



EUROPEAN CENTRAL BANK

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NO 1350 / JUNE 2011

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OF THE CENTRAL BANK
STANDING FACILITIES
CORRIDOR AND BANKS'
DAY-TO-DAY LIQUIDITY
MANAGEMENT**

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by Ulrich Bindseil² and Juliusz Jabłecki³



In 2011 all ECB publications feature a motif taken from the €100 banknote.

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Abstract

Containing short-term volatility of the overnight interest rate is normally considered the main objective of central bank standing facilities. This paper develops a simple stochastic model to show how the width of the central bank standing facilities corridor affects banks' day-to-day liquidity management and the volatility of the overnight rate. It is shown that the wider the corridor, the greater the interbank turnover, the leaner the central bank's balance sheet (i.e. the lower the average recourse to standing facilities) and the greater short-term interest rate volatility. The obtained relationships are matched with central bank preferences to obtain an optimal corridor width. The model is tested against euro area and Hungarian daily data encompassing the financial crisis that began in 2007.

Keywords: standing facilities, money market, liquidity management

JEL classification codes: E4; E5

Non-technical summary

Monetary policy implementation is about steering the short end of the yield curve, which, together with adequate communication on future policies, impacts on medium and long-term interest rates via the expectations hypothesis of the term structure of interest rates. The primary tool used by central banks to control the level and volatility of short-term interest rates are so-called standing facilities, i.e. monetary policy operations conducted at the initiative of the commercial banks, under the conditions specified by the central bank. Typically, such facilities allow banks to borrow from (“borrowing facility”), or deposit with (“deposit facility”), the central bank overnight cash, which on the one hand facilitates the process of liquidity management and on the other contains the extent of variation exhibited by the price of such reserves – the overnight interest rate. However, despite a broad consensus regarding the use of standing facilities, there is less agreement as to the price terms on which they should be offered. While in general the rates charged on the two facilities are set at a penalty level with respect to the main policy rate, the width of such standing facilities corridor varies markedly.

Thus, in the present paper we review the rationales provided by different central banks for the widths of their respective standing facilities corridors and investigate how such rationales have changed during the crisis that began in 2007. We also propose a simple modeling framework which helps understand the basic trade-offs involved in choosing the spread between the borrowing and deposit facilities. The model allows to see in a stochastic setting how the width of the standing facilities corridor affects banks’ day-to-day liquidity management, the volatility of the short-term interest rate, the length of the central bank’s balance sheet and interbank market turnover. The obtained relationships are matched with central bank preferences to obtain an optimal corridor width. For example, it is shown, that if the central bank were to impose a zero spread between the borrowing and the deposit facility, then with positive interbank transaction costs, intermediaries could not even recover the bid-ask spread and hence interbank markets would shut down leaving the central bank as the primary liquidity broker – a role it may not be comfortable with. The model is tested against euro area and Hungarian daily data encompassing the financial crisis that began in 2007.

The paper does not pretend to allow concluding generally whether a corridor of 50 basis points or 200 basis points is optimal (to refer to the two most frequently used corridor widths). This will depend in particular (i) on the preferences of central banks regarding the key variables affected by the corridor width (interest rate volatility, leanness of the central bank’s balance sheet and interbank market activity); and (ii) on the structural parameters, such as interbank transaction costs and (relative) sizes of liquidity shocks hitting the banking system. Still, it appears that the deepening of the understanding of the trade-offs involved can contribute to informed policy decision making.

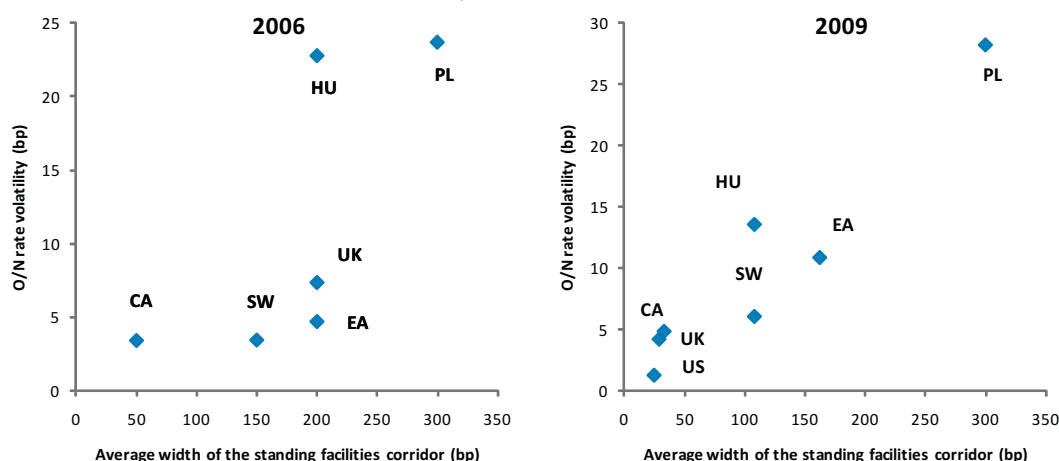
1 Introduction

Monetary policy implementation is about steering the short end of the yield curve, which, together with adequate communication on future policies, impacts on medium and long-term interest rates via the expectations hypothesis of the term structure of interest rates. The primary tool used by central banks to control the level and volatility of short-term interest rates are so-called standing facilities, i.e. monetary policy operations conducted at the initiative of the commercial banks, under the conditions specified by the central bank. Historically, they were only liquidity providing and were either a discount or a lombard (advance) facility. In a discount, the counterparty sells short-term paper to the central bank, but receives only a part of the nominal value of the asset, since the nominal value of the paper (i.e. the cash flow that arises at the maturity date) is “discounted” at the prevailing discount rate. The maturity of a discount hence depends on the maturity of the discounted paper. In a lombard loan, the counterparty in contrast obtains collateralised credit of a standardised maturity, today usually overnight. We will call a liquidity providing facility a “borrowing facility”, taking the perspective of the central bank’s counterparty. Practically all borrowing facilities today are lombard facilities. More recently, i.e. over the last 12 years or so, central banks have started to introduce liquidity absorbing facilities (“deposit facility”). A deposit facility enables counterparties to place their end-of-day surplus liquidity with the central bank on a remunerated account. Some central banks have introduced a remuneration of excess reserves held by banks with the central bank, which is equivalent to offering a deposit facility to which excess reserves are transferred automatically (excess reserves are end of day reserves held by banks with the central bank which cannot contribute to the fulfillment of required reserves, either because required reserves have already been fulfilled, or because the central bank does not impose reserve requirements).

The rates of the standing facilities are often fixed by the central bank at a “penalty level”, i.e. such that the use of the facilities is normally not attractive relative to market rates. The interest rates on the two facilities then form the ceiling and the floor of a corridor within which short-term money market rates fluctuate. A symmetric corridor has the important advantage, relative to an asymmetric approach (like the one applied for many years by the US Fed), that it creates a general symmetry of the liquidity management of the central bank and the commercial banks. This symmetry allows for instance to ignore higher order moments of autonomous factor shocks (Bindseil 2004). Systems in which standing facilities are not set at penalty level were in fact standard until the first half of the 20th century, and are still applied in some cases today. These are however one-sided systems, in which the banking sector takes systematic recourse to a borrowing facility which then also determines the short term interbank market rate (or, as introduced by the US Fed during the current turmoil, a one sided system of permanent excess liquidity, in which the deposit facility rate largely determines the interbank overnight rate).

However, despite a broad consensus nowadays regarding the use of standing facilities to contain short-term interest rate volatility, there is less agreement as to how wide the spread between the borrowing and the deposit facilities should be, apart from the fact that it should be positive. The preference for a particular width of such standing facilities seems to reflect, at least partly, the weight put by a central bank on interest rate volatility. Thus, Figure 1 plots the volatility of overnight rates against the corridor widths adopted by particular central banks right before and in the middle of the crisis. Unsurprisingly, there appears to be a positive relation between the width of the corridor chosen and interest rate volatility. For example, looking at the data from the last pre-crisis year, the central banks of Poland and Hungary seem to accept a volatility between 25 and 35 basis points and they also operate the widest corridors of 300 and 200 bp respectively. The central banks of Canada and Sweden are at the other extreme in terms of keeping the standard deviation of changes of overnight rates below 4 basis points while operating rather narrow corridors

Figure 1: Standing facilities corridor (yearly average for the relevant year) and O/N rate volatility (standard deviation of daily changes of interest rate levels) in selected currency areas.



of 50 bp and 150 bp respectively (whereby the difference between the corridor widths illustrates that also the rest of the specification of the operational framework and the open market operations practice of the central bank matter for overnight interest rate stability). The euro area and the UK with 5-7 basis points take an intermediary tolerance towards volatility, and choose somewhat wider corridors. The pattern of association remains roughly unchanged throughout the financial crisis year. In 2009 the by far lowest value of interest rate volatility is reached by the US with 1.2 basis points, reflecting a consistent excess reserves policy with a remuneration rate of reserves of 25 basis points, also setting the level of overnight rates. Similarly, in Canada and the UK interest rate volatility is kept very low, which again seems to require a very narrow corridor. Next come Sweden, euro area and Hungary – each with corridor width averaging below 150 bp and medium volatility, leaving Poland as a consistent outlier with regard to both O/N rate volatility and corridor width. Interestingly, Figure 1 illustrates how countries that narrowed their respective corridors during the crisis managed to limit the volatility of short-term interest rates. Hungary is perhaps the most spectacular example, having managed to reduce volatility by half, which however was associate with a proportional narrowing of the standing facilities corridor.

It has sometimes been argued that volatility of overnight rates is not really an issue, as e.g. already Ayuso, Haldane, and Restoy (1997) had shown empirically that deviations of overnight rates from target levels tend to be non-persistent, and therefore do normally not imply volatility of medium- and long-term rates. It would therefore be wrong to translate the overnight volatility figures into different degrees of quality of monetary policy implementation. Nevertheless, given that central banks strive to control the level of short-term interest rates, it seems warranted to ask why central banks put up with any volatility of the short-term interest rate, instead of reducing it altogether by narrowing their standing facilities corridors to zero. After all, it could be argued that an implementation of monetary policy based uniquely on such an approach could be considered superior at least in terms of the following desirable properties of an operational framework:

- Efficiency – understood as achieving an objective, the control of short term interest rates by the central bank, in line with the stance of monetary policy, with the least possible cost. If monetary policy operations are complex and regularly bear surprises because they are not fully transparent, banks will spend resources on trying to understand the logic under which the central bank operates. A

superior understanding of a complex system may allow some banks to make profits at the expense of less sophisticated competitors, who will see their funding costs rise. Therefore, complex and limitedly transparent frameworks for monetary policy implementation are likely to be inefficient.

- Parsimony – meaning that if you can achieve a certain result (effectively steering the overnight interest rate) with very few instruments and only very standardised and simple operations, then you should do so, and not try to achieve the same result through a more complex framework and operations. A zero corridor facility approach is the most parsimonious approach to monetary policy implementation that can be thought of, as it does everything just with two standing facilities.
- Automation – understood as being rule based, and thus also transparent. Discretion may sometimes be unavoidable, but often it may simply reflect a lack of ability to understand, and hence make systematic *ex ante*, the interaction between the public player and the market, or the inability to come up with a model that is able to capture a large part of this interaction. Overall, monetary policy implementation does not appear so complex that it could not be rule-based, i.e. automated, and a zero-corridor approach is by definition the most automated approach to monetary policy as it implies the total absence of discretionary decisions to be taken.

In view of these apparent advantages of a zero corridor approach to monetary policy implementation in terms of efficiently achieving stability of the overnight interest rate, this paper tries to identify factors which can motivate central banks for choosing a particular non-zero corridor width and, by corollary, also the reasons that may have deterred central banks so far from implementing a zero width corridor. While the paper does not pretend to allow concluding generally whether a corridor of 50 basis points or 200 basis points is optimal (to refer to the two most frequently used corridor widths), it presents a modeling framework which helps understand the trade-offs involved and thus can hopefully contribute to informed policymaking. In particular, we argue that the optimal choice of standing facilities corridor will depend (i) on the preferences of central banks regarding the key variables affected by the corridor width (interest rate volatility, leanness of the central bank's balance sheet and interbank market activity); and (ii) on the structural parameters, such as interbank transaction costs and (relative) sizes of liquidity shocks hitting the banking system.

