

The 2007 Subprime Market Crisis Through the Lens of European Central Bank Auctions for Short-Term Funds*

Nuno Cassola[†] Ali Hortaçsu[‡] Jakub Kastl[§]

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Abstract

We study European banks' demand for short-term funds (liquidity) during the summer 2007 subprime market crisis. We use bidding data from the European Central Bank's auctions for one-week loans, their main channel of monetary policy implementation. Our analysis provides a high-frequency, disaggregated perspective on the 2007 crisis, which was previously studied through comparisons of collateralized and uncollateralized interbank money market rates which do not capture the heterogeneous impact of the crisis on individual banks. Through a model of bidding, we show that banks' bids reflect their cost of obtaining short-term funds elsewhere (e.g., in the interbank market) as well as a strategic response to other bidders. The strategic response is empirically important: while a naïve interpretation of the raw bidding data may suggest that virtually all banks suffered an increase in the cost of short-term funding, we find that for about one third of the banks, the change in bidding behavior was simply a strategic response. We also find considerable heterogeneity in the short-term funding costs among banks: for over one third of the bidders, funding costs increased by more than 20 basis points, and funding costs vary widely with respect to the country-of-origin. Estimated funding costs of banks are also predictive of market- and accounting-based measures of bank performance, suggesting the external validity of our findings.

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[†]Research Department, European Central Bank

[‡]Department of Economics, University of Chicago and NBER

[§]Department of Economics, Stanford University and NBER

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1 Introduction

When the subprime credit crisis hit the Euro money market in August 2007, banks' cost of obtaining short-term uncollateralized loans increased sharply.¹ In Figure 1, we follow Taylor and Williams (2008, 2009), and plot the spread between the (1-week) EURIBOR², a measure of interbank uncollateralized rate, and the (1-week) EUREPO, the rate for fully collateralized loans on the interbank market. After the second week of August 2007, the gap between these rates significantly widened: the premium a lender required for an unsecured loan in the interbank market after August 2007 increased from around 4 basis points to well over 10 basis points for loans with a one-week maturity.³

In response to similar liquidity problems in the United States, the Federal Reserve System significantly expanded and diversified its facilities for providing liquidity. On the other side of the Atlantic, the European Central Bank exploited an already existing tool within its operational framework, its weekly "repo auctions".⁴

For many financial market participants seeking access to liquidity, repo auctions of the central bank were an attractive option: the collateral requirements were less strict and (market clearing) interest rates were significantly lower than for unsecured loans in the interbank market. To obtain

¹On August 9, 2007 BNP Paribas announced its decision to freeze three investment funds with exposure to high-grade segments of the U.S. subprime home-loan market. The combined value of the funds was €1.59 billion (\$2.19 billion) (Wall Street Journal, August 10-12, 2007).

²EURIBOR, Euro Interbank Offer Rate, is a daily reference rate based on the averaged interest rates at which banks offer to lend unsecured funds to other banks in the euro interbank market.

³In this paper, we focus mainly on one-week maturity rates as this is the maturity of the regular repo operations of the ECB. However, even more dramatic jumps in the unsecured-secured spread occurred for longer maturity loans. We analyze loans with 3-month maturity in section A.4. Not only did the spreads increase, but the set of securities that were acceptable as collateral in the interbank market also became much smaller, which renders the repo rate not directly comparable (see e.g., the BearingPoint Report, 2008).

⁴It is interesting to note that in the U.S. during the early stages of the crisis (2007H2) it was the Federal Home Loan Bank System, not the Federal Reserve System, which was the main provider of liquidity support to U.S. financial institutions. For example, as documented by Ashcraft, Bech and Frame (2008) Washington Mutual (which failed on September 25, 2008) received liquidity support in Q4 2007 amounting to about \$64 billion representing 20% of its total assets. Countrywide (\$48 billion in Q4 2007) and Wachovia (\$42 billion in Q4 2007) also were among the institutions that received liquidity support from the FHLB System in 2007.

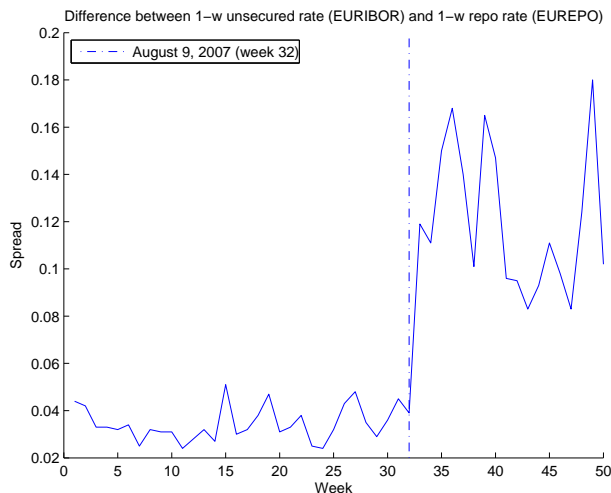


Figure 1: Spread between the unsecured and secured lending rates

a loan at the EUREPO rate in the post-turmoil period, the collateral had to be virtually risk-free – basically just high-quality government paper. Therefore, for many potential borrowers the better option might have been to obtain liquidity by participating in the auctions run by the central bank where the collateral requirements were not as stringent.⁵

This paper analyzes unique data on bidding behavior in the repo market to provide a disaggregated snapshot of the funding costs of Euro-system banks during the 2007 subprime crisis. Our work complements prior analyses providing an aggregate picture of this crisis by Taylor and Williams (2008, 2009), Michaud and Upper (2008), Wu (2008), and McAndrews, Sarkar and Wang (2008) among others, who have focused, as above, on the spread between the secured (collateralized) and unsecured lending rates in the interbank money market.⁶ These papers report a large jump in these spreads beginning in August 2007, and analyze the impact of various central bank actions on subsequent yield spreads.

While yield spreads paint a useful picture of the market-level impact of the liquidity crisis,

⁵Even in the U.S., the Federal Home Loan Bank System accepted mortgage-backed securities as collateral for its advances to financial institutions.

⁶These studies also look at the spread between the overnight interest swap rates and unsecured lending rates. The correlation between these spreads and the secured/unsecured spread is very high, as documented by Taylor and Williams (2008). We find this in our data as well: a regression of the overnight swap rate (EONIA swap)/unsecured (EURIBOR) rate spread and the secured(EUREPO)/unsecured(EURIBOR) spread has coefficient 1.05 ($t = 15.96$), with $R^2 = 0.84$, which is similar to the results reported by Taylor and Williams (2008) for U.S. equivalents.

and could be used as a “temperature gauge” for assessing the health of credit markets, it is not possible to assess the heterogeneity of the impact of the crisis across the banking system without access to information on individual banks’ funding costs. The ability to assess the heterogeneity of the impact of the crisis on individual banks is very important in order for the policy makers to find and implement any cost-minimizing solution. Unfortunately, obtaining high-frequency data on individual banks’ borrowing costs is difficult, because most interbank transactions take place on an over-the-counter basis, or through anonymized trading. Bank-level bidding data from ECB’s repo auctions therefore provide us with a unique opportunity for understanding the distribution of the severity of the liquidity crisis across the banking sector. We use structural econometric methods developed in the recent multi-unit auction literature to estimate banks’ willingness-to-pay for ECB loans from their bids and use these estimates to quantify the impact of the liquidity crisis on individual banks. In Section 5 below, we provide a simple economic model to link the participating banks’ willingness-to-pay for ECB loans in the repo auctions to their outside options of procuring liquidity through the (unsecured and/or secured) interbank markets.

We should emphasize that, unlike the Fed, the ECB does not have supervisory/regulatory authority over European banks. Such powers are exercised by national central banks and/or regulation agencies. However, the ECB can advise national central banks with regards to the “stresses” in the financial system. Bids at the repo auctions and our analysis thereof in this paper can help the ECB fulfill its advisory duty by providing high frequency country or bank-specific liquidity cost measures and analyzing their determinants.

The first characteristic of our data that is immediately visible is the sudden change in bidding behavior that occurred after the turmoil. A quick glance at the aggregate bid⁷ for auctions before and after August 9, 2007 reveals a significant change. Figure 2 shows the aggregate bids (normalized by subtracting the EONIA swap rate⁸). Before August 9, 2007 all aggregate bids (depicted with solid lines) were highly concentrated around the EONIA swap rate (i.e., around 0 on the vertical axis in the graph); it is regarded as an indicator of industry expectations of the relevant market

⁷The aggregate bid in an auction is simply a horizontal sum of individual bids submitted by all participants in that auction.

⁸An “EONIA swap” is an interest rate swap transaction, where one party agrees to receive/pay a fixed rate to another party, against paying/receiving a floating rate termed EONIA (Euro OverNight Index Average), which is an average of all actual overnight unsecured transactions.

interest rates because it can be used with overnight borrowing as an alternative to bidding in the repo auctions. After August 9, a significant upward shift and increased (both across [and within] auction) heterogeneity in aggregate bids is quite evident.

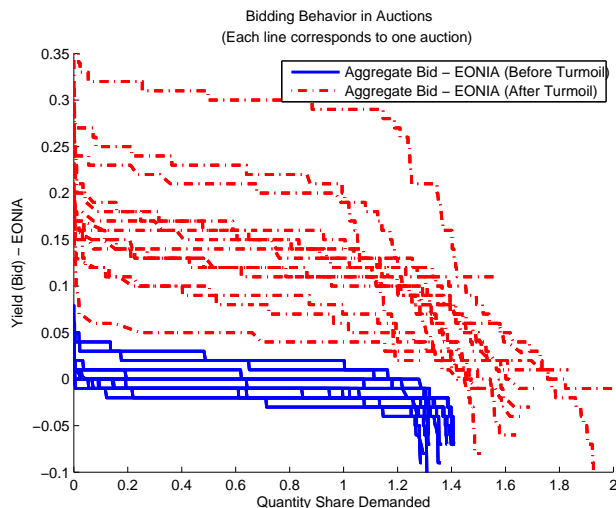


Figure 2: Aggregate bids (horizontal sum of individual bids in an auction)

While the dramatic shift in aggregate bids in ECB’s liquidity auctions parallels developments in interbank markets, our analysis shows that the distinction between “bids” and “willingness-to-pay” is very important in this market. As we illustrate in Section 4 and Section 6, although virtually all banks’ bidding behavior changed dramatically after August 9, this does not necessarily indicate a shift in all banks’ *willingness-to-pay* for ECB provided liquidity. Even if some bidders did not experience a change in their costs of short-term funds from alternative sources, presumably because of their solid balance sheets and lack of exposure to problematic assets, these bidders rationally would have to adjust their bids as a best-response to their “distressed” competitors’ higher willingness-to-pay for ECB provided liquidity. That is, the shift in bids for ECB liquidity was both “fundamentals” based, that is based on an increase in the outside funding costs of a subset of banks, and “strategic”, arising from the best-responses of strategic bidders in a competitive environment. Indeed, in Section 6 we show that for about one third of the participants, the observed change in bidding behavior was simply a strategic response: while their costs of obtaining short-term funds stayed the same (and thus willingness-to-pay also did not change), they increased

their bids in order to best-respond to the higher bids of their rivals.

As for the bidders whose willingness-to-pay for ECB-provided liquidity increased significantly after August 2007, it is important to understand the determinants of this shift and quantify it. We first demonstrate that the incidence of the liquidity “squeeze” was much more severe on some banks than others: for over $\frac{1}{3}$ of banks participating in the primary liquidity auctions the borrowing cost increased by more than 20 basis points. There is also heterogeneity in the incidence of the crisis with respect to banks’ country-of-origin, and that some of these country-specific woes may have been predictable: in Section 6.4, we show that banks from member countries that relied less on ECB funding before August 2007 appear to have suffered less from the crisis.

To further investigate what led to the shifts in demand for liquidity at the bank level, we use in Section 6.6 an auxiliary dataset on a smaller subset of banks’ credit default swap (CDS) rates and their reserve requirements with the ECB. We demonstrate that this increase in willingness-to-pay for ECB liquidity is linked to a deterioration in credit/default ratings (as measured by CDS rates) and to banks’ worries about satisfying the reserve requirements.

Although “market-based” measures of banks’ financial health such as CDS rates and stock prices are closely monitored by the ECB, the majority of banks in Europe do not have credit-default swaps traded on their bonds, and/or are not publicly traded themselves. Most of the information that is available by such non-publicly traded banks is limited to balance sheets that are disclosed quarterly and sometimes annually. A natural question to ask, therefore, is whether the individual short-term liquidity demands we estimate using the auction data are at all related to the performance measures reported in bank balance sheets. Indeed, in Section 6.7, we find that the estimated marginal valuations of banks are predictive of several widely used performance measures (return-on-equity, return-on-assets, cost-to-income ratio) that are reported at the end of 2007 (i.e. the end of the auction sample we study). Moreover, we find that marginal values are much better predictors of these performance measures than the bids themselves. This suggests that extracting away the “strategic” component of bids leads to much improved measures of banks’ liquidity costs, and eventually profits.

Another result of our analysis is that in the period beginning in August 2007, the previously

stable relationship between the banks' implied willingness-to-pay and reported interbank rates broke down. As the starkest demonstration of this point, on several occasions after the turmoil, the market clearing interest rate for *collateralized* loans issued through the primary auctions (which constitutes a lower bound on the willingness-to-pay for the marginal bank under normal circumstances) was *higher* than the reported interest rate for the *unsecured* loans issued in the interbank market. In section 6.3, we present detailed evidence that the reported unsecured interest rates (EURIBOR in the EURO context) failed to reflect the "actual" unsecured borrowing rates that were faced by a large number of banks in the EURO area.⁹

We also use our estimates of banks' willingness-to-pay to evaluate whether the discriminatory auction mechanism employed by the ECB succeeded in implementing an efficient allocation. In section 6.5 we show that while in the pre-crisis period the auction played little role in improving upon any random allocation of liquidity, after the crisis it clearly helped matching of liquidity supply with the banks with higher willingness-to-pay.

