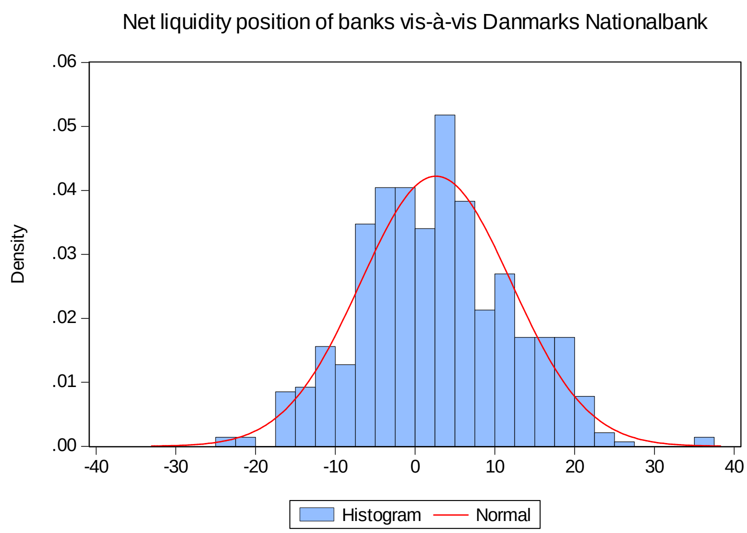


Figure 12: Net Liquidity Position Distribution, Denmark 1990 - March 1992

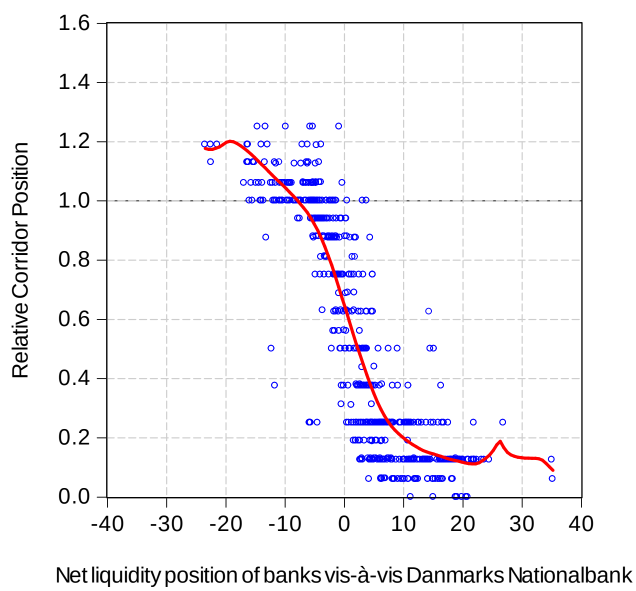


Figure 13: Relative Corridor Position and Net Liquidity Position, Denmark 1990 - March 1992

Moreover, the overnight rate was strongly dependent on the net liquidity position of the banks. The overnight rate was close to the rate of interest on the banks' current-account deposits at the central bank when the net position was positive, while it was close to the rate of interest for (collateralized) current-account overdrafts when the net position was negative. Further, to this point, Figure 13 plots the observed net liquidity positions against the relative position (within the corridor) of the overnight rate over the sample period. A nonparametric regression fit to the observations in Figure 13 suggest an inverse sigmoidal relationship between the demand for reserves and price in line with the simple model presented in the main text.

B Eurozone

The European Central Bank (ECB) offers two standing overnight facilities: the marginal lending facilities and the deposit facility. Banks can use the former to obtain overnight funds against eligible collateral and banks can use the latter to place funds with the central bank overnight. As in the United States, banks are subject to minimum reserve requirements.