The rest of this paper proceeds as follows: section 2 provides a review of the evolution of central bank doctrine and practice on the width of the corridor, and briefly relates the current paper to relevant academic literature (including to Bindseil and Jablecki (2011)). Section 3 presents the setup of the stochastic model, while sections 4 and 5 derive the basic results regarding interbank turnover and central bank balance sheet leanness. Section 6 incorporates the obtained trade-offs into a stylized analysis of central bank utility functions. Finally section 7 presents the available empirical evidence and section 8 concludes.

2 Short history of the corridor width problem

2.1 Central bank doctrine and practice before 2007

The idea of a symmetric corridor set by standing facilities around the target overnight rate is relatively new, namely 10 to 15 years old. Still, a much earlier debate of relevance for the issue is the one of „making bank rate effective” in 19th century central banking (see e.g. Bindseil 2004). 19th century monetary policy implementation was based largely on a systematic recourse to one liquidity providing facility, namely a

discount facility in which first quality trade bills could be submitted. A differentiation appears between e.g. the Bank of England, which aimed at interbank rates somewhat below bank rate (the discount rate), while e.g. the German Reichsbank accepted that interbank rates would be close to the discount rate. Of course a spread between the two, as desired by the Bank of England in the 19th century, requires that the systematic dependence of the banking system in satisfying its liquidity needs through the recourse to the facility is more limited – whereby this „more limited” is not easy to calibrate. In any case: already in the 19th century, the optimal spread between the market and the central bank facility rate was a topic of lengthy discussions, and even if these discussions were often around issues that are not easily understood from today’s perspective, it seems that they can be regarded as closely linked to the topic of the current paper – the optimal spread in a symmetric corridor approach.

The Bank of Canada appears to have been the first central bank to introduce a corridor system in 1994, with a width of 50 basis points, and called the „operating band”. Even though the framework did not evolve into a fully-fledged symmetric corridor approach until 2001, it has nonetheless from the very beginning been directed at containing the rates at which money market participants borrow and lend overnight funds within narrow bounds. This focus on interest rate volatility derived from the fact that the Bank of Canada did not impose reserve requirements on banks, and thus in principle was faced with an unstable demand for settlement balances on the part of banks, which in turn could produce erratic movements in short-term interest rates. Clinton (1997) explicitly states that a narrow corridor adopted by the Bank of Canada is “an alternative and more transparent way to smooth the overnight interest rate” in the absence of reserve requirements with averaging. However, avoiding volatility in the short-term interest rate was apparently not the only consideration, since the Bank of Canada (1995) insisted that the chosen width of the “operating band” would be enough to promote market activity, namely by being larger than interbank transaction costs:

The existence of a 50 basis point spread between the rate charged on overdrafts and that paid on surpluses would provide a fairly strong cost incentive for participants to deal in the market rather than to rely on the central bank, and the cost of overnight loans in the market would thus fluctuate between the rate on positive settlement balances and the Bank Rate. Since the typical spread between bids and offers on overnight funds in the market is not more than 1/8 per cent, in principle it should always be possible for lenders and borrowers to negotiate a rate that is mutually more favorable than the rates available at the Bank of Canada. Thus, the rate spread at the central bank would encourage the participants to hold a zero balance every day, and the Bank would expect only minimal use to be made of its end-of-day facilities.

Another occasion for from-scratch discussions on the width of the corridor problem emerge in preparatory work for the euro (see also e.g. Galvenius and Mercier 2010, sections 2.4.9 and 2.4.10). In June 1998, i.e. 6 months before the launch of the euro, Enoch and Kovanen (1998) provide the following reflection on the issue:

A narrow corridor provides an automatic operating tool to limit interest rate volatility and reduce the need for fine tuning operations. If the corridor is too narrow, however, it could undermine the development of a liquid market for the euro, since there would be less incentive for financial institutions to manage their liquidity through the interbank markets. The practical importance of this factor is not clear, however. Given the narrow margins in the European money markets, corridor limits need to be only a small distance from market interest rates to make use

of the standing facilities penal for the financial institutions. In practice, the optimal width of the corridor, including its width around market bid/ask spreads, is an empirical matter, and currently there is considerable variation in the width of the corridor among those EU central banks that operate with these limits.

Two remarks on this statement should be made. First, contrary to what Enoch et al. believe, the practical importance of the issue can in our view hardly be overestimated: the width of the corridor problem is at the same time the problem of the relative role of standing facilities in monetary policy operations. Second, the optimal width should not only be an empirical problem, but it is also a theoretical, normative one: only if one understands precisely the economic effects of narrowing the corridor both on the effectiveness of monetary policy implementation, and on the efficiency of the financial sector, one can in a second step aim at calibrating the relevant trade-offs empirically, to come to conclusions on an optimal spread. That said, the ECB initially opted for an interest rate corridor of 250 basis points on 22 December 1998, without providing public explanation of this choice. However, it also announced a three-week phase with a more narrow corridor of 50 basis points, to facilitate transition to the euro for market participants.¹ Subsequently, in April 1999 the corridor was rendered symmetric and 200 bp wide.

Another bank to adopt a corridor approach to monetary policy implementation was the Sveriges Riksbank. While discussing the costs and benefits of the system in place (corridor of 150 bp), Mitlid and Vesterlund (2001) move beyond the interest rate control-interbank turnover trade-off and stress the implications of the chosen corridor width for central bank risk-taking:

A very narrow corridor would probably be very effective in steering the overnight interest rate, but at the same time the Riksbank would take over much of the risk distribution that is currently done on the overnight market. It is uncertain how broad the corridor needs to be in order for the banks' first choice to be to even out imbalances on the overnight market, but it probably does not need to be as broad as it is now.

The issue of undue central bank exposure (and hence risk taking) is raised also in connection to the Bank of England's framework. Allen (2002) notes:

Deciding on the width of the interest rate corridor was difficult. A wide corridor or band would not bind on many days and might not have much effect. A narrower band would have more effect and would have been likely to generate more business with the Bank of England, but it would erode incentives for borrowers and lenders to meet in the commercial market. We did not want our operations to overshadow normal market trading: a key feature of our current money market arrangements is that banks must test their name in commercial credit markets regularly. Related to that, any corridor would need to allow for credit tiering, since widening credit spreads are an important signal of potential financial stress.

¹Bindseil (2004) notes that one argument in the case of the ECB against a more narrow corridor would have been that in a system with reserve averaging and the possibility of anticipated changes of target rates within the current reserve maintenance period, the corridor must be sufficiently broad to avoid situations in which expected changes of the target rate within the same reserve maintenance period would go beyond the prevailing corridor. Otherwise, banks would be invited to take massive recourse to standing facilities to reduce their total refinancing costs (intertemporal arbitrage of central bank refinancing within the reserve maintenance period). Therefore, a pre-condition for very narrow corridors could be the absence of reserve requirements with averaging.

In this context Tucker (2004) refers to the possibility of a zero corridor:

With identical lending and borrowing rates, there would be no (overnight) interbank market as the intermediaries could not even recover the bid-offer spread. This would distort ultra short-term money markets, and possibly collateral markets (because the Bank lends against high quality collateral and so at times would hold large amounts of it); would cause major and unpredictable day-to-day fluctuations in the size of our balance sheet; and apply no premium for the backstop liquidity insurance provided to banks via the standing lending facility. Our preference is to design a framework that can achieve our monetary policy/volatility objectives while leaving open the possibility of a private market in short-term money.

Eventually, in 2005, the Bank of England further reformed its corridor system with a major innovation in monetary policy implementation, namely a systematic narrowing on the last day of the reserve maintenance period of the width of the corridor from ± 100 basis points to ± 25 basis points.² This innovation seems to reflect an attempt to find a better solution to the trade-off between control of short term rates, low frequency of open market operations, and the support of interbank trading.

2.2 Central bank adjustments of corridor width and underlying reasoning during the crisis

As already suggested in Figure 1 a majority of central banks have narrowed down the standing facilities corridor during the financial crisis. This is not a priori obvious, since the two sides of the trade-off that emerged in the quotations in subsection 2.1 seem to point into different directions in terms of effects of a financial crisis on the optimal width of the standing facilities corridor. The loss of predictability of factors affecting overnight rates and hence the higher volatility of overnight rates would suggest a narrowing of the corridor, while the loss of liquidity of interbank markets during a crisis would require a widening of the spread to counteract the negative effects of the crisis on incentives for interbank activity. As central banks nevertheless uniformly narrowed down the width of the corridor, it is interesting to consider the justifications provided.

The Eurosystem narrowed its corridor from 200 to 100 basis points on 8 October 2008, explaining the following (European Central Bank 2009):

With the intensification of the turmoil, it was recognised that even solvent banks' ability to obtain funds in the interbank market was impaired, and that recourse to the standing facilities was increasingly important for banks. In order to align banks' cost of refinancing with the MRO rate, the Governing Council decided to narrow the corridor symmetrically to 100 basis points.

²Clews (2005) explains the mechanism as follows: "Particularly on the last day of the maintenance period, these standing facilities will have a role in controlling rates in the market as a whole (as explained below). On that day, the interest rate paid on the deposit facility will be just 25 basis points below the Bank's official rate; the rate charged for use of the borrowing facility will be 25 basis points above the official rate. On other days of the maintenance period, the facilities' main role will be to provide liquidity backup for individual institutions. On those days the rates will be less advantageous to the banks making use of the facilities, at 100 basis points below or above the official rate."



The narrowing is thus explained with a reference to the control of refinancing costs of banks, without any reference to its possible draw-back, the reduced interbank activity. However, interestingly, the ECB reconsidered this issue slightly later, and widened again with explicit reference to these draw-backs (European Central Bank 2009):

[...]The narrower corridor meant that usage of the deposit facility became much more attractive – compared with the interbank market – for those counterparties with excess liquidity. As a result, the Eurosystem assumed a prominent role as an intermediary for money market transactions, replacing trading on the money market, which was highly dysfunctional at the time... [The] Governing Council announced on 18 December 2008 that, as of the maintenance period starting on 21 January 2009, the corridor formed by the standing facility rates would be widened again to 200 basis points, in line with the desire to avoid crowding out money market activity any more than necessary. [...] Since late January, when the corridor was re-widened, the degree of intermediation by the Eurosystem started to decline... This could be an indication that the wider corridor left more room for the matching of demand and supply in the short-term money market, even in an environment of continuing high credit risk.

Also the Hungarian central bank first narrowed, and then re-widened its corridor. The narrowing was decided on 22 October 2008, during a special meeting of the MNB's Monetary Council, and later explained as follows (Magyar Nemzeti Bank 2009):

The MNB reduced the width of the interest rate corridor, in order to avoid (i) significant losses potentially caused by increased difficulty for credit institutions in managing liquidity in a more adverse financial market environment and (ii) an increase in the volatility of short-term interbank rates stemming from market uncertainty.

The return to the pre-crisis spread took place more than one year later, and was explained as follows (Magyar Nemzeti Bank 2009):

The move to widen the interest rate corridor is aimed at reinvigorating the interbank market, as well as to achieve that short-term interbank rates follow the path of the central bank base rate as closely as possible over the longer term. As a consequence of the financial crisis and the substantial loss of confidence among banks, liquidity in interbank forint markets has declined sharply since the autumn of 2008. Domestic banks continue to keep their counterparty limits very low and prefer to hold central bank deposits rather than to lend in the interbank market at the shortest, i.e. overnight, maturity... With an unchanged strategy, a wider interest rate corridor will result in higher costs for the banking sector, and consequently, it may encourage market participants to manage their liquidity through increased recourse to the interbank market and the two-week MNB bill.