From a broader perspective, our results suggest that the evolution of banks' willingness-to-pay for liquidity may be useful for policymakers. While many questions may be answered with balance sheet data, its questionable reliability and low frequency make the readily available data from bidding in weekly liquidity auctions more attractive. Moreover, we show that even the relatively high-frequency CDS or stock price data do not seem to explain much of the contemporaneous variation in the willingness-to-pay for liquidity. Recent advances in multi-unit auction theory and in empirical methods for modelling auction markets allow us to recover the willingness-to-pay directly from the bids very quickly.¹⁰

We now move on in Section 2 to describing the growing literature on the financial turmoil, providing context for the rest of our paper. We describe the primary repo auctions of the ECB in Section 3; in Section 4 we describe our dataset taken from these auctions and summarize several interesting facts that these data reveal. In Section 5 we sketch a simple model, and we use our data in conjunction with our model to recover bidders' willingness-to-pay for ECB loans. For interested

⁹This criticism of LIBOR (London Interbank Offer Rate which, like EURIBOR, is a rate for unsecured inter-bank loans) rates induced the British Bankers' Association to publish the consultative paper "Understanding the construction and operation of LIBOR – strengthening for the future" on June 10, 2008.

¹⁰See Athey and Haile (2005) or Hendricks and Porter (2007) for surveys of recent advances in empirical methods and Milgrom (2004) for an excellent auction theory overview.

readers, in Appendix A.2 we review a more detailed model of a discriminatory auction of a perfectly divisible unit good, its equilibrium characterization, and the estimation method that we proposed in our previous work. Section 6 contains the main messages of this paper. In there, we present our main results in a sequence of subsections and discuss implications of our findings. We argue that (i) accounting for the strategic component when analyzing bids is very important for identifying distressed banks (Section 6.2), (ii) using the publicly posted rates for secured and unsecured loans we demonstrate that the bids are informative about the collateral structure of the participating banks (Section 6.3), (iii) there are substantial cross-country differences in the extent of the impact of the crisis on the banking sector related to the quality of collateral available in banks' portfolios (which is consistent, for example, the effect of Iceland's bankruptcy being concentrated in only few countries of the EURO zone) (Section 6.4), and (iv) CDS prices and reserve requirements are indeed drivers of banks' marginal values (Section 6.6). Section 6.7 investigates the relationship between our marginal value estimates, and banks' 2007 year-end balance sheet-based performance measures. Section 6.5 discusses the efficiency properties of the allocation mechanism used by the ECB. Section 7 concludes. (Appendix A.1 is devoted to more details about the way the ECB conducts its monetary policy and its operations.)

2 Turmoil in the Literature

By now, the significance of the 2007 financial crisis for the evolution of the world economy is widely recognized. Numerous leading economists provided their thoughts on the crisis in the winter 2009 issue of the *Journal of Economic Perspectives*.¹¹ Painting an aggregate picture of the crisis in an influential series of papers, Taylor and Williams (2008, 2009) have argued that the increase in the spread between the term swap rates used to proxy the expectations of overnight lending rates of financial market participants and the rates for unsecured term loans is probably caused by an increase in the counter-party risk.¹² In particular, after the news about the extent of highly risky subprime loans among securities with highest ratings held by many banks in their portfolios, there

¹¹See e.g., Brunnermeier (2009) and Cecchetti (2009).

¹²In contrast, some papers (e.g., Wu 2008) argue that the increased spread is due to "liquidity risk" stemming from increased uncertainty about future liquidity needs of each bank, which in turn increases banks' reluctance to lend long term.

was a sudden shift in the probability of default. Looking at the difference between the secured and unsecured loan rates, Taylor and Williams argue that the increase in spread indeed seems to be due to this effect.¹³ Afonso et al. (forth.) use data from the overnight interbank market to argue that counterparty risk seemed to play a much larger role than liquidity hoarding in the time period following Lehman Brothers' bankruptcy.

In a short article, Chari, Christiano and Kehoe (2008) argue that, while there is clear evidence of a financial crisis, some of the often cited sources of this crisis, including the tougher access to liquidity in the interbank market, are not consistent with publicly available aggregate data. Cohen-Cole et al. (2008) point out that the aggregate figures may be missing a lot of details, but Christiano (2008) disagrees on the whole with their arguments. In this paper we show that by looking at aggregate data a researcher indeed might miss the relevant changes in the structure of liquidity demands: while the aggregate demand may have stayed the same, many banks substituted from the secondary (interbank) market to the primary one, and the collapse of the secondary market may have important implications for allocative efficiency and credit availability. The increased heterogeneity of willingness-to-pay for liquidity in the post-turmoil period, and the failure of the interbank market to lead to an efficient allocation of liquidity among banks render the primary auctions (or open market operations) of the central banks crucial in improving the performance of the liquidity markets by correcting the misallocation.

Bidding data from repo auctions of the ECB have been studied previously in Bindseil, Nyborg and Strebulaev (2005). They describe many interesting details of this market and compare these auctions to those of Treasury bills by studying auctions between June 2000 and June 2001. Among other things, they argue that the common value component seems much less important in the central bank repo auction than in T-bill auctions, which substantiates our using the private-values framework. A similar approach was used in Hortaçsu and Kastl (2008) to analyze Canadian T-bill auctions or in Chapman, McAdams and Paarsch's (2006) analysis of Canadian Receiver General

¹³As is the case of the U.S., the secured (EUREPO) and overnight swap rates (EONIA swap) are highly correlated in the Euro area. Taylor and Williams (2009) argue that both rates are close to being riskless, and could be considered close to perfect substitutes. Although it is a collateralized rate, there is some risk in EUREPO due to potential problems in the delivery or return of collateral. EONIA swaps are subject to some risk, in that one of the parties may default and the remaining party is subject to the differential in the fixed and overnight components of swap. In our data, EURIBOR-EUREPO spreads and the EURIBOR-EONIA spread are almost perfectly correlated.

auctions of cash. While the setting Chapman et al. analyzes is the closest to ours, the objective of their analysis is quite different. Their main interest lies in investigating whether bidders' behavior in these auctions is consistent with best-response assumptions. They find that violations of best-responses are frequent, but the extent of these violations is so minimal (in terms of the expected payoff lost) that assuming that bidders indeed play best-responses may not be a bad idea. Our approach is to assume that bidders play best-responses. Our goal is to use the estimated model to analyze the forces behind bidders' choices and to analyze the impact of the financial turmoil by studying the link between the willingness-to-pay in the repo auctions and alternative sources of funding.

3 Primary Auctions of Liquidity in the EURO Area

In this paper we focus on the auctions of liquidity, which are part of the Main Refinancing Operations (MROs)¹⁴ of the ECB. They are auctions of collateralized loans with one-week maturity, conducted every week. The main function of the MROs (at least before the turmoil period) is to provide liquidity to the market. They are pivotal in steering interest rates (through the minimum bid rate), to manage liquidity in markets, and to signal the stance of monetary policy.

Before each auction, a bank that wants to participate will submit bids specifying the rate and the quantity it is willing to transact with the ECB to the national central bank of the member state where the institution is located (has a head office or branch). The bids of an institution may be submitted by only one establishment in each member state. Banks may submit bids for up to ten different interest rate levels; hence, a bid in these auctions can be thought of as a demand function. The ECB then collects the bids and determines the maximum rate at which the demand weakly exceeds the supply. All bids for higher rates are satisfied and demands at the marginal rate are rationed proportionally. During the time span of our dataset the ECB has used only the discriminatory auction format, but it has the right to change the mechanism at any time. All winning bidders thus had to pay their full bids (i.e., rates) for the allocated liquidity.

After each auction, the ECB publicly reveals the following about the outcome: % marginal

¹⁴See Section A.1.2 in the appendix for more details.

(market clearing) bid rate, allotment at marginal rate, total amount allotted, weighted average allotment rate, total number of participating bidders, minimum rate of all bids, and maximum rate of all bids. No additional data that would provide information on demands by individual banks are revealed.

The loans obtained in these auctions have to be collateralized. In particular, banks are expected to cover the amounts allotted to them with a sufficient level of eligible assets (collateral) discussed in more detail in section A.1.3. Penalties can be applied by the national central banks in case of a failure to deliver the collateral. The eligible collateral is broader than collateral generally accepted for loans at the EUREPO rate on the interbank (secondary) market, even more so after the turmoil. Nevertheless, the ECB applies valuation haircuts as risk control measures.

Table 1 shows the relative weight for the categories of eligible assets used by Eurosystem counterparties. It illustrates that banks substitute illiquid collateral (uncovered bank bonds, asset-backed securities) for highly liquid collateral (central government securities).¹⁵ This trend accelerated after the turmoil with a sharp increase in asset-backed securities; however, it reflects a medium-term development that has been ongoing for a while and is not strictly related to the turmoil.

Table 1: Structure of Collateral Pledged Against the MROs

	2004	2005	2006	2007	2008
Central government securities	0.52	0.50	0.48	0.46	0.42
Regional government securities	0.03	0.03	0.03	0.03	0.03
Uncovered bank bonds	0.12	0.14	0.16	0.17	0.20
Covered bank bonds	0.16	0.15	0.14	0.12	0.11
Corporate bonds	0.09	0.09	0.09	0.09	0.08
Asset-backed securities	0.04	0.05	0.06	0.08	0.09
Other marketable assets	0.04	0.04	0.04	0.04	0.05
Non-marketable assets	0.01	0.01	0.01	0.01	0.02

With this relevant background, we are ready to describe our dataset in detail and go on to estimate a model of bidding in the repo auctions.

¹⁵See also Ewerhart and Tapking (2008)

4 Data

Our unique dataset consists of all submitted bids in 50 regular discriminatory (pay-your-bid) repo auctions of liquidity provided via collateralized loans with 1-week maturity conducted as part of the regular MROs of the ECB between January 4, 2007 and December 11, 2007.

Table 2 offers some summary statistics of the full sample. On average, there are 341 participating bidders (banks) in an auction. There are 733 unique bidder-identities, which suggests that only about one half of potential bidders participate in any given auction. Participants submit bids with very few steps (price-quantity pairs): only 1.66 on average. The banks on average demand about 1 billion EUR at 3.94%, which is about 4 basis points higher on average than the EONIA rate.

Table 2: Data Summary

Summary Statistics				
Auctions	50			
	Mean	St.Dev.	Min	Max
Bidders	341	28	273	395
Submitted steps	1.66	1.02	1	10
Price bid	3.94	0.22	3.50	4.36
Price bid spread ^a	0.04	0.07	-0.17	0.41
Quantity bid	0.004	0.012	$3 * 10^{-6}$	0.18
Issued Amount (billions €)	259.89	52.77	155	330.5

^a Spread against EONIA rate.

Table 3 illustrates the change in means and standard deviations following the turmoil of August 2007. There are several interesting differences: the increase in the number of steps in each bid (from 1.47 to 2.02), the decrease in the amount of liquidity offered for sale (from 292.34 to 202.19 billions EUR) and, perhaps most importantly, the increase in the spread between the bids and the EONIA rate (from 0 to 10 basis points). Recall that in a discriminatory auction, a bidder would do best if she knew the market clearing rate beforehand and thus was able to submit a single bid equal to that rate for an amount at which her marginal value equaled the rate. Therefore, the first difference likely reflects the fact that the bidders were much less certain where the market would clear and so submitted finer bids.¹⁶ An alternative potential explanation for this phenomenon might be that

¹⁶Figure 17 (appendix) shows that there is a clear first-order stochastic dominance relationship between the empirical cumulative distribution functions before and after the turmoil.

Table 3: Data Summary: Before and After August 2007

Summary Statistics				
	Mean		Std Dev	
	Before	After	Before	After
Bidders	348.6	328.1	20.88	34.37
Submitted steps	1.47	2.02	0.73	1.34
Price bid	3.80	4.13	0.20	0.06
Price bid spread ^a	0.00	0.10	0.02	0.08
Quantity bid	0.004	0.005	0.009	0.014
Issued Amount (billion €)	292.34	202.19	1.42	4.51

^a Spread against EONIA rate.

some bidders simply needed to make sure that they received at least some minimal level of liquidity in the primary market; therefore, they submitted inframarginal bids for which they were willing to pay a premium over the market clearing rate. Both of these explanations also may be consistent with the observed increase in the spread between the bids and EONIA. To distinguish between these two potential explanations, we would need to know the marginal value of that bidder at the time of placing the bids. Obtaining estimates of these marginal values thus is one of the main goals of this article.

After August 2007 the bids become much more dispersed, as shown by the aggregate bids depicted with dashed-dot lines (-.) in Figure 2. In each auction the aggregate bid also becomes much steeper relative to the aggregate bids before the turmoil, which are depicted as solid lines.

5 Model and Estimation Framework

In order to obtain estimates of the marginal values that would rationalize the observed bids, we turn to a model of bidding in these discriminatory auctions. Consider first the following simple model of bidding in the primary auction, which links the estimated marginal values to the secondary market secured and unsecured interest rates. Suppose bank i has a liquidity need (possibly due to a reserve requirement, to improve its balance sheet, or to close a funding gap) of R_i . This must be fulfilled through three alternative channels: 1) ECB primary auctions, 2) unsecured interbank lending, which is done through over-the-counter deals, or 3) secured interbank lending, which is

also done over-the-counter.^{17,18}

We assume that these methods are substitutes, but access to them is limited based on collateral availability. In particular, bank i has L_i units of “liquid”, high-quality collateral acceptable by secured interbank lending counterparties at a zero “haircut” rate. The bank also has $K_i - L_i$ units of securities that are acceptable by the ECB and perhaps by other counterparties as collateral, but are subject to haircuts. The haircuts applied to this set of securities effectively increase the interest rate at which the bank can borrow against these securities; these rates are bounded below by the “secured” interbank lending rate, s_i , that the bank faces (which assumes the use of highest quality, i.e. zero haircut collateral), and bounded above by the “unsecured” interbank lending rate, u_i , which requires no collateral. The marginal value for obtaining liquidity in the auctions run by the ECB can therefore be represented as in Figure 3, where we assume the bank’s total collateralized borrowing capacity, K_i , to be less than its liquidity need R_i . The bank’s willingness-to-pay for the first $R_i - K_i$ euros of funding, thus, is equal to its unsecured funding rate, u_i . Between the $R_i - K_i$ and $R_i - L_i$, the bank faces different haircut rates depending on its portfolio of securities it can post as collateral. The last L_i euros of funding can be obtained from the “secured” interbank market, thus the bank’s willingness-to-pay for these units is s_i .