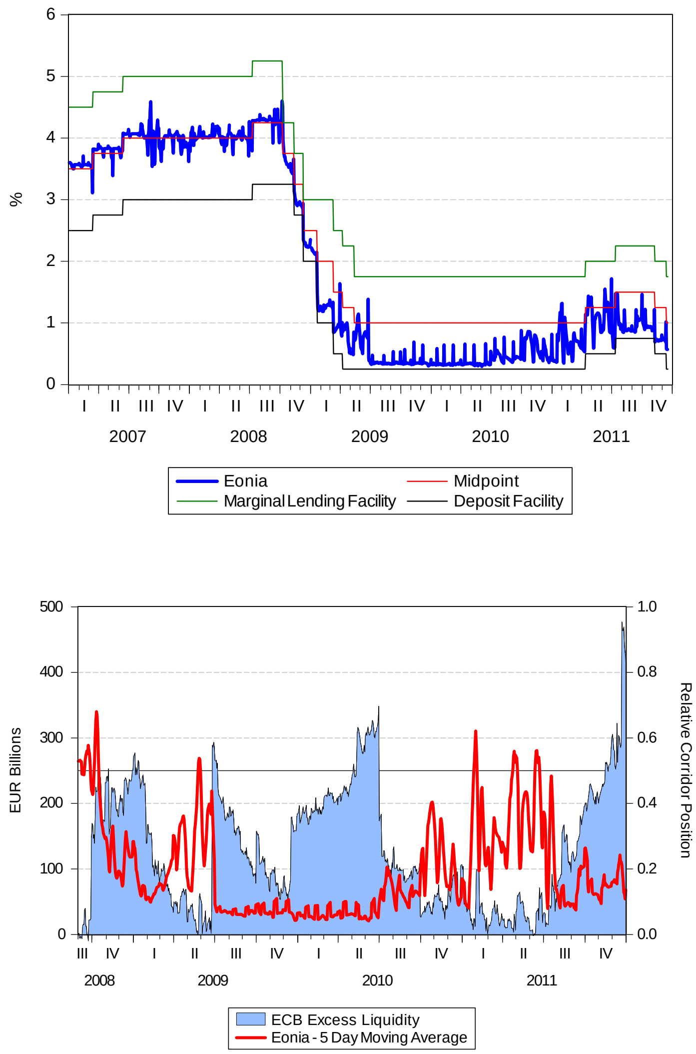


Figure 14: Eonia and ECB Excess Liquidity

Normally, the ECB seeks to guide short-term market rates via its standing facilities and a variety of open market operations. It usually conducts weekly and three-month liquidity providing operations as well as one-day liquidity absorbing fine tuning operations. The weekly operations are known as main refinancing operations (MROs) while those of longer duration are referred to as long term refinancing operations (LTROs). The liquidity providing operations are conducted as reverse transactions while absorbing operations are deposits. Funds or deposits are allocated via auctions. The auctions come in two flavors: variable or fixed rate tenders. The minimum bid rates in the MROs constitute the main indication of the monetary policy stance of the ECB. It is set at the midpoint of the corridor spanned by the deposit rate and the rate at the marginal lending facility. The Euro OverNight Index Average (Eonia®), which is the effective overnight reference rate for the euro, tend to trade close to the midpoint of the corridor.[21]

Like, other central banks, the ECB changed its policy stance and operational framework on several occasions during the financial crisis. Prior to the onset of the financial turmoil in August 2007 the minimum bid rate at MROs was at 4 percent. The ECB increased its "target" to four and a quarter percent in July 2008 before reducing it to one percent over a period of just 7 months from October 2008 to May 2009. In addition, the ECB changed the width of the standing facilities corridor three times. On October 8, 2008 the width was reduced from 200 basis points to 100 basis points – allegedly to reduce variability of the overnight rate. This decision was reversed on January 21, 2009 when the corridor was widened to 200 basis points again. However, when the policy rate was cut to one percent in May 2009, the width of the corridor was reduced to 150 basis points – presumably to avoid reducing the deposit facility rate to zero. The normal open market operations were supplemented with one month, six months and one year operations. Moreover, the Eurosystem outright bought covered bonds as well as public and private debt securities (see ECB (2010b) and footnote 1). Moreover, on October 15, 2011, the ECB began to offer full allotment at the policy rate at its MROs.

The Eonia along with the three policy rates discussed above is shown in the upper panel of Figure 14. One observes that the Eonia tracked the policy rate, with some volatility, up to October 2008. Thereafter, the Eonia started to "trade" below the midpoint of the corridor spanned by the rates at the deposit and the marginal lending facility. In fact, from mid 2009 to a year later the Eonia was very close the deposit rate. In the last part of the sample period the Eonia rate has slowly begun to move away from the floor of the corridor. The lower panel of Figure 14 plots the amount of liquidity within the Eurosystem in excess of the require reserves together with a five day moving average of the relative corridor position of the Eonia.[22] As predicted by the model in the main

[21] The Eonia is computed for the European Banking Federation by the ECB as a weighted average of all overnight unsecured lending transactions initiated by a panel of banks active in the euro area interbank money market. The banks contributing to Eonia® are the same banks as the panel banks quoting for the Euribor® rates.