The Riksbank narrowed in July 2009 its corridor from 150 to 100 basis points, and interestingly, as the only central bank in the world, set a negative deposit facility rate, which however did not raise any difficulties in practice (Sellin 2009):

On 1 July 2009, the Riksbank decided to cut the repo rate to 0.25 per cent and to retain the corridor of plus/minus 0.50 per cent. This entailed a deposit rate of minus 0.25 per cent. As the Riksbank carries out fine-tuning operations every day, only small sums remain to be transferred to the deposit facility when the payment system closes for the day. The negative deposit rate gives the banks an incentive to participate in the fine-tuning process or to lend money to each other if any of them have a deficit at the end of the day.

The US Fed reduced the spread between the fed funds target rate and the discount window in two steps from 100 to 50 and 25 basis points (on 17 August 2007 and 16 March 2008, respectively). Moreover, it introduced for the first time an effective deposit facility by starting to remunerate required and excess reserves on 6 October 2008, therefore effectively implementing a corridor of 25 basis points. The Bank of England (2008) considers that the issue of stigma of recourse to standing facilities proved to be an important one during the financial crisis, and used this as an argument for a more narrow corridor of ± 25 bp (as of 20 October 2008),³ which ultimately reduced to just 25 bp as reserves started to be remunerated at the main policy rate in March 2009.

2.3 Related academic literature

The academic literature on the optimal width of the standing facilities corridor set by central banks is rather recent (see Bindseil and Jablecki (2011) for a comprehensive review). Woodford (2003), Bindseil (2004) or Whitesell (2006) discuss the general functioning of standing facilities corridors set by central banks.

Berentsen and Monnet (2008) are the first to propose a dynamic general equilibrium model of a channel system (i.e. a standing facilities corridor) with a welfare maximizing central bank, a money market, and commercial banks subject to idiosyncratic liquidity shocks. Berentsen, Marchesiani, and Waller (2010) use dynamic general equilibrium setup with idiosyncratic liquidity shocks and explicitly ask why – if controlling the market interest rate is the monetary policy objective – then why not set the spread to zero which would allow perfect control of the money market rate.

Hoerova and Monnet (2010) also tackle the question of why central banks allow money markets to exist. Following the insight of Rochet and Tirole (1996), Hoerova and Monnet explore the idea that the function of the money market is market discipline, and that money market induced discipline is an ex ante provision of incentives to banks to conduct business in a sound manner. The bilateral interaction between a lender and borrower in the over-the-counter money market ensures that the borrower does not take any more risk than is socially desirable. The model, which assumes idiosyncratic liquidity shocks, allows to derive simultaneously an optimal width of the corridor and an optimal collateral haircut, thereby bringing together the literature

³This was also one of the major considerations behind the Fed's narrowing of its facilities. As argued in CGFS (2008): "One important observation from this experience is that, even though many central banks have standing lending facilities to serve as a liquidity backstop, these facilities provided in some cases only limited protection against upward pressure on money market rates. Most notably, in the United States, because of stigma, there was limited use of the standing lending facility (discount window), even during some periods in which interbank rates rose above the lending facility rate... This stigma is in part a legacy of the days when discount window credit was provided at a subsidised rate and involved rationing and scrutiny. Perhaps more importantly, stigma may stem as well from past instances when discount window credit was provided to assist in the resolution of troubled banks. Stigma may also exist because borrowing at a "penalty" rate sends an adverse signal about creditworthiness that adds to the reluctance of banks to use the facility."

on the optimal width of the interest rate corridor and the one on the role of interbank markets in disciplining banks.

Bindseil and Jablecki (2011) propose a structural model of a financial system (represented by a closed set of financial accounts featuring households, corporates, the banking sector and the central bank) which focuses on long-term two-sided recourse to central bank liquidity facilities, as observed notably in the euro area during the financial turmoil from Fall 2008 to 2010. Such unusual demand for central bank intermediation is explained within the model by the interplay between corridor width and the level of market transaction costs as well as structural differences among banks with regard to access to funding sources and investment opportunities. Strictly speaking, such model is only relevant for the optimal width of the central bank corridor in crisis episodes, in which interbank transaction costs may exceed the width of the corridor set by the central bank (regardless of whether the corridor width is of an order of magnitude of 50 or 200 basis points) since only then will the facilities be used in a structural way. While the model introduced by Bindseil and Jablecki (2011) explains well the observed long-term use of central bank standing facilities at penalty rates by the same banks after the Lehman default, it does not help in understanding day-to-day liquidity shocks and their impact on interbank trading and overnight rate volatility. The latter type of arguments, that were predominant in the central banks statements before (section 2.1) and partially even during the financial crisis (section 2.2) are in contrast well captured by the present model.

The present model starts from a similar balance sheet representation of the financial system as Bindseil and Jablecki (2011) but unlike the latter, it is cast in a short-term perspective as it aims at capturing those aspects of the standing facilities corridor width, which relate to daily liquidity management by commercial banks and control of the short-term interest rate by the central bank. Thus, our model differs also from Berentsen and Monnet (2008), Berentsen, Marchesiani, and Waller (2010) and Hoerova and Monnet (2010) who analyze the optimality of the standing facilities spread in a broad economic setting with consumption-production patterns determining agents' needs for central bank liquidity. Since we believe in contrast that daily shocks to banks' liquidity position and daily fluctuations of overnight rates do not feed through directly into production decisions in the real economy (and vice versa), we do not aim to integrate the real economy into our model. Instead, the model draws on the framework developed originally by Poole (1968) and subsequently elaborated i.a. by Bartolini, Bertola, and Prati (2002), Bindseil (2004) and Pérez-Quirós and Mendizabal (2006). The common feature of those models is that the determination of short-term interest rate is driven by stochastic daily liquidity shocks hitting the banking system.

3 A stochastic model of the width of the corridor and its impact on overnight rate stability

In this section, we develop a simple stochastic model which helps understand how the problem of the optimal width of the standing facilities corridor emerges in the context of daily liquidity management and normal market circumstances. To get the feel of an interbank market while at the same time keeping the exposition as straightforward as possible we consider a stylized case of a banking system comprising only two banks. The banks are ex ante identical, so the focus is not on structural differences between banks due to different technologies (the impact of such features on financial intermediation is presented e.g. in Bindseil and Jablecki, 2011) but on the impact of partially symmetric, partially asymmetric daily liquidity shocks on otherwise identical banks. To outline the logic of monetary policy implementation in the context of a symmetric interest rate corridor, we consider first a stylized balance sheet of the economic system comprised of households, a central bank and two commercial banks. There is no corporate sector and no lending of

banks to corporates, as this is indeed an activity with a more limited role for the daily liquidity management of banks. We assume that the central bank imposes no reserve requirement on banks and offers a borrowing as well as a deposit facility, setting the rates on these two facilities symmetrically around the target interest rate. The implementation of monetary policy in such a regime consists in steering the scarcity of reserves such that there is an equal probability that at day end, the banking system will need the one or the other facility (i.e. will have a positive or negative balance vis a vis the central bank). Then, the equilibrium (or “fair”) interbank interest rate is the mid point of the corridor set by standing facilities. Changes of the level of the target interest rate (monetary policy changes) are carried out by moving the corridor set by the standing facilities and the target rate (in its middle) in parallel up or down, while not changing the scarcity of reserves (see e.g. Bartolini, Bertola, and Prati, 2002; Bindseil, 2004; Pérez-Quirós and Mendizabal, 2006).

The timeline every day is as follows:

- i. **Central bank open market operation.** In the morning, the central bank adjusts its securities position S by means of an open market operation, such that $S = \mathbb{E}(B)$, where $B = B_0 + 2\eta_1 + 2\eta_2$ are the banknotes in circulation at day end (we will also sometimes write $\eta = 2\eta_1 + 2\eta_2$). B_0 is the deterministic component and level of banknotes in the morning, while η_1, η_2 are stochastic shocks hitting each bank in the course of the day, with $\mathbb{E}(\eta_1) = \mathbb{E}(\eta_2) = 0$ and with a symmetric density function. Therefore, $S = B_0$, and in the morning, the total bank reserves R will be equal zero.
- ii. **First liquidity shock.** After the central bank operation, a first stochastic component of banknotes in circulation realizes itself and becomes publicly known: $2\eta_1$. At the same time, a deposit shift shock occurs, μ , which is neutral in terms of aggregate liquidity, but reflects that deposits of households move from one bank to another.
- iii. **Interbank trading session.** At mid day, a trading session takes place, in which in a competitive market (assume a large number of banks trading, with some of them short of liquidity and others long – while in fact we explicitly model only two banks), the interbank rate is set as the weighted average of the two standing facility rates, the weights being the perceived probabilities of the banking system being short or long at day end. It is assumed here for the time being that the banks neutralize through interbank trading the deposit shift shock.
- iv. **Second liquidity shock.** In the afternoon, the true demand for banknotes is revealed, as the last stochastic variable $2\eta_2$ gets realized.
- v. **Day-end and recourse to standing facilities.** Accordingly, the banks need to take recourse to one or the other standing facility.

The daily timeline is summarized in Figure 2.

Figure 2: Daily timeline of central bank operations and interbank trading

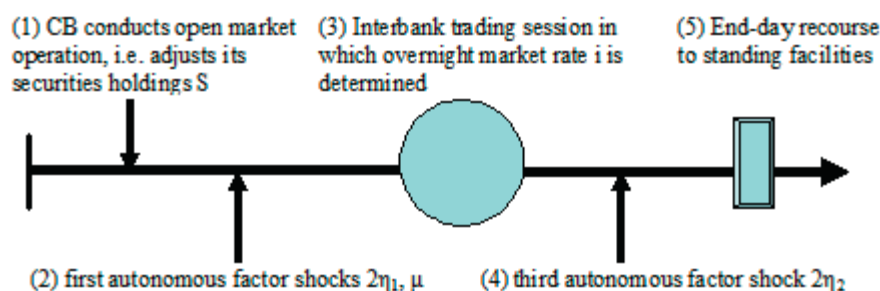


Table 1: End of day financial accounts representation

Households			
Assets		Liabilities	
Real assets	600	Equity	1000
Banknotes	$B_0 + \eta$		
Deposits Bank 1	$200 - \frac{B_0 + \eta}{2} + \mu$		
Deposits Bank 2	$200 - \frac{B_0 + \eta}{2} - \mu$		
Total assets	1000	Total liabilities	1000

Bank 1			
Assets		Liabilities	
Securities	$200 - \frac{1}{2} B_0$	Households' deposits	$200 - \frac{B_0 + \eta}{2} + \mu$
Interbank lending	$\sup(\mu, 0)$	Interbank borrowing	$\sup(-\mu, 0)$
Deposit facility	$\frac{1}{2} \sup(-\eta, 0)$	Borrowing facility	$\frac{1}{2} \sup(\eta, 0)$
Total: $200 - \frac{1}{2} B_0 + \sup(\mu, 0) + \frac{1}{2} \sup(-\eta, 0)$			

Bank 2			
Assets		Liabilities	
Securities	$200 - \frac{1}{2} B_0$	Households' deposits	$200 - \frac{B_0 + \eta}{2} - \mu$
Interbank lending	$\sup(-\mu, 0)$	Interbank borrowing	$\sup(\mu, 0)$
Deposit facility	$\frac{1}{2} \sup(-\eta, 0)$	Borrowing facility	$\frac{1}{2} \sup(\eta, 0)$
Total: $200 - \frac{1}{2} B_0 + \sup(-\mu, 0) + \frac{1}{2} \sup(-\eta, 0)$			

Central bank			
Assets		Liabilities	
Borrowing facility	$\sup(\eta, 0)$	Banknotes	$B_0 + \eta$
Securities	B_0	Deposit facility	$\sup(-\eta, 0)$
Total	$B_0 + \sup(\eta, 0)$	Total	$B_0 + \sup(\eta, 0)$

Table 1 presents the situation in the end of day financial accounts. In terms of external structural parameters, it is assumed that the household equity is 1000, being equal to the total real assets in the economy. Recall that for now interbank intermediation is assumed to be costless, which allows banks to fully buffer deposit shifts μ and makes them equal in terms of probability of being short or long at day end (this assumptions will be relaxed later on).