5.1 Model of Bidding and Econometric Framework

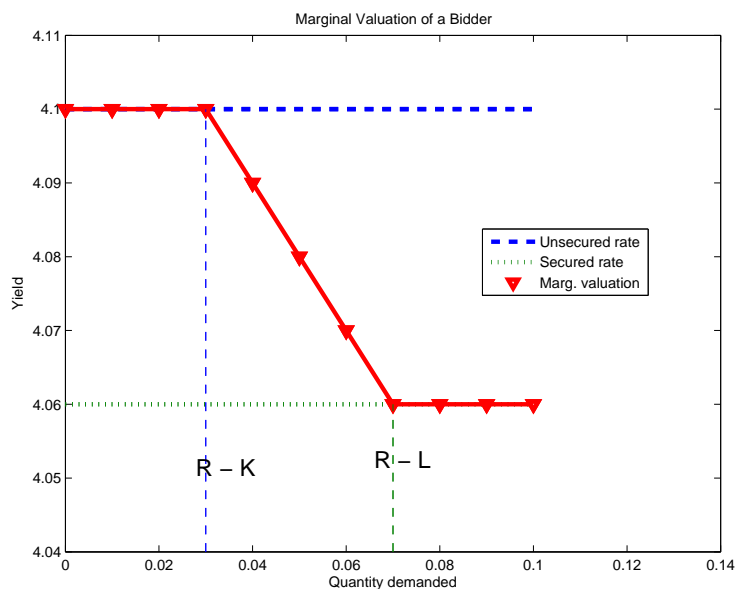
In the previous section we discussed the origin of banks’ marginal valuations for ECB loans in terms of the “outside” sources of funding the bank can access through the use of its collateralizable securities.¹⁹ We now have to impose assumptions regarding the information structure of the auction,

¹⁷Managing the maturity mismatch between assets (long-term) and liabilities (short-term) is the essence of banking. Before the crisis, a variety of instruments allowed banks to fund their assets without major constraints. Short-term funding was available in the form of interbank loans, issuance of Certificate of Deposits (CDs), and central bank refinancing; longer-term funding was available from bond issuance (covered or uncovered) and through securitization. The securitization and the interbank funding channels were among the most severely disrupted sources of liquidity immediately after August 2007. Bond issuance without government guarantees also was impaired. Any such alternative ways of obtaining liquidity get lumped into the “outside option” that generates the willingness to pay at the repo auction.

¹⁸ The interbank market operates to a large degree as an over-the-counter (OTC) market, for which (to the best of our knowledge) there is hardly any transaction-level data that could be used for our purposes. The impact of liquidity shocks and other frictions on prices in OTC markets has been studied in Duffie, Gârleanu and Pedersen (2007). Their model of the OTC market is based on the search and bargaining model proposed in Duffie, Gârleanu and Pedersen (2005), which provides conditions under which asset prices are adversely affected by frictions in the OTC market, such as increased difficulty to find a counterparty.

¹⁹See Ewerhart, Cassola and Valla (2009) for a similar model with more detailed discussion.

Figure 3: Marginal Value for Liquidity in ECB Auctions



i.e. what is the nature of private information, if any, possessed by bidders who participate in the ECB’s main refinancing operations.

Given the opaque, over-the-counter nature of interbank-lending markets, we will assume that the interest rates at which a bank can secure liquidity in the market (s_i, u_i) are private information for bank i . Similarly, we will assume that the liquidity requirement, R_i and the bank’s collateral structure, L_i, K_i , and the haircut rates applicable to the bank’s collateralizable securities, are also private information. Although some proxies for these variables are disclosed in quarterly balance sheets, certain securitization practices, such as the use of structured investment vehicles, could easily mask a bank’s underlying asset-liability structure (Acharya, Schnabl and Suarez (2009)). Moreover, the weekly frequency of the auctions can presumably allow bidders to keep information about short-term changes in their portfolios and funding requirements confidential.

The main informational assumption we will impose in the rest of the paper is that the environment is one of *conditionally independent* private values. That is, conditional on variables commonly observed by bidders, bidders’ marginal willingness-to-pay depends on their own private information, which is distributed independently across bidders, and, importantly, does not depend on other bidders’ information. The private values assumption was implicit in our discussion in the

previous subsection, where we argued that a bidder’s marginal willingness-to-pay will depend on $\{R_i, K_i, L_i, u_i, s_i\}$ and haircut rates on its asset portfolio. This assumption is partially motivated by earlier work by Bindseil, Nyborg, and Strebulaev (2005) who find that bidders’ reserve balances are an important factor in how they bid. Yet another piece of evidence for private values is the observation that since after the crisis the interbank markets dried out, the speculative reasons for obtaining liquidity in the ECB’s auctions motivated by potential resale opportunities were not likely present.

An interdependent values specification would be more appropriate if other bidders’ funding requirements and opportunities are also relevant for bidder i ’s willingness-to-pay. Although banks’ exposure to each other through interbank lending may lead to such interdependencies, we will assume that these interdependencies enter into the bidder’s willingness-to-pay through variables commonly observed by all bidders, such as publicly available (to the bidders) interbank rate and liquidity information, and other financial news and data. Our econometric approach will allow bidders to condition their bids on *publicly observable* common valuation components, some of which may be unobservable to the econometrician.²⁰

We now move on to describing how banks will bid in the auctions. The ECB allows bidders to place multiple price/quantity bids: in effect, bidding demand schedules. Therefore, our model is based on Wilson’s (1979) share auction model, in which bidders compete for one unit of a perfectly divisible good, submit demand curves and their choice of quantity is continuous. We view this model as appropriate for our setting because the amount of credit to be sold in each auction is over €2 billion and the minimum bid increment is only €100,000.

Kastl (2008) analyzes a variant of Wilson’s model with bidding in step functions, which is also the appropriate modification for our application. He proves that there exists an equilibrium of a discriminatory auction in distributional strategies in this constrained game when signals are independent and price is assumed to be continuous. The model and its assumptions are formally

²⁰Our econometric analysis is applicable even if there is an interdependent value component beyond what can be conditioned on commonly observed (by bidders) variables, but using the equilibrium conditions given by (1) below we estimate roughly the expected marginal value for liquidity conditional on k^{th} step being marginal and thus q_k allocated to type θ_i , $E_{\theta_{-i}|\theta_i, P^c \in [b_{k+1}, b_k], q_k} [v(q_k, \theta_i, \theta_{-i})]$, rather than the (realized) private value $v(q_k, \theta_i)$. While the estimation method is not affected, we would have to work with thinner data, since we can only use estimates at which the conditioning event $P^c \in [b_{k+1}, b_k]$ is actually satisfied. See Hortaçsu and Kastl (2008) for more details.

spelled out in the appendix section A.2. The necessary conditions for equilibrium bidding by bank with private information θ_i are (for demand q_k at every step k at which the marginal valuation function is continuous in q):

$$v(q_k, \theta_i) = b_k + \frac{\Pr(b_{k+1} \geq P^c)}{\Pr(b_k > P^c > b_{k+1})} (b_k - b_{k+1}) \quad (1)$$

where P^c is the market clearing price, which is random from the perspective of each bidder, q_k is the quantity demanded at step k and b_k is the associated bid.

Equation (1) is the main identification equation in our analysis; it simply describes the equilibrium relationship between bids and values. In our earlier discussion, we tied these values to the bank’s “outside options” of procuring liquidity through secured and unsecured interbank markets.

The intuition for the underlying trade-off is quite similar to that of the single-unit first-price auction. The intuition can also be seen when we rewrite the optimality conditions as $\Pr(b_k > P^c > b_{k+1}) (v(q_k, \theta_i) - b_k) = \Pr(b_{k+1} \geq P^c) (b_k - b_{k+1})$. This equation states that the marginal loss of surplus due to decreasing the demand at price b_k whenever the k^{th} step is the marginal step in i ’s demand (and thus the market clearing price must be between b_k and b_{k+1}) should be traded-off against the possible gains when the k^{th} step is inframarginal (and thus the market clearing price must be weakly lower than b_{k+1}). Thus, by shifting some demand to the subsequent $(k+1)^{st}$ step, we would decrease the payment by the difference between the bids (times the quantity shifted). It is important to emphasize that the necessary conditions given by (1) have to hold at each step k . Therefore, we do not need to directly model the choice of the number of steps, $K_i(\theta_i)$, that bidder i submits.

Since, in practice, the continuity in q of the marginal valuation function might be questionable at the last step, we use the optimality equation with respect to bid given by equation (A-3) in the appendix to identify the marginal value corresponding to the last step in a bid function.

Using these necessary conditions, we obtain point estimates of the marginal values at submitted quantity-steps nonparametrically using a resampling method proposed and analyzed in our earlier work.²¹ We extend this method in this paper to allow for latent types. The basic resampling

²¹See Hortaçsu and Kastl (2008) for formal treatment of the estimation and Athey and Haile (2005) for a recent

method is based on simulating different possible states of the world (realizations of the vector of private information) using the data available to the econometrician and leveraging the assumption of conditional independence of private information, thus obtaining an estimator of the distribution of the market clearing prices. It works as follows:

Suppose there are two groups with N_h, N_b potential bidders that are (ex ante) symmetric within groups.²² Fix a bidder's bid from group h (the argument for a bidder from group b is analogous). From the observed data, draw (with replacement) $N_h - 1$ and N_b actual bid functions. This simulates one possible state of the world from the perspective of the fixed bidder from group h – a possible vector of private information – and thus results in one potential realization of the residual supply. Intersecting this residual supply with the fixed bid, we obtain a market clearing price. Repeating this procedure many times, we obtain an estimate of the full distribution of the market clearing price conditional on the fixed bid. Using this estimated distribution of market clearing price, we can obtain our estimates of marginal values at each submitted step using (1). It is important to point out that since we have over 300 participants in every auction, we conduct our estimation auction-by-auction and hence our estimates are less susceptible to unobserved heterogeneity across auctions.²³ Also, by estimating auction-by-auction, for the resampling method we only need to require that bidders' private signals are *conditionally* independent where the conditioning is on all public information available at the time of the auction.

Hortaçsu and Kastl (2008) show that this estimator is asymptotically normally distributed and well-behaved, in the sense that its asymptotic distribution can be approximated by bootstrap, which is also how we obtain standard errors in this application.

Since we do not observe ex-ante which group a bidder belongs to, in the following subsection we extend this method to allow for latent types which are also estimated.

survey of nonparametric estimation techniques for auction data.

²²Additional observed ex-ante heterogeneity among bidders (such as size) is easily incorporated by introducing additional groups. The cost of adding more dimensions is the lower number of observations used for resampling.

²³For readers unfamiliar with this terminology, we might be worried that there are factors observed by the bidders before each auction, which are not observed by the econometrician. This would of course undermine the ex-ante symmetry across auctions and hence focusing on bids within an auction eliminates this particular problem.

5.1.1 Asymmetric bidders

Because one of the goals of this paper is to identify bidders (banks) that likely have been hit harder by the financial turmoil than their rivals, in the sense that their value for liquidity obtained in the primary market (stochastically) increased, the assumption that all banks are ex-ante symmetric might of course not be appropriate. In particular, the distributions from which the private information is drawn would very likely differ between the banks that suffered from the crisis (group indexed with b for “bad” banks) and those that did not (group indexed with h for “healthy” banks). We adopt an iterative procedure and estimate an asymmetric model with two groups of banks as follows: in the first step, we start the algorithm by arbitrarily allocating bank identities across the two groups²⁴. The resampling method is modified to allow for two groups of bidders that are symmetric within a group, but not necessarily across the groups. This is achieved by drawing with replacement from observed bids from each group separately. We thus obtain estimates of the marginal values of each bidder in every auction. In the second step, we use these estimated values to find a subset of bidders who experienced a stochastic increase in their estimated values for liquidity in the post-turmoil period. We assume that experiencing financial distress in our model translates into a shift in the distribution of marginal values in the sense of first-order stochastic dominance. There are many alternatives to check for this shift, and the test we use is based on comparing means of the distributions before and after turmoil for each bidder. This test is operationalized by regressing the quantity-weighted average of the marginal value estimates (normalized by EONIA to take out the level effect of interest rates²⁵) on the turmoil dummy for each bidder separately. If the estimated coefficient on the turmoil dummy is significant at 5% level – i.e., if the mean marginal value increased – we classify this bidder as one who experienced financial distress in the post-turmoil period. In the third step of our algorithm, we re-estimate the model using the newly obtained two groups of bidders.²⁶ In the fourth step, we again estimate the subset of bidders that experienced an increase in their values by using the estimates from the asymmetric model. If this

²⁴In practice, we started both with allocating all banks into the Healthy Group and with a random allocation, both of which led to statistically indistinguishable estimates.

²⁵See Piazzesi (2003) for a thorough discussion of the recent literature on the structure of interest rates.

²⁶Bidders are treated asymmetrically in all auctions. That is, we fix the two groups even before turmoil. Had the bidders been actually symmetric before turmoil, our approach would result only in loss of efficiency, but the estimates of the distribution of the market clearing price would still be consistent.

subset coincides with the two groups used in step 3, then we stop; otherwise, we repeat step 3.²⁷ In practice, we stop the algorithm when weakly less than 5 bidder identities switch groups. We are able to classify 482 bidder identities out of the 733 in our data. The remaining bidder identities do not submit bids both before and after the turmoil.

That the initial assignment of banks into groups does not seem to matter in our application is due to the fact that we have a large number of banks in each group. Therefore the distributions of market clearing price from perspective of a bidder from group b or h submitting the same bid are virtually indistinguishable since with large N_b and N_h , whether we are drawing $N_b, N_h - 1$ or $N_b - 1, N_h$ does not make much difference. This in turn results in virtually the same estimates of marginal values (whether a bidder was assigned to b or h) and hence essentially unique allocation of bidders into the two groups. We conjecture that the impact of the asymmetry on the estimates of marginal values and thus on the identification of the latent types would likely be much more profound with small number of bidders in each group.