[22] Excess liquidity is given by the banks' deposits under the deposit facility, current-account deposits with the

text there appears to be an inverse relationship albeit with deviations.

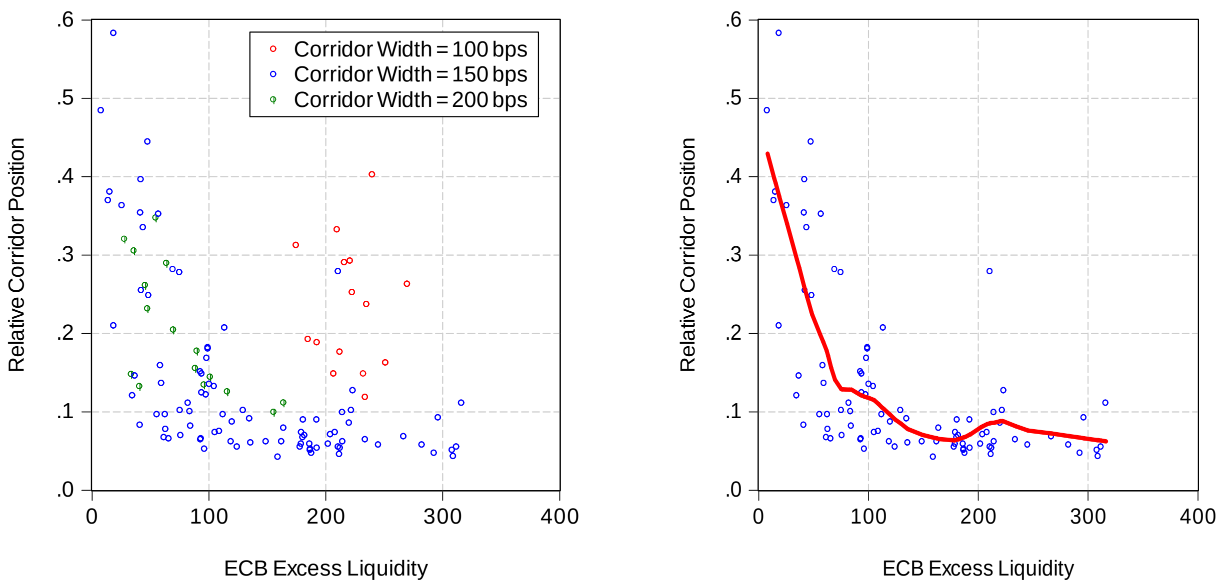


Figure 15: Inverse Demand for Reserves - Sep 2008 - Oct. 2010

Further to this point, the right panel of Figure 15 shows a scatter plot between the relative corridor position of the Eonia® rate and excess reserves in the euro zone. The figure is based on weekly average data over the period from October 15, 2008 through January 2011. Different colored symbols indicate the width of the corridor at the time of the data point. Overall, it is hard discern any particular relationship. However, the right panel shows the same plot but only for points sampled during the period during which the corridor was at 150 basis points. Here a clear (half) inverse sigmoidal relationship appears as suggested by the fitted (non-parametric) curve. With the exception of the period when the ECB operated with a narrow 100 basis point corridor the aggregate inverse demand for reserves appears to resemble to the inverse sigmoidal curve predicted by the model with a Gaussian payment shock above. Figure 15 plots the amount on ECB excess reserves against the relative corridor position over the period. We take this as *prima facie* evidence that the demand curve might have shifted during the period when the corridor was

Eurosystem and the ECB's fine-tuning market operations less the ECB's reserve requirements and the banks' use of the marginal lending facility.

only 100 basis points.

To further test our hypothesis that the demand curve will shift to the right when credit risk concerns increases or the central banks narrows to corridor, we run simple non-linear regression of the following type:

$$\tilde{\rho}_t = \frac{1}{1+e^{-z}} + \varepsilon_t \tag{25}$$

where $z = \beta_0 + \beta_1 \times$ Excess Reserves$_t$ $+ \beta_2 \times$ Credit Risk Proxy$_t$ $+ \beta_3 \times$ Corridor Width$+\beta_4 \times$ End of Maintenance Period$_t$ or $z = \beta_0 + \beta_1 \times$ Excess Reserves$_t$ $+ \beta_5 \times$ (Credit Risk Proxy$_t$/Corridor Width$_t$) $+\beta_4 \times$ End of Maintenance Period$_t$. .