How exactly will the interbank interest rate i be determined? The basic idea is that for risk-neutral banks, arbitrage requires that the overnight interbank market rate is equal to the expected end of day marginal value of reserves, which itself is a weighted average of the two standing facility rates, the weights being the probabilities associated with the needs to take recourse to the two facilities, respectively. If the banking

system is “short” of reserves at day end because of higher than expected banknotes in circulation, banks will have to take recourse to the borrowing facility. If the banking system is “long” of reserves at day end because of lower than expected banknotes in circulation, banks will have to take recourse to the deposit facility. This arbitrage condition is summarized in the following equation:

$$i = \Pr(\text{“short”})i_B + \Pr(\text{“long”})i_D = \Pr(S \leq B_0 + 2\eta_1 + 2\eta_2)i_B + \Pr(S > B_0 + 2\eta_1 + 2\eta_2)i_D \quad (1)$$

Substituting $S = B_0$ we immediately get:

$$i = i_D + \Pr(0 \leq \eta_1 + \eta_2)(i_B - i_D) \quad (2)$$

Hence, with a frictionless market, the interest rate will only be determined by the aggregate shocks. The recourse to the standing facilities will simply be equal $\eta = 2(\eta_1 + \eta_2)$, with the recourse to the borrowing facility being $\sup(\eta, 0)$ and the recourse to the deposit facility being $\sup(-\eta, 0)$. A tractable case is when $\eta_1 \sim N(0, \sigma_1)$, $\eta_2 \sim N(0, \sigma_2)$ and the interest rate on the deposit facility is zero. Note that the latter assumption involves no loss of generality and implies that changes in corridor width are brought about simply by increasing or decreasing the rate on the borrowing facility (the central bank’s target interest rate lies still in the middle of the corridor, $i^* = \frac{1}{2}i_B$). Given that $S = B_0 = \mathbb{E}(B)$ and thus liquidity conditions before the realization of autonomous factor shocks are a priori balanced, the unconditional interest rate (2) equals the central bank’s target $\frac{1}{2}i_B$. Conditional on the realization of η_1 , (2) can be expressed by the cumulative distribution function as $i = \Phi\left(\frac{\eta_1}{\sigma_2}\right)i_B$. The formula for the unconditional variance of the interest rate is given in the following proposition.

Proposition 1. *Let $\eta_1 \sim N(0, \sigma_1)$, $\eta_2 \sim N(0, \sigma_2)$ and $s = \frac{\sigma_1}{\sigma_2}$. Denote by $\Phi(\bullet)$ and $\phi(\bullet)$ the cumulative distribution function and the density function of the standard normal distribution respectively. Then, the following equalities hold:*

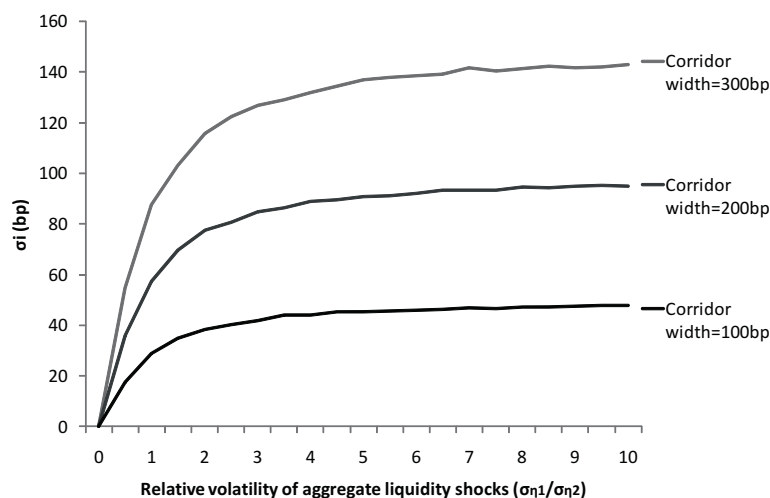
$$\text{var}(i) = \mathbb{E}(i^2) - (\mathbb{E}(i))^2 = \int_{-\infty}^{\infty} \left(\Phi\left(\frac{\eta_1}{\sigma_2}\right)i_B \right)^2 \frac{1}{\sigma_1} \phi\left(\frac{\eta_1}{\sigma_1}\right) d\eta_1 - \frac{i_B^2}{4}; \quad (3)$$

$$\lim_{s \rightarrow \infty} \sqrt{\text{var}(i)} = \frac{1}{2}i_B. \quad (4)$$

Proof. See Appendix. □

As stated in the proposition, the volatility of the interest rate depends on the relative volatilities of the two random shocks η_1, η_2 , and is linear in the width of the corridor set by standing facilities. Moreover, interest rate volatility increases monotonously as the volatility of aggregate liquidity shocks declines over the day, stabilizing at $\sigma_i = \frac{1}{2}i_B$ when $\frac{\sigma_1}{\sigma_2}$ approaches infinity. The functional relationship between $\frac{\sigma_1}{\sigma_2}$ and σ_i is plotted in Figure 3. To see the logic behind the evolution of interest rate volatility curves, consider for a moment that σ_2 is fixed and changes in s are brought about simply by changes in σ_1 . Recall that the overnight interest rate is determined during the market session on the basis of banks’ expectations regarding their end-of-day liquidity positions. Hence, as long as the distribution of the second autonomous factor shock is symmetric, expectations regarding the impact of η_2 on banks’ liquidity position will be balanced, stabilizing the interest rate around the mid-point of the corridor. In contrast, the morning shock is revealed before the market session and introduces bias into the a priori balanced liquidity expectations. When σ_1

Figure 3: The relationship between the volatility of the interest rate and the relative volatilities of liquidity shocks



is large (in relation to σ_2), banks' expectations regarding their end-of-day liquidity positions are likely to vary, reflecting different realizations of η_1 , and translating into higher variance of overnight interest rates. However – as stated in the proposition – even such volatility can be contained.

4 The impact of the corridor width on market turnover

Now the crucial issue can be addressed of how wide the corridor should be and what the trade-offs involved are. In particular, how does the spread between the borrowing and the deposit facility affect the interbank market and central bank transactions? What is, in the model proposed, the trade-off between overnight interest rate stability and interbank-market volumes, depending on the width of the interest rate corridor?

As we saw above, if there were no transaction costs related to interbank trading, then banks would always trade until the interbank shock could be fully offset. In contrast, if there is a cost c associated with transacting in the market, the average volume of interbank trading t will depend both on c and on the width of the standing facilities corridor, i.e. on the penalty associated with dealing with the central bank. If $c > 0$ and the corridor is zero, then – as we show below – there will never be any trading. In general, what needs to be traded off against the interbank transaction cost when deciding how much to trade in the interbank market is the expected total cost of recourse to the penalty rate facilities, the index indicating the bank, and “CSF” standing for Cost of Standing Facilities. The cost of using the central bank's facilities will depend on each bank's current and expected liquidity position before the market session and conditional on the information set $\Omega = (S, \eta_1, \mu)$, i.e. once the first autonomous factor shock and the interbank shock are both common knowledge. This intuition is formalized in the following proposition.

Proposition 2. *Under the assumptions of Proposition 1, the equilibrium amount of interbank turnover is the t^* that minimizes the total cost function $TC = \mathbb{E}(CSF_1) + \mathbb{E}(CSF_2) + tc$ where*

$$\mathbb{E}(CSF_1) = (i_B - i)\mathbb{E}[\max(0, \eta_2 - (-\eta_1 + \mu - t))] + i\mathbb{E}[\max(0, -\eta_2 + (-\eta_1 + \mu - t))] \quad (5)$$

$$\mathbb{E}(CSF_2) = (i_B - i)\mathbb{E}[\max(0, \eta_2 - (-\eta_1 - \mu + t))] + i\mathbb{E}[\max(0, -\eta_2 + (-\eta_1 - \mu + t))] \quad (6)$$

Furthermore, if TC has a minimum, then it is given implicitly by the equation:

$$i_B \left(1 - \Phi\left(\frac{\eta_1}{\sigma_2}\right)\right) \left[\frac{1}{\sigma_2} \Phi\left(\frac{-\eta_1 + \mu - t}{\sigma_2}\right) + \frac{1}{\sigma_{\eta_2}} \Phi\left(\frac{-\eta_1 - \mu + t}{\sigma_2}\right)\right] - \Phi\left(\frac{\eta_1}{\sigma_2}\right) \frac{i_B}{\sigma_2} \left[\Phi\left(\frac{-\eta_1 + \mu - t}{\sigma_2}\right) - \Phi\left(\frac{-\eta_1 - \mu + t}{\sigma_2}\right)\right] + c = 0. \quad (7)$$

Proof. See Appendix. □

Hence, interbank turnover is some function of the size of the initial and the interbank shocks, the volatility of the end of day aggregate shock, the width of the standing facilities corridor and the level of transaction costs. Though mathematically consistent, the result postulated in Proposition 2 provides little insight into how interbank turnover is determined in the process of daily liquidity management of banks since it is assumed that all market transactions take place simultaneously at the competitive market-clearing interest rate. To develop further intuition, consider the following “discrete” case which shows how interbank trading emerges step-by-step in response to different assessments of liquidity positions of the respective banks and allows for simple simulations.

Simulation procedure

Note first, that what determines the incentives to trade in the interbank market is the rent that can be obtained from such trading. The latter in turn derives from the cost of funds determined by each bank’s initial and expected liquidity position and the width of the standing facilities corridor as well as the transaction cost. If there were no interbank market, the marginal value of funds for the two banks respectively, i_1 , i_2 would be given by the following:

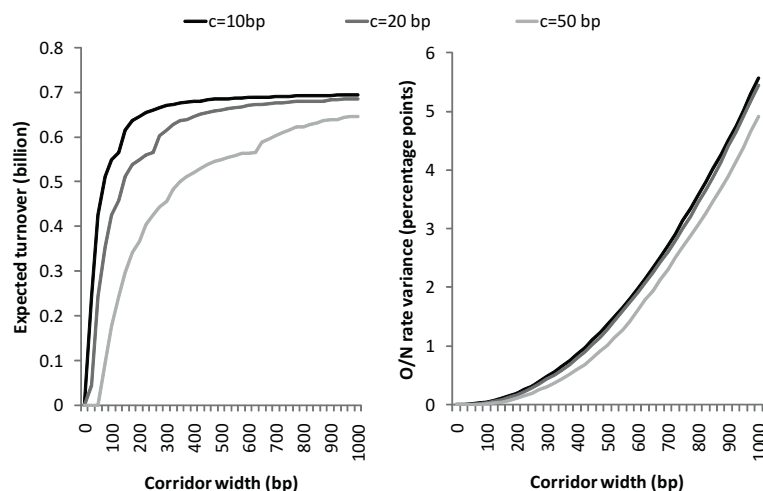
$$i_1 = \Phi\left(\frac{\eta_1 - \mu}{\sigma_2}\right) i_B \quad (8)$$

$$i_2 = \Phi\left(\frac{\eta_1 + \mu}{\sigma_2}\right) i_B \quad (9)$$

Obviously, if the rent from trading is positive, i.e. if $|i_1 - i_2| > c$, then banks should transact overnight funds in the market. Assuming equal bargaining power, the rate at which each transaction will be settled should be around $i = 1/2(i_1 + i_2)$. With each transaction, the difference in marginal valuations of funds will decline, and eventually reach the level of transaction cost c , at which point trading will stop, as banks will consider it more profitable to turn to the central bank. Thus, simulating the initial and the interbank shocks yields the expected level of interbank turnover, $\mathbb{E}(t)$, as well as interest rate volatility conditional on the set corridor width and transaction cost.