5.1.2 Supply Uncertainty

In the pre-turmoil period the actual amount of liquidity allocated in the auction by the ECB differed only slightly from the pre-announced supply, but as Figure 22 illustrates the deviations became quite substantial in the post-turmoil period. We assume that bidders rationally expected the ECB to deviate from the announced benchmark. To incorporate this feature into our estimation framework, we use the empirical distributions of deviations from the pre-announced supply in the pre- and post-turmoil period. At each iteration of our resampling algorithm, we resample independently from the corresponding empirical distribution of supply deviations. Appendix A.3 provides more details about the way supply is determined in the weekly repo auctions.

²⁷While we do not have a formal proof of whether this method converges, if it does, it is easy to see that the resulting estimates are consistent estimates of the primitives of the asymmetric model. In the actual application, it turns out that after very few iterations, the two groups of bidders are very stable – both in terms of size and in terms of identities of bidders contained in each. The asymmetry therefore seems not to play as important a role in the estimation stage, which is probably due to the large number of participants. We experimented with a random initial assignment of bidders into the two groups; after very few iterations, we obtained virtually the same bidder groups as those arrived at when starting with the symmetric model.

6 Results

Having laid out the model and the estimation method in the previous sections, we now move on to discuss the results. Using the estimated willingness-to-pay for each bank in each auction we analyze the impact of the crisis on the individual banks and on the whole banking sector of the EURO area. We show that more than 50% of banks cannot borrow at the published unsecured rates. We also document that the impact of the crisis was quite heterogeneous across countries and could to a certain extent be predicted on a country-level based on the banks' bidding behavior before the turmoil. On a subsample of 19 banks for which we obtained additional data, we analyze the determinants of the willingness-to-pay and show that our estimates covary in an expected way with reserve requirements and prices of credit default swap contracts. Lastly, merging our estimates with Bankscope data, we show that our estimates of marginal values are (unlike the bids) predictive of various accounting measures of bank performance.

6.1 Estimated willingness-to-pay

Figures 4 and 5 depict the estimated marginal values for the same bidder in two auctions, one before and one after the turmoil. We can make two observations: 1) This bidder's demand increased substantially, from about 8% of the supply before the turmoil to 14% of the supply after the turmoil;²⁸ and 2) Uncertainty about where the market would clear substantially increased and therefore this bidder submitted a more detailed demand curve. (Recall that if a bidder knew with certainty that the market would clear at a price p^* in a discriminatory auction, then the optimal bidding strategy would be to submit only one bid at this price, and for a quantity such that the marginal value of the expected allocation after rationing would be equal to p^* .) Finally, notice that the estimated (quantity-weighted) marginal value before the turmoil is just slightly higher than the EONIA swap rate (which corresponds to 0 on the vertical axis). This suggests that buying the fixed leg of the swap and borrowing overnight was indeed an option for many banks. After the turmoil, though, the estimated marginal values were significantly above the EONIA swap rate, suggesting that this particular bank valued the liquidity obtained in the repo auctions of the ECB

²⁸Recall that the supply declined by about one third after the turmoil, which makes the demand increase perhaps not as large, but still this increase amounts to about €5 billion.

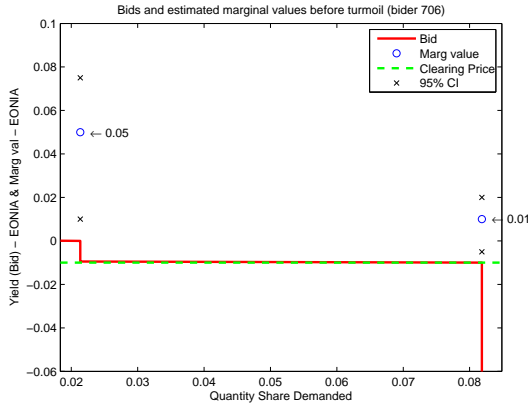


Figure 4: Bid and Estimated Marginal Value (Before Turmoil)

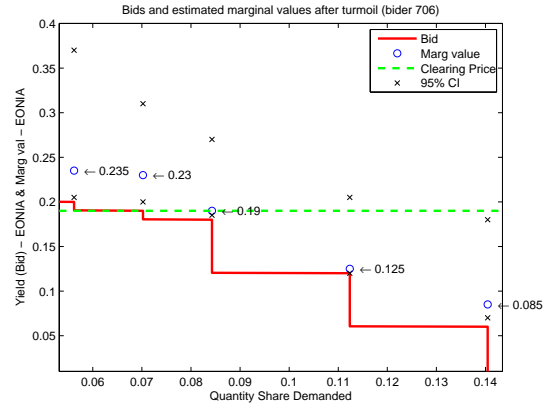


Figure 5: Bid and Estimated Marginal Value (After Turmoil)

more, perhaps because its access to the EONIA rate may have been limited, and/or it did not have enough high-quality collateral to participate in the collateralized interbank market to obtain loans at the EUREPO rate. This change in values, and thus indirectly the implied ability of an individual bank to access liquidity in the interbank market, would be missing if we were to analyze aggregate data, such as in Chari, Christiano and Kehoe (2008).

Overall, we find a profound effect of the August 2007 turmoil on marginal valuations that bidders attach to liquidity offered for sale in the primary markets. Figure 6 illustrates this effect in more detail. The solid lines depict estimated aggregate (i.e., horizontal sum of) marginal valuation curves before the turmoil (normalized by subtracting the EONIA swap rate), and the dash-dotted lines (-.) depict the estimated aggregate marginal valuation curves after the turmoil of August 2007.²⁹ It is apparent that an outward shift in marginal values (towards north-east) has taken place, suggesting that, at least for some bidders, the liquidity provided in the primary market became very valuable relative to the period before August 2007.

To further illustrate this effect, consider Figures 7 and 8 which depict the aggregate bids and aggregate marginal valuation curves for two auctions, one before and one after the turmoil. Again, it clearly illustrates that the EONIA swap rate which played a role of a reference point for bidding in

²⁹The high marginal values on the left portion of the aggregate marginal valuation curves are usually imprecisely estimated and hence we chose to trim the figure at a mark-up of 50 basis points. These are values corresponding to so high bids that are almost certainly going to be accepted and hence the term $\Pr(b_k > P^c > b_{k+1})$ in (1) is very small and imprecisely estimated.

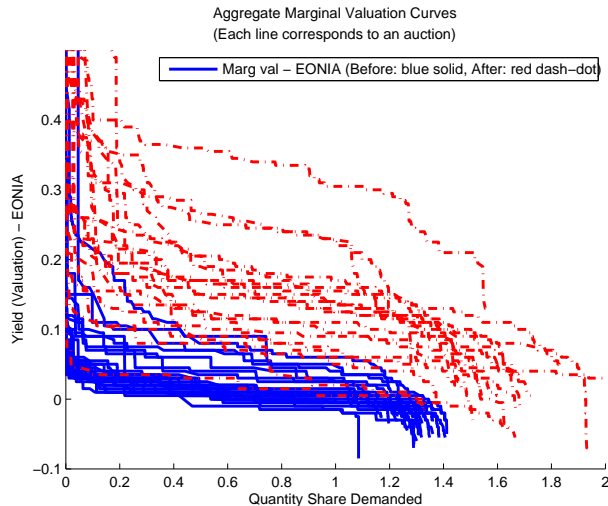


Figure 6: Estimated Aggregate Marginal Valuation Curves

the pre-turmoil period, most likely no longer served this role after the turmoil. More importantly, the amount of shading (the area between the aggregate marginal value and the aggregate bids) increased substantially in most auctions. For example, at the market clearing price (i.e., where the vertical line at $Q = 1$ intersects the marginal value and the bid), the amount of shading in Figure 7 is about 1.5 basis points, whereas it increases to over 3 basis points in Figure 8. This is a consequence of the change in the slope of the aggregate bids and hence of increased market power of marginal bidders and/or uncertainty about the market clearing price. More importantly, in auction 32 before turmoil, the bidding is concentrated on the EONIA and repo rates and the market clears at exactly the repo rate. After turmoil (in auction 45), neither EUREPO, EONIA, or EURIBOR seem to be a focal point of bids. Moreover, the market clears at significantly above all three rates.³⁰

Figure 9 depicts the estimated quantity-weighted average marginal values in each auction normalized by subtracting the corresponding EONIA swap rate (a very similar pattern obtains if we normalized by the EUREPO rate). The emerging pattern again suggests that the (normalized) marginal values for liquidity provided in the primary market increased substantially following the

³⁰Since the goal of the ECB is to target the overnight interest rate, of which the 1-w EONIA swap rate is an expectation, this suggests that the ECB might have faced some problems with achieving its objectives in the post-turmoil period.

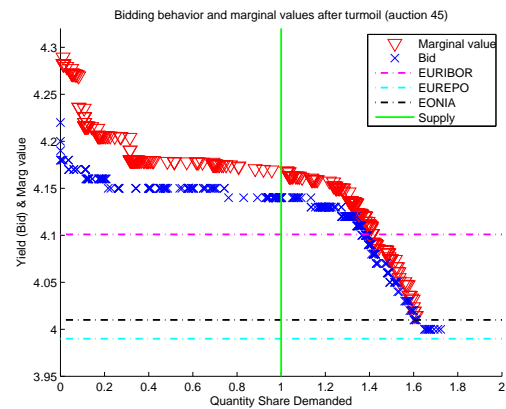
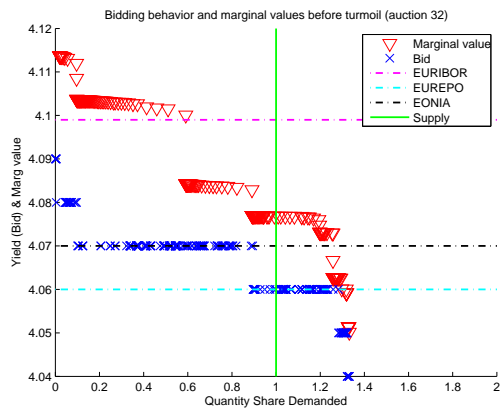


Figure 7: Aggregate Bids and Estimated Aggregate Marginal Values (Before Turmoil)

Figure 8: Aggregate Bid and Estimated Aggregate Marginal Values Curve (After Turmoil)

turmoil in August 2007. In fact, it still seems to be increasing, in the most recent auctions in our data reaching over 20 basis points premium over the EONIA swap rate. Even more importantly, the marginal values have become quite heterogeneous, which is evidenced by the increased slope of aggregate marginal valuation curves in Figure 6.

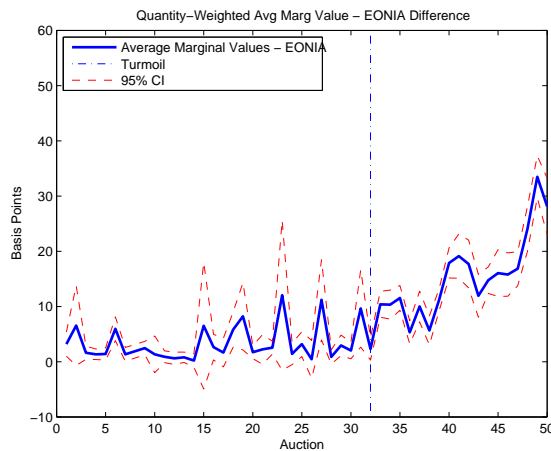


Figure 9: Quantity-weighted average marginal values (across all bidders)

6.2 Identification of “Distressed” Bidders

The model helps us identify the shift in the distribution of marginal values, since the shading factor $\frac{\Pr(b_{k+1} \geq P^c)}{\Pr(b_k > P^c > b_{k+1})} (b_k - b_{k+1})$ can be estimated for every bidder in every auction. For some bidders, the bids change only enough to compensate for the increased aggressiveness of their rivals (which in turn affects the distribution of the market clearing price), while maintaining the trade-off between the surplus on the last Euro won and the probability of winning it given by (1). For such bidders, we therefore obtain the same estimates of marginal values. For other bidders, the bids change in a way that is inconsistent with maintaining that trade-off for a given marginal value and hence for such bidders, marginal values had to change as well. Having estimated the marginal values for each bidder before and after the turmoil, we now can look for the effect of the turmoil on these values. In particular, for 482 bidders who participate at least once before and after the turmoil, we regress the quantity-weighted estimates of marginal values for each bidder on a turmoil dummy. Figure 10 plots the histogram of the significant coefficients from these regressions. For almost 100 bidders, the (normalized) marginal values have risen by more than 20 basis points in the post-turmoil period. This exercise reveals another interesting point: the turmoil seemed to be accompanied by an increase in marginal value for liquidity in the primary market for about two thirds of the participants, whereas the remaining one third experienced no significant increase.

Our conclusions might be quite different if we based the analysis solely on bids and hence we believe that using a model to separate out the strategic effect is quite important. Running the same type of regressions, but using quantity-weighted bids (again normalized by EONIA) rather than marginal values would result in a significantly positive relationship for virtually all bidders. Table 4 shows that the predictions differ for over 20% of the banks. Given the amounts of money that often are mentioned in connection with helping the struggling banking sector, whether 20% of banks seem to be healthy or not might potentially be quite important.

As a placebo test of the last exercise, we also tried focusing exclusively on the time period before the turmoil (we observe 32 auctions before the turmoil in our data) and splitting this subset of data into two halves, before and after auction 16.³¹ Regressing bids and values, respectively, on

³¹Once again we obtained virtually the same results initializing our algorithm with symmetric bidders or with random assignment of bidders into two groups.