	Eonia Relative Corridor Position			
	Daily		Weekly	
Constant	0.642	−1.986	0.401	−2.200
	(0.842)	(0.290)	(0.842)	(0.398)
Excess Reserves	−0.007**	−0.006**	−0.006**	−0.006**
	(0.001)	(0.001)	(0.001)	(0.001)
CDS Spread	0.006**		0.007*	
	0.003		(0.004)	
Corridor Width	−1.502**		−1.476**	
	(0.331)		(0.467)	
CDS/Corridor Width		0.012**		0.014*
		(0.004)		(0.005)
End of MP	0.665**	0.662**	0.326**	0.323**
	(0.109)	(0.111)	(0.112)	(0.115)
Observations	590	590	121	121
Adjusted R^2	0.37	0.35	0.40	0.36

Notes: Newey-West standard errors in parentheses
** and * denotes significance at the 5% and 10% level, respectively
MP: Maintenance Period

Table 4: ECB Excess Reserves Demand Function

The results of our two specifications, based on both daily data and weekly averages, are shown in Table 4. The amount of excess reserves has the expected negative sign and is significant across all specification. An increase in the CDS spread for European financial institutions increases the relative position of the Eonia within the corridor and the corridor width also have the expected inverse effect. Indeed, in our alternative specification the ratio of the CDS spread and the corridor width comes in positive (and significant) as suggested by the model with credit risk. Finally, the end of maintenance period dummy shows that there are important calendar effects that we did not consider explicitly in our model

C Minimum Bid

The profit of a bank holding D_i in term deposits is from Eq. (14)

$$\begin{aligned} E[\Pi(D_i)] = a_i D_i + (r_{ior} - \rho^l(\cdot, \bar{Q} - D))P[B_i > 0]E[B_i | B_i > 0] \\ +(r_{dw} - \rho(\cdot, \bar{Q} - D))P[B_i < 0]E[B_i | B_i < 0] \end{aligned} \tag{26}$$

Unpacking the expectations operators, we have

$$\begin{aligned} E[\Pi(D_i)] &= a_i D_i + r_{ior} \int_{D_i - \bar{Q}}^{\infty} (\bar{Q}_i - D_i + \varepsilon_i) dF_i(\varepsilon_i) \\ &\quad +(r_{dw} - \delta) \int_{-\infty}^{D_i - \bar{Q}_i} (\bar{Q}_i - D_i + \varepsilon_i) dF_i(\varepsilon_i) \\ &\quad -\rho_D^l \bar{Q}_i \end{aligned} \tag{27}$$

where $\rho_D^l = \rho^l(\cdot, \bar{Q} - D)$. The difference between holding zero and D_i in term deposits is

$$\begin{aligned} E[\Pi_i(D_i) - \Pi_i(0)] &= aD_i + r_{ior} \left(\int_{D_i - \bar{Q}_i}^{\infty} (\bar{Q}_i - D_i + \varepsilon_i) dF_i - \int_{-\bar{Q}_i}^{\infty} (\bar{Q}_i + \varepsilon_i) dF_i \right) \\ &\quad +(r_{dw} - \delta) \left(\int_{-\infty}^{D_i - \bar{Q}_i} (\bar{Q}_i - D_i + \varepsilon_i) dF_i - \int_{-\infty}^{-\bar{Q}_i} (\bar{Q}_i + \varepsilon_i) dF_i \right) \\ &\quad -(\rho_D^l - \rho_0^l)\bar{Q}_i \qquad (28) \\ &= aD_i + r_{ior} A + (r_{dw} - \delta) B - (\rho_D^l - \rho_0^l)\bar{Q}_i \end{aligned}$$

where $\rho_0^l = \rho^l(\cdot, \bar{Q})$ and A and B are short hands for the two differences of integrals. For the ease of notation, let $y = \bar{Q}_i$ and $x = D_i$. We have that the first difference of integrals in Eq. (28) is

$$\begin{aligned} A &= (y-x)\int_{x-y}^{\infty} dF + \int_{x-y}^{\infty} \varepsilon dF - y\int_{-y}^{\infty} dF - \int_{-y}^{\infty} \varepsilon dF \\ &= (y-x)(1-F(x-y)) - y(1-F(-y)) - \int_{-y}^{x-y_i} \varepsilon dF \\ &= yF(-y) - (y-x)F(x-y) - x - \int_{-y}^{x-y_i} \varepsilon dF \end{aligned} \tag{29}$$