The results of the simulation are presented in Figure 4. It is assumed that the morning and afternoon aggregate shocks as well as the interbank shocks have a standard deviation of one billion and that transaction costs increase from 10 basis points (bp), to 20 bp and 50 bp (and that $\sigma_1 = \sigma_2 = \sigma_\mu = 1$). Unfortunately, there is no readily available indicator of market transaction costs. In general, to be able to transact in the market, a bank needs to employ first some traders, back office staff and risk management specialists, not to mention providing a venue, setting up a proper IT infrastructure and obtaining access to the payment system. For example, each transaction via the Eurosystem’s TARGET2 payment infrastructure (depending on the chosen pricing scheme) costs some 0.80 euro on top of the 100 euro monthly fee. When transactions are additionally handled by a broker (an option popular during the recent crisis) another fee of the order

Figure 4: Expected volumes of interbank trading (left-hand panel) and interest rate volatility (right-hand panel) for different widths of the standing facilities corridor and transaction costs equal to 10 basis points (bp), 20 bp and 50 bp ($\sigma_1 = \sigma_2 = \sigma_\mu = 1$).



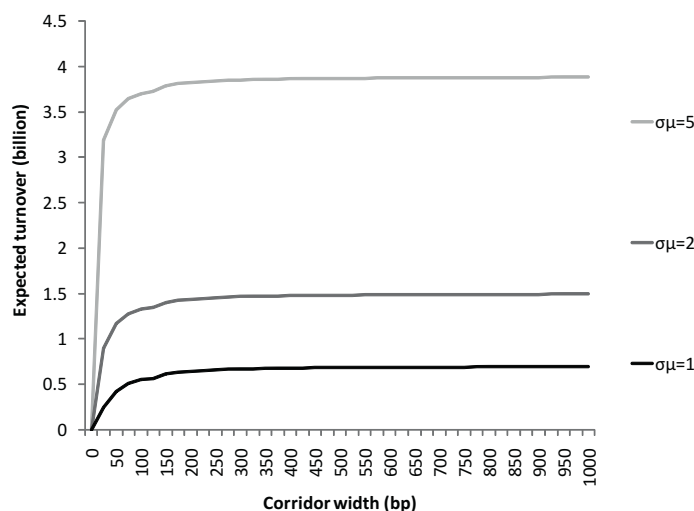
of 0.5 bp has to be added. Though perhaps not prohibitive, such costs have to be taken into account and weighed against the costs of dealing solely with the central bank, and the balance will – as argued above – ultimately determine the extent of interbank market activity.⁴ For lack of a more comprehensive measure, we use the bid-ask spread in the market for overnight interbank deposits in the euro area, which seems a good enough proxy for our purposes. In normal times the spread is below 10 bp, however in mid-2007, when the subprime turmoil was beginning to unfold, it increased to roughly 20 bp – on the back of increased costs of risk-managing interbank exposures – and on a number of occasions even exceeded 80 bp in the fourth quarter of 2008, while remaining persistently high. That said, it should be borne in mind that the units used to quantify liquidity shocks, interbank turnover and transaction costs are chosen for illustrative purposes only and are not meant as a calibration of the model.

The simulations illustrate how wider standing facilities corridors are associated with greater interbank trading volumes (left-hand panel) and greater volatility of the overnight interest rate (right-hand panel). To see why interest rate volatility depends negatively on the level of transaction costs, consider that if c were too high, no interbank trading would take place and σ_i would not even be defined; as c decreases, more trading is about to take place, and – as a result – volatility picks up⁵. Initially, in a zero corridor regime, there is no interbank trade independently of the level of transaction costs. As the corridor gets wider, interbank transactions appear more profitable and interbank trade kicks in, however the turnover for a given corridor width depends on the level of transaction costs. For example, when transaction costs equal 10 bp, interbank trade starts already in a 25 bp-wide corridor, while if transaction costs increase to 50 bp a corresponding interbank turnover is achieved only after the corridor is widened to 150 bp. Furthermore, while it is generally the case that once the corridor widens beyond a certain threshold subsequent increases in the spread between the two penalty rates induce little additional turnover while contributing to greater interest rate volatility

⁴The importance of transaction costs for market turnover is stressed by Baba, Nishioka, Oda, Shirakawa, Ueda, and Ugai (2005). The authors argue that during the zero interest rate policy of the Bank of Japan in the early 2000s, the return on an average-sized O/N interbank transaction was only ¥ 273, falling short of the sum of the commission fee for brokers (¥ 137), the charge for using the Bank of Japan Financial Network System (¥ 40), and the contract-confirmation fee (¥ 200), with possible taxes on top of that. As a result, the daily trading volume in the uncollateralized call market fell from over ¥ 9 trillion to ¥ 1.7 trillion in April 2004.

⁵We are indebted to an anonymous referee for pointing this out to us

Figure 5: Expected interbank turnover for interbank liquidity shocks with a standard deviation of 1, 2, and 5 billion, holding transaction costs and standard deviations of aggregate shocks constant ($\sigma_1 = \sigma_2 = 1$, $c = 10$ bp)



(because the volatility curve is exponential), the threshold itself varies with the level of transaction costs. Specifically, for transaction costs equal 10 bp the turnover curve flattens out around a 150-200 bp corridor as subsequent increases in turnover do not exceed 10 million. Conversely, for transaction costs equal 20 bp and 50 bp, gains in turnover do not fall below 10 million until the corridor width reaches 325 bp and 450 bp respectively.

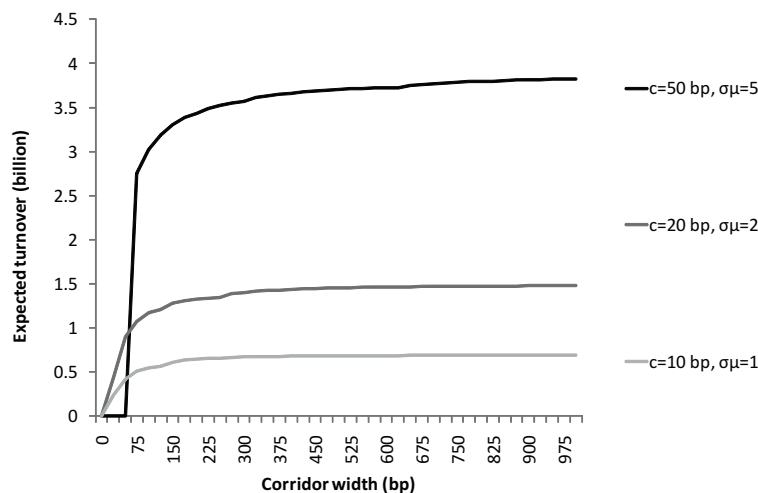
Our simulation framework allows also to analyse how the normal situation presented in Figure 4 is likely to change in a time of financial crisis. In such a case, (i) the standard deviation of interbank liquidity shocks is likely to increase relative to that of the aggregate shocks and (ii) the costs of transacting in the interbank market are also likely to rise, relating to increased credit risk and hence monitoring needs. Figure 4 already provided an idea of the effect of a crisis which would be characterized solely by an increase in transaction costs: as transacting in the interbank market gets more expensive, it requires a considerably wider corridor – providing greater incentives to trade – for interbank turnover to remain unchanged. Figure 5 in turn, provides, for a transaction cost level of 10 bp, the plot of trading volumes for interbank liquidity shocks with a standard deviation of 1, 2, and 5 billion (keeping the standard deviation of aggregate shocks constant at 1 billion).

One obvious implication of increasing the standard deviation of interbank liquidity shocks – holding transaction costs constant – is that one gets greater interbank turnover for a given corridor width. Interestingly however, changes in the standard deviation of liquidity shocks appear to have less impact on the threshold beyond which the turnover curve flattens out than it was the case with falling transaction costs.

Finally, Figure 6 shows the trading volume plot for a normal situation and two crisis scenarios in which transaction costs and the relative size of liquidity shocks increase proportionally, namely with the following transaction cost-interbank shock volatility pairs: (10 bp, 1 billion), (20 bp, 2 billion), and (50 bp, 5 billion).

Figure 6 allows to compare how the two crisis features – namely rising volatility of interbank shocks and increasing transaction costs – interact with each other. Interestingly, the effect of increasing volatility of interbank shocks – which boosts turnover – seems to dominate that of rising transaction costs – which depresses interbank trade – however in the worst crisis scenario this is true only after corridor width exceeds 50 bp. When the standing facilities corridor is very narrow to begin with, say 20 bp, then the expected turnover

Figure 6: Expected interbank turnover for the following transaction cost – interbank shock volatility pairs: (10 bp, 1 billion), (20 bp, 2 billion), and (50 bp, 5 billion). The volatilities of aggregate shocks are held constant and equal 1.



is likely to drop if transaction costs increase to 50 bp, despite a heightened volatility of liquidity shocks, and thus greater liquidity needs. There is an inflection point, though, and for wider corridors high volatilities of interbank shocks coupled with higher transaction costs imply greater expected turnover. Moreover, there is some divergence across the three cases in terms of threshold values of corridor width above which gains in interbank turnover significantly diminish. While in a normal situation (i.e. with transaction costs equal 10 bp and the standard deviation of interbank shocks equal 1) the expected turnover curve flattens out once the corridor width reaches 150-200 bp, in a crisis scenario (i.e. with transaction costs equal 50 bp and the standard deviation of interbank shocks equal 5 billion) interbank trading continues to grow until the corridor width reaches 500 bp.

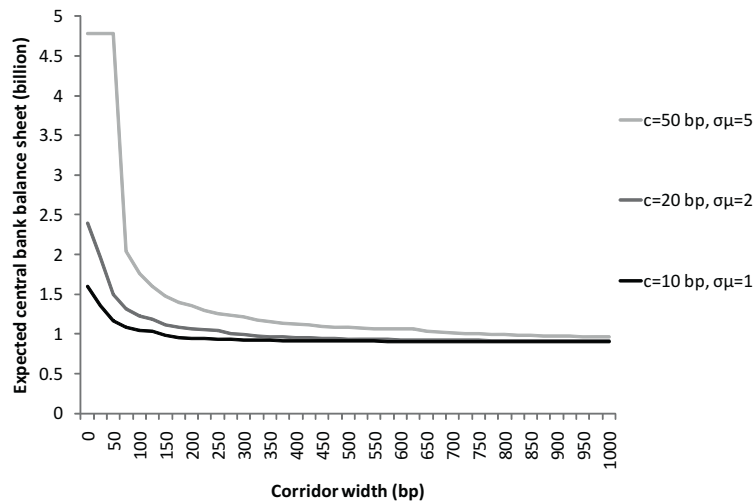
5 The width of the corridor and the length of the central bank balance sheet

The other side of the coin of changes in interbank turnover is the length of the central bank balance sheet. In fact, the two are codetermined in the proposed model since the expected central bank balance sheet length equals the expected value of the aggregate and the interbank shocks less the expected interbank turnover (conditional on the set corridor width and transaction cost). Figure 7 plots the expected central bank balance sheet length for the following transaction cost-interbank shock volatility pairs: (10 bp, 1 billion), (20 bp, 2 billion), and (50 bp, 5 billion).

Figure 7 confirms the basic intuition that – with constant transaction costs – the central bank balance sheet shrinks as the width of the standing facilities corridor increases and liquidity shocks are offset by transactions in the interbank market.⁶ The simulations allow also to trace the impact of a crisis on central bank balance sheets. Consistently with the experiences from the recent crisis, when the volatility of interbank

⁶The somewhat disturbing discontinuity in the plot of balance sheet length for the (50 bp, 5 billion) couple stems from the fact that as shown in Figure 6 interbank lending does not kick in until the corridor is widened to 75 bp at which point it rises markedly, leading to a sharp drop in central bank intermediation.

Figure 7: Expected central bank balance sheet length for the following transaction cost – interbank shock volatility pairs: (10 bp, 1 billion), (20 bp, 2 billion), and (50 bp, 5 billion). The volatilities of aggregate shocks are held constant and equal 1.