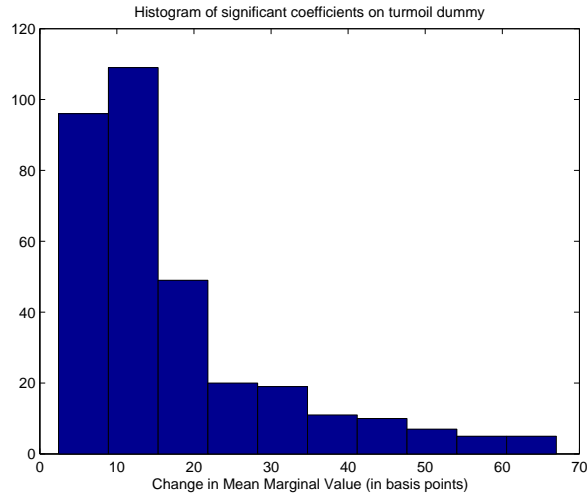


Figure 10: Histogram of Significant Turmoil Effects

Table 4: Predicting Potential Problems

Based on	Bids	
	Yes	No
Values	Yes 326	5
	No 96	55

a dummy for auctions 16 – 32 results in data on both bids and values showing no effect for 398 banks; exhibiting a significant effect for 6 banks; and for 19 and 20 banks, respectively, they seem to have been significantly affected based either on bids or on values data, but not both. This exercise suggests that the difference in predictions based on values and bids reported in Table 4 appears likely not to be by chance. In fact, it suggests that the turmoil had an important effect, causing significant changes in bids for most banks, but with the underlying values actually changing only for a smaller subset of banks.

Figures 11 and 12 provide another illustration of why accounting for the strategic effect maybe very important in identifying banks whose demand for liquidity was affected by the crisis. In Figure 11, we plot the density of the average difference in quantity-weighted price bids in the post vs. pre-crisis period auctions. We plot the densities separately for the banks that we identified as being “hard-hit” vs. “not hard-hit.” As can be seen, although there are some visible differences

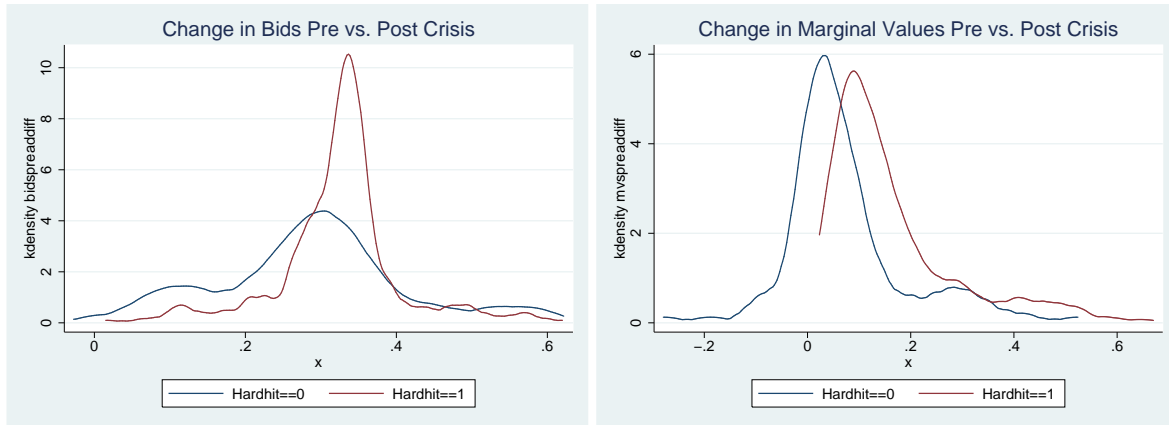


Figure 11: Distributions of the change in quantity-weighted bids pre- vs. post-crisis
 Figure 12: Distributions of change in quantity-weighted marginal values pre- vs. post-crisis

across the two densities, the means are very similar, and the supports of the two densities largely overlap. In contrast, when we plot the densities of the difference in estimated marginal values across the post vs. pre-crisis auctions, we see a much more visible difference across the “hard-hit” vs. “not hard-hit” groups; while the mean marginal value change for the not hard-hit group is at zero, the mean of the “hard-hit” group, indeed the entire density, has shifted to the right.

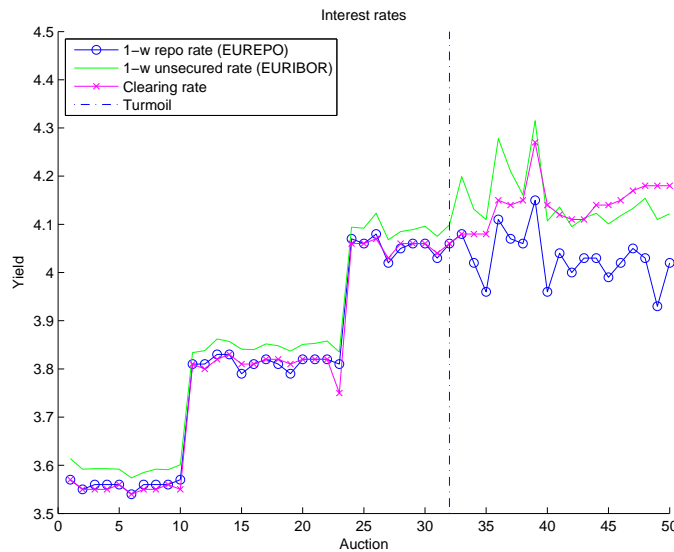


Figure 13: EUREPO, EURIBOR and primary auction clearing rates

6.3 Bidders' Marginal Valuations and Secondary Market Rates

Our application also is naturally suited to subjecting the estimates from the structural model to a quick reality check. In particular, as Section 5 suggested, the values (bid plus markup) of each bank should lie between the fully unsecured lending rate (riskiest) and the risk-free rate whenever these rates reflect the true market clearing prices. We will use EURIBOR as the unsecured lending rate and EUREPO as the risk-free rate, because only the highest quality collateral (such as government treasury bills) may be used against loans obtained at this rate.³² Indeed, in Figure 7 the estimated marginal values for the most part are bounded from above by the EURIBOR rate and from below by EUREPO. This suggests that the estimates produced by our structural model are reasonable. In many auctions in the post-turmoil period, however, this relationship fails (see Figure 8). In particular, as figure 13 illustrates, there are many auctions that clear at rates that are above the unsecured rate (EURIBOR), which suggests that this is not the rate at which any bank can borrow!

We use our estimates to ask what convex combination of the secured rate, EUREPO (with weight α_i), and the unsecured rate, EURIBOR (with weight $1 - \alpha_i$), would equal to the estimated values. For this, we use the (quantity-weighted average) estimates of bid+markup/marginal values. This hypothetical exercise thus assumes that everyone can get a loan at the reported unsecured rate, which is unrealistic. Nevertheless, the relative ordering of α_i 's is still meaningful: higher α corresponds to better collateral (marginal values closer to the EUREPO rate) and vice versa. If EURIBOR was the upper bound for marginal values for every bank, then our estimates of α 's should lie between 0 and 1; yet we quite often obtain negative values. This suggests that the unsecured interest rate which would rationalize banks' marginal value in the primary auction lies above EURIBOR – the reported unsecured rate – and hence that these banks could not borrow at this rate. Restricting attention to $\alpha \in (-1, 1)$ and taking the mean of α_i across all bidders pre-turmoil, we get 0.17, with a median of 0.29. In the post-turmoil period, the average α decreased to -0.01 , and the median to -0.02 , which suggests that the average bank did not have usable collateral in the interbank market, and that many banks could not borrow unsecured at EURIBOR, either.³³

³²Results are similar if we use the EONIA swap rate instead of the EUREPO.

³³ Because the EURIBOR (or its counterpart, LIBOR) also play a crucial role in anchoring most of the consumer loans, such as mortgages, it is important to understand why this rate may have failed to reflect market clearing prices and the increase in the heterogeneity of funding costs among market participants. The first potential explanation is

A more interesting finding obtains, however, when we decompose these changes in the hypothetical collateral structure based on our classification of bidders: the ones that we labeled as financially distressed after the turmoil (because of a significant increase in marginal values) see a change in mean α_i from 0.18 to -0.02 , and the median α_i decreases from 0.28 to -0.04 . This suggests that the bidders who we label as significantly affected indeed suffered from a big hit in the way that their collateral pool was valued in the secondary market. In fact, the “non-distressed” bidders’ mean α in fact even increases slightly from 0.466 to 0.474, but the median decreases from 0.18 to 0.10.³⁴

In our second exercise, we abandon the assumption that everybody can get a loan at the unsecured interest rate and instead directly compare the estimated v_i ’s and the published secured and unsecured rates at the time of the auction. We normalize our results by dividing by the number of auctions (since we have 32 auctions pre-turmoil and 18 post-turmoil). Averaging across all auctions, we have 156 bidders per auction whose values exceed the unsecured interest rate, EURIBOR, and 184 whose values fall short of it. We find that before turmoil, about 138 bidders have values higher than the reported EURIBOR, which suggests that even before turmoil not every bank was able to borrow at the reported unsecured rate. After turmoil, this number increases by

that the EURIBOR is not based on actual transactions, but rather on a survey of a subset of banks: “A representative panel of banks provide daily quotes of the rate, rounded to two decimal places, that each panel bank *believes* one prime bank is quoting to another prime bank for interbank term deposits within the euro zone.” Note that the EURIBOR is based on the declared beliefs of banks regarding market transactions, and that the rate pertains to transactions between a selected group of banks with superior credit ratings. Thus, in times of uncertainty, it is likely that the EURIBOR will not accurately represent the unsecured loan rates available to a large number of non-prime banks.

A second explanation is that of a market failure in the form of credit rationing attributable to increased informational asymmetries after the turmoil, as in the model of Stiglitz and Weiss (1981). We thus might expect rationing of unsecured loans at the reported rates, with the unfulfilled demanders seeking liquidity at the ECB repo auctions instead. However, the market for unsecured loans may have failed to function for reasons other than informational asymmetries, especially because credit rationing equilibria typically are difficult to generate quantitatively (Arnold and Riley, 2008). Brunnermeier (2009), for example, argues that the troubles in the interbank lending market in 2007 are due to the precautionary hoarding by individual banks. He argues that banks funding highly leveraged investment funds became more worried about these funds drawing on their credit lines. This increased each bank’s uncertainty about its own liquidity needs. At the same time, banks became more uncertain as to whether they could rely on the interbank market, because it was not known to what extent other banks faced similar problems. Thus the supply of liquidity decreased and the demand for liquidity increased at the same time, driving up interbank rates. However, although this provides an explanation as to why the EURIBOR-EUREPO spreads increased, it does not explain why the primary auction rate for secured loans exceeded the EURIBOR rate.

³⁴Recall that we were able to classify only 482 bidders (out of the total of 733 identities appearing throughout our sample). While we have estimated α_i for the remaining bidders and estimated their marginal values whenever they submitted a bid, they did not submit bids both pre- and post-turmoil, and therefore our procedure cannot classify them. This explains why the reported means of the insignificantly and significantly affected bidders lie above the overall mean of α across all bidders.

almost 40% to 189 bidders per auction! Given that on average there are slightly more than 330 participants in an auction, this means that over 50% of the participating bidders cannot transact at the published EURIBOR. Again decomposing this increase, we find that among the significantly affected bidders, the number of bidders with values higher than EURIBOR increased from 92 to 137, while for the insignificantly affected bidders it actually decreased slightly from 34 to 33. Similarly, the number of bidders whose estimated marginal value falls short of the unsecured rate, $v_i \leq u$, drops from 209 pre-turmoil to 138 post-turmoil. This change is due mainly to changes among the bidders who have been significantly affected by the turmoil: there are 158 such bidders per auction pre-turmoil and only 93 post-turmoil, whereas among the insignificantly affected bidders the drop is only from 38 to 34.

We also can compare estimated marginal values with the secured rate in the secondary market, s (EUREPO). By doing this, we find that for over 322 bidders in an auction, $v_i \geq s$ (325 pre-turmoil and 318 post-turmoil), while for only 18 bidders the reverse is true. This suggests that s indeed places a lower bound on the marginal value of liquidity obtained in the primary market.

6.4 Cross-country differences in banks' marginal values

Our data allows us to identify the country-of-origin for the bidders in our dataset. Although we are not allowed to report the identities of countries, we can investigate whether banks in different countries in the Euro system were affected differently by the crisis.

In Figure 14, we plot the mean α values across bidders before and after the crisis by country. Recall that α is close to 1 if a bidder's marginal value for ECB loans is close to EUREPO, the interbank secured interest rate, and close to 0 if the bidder's marginal value is the EURIBOR, the interbank unsecured interest rate. An α value that is negative indicates that the bidder has marginal value above the reported EURIBOR; i.e. the bidder cannot satisfy its funding needs at the EURIBOR rate.

In the figure, we see that there is considerable heterogeneity across countries, both pre and post-crisis. First notice that pre-crisis, some countries' banks have α values close to 1, while others' banks have α values close to zero (and, in one case, slightly negative). There is high positive

correlation between pre- and post-crisis α s; the Pearson correlation coefficient is 0.9. After the crisis, α values appear to have declined across the board, with the low α countries' banks being pushed into the negative α zone.

Because of non-disclosure requirements, we cannot investigate how country characteristics, especially attributes of their respective financial systems, are correlated with the funding costs of their banks. However, the exercise above may be instructive, in that α values are quite highly correlated before and after the crisis: the countries whose banks are likely to suffer are those whose banks had high liquidity funding costs to begin with.

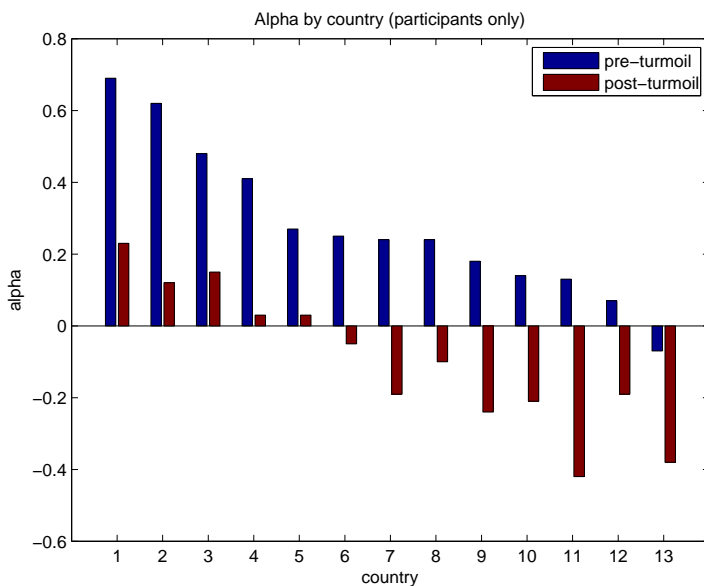


Figure 14: Pre and Post-Crisis Marginal Values across Euro-zone Countries

6.5 Efficiency of the Allocation

Using the estimated marginal values, we can also evaluate whether the allocations implemented in each auction were efficient. In particular, we can compute the (estimated) surplus from an allocation in which banks with highest values would be awarded the liquidity and compare this surplus to the surplus from the actual allocation.