Similarly, the second difference of integrals in Eq. (28) is

$$\begin{aligned} B &= (y-x)\int_{-\infty}^{x-y} dF + \int_{-\infty}^{x-y} \varepsilon dF - y\int_{-\infty}^{-y} dF - \int_{-\infty}^{-y} \varepsilon dF \\ &= (y-x)\,F(x-y) - yF(-y) + \int_{-y}^{x-y} \varepsilon dF \end{aligned} \tag{30}$$

Note that $A = -B - x$. Hence, we can write Eq. (28) as

$$E[\Pi_i(D_i) - \Pi_i(0)] = (a - r_{ior})D_i + (r_{dw} - r_{ior} - \delta)B - (\rho_D^l - \rho_0^l)\bar{Q}_i \tag{31}$$

Recall from Eq.(11) that we have

$$\frac{\rho - r_{ior}}{c} = (1 - \frac{\delta}{c})F(-\frac{R^S}{n}) + \frac{\delta}{c} \Rightarrow F(-\frac{R^S}{n}) = \frac{\rho^l - r_{ior}}{c - \delta} \tag{32}$$

Hence, in equilibrium where $F(D_i - \bar{Q}_i) = F(-R_i^*) = F(-\frac{R^S}{n})$ we have

$$\begin{aligned} B &= \left(\bar{Q}_i - D_i\right) F(D_i - \bar{Q}_i) - \bar{Q}_i F(-\bar{Q}_i) + \int_{-\bar{Q}_i}^{D_i - \bar{Q}_i} \varepsilon_i dF_i \\ & \left(\bar{Q}_i - D_i\right) \frac{\rho_D^l - r_{ior}}{r_{dw} - r_{ior} - \delta} - \bar{Q}_i \frac{\rho_0^l - r_{ior}}{r_{dw} - r_{ior} - \delta} + \int_{-\bar{Q}_i}^{D_i - \bar{Q}_i} \varepsilon_i dF_i \end{aligned} \tag{33}$$

Substituting back into Eq. (31) we get

$$\begin{aligned}
E[\Pi_i(D_i) - \Pi_i(0)] &= (a_i - r_{ior})D_i + \left(\bar{Q}_i - D_i\right)\left(\rho_D^l - r_{ior}\right) - \\
&\quad \bar{Q}_i\left(\rho_0^l - r_{ior}\right) + (c-\delta)\int_{-\bar{Q}_i}^{D_i-\bar{Q}_i} \varepsilon_i dF_i - (\rho_D^l - \rho_0^l)\bar{Q}_i \\
&= (a_i - \rho_D^l)D_i + (c-\delta)\int_{-\bar{Q}_i}^{D_i-\bar{Q}_i} \varepsilon_i dF_i \qquad (34)
\end{aligned}$$

Setting equal to zero and solving for the minimum rate banks would accept gives

$$a_i^{\min} = \rho^*_{\bar{Q}-D} - \delta - \frac{(c-\delta)}{D_i}\int_{-\bar{Q}_i}^{D_i-\bar{Q}_i} \varepsilon_i dF_i \qquad (35)$$

and in terms of relative corridor position

$$\tilde{a}_i^{\min} = \tilde{\rho}^*_{\bar{Q}-D} - \frac{\delta}{c} - \frac{(1-\frac{\delta}{c})}{D_i}\int_{-\bar{Q}_i}^{\bar{D}-\bar{Q}_i} \varepsilon_i dF_i \qquad (36)$$

D Minimum Rate Derivatives

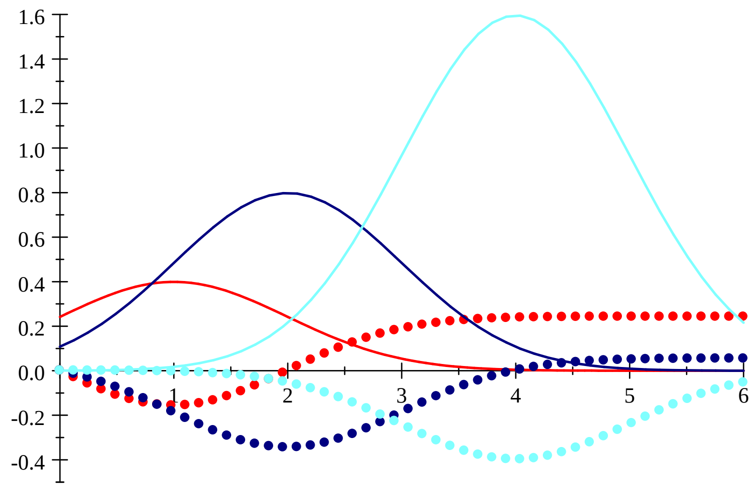
Differentiating Eq. (16) with respect to δ yields