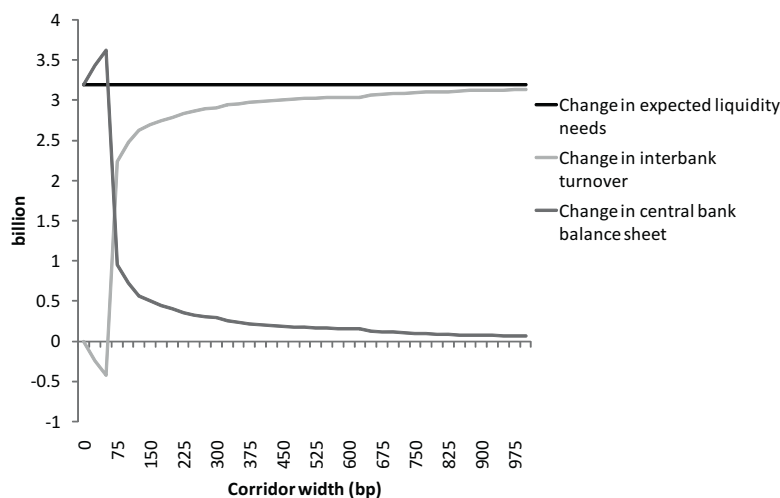
shocks rises and – at the same time – transactions in the interbank market become relatively more expensive (reflecting heightened risk management and monitoring costs), central bank balance sheets expand. However, as we saw in Figure 6, market turmoil has also the opposite effect, namely one of inducing interbank turnover. Thus, in times of crisis, the scope of both central bank and market intermediation increases, with the exact share in liquidity provision between the two sources depending on the width of the standing facilities corridor in place. Figure 8 shows the adjustment of interbank turnover and central bank balance sheet length following a move from a normal situation (transaction costs equal 10 bp and standard deviation of interbank shocks equal 1 billion) to market turmoil (transaction costs equal 50 bp and standard deviation of interbank shocks equal 5 billion).

The results suggest that up to a certain corridor width, roughly 100 bp, it is the central bank that bears the brunt of adjustment to the crisis environment.⁷ The reason behind such an effect is that with heightened transaction costs and low values of the spread between penalty rates on the two standing facilities, transactions with the central bank appear more profitable than dealing with private counterparties. Once the threshold is breached, though, the interbank market assumes the major role in distributing liquidity and already for a 300-bp-corridor about 90% of the increased liquidity needs are satisfied via interbank transactions.

What needs to be borne in mind, however, is that just like market intermediation is not costless, so too does central bank intermediation have a cost. Even though liquidity provision by the central bank is typically secured, the market and credit risk of collateral provided by commercial banks cannot be totally eliminated. Probably, central bank intermediation is somewhat more costly than interbank intermediation in normal times, reflecting the lack of a comparative advantage of the central bank in managing credit operations with commercial banks. There are however at least two reasons to believe that in a financial crisis situation, central bank intermediation becomes competitive (even if the costs of both market and central bank intermediation increase in absolute terms). First, the central bank continues to be perceived as risk

⁷Note that the chart presents changes in the level of central bank and market-based intermediation relative to the pre-crisis levels. Thus, the initially negative levels of changes in interbank turnover do not imply that turnover became negative, but that it declined relative to the initial situation of transaction costs equal 10 bp and standard deviation of interbank shocks equal 1 billion.

Figure 8: Adjustment of central bank balance sheet length and interbank turnover to a simultaneous increase in transaction costs from 10 bp to 50 bp and the standard deviation of interbank shocks from 1 to 5 billion.



free, and can manage credit risk in lending through imposing high haircuts. Since in a systemic crisis, all banks become credit risky, haircuts in collateralized interbank operations are no longer a fully satisfactory risk management tool (because a haircut creates an exposure for the party providing the collateral leg). Second, the drying up of lending may reflect funding liquidity fears of potential interbank lenders. Since the central bank is itself never subject to funding liquidity risk, it is not affected by this effect. Thus, in what follows we assume a constant marginal cost of liquidity provision by the central bank which is greater than market transaction cost in normal times and increases in a crisis, albeit becomes eventually lower than the market transaction cost.

Naturally, central banks will be interested in minimizing their intermediation costs, and hence the exposure towards market and credit risk. This can be achieved, for instance, by widening the corridor width and letting the interbank market do most of the liquidity allocation resulting from interbank shocks. A wide corridor, imposing stringent penalty rates for dealing with the central bank rather than transferring funds via the market will promote interbank trade, however at a price of increased volatility of short-term interest rates. Importantly, as we saw in Figures 4 and 7, a very wide corridor is unlikely to stimulate much additional trading or, equivalently, allow a substantially leaner central bank balance sheet, while causing interest rates to vary markedly. What, then, should be the optimal width of the standing facilities corridor?

6 The optimal width of the corridor

The reaction of central banks to these trade-offs will obviously depend on their preferences. For instance, one may assume that the central bank's utility function (which ideally corresponds to the social welfare function) is given by the following formula:⁸

⁸As far as we know, the proposed utility function has no clear counterpart in monetary theory. The basic idea behind the adopted form is to provide an analytically tractable yet plausible framework for analyzing policy choices. As an alternative, a quadratic loss function could be considered in the vein of (Woodford, 2003, pp. 428-429): $L(\sigma_i) = \lambda(\sigma_i - \sigma^*)^2$, penalizing the central bank for deviations from some optimal level of volatility, whereby σ is a function of l and t such that $\partial\sigma_i/\partial l < 0$ and $\partial\sigma/\partial t < 0$. Though the choice of the utility/loss function is of considerable importance in general equilibrium considerations, where it is used for policy evaluation, here the purpose is more modest – namely to provide some idea regarding the menu of choices that central banks face with respect to standing facilities corridor width, balance sheet length and interest rate volatility.

Table 2: Width of the standing facilities corridor chosen by the central bank with a preference function $U = t^\alpha \sigma_i^{-\beta} l^{-\gamma}$ in a normal situation and a financial crisis characterized by increasing interbank transaction costs (10 bp, 20 bp, 50 bp) and the marginal cost of liquidity provision by the central bank (13 bp, 16 bp and 30 bp) as well as rising volatility of interbank liquidity shocks (1 billion, 2 billion, 5 billion).

		Interbank transaction costs and marginal cost of liquidity provision pairs (in bp)			
		(10, 13)	(20, 16)	(50, 30)	
		equal weights ($\alpha = \beta = \gamma = 0.33$)			
		1	25	75	175
		2	25	50	125
		5	25	25	75
		market-promoting ($\alpha = 0.6, \beta = 0.1, \gamma = 0.3$)			
		1	175	350	975
		2	150	350	875
		5	75	175	375
		volatility averse ($\alpha = 0.3, \beta = 0.6, \gamma = 0.1$)			
		1	25	50	100
		2	25	25	75
		5	25	25	75
		risk averse ($\alpha = 0.3, \beta = 0.1, \gamma = 0.6$)			
		1	150	350	875
		2	100	350	875
		5	75	350	875

Volatility of interbank liquidity shocks
(in billion, and relation to aggregate shocks)

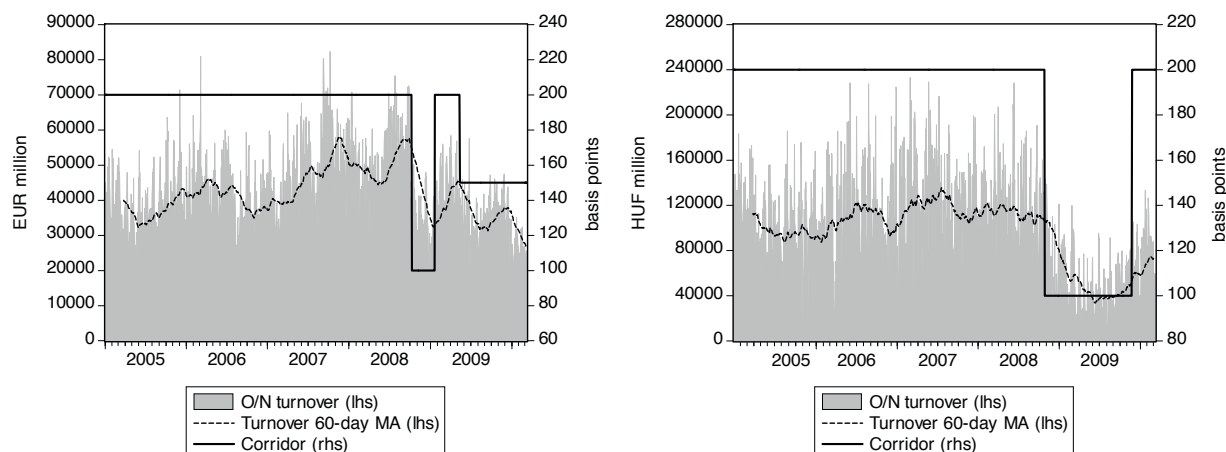
$$U = \frac{t^\alpha}{\sigma_i^\beta l^\gamma} \quad (10)$$

where t stands for the interbank trading volume, σ_i denotes overnight rate volatility (in basis points), l is the total cost of central bank intermediation which are assumed to be proportional to central bank balance sheet length, and α, β, γ are positive constants smaller than 1. Table (2) shows how the optimal corridor width depends on the exogeneous crisis parameters as well as the specification of central bank's utility function.

We consider four different specifications of the central bank utility function: (i) neutral, putting equal weights on interbank turnover, volatility and balance sheet size; (ii) market-promoting with greater emphasis on stimulating interbank trade; (iii) volatility averse, focused most on avoiding volatility of short-term interest rates; and (iv) risk averse, putting most weight on a lean balance sheet.

Thus, according to our model, a market-promoting central bank will in a normal situation (transaction costs=10 bp, marginal cost of liquidity provision=13 bp, standard deviation of interbank shocks=1 billion) choose a 175 bp-wide corridor. A risk averse central bank will find a 150 bp-corridor to be optimal in such a case, while neutral and volatility averse central banks will choose narrow corridors of 25 bp each. In a crisis scenario in which transaction costs and the relative size of liquidity shocks increase proportionally, all central banks react by increasing the width of their standing facilities corridors, albeit the corridors widths

Figure 9: Overnight turnover and corridor width in the euro area (left-hand panel) and Hungary (right-hand panel).



ultimately chosen vary significantly, from as high as 875 bp chosen by a risk-averse central bank to merely 75 bp adopted in case of volatility averse and neutral preferences.

Interestingly, central banks' reaction to a crisis seems to be conditional on the underlying factors driving market tensions. Specifically, when the crisis manifests itself only in rising standard deviation of interbank liquidity shocks, with unchanged transaction costs, central banks tend to narrow down their corridors. This seems to reflect the fact that heightened volatility of interbank shocks stimulates interbank transactions, thus allowing the central bank to narrow down its corridor and reduce interest rate volatility, while preserving its target for market activity. Conversely, when it is an increase in transaction costs that drives the turmoil, central banks see market turnover dwindling and their balance sheets inflating, and hence they are inclined to increase corridor width, though the extent of the widening will depend on how much more interest rate volatility they are willing to put up with (as captured by the coefficient β in the utility function).

7 Empirical applications: the euro area and Hungarian cases during the financial turmoil

The stochastic model developed in the preceding sections predicts that – holding transaction costs constant – both interbank turnover and interest rate volatility should increase with the width of the standing facilities corridor. Conversely, an increase in the level of transaction costs should reduce interbank trade for any given corridor width, and correspondingly increase the extent of central bank intermediation, having however no impact on interest rate volatility. The recent crisis provides a good opportunity to investigate the impact of standing facilities corridor on interbank turnover, since it has prompted a number of central banks to ease the conditions on which their standing facilities operate (or create such facilities if none had been in place). Hence, in what follows we present the available empirical evidence from the ECB and the Hungarian Central Bank (MNB), both of which apply the most straightforward versions of the symmetric corridor approach modeled in the preceding section and have, over the course of the turmoil, narrowed and then widened their respective corridors.

Figure 9 shows volumes of overnight interbank turnover in the euro area and Hungary against changes in

the width of the standing facilities corridors applied by the respective central banks. In both countries there is a clearly discernable fall in overnight turnover around the latter half of 2008, when significant problems of a number of large financial institutions and the bankruptcy of Lehman Brothers sent the markets into utter disarray. Prior to the collapse of Lehman, the interbank market in Hungary appears to function normally and turnover in the euro area actually increases somewhat around mid-2007. The increasing O/N turnover appears to reflect the tendency of banks and other financial institutions to reallocate liquidity from longer- to short-term maturities in response to growing credit and liquidity risks.