Figure 15 shows that the auction comes close to implementing the efficient allocation both

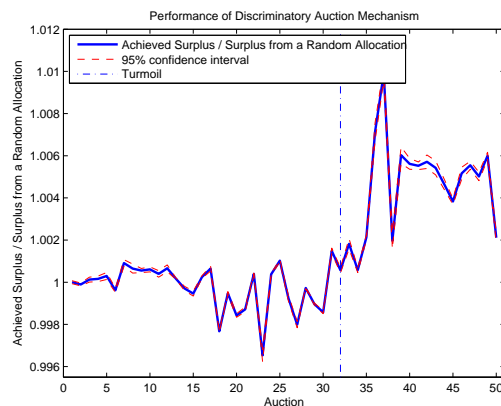
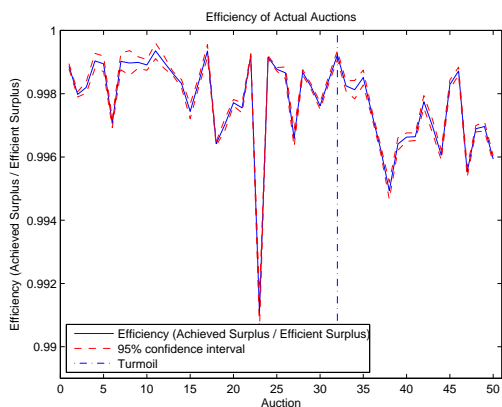


Figure 15: Efficiency of Discriminatory Auctions of Liquidity Figure 16: Comparing Auction to Random Allocation

before and after August 2007. This result is perhaps not surprising for the pre-crisis period, since values seemed to have been very homogeneous and thus even a random allocation of liquidity among banks would have been close to efficient. In the post-crisis period, on the other hand, the increased heterogeneity of values implies that which bank obtains liquidity can have important efficiency consequences. Nevertheless, given the amounts involved, the half-a-percentage point loss of surplus could be very costly if the secondary markets have frictions and hence during a crisis there might be a reason for policy makers to think about using an auction mechanism which implements an efficient allocation, such as the Vickrey auction, even at the cost of some potential decline in revenues.

In Figure 16 we compare the surplus resulting from the allocation achieved by the auction mechanism to a random allocation. It is immediately visible that indeed in the pre-crisis period there is virtually no difference, but in the post-crisis period, the auctions play an important role in allocating liquidity to banks with higher willingness-to-pay and improve upon the random allocation.

6.6 The determinants of banks' willingness-to-pay for liquidity

We motivated our model with private values by arguing that banks' values for liquidity obtained in the primary market likely are driven to a large extent by the collateral value of each bank's asset portfolio and by the private information each bank has about its liquidity position, i.e., its need to

satisfy the prescribed reserve requirements. To test these assumptions, we complement our dataset and our estimates of marginal values with additional detailed bank-level data for a subsample of banks. In this exercise we use three types of data: (1) data that is common to all banks and specific to each tender – the one-week Eurepo rate³⁵; (2) bank-specific data that is publicly available, for example bank’s CDS and asset sizes; and (3) non-public bank-specific data, including volumes allotted at ECB’s long-term refinancing operations (LTRO), banks’ current accounts with the national central banks, and reserve requirements.³⁶ Unfortunately, the intersection of banks for whom there are publicly traded CDSs and banks for whom we have data on reserve requirements leaves us with only 19 banks to work with.

Let us briefly summarize which effects we expect from each variable included in the analysis that follows. As mentioned earlier, the *one-week Eurepo rate* normally sets a floor for bid rates (if it is above the minimum bid rate) and marginal values because it measures the cost of “alternative” funding in the secondary market against highly liquid collateral. Thus this rate sets the common floor level for the bids and marginal values for all banks.

The (relative) *CDS premium* captures the impact of credit risk premia in the inter-bank market; higher values of this variable should lead to an increase in the bids and marginal values of liquidity at the central bank auctions.³⁷

Volumes allotted at the LTROs captures the impact of term liquidity funding pressure. With a liquid interbank lending market, the term-liquidity that a bank receives from the central bank (LTROs) should have little or no impact on the marginal value for liquidity in the short-term auction (MRO). However, if the ECB becomes the primary funding source for a bank, then we might expect a noticeable link between the two auctions. Accordingly, our *LTROout_{it}* variable measures the outstanding volume of loans obtained in LTROs that bank *i* owns in week *t* (in billion €).

The *reserve deficiency* is calculated from banks’ current accounts with the national central

³⁵See Piazzesi (2003) for an argument about why it is important to control for the levels of interest rates.

³⁶The source for these data are: ECB (current accounts; bidding data); Reuters (Eurepo rate); and KMV (CDS).

³⁷We use the price of a (5-year) CDS contract on the day before each auction, and define a relative credit default swap variable as the bank’s CDS minus the average of all banks’ CDS, in order to remove any possible trends that are correlated with the other variables used, i.e. $RCDS_{it} = CDS_{it} - \frac{\sum_{j \neq i} CDS_{jt}}{N_{j \neq i}}$.

banks: the marginal value of liquidity should increase in the amount that a bank has to accumulate until the end of the reserve maintenance period.³⁸

Finally, *Turmoil* is a dummy variable equal to 1 in the post-turmoil period. We also included interactions of all variables with this dummy.

We estimated Fixed Effects (FE) and Random Effects (RE) Panel Data Models.³⁹ The estimates for the specification with Eurepo 1-week and the alternative interest rate measures as explanatory variables are reported in Table 5 below.⁴⁰

The estimates show that the Eurepo 1-week rate does very well at explaining the level of marginal values before the turmoil. Indeed, because the constant term is insignificant, our model predicts highly concentrated bidding before the crisis at rates between the Eurepo 1-week rate and a level 3 basis points above it. Marginal values increased significantly after the crisis. Liquidity shocks (captured by deficiency) have a positive and statistically significant impact on marginal values only after the crisis. The impact of the outstanding volumes in LTROs is not statistically significant for marginal values either before or after the crisis. Nevertheless, the change in sign on these coefficients pre- and post-turmoil might suggest that LTROs substitute for MROs before the

³⁸A bank's reserve deficiency varies with unexpected liquidity shocks, which may be driven by unexpected mismatches between cash inflows and outflows from that bank's accounts; it also may reveal the failure to guarantee a targeted allotment at a previous auction. The *Deficiency* variable is calculated for each bank i as follows. First:

$$D_{it} = T * RR_i - \sum_{s=1}^t CA_{is}$$

where D_{it} is the accumulation of reserves needed to fulfill its requirement until the last day of the reserve maintenance period for bank i on day t . RR_i is the daily average reserve requirement of bank i (set by the ECB at the beginning of each reserve maintenance period) and T is the number of days in the maintenance period; $T - t$ is the number of days until the end of the reserve maintenance period. If a bank follows a smooth (linear) reserve fulfilment path, it targets as its daily current account the daily average reserve requirement D_{it}^* :

$$D_{it}^* = T * RR_i - t * RR_i \Leftrightarrow \frac{D_{it}^*}{RR_i} = T - t$$

Deficiency is therefore defined as:

$$Deficiency_{it} = \frac{D_{it}}{RR_i} - \frac{D_{it}^*}{RR_i} = \frac{D_{it}}{RR_i} - (T - t)$$

We use the *Deficiency* value on the day before the MRO. This is a normalized variable that has a days-in-the-reserve maintenance period dimension.

³⁹We performed the Breusch-Pagan test (for specification (1) in Table 5). The random effects model is not rejected at the 5% level; however, it is rejected at the 10% level. The results reported in the table suggest that the estimates from an RE and FE models are qualitatively and quantitatively very similar.

⁴⁰Since not all banks participate in every auction, we also used a two-step Heckman selection model (Heckman (1976, 1979)). The estimates obtained with correction for sample selection are very similar to those obtained with FE and RE and can be obtained upon request.

Table 5: Analysis of Marginal Values

	Marginal Value			
	(1)	(2)	(3)	(4)
EUREPO	1.03*** (0.04)			1.033*** (0.036)
EUREPO*Turmoil	-0.35* (0.19)			-0.39** (0.19)
EONIA		1.02*** (0.04)		
EONIA*Turmoil		-0.53*** (0.16)		
EURIBOR			1.02*** (0.04)	
EURIBOR*Turmoil			-0.32** (0.16)	
Turmoil	1.53** (0.77)	2.28*** (0.65)	1.36** (0.67)	1.70** (0.77)
Deficiency	0.000008 (0.002)	0.00017 (0.002)	-0.0001 (0.002)	-0.003 (0.002)
Deficiency*Turmoil	0.0226*** (0.003)	0.0226*** (0.003)	0.023*** (0.003)	0.024*** (0.003)
LTROout	-0.006 (0.008)	-0.005 (0.008)	-0.006 (0.008)	-0.013 (0.01)
LTROout*Turmoil	0.009 (0.008)	0.008 (0.008)	0.01 (0.008)	0.016 (0.01)
RCDS	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.0005 (0.002)
RCDS*Turmoil	0.006*** (0.001)	0.006*** (0.0015)	0.0059*** (0.0015)	0.006*** (0.0018)
Constant	-0.08 (0.14)	-0.04 (0.14)	-0.1 (0.13)	-0.09 (0.14)
Observations	690	690	690	690
Random effects	19	19	19	
Fixed effects				19
Within R ²				0.74

^a Specifications (1)-(3): Bank random effects GLS regression

^b Specification (4): Bank fixed effects regression

^c Standard errors clustered at the bank level in parentheses.

* Significant at 10% level.

** Significant at 5% level.

*** Significant at 1% level.

turmoil, but are a complementary source of liquidity in the post-turmoil period. The credit risk variable (measured by the relative CDS) is statistically significant. A bank with CDS above the average tends to have higher marginal valuations for liquidity. The liquidity and credit risk factors seem to only partially capture the increase in the spread between marginal valuations and the reference rate (Eurepo 1-week) after the crisis, because the turmoil dummy variable is significant even when these variables are added to the regression. These results are robust to changing the reference rate in the regression, as shown by the different specifications⁴¹. We also performed a Hausman test to check for equality of the coefficient estimates of the RE and FE models. We failed to reject the hypothesis that the coefficients are equal across the two models (p-value of 0.33).

In order to assess the economic significance of the results, we calculated the predicted difference between the marginal valuations for two banks under the following assumptions: Eurepo rate 1-week at its highest in-sample value (4.15%); one bank with CDS differential at highest in-sample value (44.64); the other bank at minimum sample value (-30.91); one bank with deficiency at highest in-sample value (21.22 days); the other bank at zero. These assumptions are intended to capture the hypothetical situations of “good” and “bad” banks in the sample. The FE model predicts a marginal value of 4.07% for the “good” bank and a marginal value of 5.05% for the “bad” bank, that is a whole percentage point difference in short-term funding costs across these two banks. Note that in relative terms, after the crisis the Eurepo 1-week rate “explains” about 52% of the marginal valuation, the deficiency 9%, the CDS differential 6%, and the turmoil dummy 33%.

6.7 Estimated marginal values and bank balance sheets

Finally, as a test of the external validity of our marginal valuation estimates utilizes data on balance sheets of system banks obtained from Bankscope. Most of the bidders in our data set are not publicly traded, thus publicly available information on these institutions is largely limited to quarterly or sometimes annual financial statements that are disclosed by these firms. Using Bankscope, we construct measures of return-on-equity (ROE) and return-on-assets (ROA),⁴² which are standard performance indicators in the banking literature (Madura (2008)). We also compute the cost-to-

⁴¹The same results were obtained when estimating the fixed-effects models with different interest rates.

⁴²ROE is defined as net income / average total equity, and ROA is defined as net income / average total assets, where the averages are taken yearly.

income ratio (CTI), and net-interest margin (NIM), which are proxies for the profit generation ability of the bank.⁴³ These widely-used ratios are of course not immune to criticism (ECB (2010)), but can be constructed for a large number of banks for whom market-based performance measures (based on traded securities) are not available.

We construct these measures for both the end of 2006, and the end of 2007, which comprise the endpoints of our auction data set. In Table 6.7, we regress the end-of 2007 performance indicators on their lagged values in 2006, along with the changes in the banks quantity-weighted average bids and marginal valuations across the pre- vs. post-crisis periods; i.e. we investigate whether any of the change in the profitability of the bank from 2006 to 2007 can be explained using our auction-based measures of the short-term funding costs faced by these banks.

The results (in columns 1,4, 7, and 10) indicate that the change in the bidding behavior of the banks across the pre- vs. the post-crisis periods in our sample is not significantly correlated with the change in the bank's performance measure from the end of 2006 to the end of 2007. However, for ROE and CTI, the change in the marginal valuations do show significant correlations. Indeed, when we include both bids and marginal valuations in the regressions, the change in marginal valuations are significant at 5% for ROE and CTI, and at 10% for ROA. The effects are also economically significant – based on the coefficient estimates, a 1 percentage point (100 basis point) increase in the bank's marginal value for liquidity is associated with an 18.8% drop in ROA, 5.6% drop in ROE, and a 28% increase in CTI. Among the four measures we consider, only the net-interest margin does not display a significant association with the changes in bids or marginal values. One potential explanation might be that unlike the other three measure the NIM is highly persistent as evidenced by the high coefficient on the lagged value and high R^2 , there is therefore very little residual variation left to explain.