$$\frac{\partial \tilde{a}^{\min}(\delta, c, \bar{Q}-D)}{\partial \delta} = -\frac{1}{c}\left(F(\frac{D-\bar{Q}}{n}) - \frac{1}{D_i}\int_{-\bar{Q}_i}^{D_i-\bar{Q}_i} \varepsilon_i dF(\varepsilon_i)\right) \leq 0 \qquad (37)$$

as $\int_{-\bar{Q}_i}^{D_i-\bar{Q}_i} \varepsilon_i dF(\varepsilon_i) < 0$. Differentiating with respect to D yields

$$\begin{aligned}
\frac{\partial \tilde{a}^{\min}(\delta, c, \bar{Q}-D)}{\partial D} &= (1-\frac{\delta}{c})\left(f_i(\bar{Q}_i - D_i) + \frac{1}{D_i^2}\int_{-\bar{Q}_i}^{D_i-\bar{Q}_i} \varepsilon_i dF_i - \frac{1}{D_i}(D_i - \bar{Q}_i)f_i(D_i - \bar{Q}_i)\right) \\
&= (1-\frac{\delta}{c})\frac{1}{D_i}\left(f(D_i - \bar{Q}_i)\bar{Q}_i + \frac{1}{D_i}\int_{-\bar{Q}_i}^{D_i-\bar{Q}_i} \varepsilon_i dF_i\right) \qquad (38)
\end{aligned}$$

The sign of the derivative is determined by $f(D_i - \bar{Q}_i)\bar{Q}_i + \frac{1}{D_i}\int_{-\bar{Q}_i}^{D_i-\bar{Q}_i} \varepsilon_i dF_i$. The derivative is positive for normal payment shocks as illustrated in Figure **??**



Styles: $f(D-\bar{Q})\bar{Q}$: $-$, $\frac{1}{D}\int_{-\bar{Q}}^{D-\bar{Q}} \varepsilon dF(\varepsilon)$: ●●, Colors: $\bar{Q}$=1, $\bar{Q}$=2 and $\bar{Q}$=4

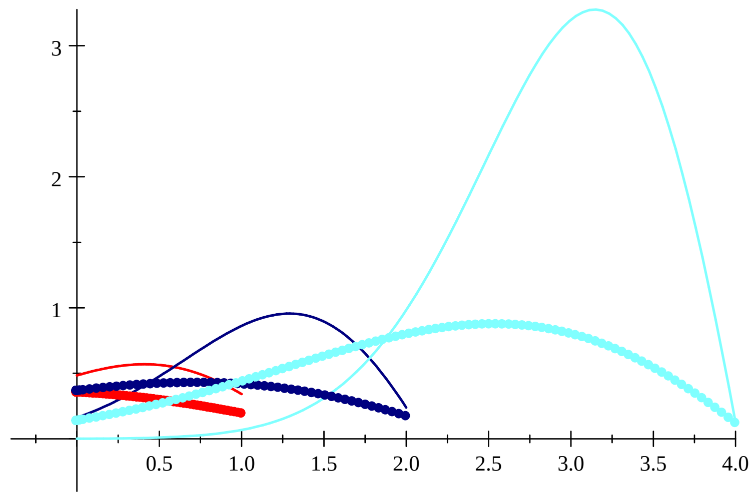
Figure 16: $\frac{\partial \tilde{b}_{min}(\delta,c,\bar{Q}-D)}{\partial D}$

E Standing Term Deposit Facility

Differentiating the spread with respect to D yields

$$\frac{\partial(\tilde{r}_{tdf}(D) - \tilde{a}^{\min}(D)}{\partial \bar{D}} = \frac{1}{\bar{D}}\left(\underbrace{f'(\bar{D}-\bar{Q})\bar{Q}\bar{D}}_{>0} + \underbrace{\frac{1}{\bar{D}}\int_{-\bar{Q}}^{\bar{D}-\bar{Q}} \varepsilon dF(\varepsilon)}_{<0} - \underbrace{(\bar{D}-\bar{Q})f(\bar{D}-Q)}_{<0}\right)$$