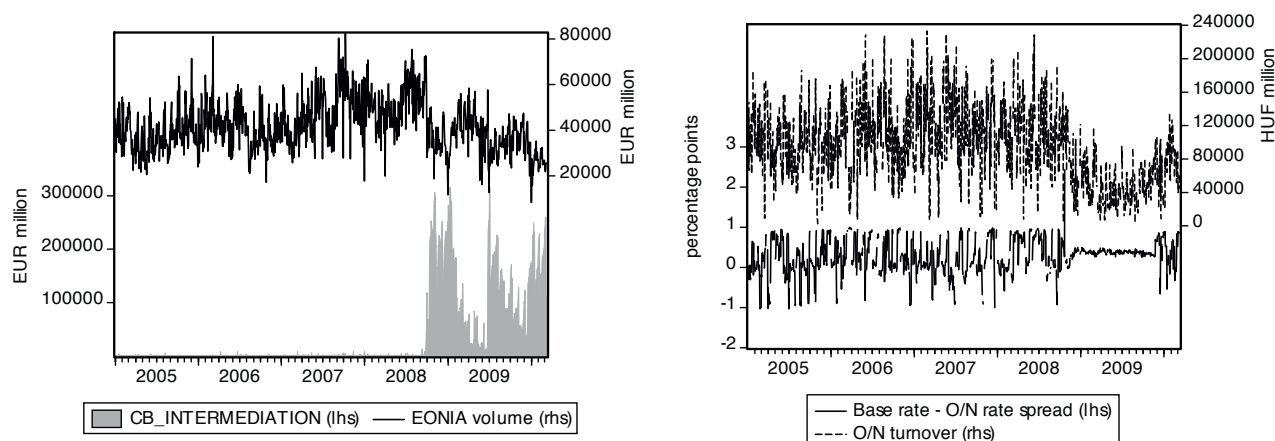
The chart also illustrates how the ECB, first, and the MNB, shortly afterwards, narrowed their respective standing facilities corridors. Specifically, on 8 October 2008, the ECB narrowed its standing facilities corridor from 200 to 100 bp, and restored it back to 200 bp as of 21 January 2009. However, subsequent interest rate cuts brought the main policy rate to 1.00% by May 2009 which – given a symmetric corridor of 200 bps – would imply the interest rate on the deposit facility at zero. Possibly striving to avoid that, the Governing Council decided again to reduce the corridor from 200 bps to 150 bps, i.e. ± 75 bps around the policy rate, leaving the interest rate on the deposit facility at 0.25%. The MNB followed suit, cutting the spread on its standing facilities in late October 2008 from the usual 200 bp to 100 bp (see section 2.2). The MNB remained well aware of the fact that “due to the narrow interest rate corridor and banks’ high liquidity surpluses, turnover in the interbank market is low” and has eventually decided to re-widen the corridor in November 2009 with the announced purpose of “reinvigorating the interbank market”. Thus, apart from market turmoil (which in the logic of the stochastic model can be interpreted as a rise in transaction costs), turnover in the interbank market could also have been to some extent crowded out by cheapened intermediation offered by the two central banks.

Figure 10 plots again interbank turnover, this time against measures of central bank intermediation. For the euro area, the relevant measure is aggregate recourse to the Eurosystem’s deposit facility which – given the banking system’s net liquidity deficit vis-a-vis the central bank – represents simultaneous use by the banking system of central bank liquidity providing and absorbing facilities. Unfortunately, no corresponding data for Hungary is publicly available in a sufficiently long time horizon, and thus resort to some other proxy had to be taken. A possible candidate seems to be the spread between the MNB base rate and the O/N interest rate.⁹ As is clear from Figure 10, central bank intermediation increased massively in the euro area and also Hungary (as indicated by the structural shift in the spread), which appears to be associated with a fall in interbank turnover, as predicted by the stochastic model.

Having presented some stylized facts, the following presents a simple econometric analysis. Specifically, we conduct a standard OLS estimation, regressing (logarithm of) the volume of O/N interbank turnover on the standing facilities spread, central bank intermediation, as well as period and calendar effects. We use daily data on interbank turnover available from the central banks’ websites spanning January 2005–March 2010 (1352 observations). Table 3 presents the basic descriptive statistics for the variables of interest. Average overnight turnover in the euro area in the whole period analyzed stood at EUR 42 billion, however it rose from 40.5 billion in the pre-crisis period to 51.1 on average in the first phase of the crisis (August 2007–September 2008), before falling to just 36 billion after the collapse of Lehman Brothers. In contrast, central bank intermediation – defined as the daily recourse to the deposit facility – was marginal, just EUR

⁹ Recall from the stochastic model that in normal times, when the central bank steers liquidity conditions in such a way that recourse to standing facilities is stochastic and the market effectively distributes liquidity across the banking system, the overnight rate should be close to the mid-point of the standing facilities corridor, i.e. the base rate, putting the spread roughly at zero. However, when recourse to deposit facility becomes structural, implying the lengthening of the central bank balance sheet, the overnight rate will be close to the rate on the deposit facility and the spread to the base rate will widen.

Figure 10: Interbank overnight trading volumes and central bank intermediation* in the euro area (left-hand panel) and Hungary (right-hand panel)



*) For the euro area intermediation is defined as recourse to deposit facility, for Hungary – due to lack of data – as the spread between the O/N rate and the deposit facility rate.

0.2-0.6 billion, before the intensification of the financial crisis in September 2008 and skyrocketed to EUR 126.7 billion after the collapse of Lehman Brothers. In Hungary, there is little evidence of any reallocation of liquidity from term markets to the overnight segment (O/N turnover averaging HUF 108 billion in the period January 2005 - August 2007 compared to 112 in August 2007 - September 2008), consistent with the view that emerging economies with no exposition to subprime-related assets did not experience significant perturbations until the latter half of 2008. However, when the crisis did eventually hit Hungary after the collapse of Lehman Brothers, the associated drop in interbank activity was much more significant than in the euro area. A similar pattern is exhibited by the spread between overnight rate and the rate on the MNB deposit facility, which is used as a proxy for the extent of central bank intermediation. The spread narrowed by more than a half from almost 80 bp before the crisis to 27 bp after the Lehman fallout, averaging 62 bp in the whole period.

Table 4 has the regression results and the accompanying legend definitions of the variables used. Overall, in both cases the fit seems relatively good. The variables included explain 65% of the variation in interbank turnover in the euro area and 47% in Hungary. Most importantly, in both cases the width of the standing facilities corridor has a strong, statistically and economically significant effect on interbank turnover. Specifically, the narrowing of the corridor by 100 bp correlates with a reduction in turnover by roughly 20% in the euro area and as much as 33% in Hungary. Measures of central bank intermediation in both cases seem to correlate positively with interbank turnover. This is easy to interpret in Hungary: as the O/N rate rises above the deposit facility rate, indicating a decline in central bank intermediation, turnover increases accordingly. However, the positive association in the euro area – where intermediation is defined as (logarithm of) recourse to Eurosystem’s deposit facility – is counterintuitive. There is some evidence that the collapse of Lehman Brothers, which we identify as a shift to a regime of high-transaction costs (both due to heightened credit and liquidity risks and prohibitive costs of managing those risks) had strong negative effect on turnover, depressing O/N trading in euro area by some 28%. Importantly, the results also confirm that overnight trading in the euro area picked up markedly (by some 15%) in the first phase of the crisis (mid 2007), reflecting a shift of many financial institutions from longer- to short-term interbank exposures.

Table 3: Overnight market turnover and central bank intermediation in the euro area and Hungary, 2005-2010.

	Mean	Median	Maximum	Minimum	Std. Dev.
Euro area (full sample: January 2005-March 2010)					
Overnight turnover (EUR billion)	41.5	40.2	82.3	8.4	10.9
ECB intermediation (EUR billion)	37.2	0.3	316.7	0.0	72.8
January 2005 - August 2007					
Overnight turnover (EUR billion)	40.5	39.2	81.0	17.1	8.9
ECB intermediation (EUR billion)	0.2	0.0	8.1	0.0	0.7
August 2007 - September 2008					
Overnight turnover (EUR billion)	51.1	50.8	82.3	17.7	10.4
ECB intermediation (EUR billion)	0.6	0.3	12.4	0.0	1.3
September 2008 - March 2010					
Overnight turnover (EUR billion)	36.1	35.7	73.0	8.4	9.7
ECB intermediation (EUR billion)	126.7	123.4	316.0	0.0	81.3
Hungary (full sample: January 2005-March 2010)					
Overnight turnover (HUF billion)	95.0	94.4	233.1	2.3	44.4
O/N rate - deposit facility spread (bp)	62.0	59.0	204.0	-143.0	48.4
January 2005 - August 2007					
Overnight turnover (HUF billion)	108.0	105.5	233.1	2.3	40.7
O/N rate - deposit facility spread (bp)	79.6	86.0	203.7	0	46.4
August 2007 - September 2008					
Overnight turnover (HUF billion)	112.2	111.4	228.3	8.0	39.1
O/N rate - deposit facility spread (bp)	66.1	79.0	200.0	2.0	45.7
September 2008 - March 2010					
Overnight turnover (HUF billion)	59.2	52.5	190.8	3.2	32.6
O/N rate - deposit facility spread (bp)	26.9	15.0	193.0	-143.0	32.7

Table 4: Regression results

Variable	Euro area		Hungary	
	Coefficient	Std. Error	Coefficient	Std. Error
Corridor	0.002***	0.00	-0.48***	0.08
Intermediation	0.02***	0.01	-0.16***	0.05
Pre crisis	-0.16***	0.06		
Lehman	-0.32***	0.07		
RR			-0.40***	0.08
End of RMP	0.09***	0.02	0.13**	0.05
End of month	-0.18***	0.02		
End of quarter	-0.31***	0.06		
C	10.21***	0.16	11.38***	0.05
AR(1)	0.83***	0.02	0.45***	0.04
MA(1)	-0.29***	0.05		
\bar{R}^2		0.65		0.47

Legend: Corridor is treated as a continuous variable, expressed in bp, for the euro area and a dummy for Hungary equal to 1 from October 23, 2008 to November 24, 2009 (when the spread on the MNB's standing facilities was compressed to 100 bp) and zero elsewhere; Intermediation is logarithm of recourse to deposit facility for the euro area and spread between the base rate and the O/N rate for Hungary; Pre crisis – dummy equal to 1 until 1 August 2007 and 0 elsewhere; Lehman – dummy equal to 1 from 15 September 2008 onwards; RR – Hungary-specific dummy equal 1 from 1 January 2009 onwards; End of RMP – end of reserve maintenance period (in Hungary also end of month). Standard errors are heteroskedasticity consistent. ***) and **) denote significance at 1% and 5% respectively.

Moreover, such pattern could be explained by the sudden deterioration of the deposit collection abilities of some banks, a “static bank run”, as modeled in Bindseil and Jablecki (2011). Since neither of the dummies came out significant in the regression for Hungary, the coefficients are not reported in the table. That said, Hungary does have one specific feature – the cut in required reserve ratio from 5% to 2% as of January 2009. Though the measure was partly rationalized as bringing Hungarian monetary policy implementation framework more in line with the one of the Eurosystem, it has undoubtedly increased liquidity of the banking sector, relieving banks to some extent of the need to refinance on the market. Thus, the decrease in required reserve ratio is associated with turnover lower by some 33%. Furthermore, in both the euro area and Hungary interbank trading seems to pick up towards the end of the reserve maintenance period (by 9% and 14% respectively). In addition, in the euro area the end of month and end of quarter typically see a decline in turnover, reflecting possibly window dressing behavior. In Hungary the end of each reserve maintenance period coincides with the end of month, so is reported in the previous row, while end of quarter came out insignificant and thus was excluded from the regression.

Hence, even though the presented empirical models differ slightly in formulation, the conclusions implied by both are broadly consistent with the predictions of the stochastic model and also – as indicated above – with the results of Bindseil and Jablecki (2011).