These regressions suggest that not only auction-based measures of short-term funding costs, which are observable at high-frequency by the ECB, may be an important predictor of bank profitability, but that accounting for the strategic component of the auctions by estimating the marginal valuations helps provide more accurate predictions. Since bank balance sheets are available only

⁴³CTI is calculated as the ratio of operating expenses to operating revenues; thus a higher CTI proxies for lower profitability. NIM is the ratio of the net interest income over interest bearing assets.

at quarterly or sometimes annual frequencies, this suggests that auction data could be very useful for policymakers when assessing the health of the financial system.

7 Conclusion

We used an economic model of bidding in the ECB’s main refinancing operations to recover participant banks’ marginal valuations for ECB provided short-term loans, which also can be linked to the banks’ outside funding opportunities in the interbank market. Our econometric approach allows us to decompose into two main effects the dramatic upward shift in banks’ bids beginning in August 2007: a “fundamental” effect linked to a genuine increase in the willingness-to-pay for ECB loans because of dwindling funding opportunities elsewhere, and a “strategic” effect, in which banks without a shift in their willingness-to-pay best-respond to their competitors’ more aggressive bidding behavior. We showed that the “strategic” effect is non-negligible: while a naïve analysis of bids would indicate that all bidders’ willingness-to-pay for short-term ECB funding increased because of the subprime crisis, accounting for the strategic effect reveals that one third of the bidders did not experience such a statistically significant shift.

Our results also shed light on the linkages between primary and secondary money market rates, and the shortcoming of “survey” based market rate reporting. We showed that before August 2007, participant banks’ marginal valuations were in close agreement with the EUREPO and EURIBOR: published secured and unsecured lending rates reported based on surveys of money-center banks. After August 2007, though, we find that banks’ marginal valuations and, sometimes their bids for secured ECB loans, far exceed the EURIBOR. That suggests that a large number of banks were not able to borrow at published rates. These results together suggest that monitoring primary market activity may allow policymakers and market observers to gain a more detailed understanding of the depth of similar financial crises.

The primary market activities of banks also allowed us to paint a more disaggregated picture of the 2007 subprime crisis. We noted that there was considerable heterogeneity in banks’ willingness-to-pay for ECB loans across different Eurozone countries. Perhaps more significantly, banks from member countries that relied less on ECB funding before August 2007 appear to have suffered less

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	ROA'07	ROA'07	ROA'07	ROE'07	ROE'07	ROE'07	CTI'07	CTI'07	CTI'07	NIM'07	NIM'07	NIM'07
Δ bids	0.0520 (0.133)		0.126 (0.140)	-0.00613 (0.0288)		0.0156 (0.0302)	0.0734 (0.150)		-0.0370 (0.157)	0.0138 (0.103)		-0.000176 (0.109)
Δ marginal values		-0.156 (0.107)	-0.188* (0.113)		-0.0514** (0.0230)	-0.0553** (0.0242)		0.274** (0.119)	0.283** (0.126)		0.0357 (0.0832)	0.0357 (0.0877)
ROA'06	0.561*** (0.0260)	0.562*** (0.0259)	0.564*** (0.0260)									
ROE'06				0.240*** (0.0299)	0.241*** (0.0297)	0.242*** (0.0298)						
CTI'06							0.568*** (0.0860)	0.568*** (0.0853)	0.569*** (0.0855)			
NIM'06										0.916*** (0.0114)	0.916*** (0.0114)	0.916*** (0.0115)
Constant	0.0782* (0.0457)	0.116*** (0.0225)	0.0798* (0.0456)	0.0399*** (0.00974)	0.0450*** (0.00474)	0.0407*** (0.00969)	0.299*** (0.0716)	0.284*** (0.0585)	0.294*** (0.0712)	0.0628 (0.0410)	0.0626** (0.0276)	0.0627 (0.0411)
Observations	390	390	390	390	390	390	386	386	386	390	390	390
R-squared	0.546	0.549	0.550	0.143	0.154	0.155	0.104	0.116	0.116	0.943	0.943	0.943

The dependent variables in this table are bank performance ratios (ROA, ROE, CTI and NIM) reported year-end 2007. The independent variables are the pre- vs. post-crisis (Aug. 9, 2007) change in a bank's quantity-weighted average price bids (Δ bids) and estimated marginal valuations (Δ marginal values). We also control for the year-end 2006 performance ratios. Standard errors are in parentheses, with (***) indicating $p < 0.01$, (**) $p < 0.05$, and (*) $p < 0.1$.

Table 6: Correlation between bank performance ratios and marginal values/bids

from the crisis. Our estimates for the short-term funding costs of the banks during the crisis also survive a number of external validity checks: the estimated funding costs are bounded between published collateralized and uncollateralized rates in the “pre-crisis” period, even though this is not imposed by our estimation exercise. Moreover, for a small subsample of banks for whom credit default swaps are traded, we also noted a significant correlation between the bank’s estimated short-term funding cost, and its creditworthiness (as measured by its CDS price) that potentially could be monitored as the leading indicators for distress in crisis situations. This findings suggest that our method of measuring short-term funding costs of Euro-system banks may be useful in constructing high-frequency bank-specific indicators of financial distress.

References

- [1] Acharya, V., Schnabl, P., and Suarez, G., “Securitization Without Risk Transfer,” mimeo, 2010.
- [2] Afonso, Gara, Anna Kovner, and Antoinette Schoar, “Stressed, Not Frozen: The Federal Funds Market in the Financial Crisis,” *Journal of Finance*, forthcoming.
- [3] Arnold, Lutz, and Riley, John, “On the Possibility of Credit Rationing in the Stiglitz-Weiss Model,” *The American Economic Review*, Vol.99, No.5, pp.2012-21, 2009.
- [4] Ashcraft, A., M. Bech, W. S. Frame, “The Federal Home Loan Bank System: The Lender of Next to Last Resort?”, mimeo, 2008.
- [5] Athey, S., and Haile, P., “Nonparametric Approaches to Auctions,” forthcoming in J. Heckman and E. Leamer, eds., *Handbook of Econometrics*, Vol. 6, Elsevier, 2005
- [6] Ausubel, Lawrence, and Cramton, Peter, “Demand Reduction and Inefficiency in Multi-Unit Auctions,” mimeo, 2002
- [7] Back, Kerry, and Zender, Jamie, “Auctions of Divisible Goods: On the Rationale for the Treasury Experiment,” *The Review of Financial Studies*, Vol. 6., No. 4, pp. 733-764, 1993

- [8] Bindseil, Ulrich, Nyborg, Kjell and Strebulaev, Ilya, “ Bidding and Performance in Repo Auctions: Evidence from ECB Open Market Operations,” mimeo 2005
- [9] Breusch, Trevor and Pagan, Adrian, “The Lagrange Multiplier Test and Its Applications to Model Specification in Econometrics,” *Review of Economic Studies*, Vol. 47, pp. 239-53, 1980
- [10] Brunnermeier, Markus, “Deciphering the Liquidity and Credit Crunch 2007-08,” *Journal of Economic Perspectives*, Vol. 23, pp. 77-100, 2009.
- [11] Cecchetti, Stephen, “Crisis and Responses: The Federal Reserve in the Early Stages of the Financial Crisis,” *Journal of Economic Perspectives*, Vol. 23, pp. 51-76, 2009.
- [12] Chapman, James, McAdams, David, and Paarsch, Harry, “Bounding Best-Response Violations in Discriminatory Auctions with Private Values,” mimeo, 2006
- [13] Chari, V.V., Christiano, Lawrence, and Kehoe, Patrick, “ Facts and Myths about the Financial Crisis of 2008,” mimeo 2008
- [14] Christiano, Lawrence, “Looking Behind the Aggregates: A Reply to “Facts and Myths About the Financial Crisis of 2008”,” mimeo, 2008
- [15] Cohen-Cole, Ethan, Duygan-Bump, Burcu. Fillat, Jose, and Montoriol-Garriga, Judit, “Looking Behind the Aggregates: A Reply to “Facts and Myths About the Financial Crisis of 2008”,” Federal Reserve Bank of Boston, 2008
- [16] Duffie, Darrell, Gârleanu, Nicolae, and Pedersen, Lasse, “Over-the-Counter Markets,” *Econometrica*, Vol. 73, pp. 1815-1847, 2005
- [17] Duffie, Darrell, Gârleanu, Nicolae, and Pedersen, Lasse, “Valuation in Over-the-Counter Markets,” *The Review of Financial Studies*, Vol. 20, pp. 1865-1900, 2007
- [18] Eisenschmidt, Jens and Tapking, Jens, “ Liquidity Risk Premia in Unsecured Interbank Money Markets,” mimeo, 2008
- [19] Eisenschmidt, Jens, Astrid Hirsch and Tobias Linzert, “Bidding Behaviour in the Main Refinancing Operations During the Financial Crisis,” mimeo 2009

- [20] The European Central Bank, “Beyond ROE – How to Measure Bank Performance: Appendix to the Report on EU Banking Structures,” September 2010.
- [21] Ewerhart, Christian, Cassola, Nuno, and Valla, Natacha, “Declining Valuations and Equilibrium Bidding in Central Bank Refinancing Operations,” *International Journal of Industrial Organization*, forthcoming, 2008
- [22] Ewerhart, Christian, and Tapping, Jens “Repo Markets, Counterparty Risk and the 2007/2008 Liquidity Crisis,” ECB Working Paper No. 909, June 2008
- [23] Heckman, James “The common structure of statistical models of truncation, sample selection, and limited dependent variables and a simple estimator for such models,” *Annals of Economic and Social Measurement*, 5, 475-492, 1976
- [24] Heckman, James, “Sample selection bias as a specification error,” *Econometrica*, 47(1), pp. 153-161, 1979
- [25] Holmstrom, Bengt, and Tirole, Jean, “ Private and Public Supply of Liquidity,” *Journal of Political Economy*, Vol. 106, No. 1, pp. 1-40, 1998
- [26] Hortaçsu, Ali, “Mechanism Choice and Strategic Bidding in Divisible Good Auctions: An Empirical Analysis of the Turkish Treasury Auction Market,” mimeo, 2002
- [27] Hortaçsu, Ali and Kastl, Jakub, “Do Bidders in Canadian Treasury Bill Auctions Have Private Values?,” mimeo 2008
- [28] Kastl, Jakub, “Discrete Bids and Empirical Inference in Divisible Good Auctions,” mimeo, 2006
- [29] Kastl, Jakub, “On the Properties of Equilibria in Private Value Divisible Good Auctions with Constrained Bidding,” mimeo, 2008
- [30] Madura, Jeffrey, *Financial Markets and Institutions*, 9th Edition, 2008, Thomson-SouthWestern, Mason, OH.

- [31] Michaud, Francois-Louis, and Upper, Christian, "What drives interbank rates? Evidence from the Libor panel," *BIS Quarterly Review*, March 2008
- [32] Milgrom, Paul, *Putting Auction Theory to Work*, Cambridge University Press, 2004
- [33] Piazzesi, Monika, "Affine term structure models," mimeo, 2003
- [34] Stiglitz, Joseph, and Weiss, Andrew, "Credit Rationing in Markets with Imperfect Information," *American Economic Review*, Vol. 71, pp. 393-410, 1981
- [35] Taylor, John, and Williams, John, "A Black Swan in the Money Market," *AEJ: Macroeconomics*, forthcoming, 2009
- [36] Taylor, John, and Williams, John, "Further Results on a Black Swan in the Money Market," mimeo, 2008
- [37] Wang, Jim and Zender, Jamie, "Auctioning Divisible Goods," *Economic Theory*, 19, pp.673–705, 2002
- [38] Wilson, Robert, "Auctions of Shares," *Quarterly Journal of Economics*, 1979
- [39] Wu, Tao, "On the effectiveness of the Federal Reserve's new liquidity facilities," Federal Reserve Bank of Dallas Working Paper 0808, 2008

A NOT FOR PUBLICATION: Appendix

A.1 Institutional Background

A.1.1 Objectives and Tools of the ECB

The operational framework for monetary policy implementation by the ECB has three main objectives: signalling of the monetary policy stance, steering of very short-term interest rates, and provision of refinancing to the banking system in an efficient way and under all circumstances. The ECB has three main tools to implement its objectives: minimum reserve requirements with averaging provision, standing facilities, and open market operations. The main focus of this paper is on open market operations, but below we briefly describe each of the three components because all are quite relevant for banks' behavior in the open market operations .

Reserve requirements have two main functions. They contribute to stabilise money market interest rates and enlarge the structural liquidity shortage of the banking system. Euro area banks have to keep minimum reserves (current accounts with national central banks⁴⁴). They are computed on a lagged accounting basis by applying a reserve ratio (currently at 2%) to the reserve base. The reserve base includes short-term liabilities of banks (deposits and debt securities with maturity below or equal to two years). Reserves must be kept on average over a maintenance period (averaging mechanism) which has approximately one month duration. Required reserves are remunerated - at a rate linked to the marginal rate of the Main Refinancing Operations (MROs) described below. Current account holdings beyond the minimum requirement are not remunerated (excess reserves).

There are two types of *standing facilities*, one providing liquidity (against collateral), which is a marginal lending facility and another, absorbing liquidity, which is a deposit facility. Both are overnight facilities taken at the discretion of the banks, and, in general, there are no limits set by the ECB to their recourses by banks. Standing facilities have penalty rates: marginal lending +100 basis points above the Minimum Bid Rate (henceforth MBR, which is a policy rate, see below for more details) and deposit facility -100 basis points below the MBR.⁴⁵ These two rates set a corridor

⁴⁴National Central Banks

⁴⁵The interest rate corridor was narrowed to ± 50 basis points as of October 9, 2008.

for the interbank market overnight interest rate.