The sign of the derivative depends on the term in parentheses. Assuming that the payment shocks are normal then this term is positive as shown in Figure 17



Styles: $\sigma = 1 : -, \sigma = 2 : \cdot\cdot$, Colors: $\bar{Q}$=1, $\bar{Q}$=2 and $\bar{Q}$=4

Figure 17: $f'(\bar{D}-\bar{Q})\bar{Q}\bar{D} + \frac{1}{\bar{D}}\int_{-\bar{Q}}^{\bar{D}-\bar{Q}} \epsilon dF(\epsilon) - (\bar{D}-\bar{Q})f(\bar{D}-\bar{Q})$

F Multi-day term deposit facility

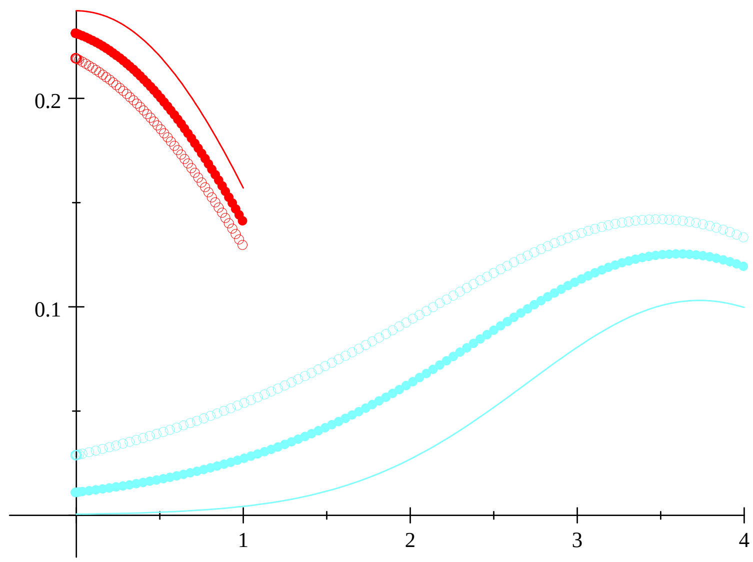
From Eq. (**??**) we have

$$\tilde{b}^T_{\min} = \tilde{\rho}(\bar{Q} - D_T) + \frac{-\sum\limits_t \int_{-\bar{Q}}^{D_T-\bar{Q}} z_t dG_t(z_t)}{TD_T} \tag{39}$$

and hence

$$\begin{aligned}
\tilde{b}^T_{\min} - \tilde{b}^{T-1}_{\min} &= \frac{-\sum\limits_{t=1}^{T} \int_{-\bar{Q}}^{D_T-\bar{Q}} z_t dG_t(z_t)}{TD} - \frac{-\sum\limits_{t=1}^{T-1} \int_{-\bar{Q}}^{D_T-\bar{Q}} z_t dG_t(z_t)}{(T-1)D} \\
&= \frac{1}{(T-1)D}\left(\sum_t^{T-1} \int_{-\bar{Q}}^{D_T-\bar{Q}} z_t dG_t(z_t) - \frac{T-1}{T}\sum_t^{T} \int_{-\bar{Q}}^{D_T-\bar{Q}} z_t dG_t(z_t)\right) \\
&= \frac{1}{(T-1)D}\left((1-\frac{T-1}{T})\sum_{t=1}^{T-1} \int_{-\bar{Q}}^{D-\bar{Q}} z_t dG_t(z_t) - \frac{T-1}{T}\int_{-\bar{Q}}^{D-\bar{Q}} z_T dG_T(z_T)\right)
\end{aligned} \tag{40}$$

as $T \to \infty$ then the term $(1-\frac{T-1}{T})$ vanishes and as $\int_{-\bar{Q}}^{D-\bar{Q}} z_T dG_T(z_T) < 0$ the minimum bid increases regardless of distribution for T large. For normal payment shocks the minimum bid increase for even small T as illustrated in Figure 18.



Styles: $T = 1 : -, T = 2 : \cdot\cdot, T = 3 : \circ$, Colors: $\bar{Q}$=1 and $\bar{Q}$=4

Figure 18: $\tilde{b}^T_{min} - \tilde{b}^{T-1}_{min}$

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