8 Conclusions

It is not exaggerated to say that the width of the corridor problem is at the center of understanding monetary policy implementation techniques. The question why going for the complex to steer short term interest rates – namely through the sporadic conduct of open market operations, instead of the simple and effective – through standing facilities at the target interest rate, has to be addressed before discussing in a meaningful way further details of monetary policy implementation. While references to the key trade-offs

involved (interest rate control and simplicity, against interbank market activity and a lean central bank balance sheet) can be found in the literature since the late 1990s, a simple model-based representation of these trade-offs has been missing so far. This paper makes a step directed at closing this gap.

In particular, we develop a simple stochastic model which demonstrates how the width of the standing facilities corridor affects banks' day-to-day liquidity management. It is shown that the wider the corridor, the greater the interbank turnover, the leaner the central bank's balance sheet (i.e. the lower the average recourse to standing facilities) and the greater short-term interest rate volatility. However, the captured trade-offs are sensitive to changes in the structural parameters of the financial system, such as the (relative) size of aggregate and idiosyncratic liquidity shocks hitting the banking system and the level of interbank transaction costs. The predictions of the model are confirmed by a regression analysis of interbank turnover in the euro area and Hungary. In both countries there is a strong statistically and economically significant effect of narrowing the width of the standing facilities corridor on interbank trading. Hungarian data also point to a negative association between interbank activity and the extent of intermediation offered by the central bank, while the euro area data show that the shift to a high-transaction costs regime (which we identify with the collapse of Lehman Brothers in September 2008) had a strong depressing effect on turnover.

While the paper does not pretend to allow concluding generally whether a corridor of 50 basis points or 200 basis points is optimal (to refer to the two most frequently used corridor widths), it provides a useful framework for analyzing the costs and benefits of changing corridor width given the preferences of the central bank with regard to the relevant trade-offs. Further research in this area should aim at extending the short-term focus of the paper to capture the heterogeneity of the banking system and the longer-term impact of the width of standing facilities corridor on liquidity intermediation in the financial system. In particular, what needs additional clarification are the determinants of the two-sided, structural recourse of the banking system to the standing facilities, as observed in the euro area and elsewhere in the recent crisis.

Appendix

Proof of Proposition 1.

(3) follows immediately once it is recalled that the unconditional mean of i equals $\frac{i_B}{2}$. To obtain (4), first normalize η_2 to 1 and simplify the notation slightly by denoting $\eta_1 = Z$ with $Z \sim N(0, s)$. Then (3) takes the form:

$$\text{var}(i) = \int_{-\infty}^{\infty} (\Phi(z) i_B)^2 \frac{1}{s} \phi\left(\frac{z}{s}\right) dz - \frac{i_B^2}{4} \quad (11)$$

Note that

$$\int_{-\infty}^{\infty} \Phi(z)^2 \frac{1}{s} \phi\left(\frac{z}{s}\right) dz = \int_{-\infty}^{\infty} \Phi(z) \Phi(z) \phi_Z(z) dz \quad (12)$$

which is equivalent to

$$\int_{-\infty}^{\infty} \mathbb{P}(X \leq z) \mathbb{P}(Y \leq z) \phi_Z(z) dz = \int_{-\infty}^{\infty} \mathbb{P}(X \leq z, Y \leq z) \phi_Z(z) dz = \mathbb{P}(X \leq Z, Y \leq Z), \quad (13)$$

for some $X, Y \sim N(0, 1)$. Observe further that:

$$\mathbb{E}\left(\frac{X - Z}{\sqrt{1 + s^2}}\right) = \frac{1}{\sqrt{1 + s^2}} \mathbb{E}(X) - \frac{1}{\sqrt{1 + s^2}} \mathbb{E}(Z) = 0 = \mathbb{E}\left(\frac{Y - Z}{\sqrt{1 + s^2}}\right) = 0, \quad (14)$$

$$\text{var} \left(\frac{X - Z}{\sqrt{1 + s^2}} \right) = \frac{1}{1 + s^2} + \frac{s^2}{1 + s^2} = 1 = \text{var} \left(\frac{Y - Z}{\sqrt{1 + s^2}} \right) \quad (15)$$

and

$$\text{cov} \left(\frac{X - Z}{\sqrt{1 + s^2}}, \frac{Y - Z}{\sqrt{1 + s^2}} \right) = \rho \left(\frac{X - Z}{\sqrt{1 + s^2}}, \frac{Y - Z}{\sqrt{1 + s^2}} \right) = \frac{s^2}{1 + s^2}. \quad (16)$$

Hence,

$$\int_{-\infty}^{\infty} \Phi(z)^2 \frac{1}{s} \phi\left(\frac{z}{s}\right) dz = \mathbb{P} \left(\frac{X - Z}{\sqrt{1 + s^2}} \leq 0, \frac{Y - Z}{\sqrt{1 + s^2}} \leq 0 \right) = \Phi \left(0, 0, \frac{s^2}{1 + s^2} \right). \quad (17)$$

Since $\lim_{s \rightarrow \infty} \frac{s^2}{1 + s^2} = 1$, then by continuity of the CDF:

$$\lim_{s \rightarrow \infty} \Phi \left(0, 0, \frac{s^2}{1 + s^2} \right) = \Phi(0, 0, 1) = \frac{1}{2}. \quad (18)$$

Thus,

$$\lim_{s \rightarrow \infty} \text{var}(i) = \lim_{s \rightarrow \infty} \left(\int_{-\infty}^{\infty} (\Phi(z) i_B)^2 \frac{1}{s} \phi\left(\frac{z}{s}\right) dz - \frac{i_B^2}{4} \right) = \frac{i_B^2}{2} - \frac{i_B^2}{4} = \frac{i_B^2}{4} \quad (19)$$

and obviously $\lim_{s \rightarrow \infty} \sqrt{\text{var}(i)} = \frac{1}{2} i_B$ which completes the proof.

Proof of Proposition 2.

Consider first the functional form of TC . Given open market operations aiming at a zero expected recourse to facilities and no reserve requirements the reserves of each bank, r_1 and r_2 respectively, before end of day recourse to standing facilities will be:

$$\begin{aligned} r_1 &= -\eta_1 + \mu - t - \eta_2 \\ r_2 &= -\eta_1 - \mu + t - \eta_2 \end{aligned} \quad (20)$$

where t denotes the volume of interbank transactions carried out to buffer out the deposit shift shock. Recall that the decision on interbank trading is taken during the market session, before the last aggregate shock of the day, i.e. on the basis of the information set $\Omega = (S, \eta_1, \mu)$, and thus it has to take into account the effect of the remaining shock. If at the end of day, $r_i > 0$ then bank $i = 1, 2$ takes a recourse to the deposit facility for an amount equal to r_i . If, in turn, $r_i < 0$ then bank i takes a recourse to the borrowing facility for an amount equal to $-r_i$. For instance, a recourse to the borrowing facility is needed for Bank 1 if $r_1 < 0$. Substituting, $-\eta_1 + \mu - t - \eta_2 < 0$, which implies $\eta_2 > -\eta_1 + \mu - t$. Recourse to the borrowing facility has to make up for the shortfall of reserves, thus the amount borrowed will be $\eta_2 - (-\eta_1 + \mu - t)$. The cost per unit of recourse will be $(i_B - i)$, i.e. the spread between the borrowing facility rate and the market rate. Similarly, Bank 1 needs to take a recourse to the deposit facility if $r_1 > 0$, which is equivalent to $\eta_2 < -\eta_1 + \mu - t$. Since in a regime with no required reserves, banks only need to end each day with a non-negative reserve position, Bank 1 will seek to park with the central bank its whole end of day balance: $-(\eta_2 - (-\eta_1 + \mu - t)) = -\eta_1 + \mu - t - \eta_2$. The cost per unit of recourse will be i , i.e. the spread between the market rate and the deposit facility rate (normalized to zero). Applying an analogous reasoning for the second bank, we obtain the expected costs of using standing facilities at penalty rates:

$$\mathbb{E}(\text{CSF}_1) = (i_B - i) \mathbb{E} [\max(0, \eta_2 - (-\eta_1 + \mu - t))] + i \mathbb{E} [\max(0, -\eta_2 + (-\eta_1 + \mu - t))] \quad (21)$$

$$\mathbb{E}(\text{CSF}_2) = (i_B - i) \mathbb{E} [\max(0, \eta_2 - (-\eta_1 - \mu + t))] + i \mathbb{E} [\max(0, -\eta_2 + (-\eta_1 - \mu + t))] \quad (22)$$

as postulated in the proposition. Given the distributional assumptions on the liquidity shocks, equations 21 and 22 take on the form:

$$\begin{aligned} \mathbb{E}(\text{CSF}_1) &= (i_B - i) \left[\int_{-\eta_1 + \mu - t}^{\infty} [x - (-\eta_1 + \mu - t)] \phi_{\eta_2}(x) dx \right] + \\ &+ i \left[\int_{-\infty}^{-\eta_1 + \mu - t} [-x + (-\eta_1 + \mu - t)] \phi_{\eta_2}(x) dx \right] \end{aligned} \quad (23)$$

$$\begin{aligned} \mathbb{E}(\text{CSF}_2) &= (i_B - i) \left[\int_{-\eta_1 - \mu + t}^{\infty} [x - (-\eta_1 - \mu + t)] \phi_{\eta_2}(x) dx \right] + \\ &+ i \left[\int_{-\infty}^{-\eta_1 - \mu + t} [-x + (-\eta_1 - \mu + t)] \phi_{\eta_2}(x) dx \right] \end{aligned} \quad (24)$$

Assuming that banks trade efficiently, i is determined as before only by the aggregate shocks $i = \Phi\left(\frac{\eta_1}{\sigma_2}\right)i_B$. The first order condition for TC is:

$$\frac{\partial \mathbb{E}(\text{CSF}_1)}{\partial t} + \frac{\partial \mathbb{E}(\text{CSF}_2)}{\partial t} + c = 0 \quad (25)$$

Since the integrand of the first intergral in equations 23 and 24 is zero when evaluated at its lower bound and the integrand of the second intergral is zero when evaluated at its upper bound, the Leibniz rule yields (note that ϕ_{η_2} is transformed into standard normal density)¹⁰ :

$$\frac{\partial \mathbb{E}(\text{CSF}_1)}{\partial t} = (i_B - i) \left[\int_{-\eta_1 + \mu - t}^{\infty} \frac{1}{\sigma_2} \phi\left(\frac{x}{\sigma_2}\right) dx \right] + i \left[\int_{-\infty}^{-\eta_1 + \mu - t} \frac{1}{\sigma_2} \phi\left(\frac{x}{\sigma_2}\right) dx \right] \quad (26)$$

and

$$\frac{\partial \mathbb{E}(\text{CSF}_2)}{\partial t} = (i_B - i) \left[\int_{-\eta_1 - \mu + t}^{\infty} \frac{1}{\sigma_2} \phi\left(\frac{x}{\sigma_2}\right) dx \right] + i \left[\int_{-\infty}^{-\eta_1 - \mu + t} \frac{1}{\sigma_2} \phi\left(\frac{x}{\sigma_2}\right) dx \right] \quad (27)$$

Hence, after some manipulation (25) becomes :

$$\begin{aligned} i_B \left(1 - \Phi\left(\frac{\eta_1}{\sigma_2}\right) \right) \left[\frac{1}{\sigma_2} \Phi\left(\frac{-\eta_1 + \mu - t}{\sigma_2}\right) + \frac{1}{\sigma_{\eta_2}} \Phi\left(\frac{-\eta_1 - \mu + t}{\sigma_2}\right) \right] - \\ - \Phi\left(\frac{\eta_1}{\sigma_2}\right) \frac{i_B}{\sigma_2} \left[\Phi\left(\frac{-\eta_1 + \mu - t}{\sigma_2}\right) - \Phi\left(\frac{-\eta_1 - \mu + t}{\sigma_2}\right) \right] + c = 0. \end{aligned} \quad (28)$$

If there exists t^* satisfying (28), and in addition t^* is a minimum, then (28) yields an implicit function for interbank turnover which completes the proof.

¹⁰We are indebted to Philipp König for this point.

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