There are three main types of *open market operations*. The Main Refinancing Operations (MROs), which are the main focus of our analysis, The Longer Term Refinancing Operations (LTROs) are liquidity providing reverse transactions, with three-month maturity, conducted once a month, every month. The main function of the LTROs is to provide additional longer-term liquidity to the market. They are not intended to signal the (future) stance of monetary policy. Fine Tuning Operations (FTOs) provide or absorb liquidity. They have neither fixed frequency nor maturity. Provision of liquidity is made via reverse transactions or foreign exchange swaps, and absorption of liquidity is normally achieved via collection of fixed term deposits or foreign exchange swaps. The main function of the FTOs is to smooth the effects on interest rates caused by unexpected liquidity fluctuations in the market. Since 2005 the ECB conducts (almost) systematically an FTO on the last day of each reserve maintenance period.

A.1.2 More Details on the Main Refinancing Operations

MROs are executed weekly according to an indicative calendar published by the Eurosystem. Normally, the announcement of the operation is on Monday⁴⁶, the execution on Tuesday⁴⁷ and settlement on Wednesday. On the announcement day (Monday) the ECB publishes an estimate of the average autonomous factors⁴⁸ from the announcement day until the maturity of the operation (9 days ahead forecast) as well as the benchmark allotment. On the execution day (Tuesday) the ECB publishes a revised estimate of the average autonomous factors and benchmark amount.

As we mentioned earlier, a bid may consist of up to ten interest rates and associated quantities a bank is willing to transact with the ECB. The interest rate bid must be expressed as multiples of a basis point, i.e., of 0.01 percentage points. The minimum bid amount is EUR 1,000,000. Bids exceeding this amount must be expressed as multiples of EUR 100,000. The ECB may impose a maximum bid limit in order to prevent disproportionately large bids.

In the allotment, bids are listed in descending order of offered interest rates. Bids with the

⁴⁶Info in Reuters page ECB16.

⁴⁷Info in Reuters page ECB17.

⁴⁸Defined as Autonomous factors (AF) = Net Foreign Assets (NFA) + Net Assets Denominated in Euro (NDA) - Banknotes (BN) - Government deposits (GOV) - Other (O).

highest interest rate levels are satisfied first and subsequently bids with successively lower interest rates are accepted until the total liquidity to be allotted is exhausted. If at the lowest interest rate level accepted (i.e., the marginal interest rate), the aggregate amount bid exceeds the remaining amount to be allotted, the remaining amount is allocated pro rata among the bids according to the ratio of the remaining amount to be allotted to the total amount bid at the marginal interest rate (a.k.a. rationing rule pro-rata on-the-margin). The amount allotted to each bank is rounded to the nearest euro.

The ECB may apply either single rate (uniform price) or multiple rate (discriminatory) auction procedures. So far only the latter has been used, and thus our data includes only discriminatory auctions. In a discriminatory auction, the allotment interest rate is equal to the interest rate offered by each individual bid. Since October 15 2008 the weekly main refinancing operations have been carried out with a fixed-rate tender procedure with full allotment.

A.1.3 Collateral (Eligible Assets)

All Eurosystem liquidity-providing operations (including marginal lending and intraday credit) are based on underlying assets that must fulfill certain criteria in order to be eligible. A European credit assessment framework (ECAAF) has been set up in order to evaluate the eligible collateral. The collateral accepted by the Eurosystem is very broad. Two types of assets are included in the list: marketable and non-marketable. The ECB publishes daily a list of eligible marketable assets on its website.⁴⁹ Marketable assets must be debt instruments meeting high credit standards which are assessed by the ECAAF rules. The issuers can be central banks, public sector, private sector, and international institutions; the place of issue must be EEA⁵⁰, the place of establishment of the issuer must be the EEA and non-EEA G10 countries, the currency must be EUR.⁵¹ Both regulated and non-regulated markets are considered; the latter must be, however, accepted by the ECB. Non-marketable assets are credit claims and Retail Mortgage Backed Debt Instruments (RMBD). For credit claims the debtor/guarantor must meet high credit standards which are assessed by the ECAAF

⁴⁹Eligible assets are listed at: https://mfi-assets.ecb.int/dla_EA.htm

⁵⁰European Economic Area

⁵¹Since November 14, 2008 the list of eligible marketable debt instruments was enlarged to include instruments denominated in US dollar, yen and sterling, issued by EEA issuers.

rules. The debtor/guarantor can be public sector, non-financial corporations, and international institutions; the place of establishment of the debtor/guarantor must be the euro area and the currency must be EUR. Minimum size rules apply. For RMBD the asset must meet high credit standards which are assessed by the ECAF rules. The issuers can be credit institutions; the place of establishment of the issuer must be the euro area, and the currency must be EUR. A bank may not submit as collateral any asset issued or guaranteed by itself or by any other entity with which it has close links.

In the assessment of credit standard of eligible assets the Eurosystem takes into account the following sources: external credit assessment institutions (ECAIs), national central banks in-house credit assessment systems (ICAS exist in Deutsche Bundesbank, Banco de España, Banque de France and Oesterreichische Nationalbank), counterparties internal ratings-based systems (IRB) or third-party providers rating tools. The Eurosystems credit quality threshold is defined in terms of a “single A” credit assessment (meaning “A-” by Fitch or S&P; or “A3” by Moody).⁵² The Eurosystem considers a probability of default (PD) over a one-year horizon of 0.10% as equivalent to a “single A” credit assessment. Prudential information can be used by the Eurosystem as a basis for rejecting assets. In countries, in which RMBDs are mobilised, the respective national central bank must implement a credit assessment framework for this type of asset. The performance of the credit assessment systems is reviewed annually. It consists of an ex post comparison of the observed default rate for the set of all eligible debtors and the credit quality threshold defined by the benchmark PD.

Risk control measures are applied to protect the Eurosystem against the risk of a financial loss if underlying assets have to be realised owing to the default of a counterparty. The following measures are applied: i) valuation haircuts (increasing with the maturity and illiquidity of the asset); ii) margin calls (i.e. marking to market): if the value of the underlying collateral falls below a certain level the national central bank will require the counterparty to supply additional assets or cash. The Eurosystem may apply limits to the exposure vis-a-vis issuers/debtors or guarantors and may exclude certain assets from use in its monetary policy operations. The last two are, however,

⁵²As of October 25 2008 and until December 2009 the ECB lowered the threshold to BBB- (except for asset-backed securities, which were still A-).

currently not applied.⁵³

In pooling systems the counterparty makes a pool of sufficient underlying assets available to the national central bank to cover the related credits thus implying that individual assets are not linked to specific credit operations. In an earmarking system each credit operation is linked to specific identifiable assets. Assets are subject to daily valuation.

A.2 Model of Bidding in the Primary Market for Liquidity

The basic model underlying our analysis is based on the share auction model of Wilson (1979) with private information, in which both quantity and price are assumed to be continuous.⁵⁴ In summary, there are N (potential) bidders, who are bidding for a share of a perfectly divisible good. Q denotes the amount of liquidity offered for sale by the central bank, i.e., the good to be divided between the bidders. Q is itself a random variable since the ECB augments the supply based on current situation after the bids have been submitted. We assume that the distribution of Q is common knowledge among the bidders. Furthermore, the number of potential bidders participating in an auction, N , is also commonly known. This assumption is reasonable in the context of our empirical application as all participants have to register with the auctioneer before the auction and the list of registered participants is publicly available. Each bidder receives a private (possibly multidimensional) signal, θ_i , which is the only private information about the underlying value of the auctioned goods. The joint distribution of the signals will be denoted by $F(\theta_1, \dots, \theta_N)$. We assume independent private values (IPV) paradigm.⁵⁵ In this case the θ_i 's are distributed independently across bidders, and bidders' values do not depend on private information of other bidders, i.e., the marginal valuation function has the form $v_i(q, \theta_i)$.

⁵³Additional haircuts will be applied to all newly eligible marketable assets.

⁵⁴Since the main goal of this article is not to provide tools and methodology for estimating this type of models, we refer the reader to our earlier work for more detailed discussion and analysis. The discriminatory auction version of Wilson's model with private values has been studied in Hortaçsu (2002a) in the context of Turkish treasury bill auctions. Kastl (2006 and 2008) extends this model to an empirically relevant setting, in which bidders are restricted to use step functions with limited number of steps as their bidding strategies. The estimation of this extended model (which is also utilized in this paper) and the relevant asymptotic behavior of the resulting estimates are described in detail in Hortaçsu and Kastl (2008). Several related theoretical papers on divisible good auctions, such as Ausubel and Cramton (2002), Back and Zender (1993) or Wang and Zender (2002) focus on properties of equilibria.

⁵⁵Bindseil, Nyborg and Strebulaev (2005) provide some econometric evidence that private values might be appropriate in case of repo auctions.

Assumption 1 Bidder i 's signal θ_i is drawn from a common support $[0, 1]^M$, where $M = \dim(\theta_i)$, according to an atomless marginal d.f. $F_i(\theta_i)$.

Assumption 2 $v_i(q, \theta_i)$ is measurable and bounded, strictly increasing in (each component of) θ_i $\forall q$ and weakly decreasing in q $\forall \theta_i$.

$V_i(q, \theta_i)$ denotes the gross utility: $V_i(q, \theta_i) = \int_0^q v_i(u, \theta_i) du$. Bidders' pure strategies are mappings from private signals to bid functions: $\sigma_i : \Theta_i \rightarrow \mathcal{Y}$. Since in most divisible good auctions in practice, including the liquidity auctions of the ECB, the bidders' choice of bidding strategies is restricted to non-increasing step functions with an upper bound on the number of steps, $K = 10$, we impose the following assumption:

Assumption 3 Each player $i = 1, \dots, N$ has an action set:

$$A_i = \left\{ \begin{array}{l} (\vec{b}, \vec{q}, K_i) : \dim(\vec{b}) = \dim(\vec{q}) = K_i \in \{0, \dots, 10\}, \\ b_{ik} \in B = \{l\} \cup [0, \bar{b}], q_{ik} \in [0, Q], b_{ik} \geq b_{ik+1}, q_{ik} \leq q_{ik+1} \end{array} \right\}$$

Therefore the set \mathcal{Y} includes all non-decreasing step functions with at most 10 steps, $y : \mathbb{R}_+ \rightarrow [0, Q]$, where $y_i(p) = \sum_{k=1}^K q_{ik} I(p \in (b_{ik+1}, b_{ik}])$ where I is an indicator function. A bid function for type θ_i specifies for each price p , how big a share $y_i(p|\theta_i)$ of the securities offered in the auction (type θ_i of) bidder i demands.

Finally, since bidders use step functions, a situation may arise in which multiple prices would clear the market. If that is the case, we assume consistently with our application that the auctioneer selects the most favorable price from his perspective, i.e., the highest price.

Assumption 4 If in any auction $\exists \underline{p}, \bar{p}$ such that $\forall p \in [\underline{p}, \bar{p}] : TD(p) = Q$, then $P^c = \max_p \{p : TD(p) = Q\}$, where $TD(p)$ denotes total demand at price p .

Because bidders' strategies are step functions, the residual supply will be a step function and hence but for knife-edge cases any equilibrium will involve rationing with probability one. Consistently with our application, we only consider the rationing rule pro-rata on-the-margin, under which the auctioneer proportionally adjusts the marginal bids so as to equate supply and demand.

Assumption 5 *The rationing rule employed is pro-rata on-the-margin, under which the rationing coefficient satisfies*

$$R(P^c) = \frac{Q - TD_+(P^c)}{TD(P^c) - TD_+(P^c)}$$

where P^c is the market clearing price, $TD(P^c)$ denotes total demand at price P^c , and $TD_+(P^c) = \lim_{p \downarrow P^c} TD(p)$. Only the bids exactly at the market clearing price are adjusted.

These last two assumptions, which are both consistent with our application, make sure that no bidder would prefer to tie with another bidder when gaining strictly positive marginal surplus at the quantity allocated after rationing.

Our solution concept is Bayesian Nash Equilibrium. The expected utility of type θ_i of bidder i who employs a strategy $y_i(\cdot|\theta_i)$ in a discriminatory auction given that other bidders are using $\{y_j(\cdot|\theta_j)\}_{j \neq i}$ can be written as:

$$EU_i(\theta_i) = E_{Q, \theta_{-i}|\theta_i} \left[\begin{array}{c} \int_0^{q_i^c(Q, \theta, \mathbf{y}(\cdot|\theta))} v_i(u, \theta_i) du \\ - \sum_{k=1}^K \mathbf{1}(q_i^c(Q, \theta, \mathbf{y}(\cdot|\theta)) > q_k) (q_k - q_{k-1}) b_k \\ - \sum_{k=1}^K \mathbf{1}(q_k \geq q_i^c(Q, \theta, \mathbf{y}(\cdot|\theta)) > q_{k-1}) (q_i^c(Q, \theta, \mathbf{y}(\cdot|\theta)) - q_{k-1}) b_k \end{array} \right] \quad (\text{A-1})$$

where $q_i^c(Q, \theta, \mathbf{y}(\cdot|\theta))$ is the (market clearing) quantity bidder i obtains if the state (bidders' private information and the supply quantity) is (θ, Q) and bidders bid according to strategies specified in the vector $\mathbf{y}(\cdot|\theta) = [y_1(\cdot|\theta_1), \dots, y_N(\cdot|\theta_N)]$, and similarly $P^c(Q, \mathbf{s}, \mathbf{y}(\cdot|\theta))$ will denote the market clearing price associated with state (θ, Q) , which turns out to be the random variable that is most crucial to the analysis. The first term in (A-1) is the gross utility the type θ_i enjoys from his allocation, the second term is the total payment for all units allocated at steps at which the type θ_i was not rationed and the final term is the payment for units allocated during rationing. A Bayesian Nash Equilibrium in this setting is thus a collection of functions such that almost every type θ_i of bidder i is choosing his bid function so as to maximize his expected utility: $y_i(\cdot|\theta_i) \in \arg \max EU_i(\theta_i)$ for a.e. θ_i and all bidders i . Part (i) of the following proposition proved in Kastl (2008) provides necessary conditions characterizing the equilibrium in discriminatory auctions with private values when marginal valuation function is continuous in q . Since continuity of the

marginal valuation function might be questionable at the last step (in particular for bidders who submit just one step), we make use of the necessary conditions for optimality with respect to the bid (part (ii)).

Proposition 1 *Under assumptions 1-5 in any Bayesian Nash Equilibrium of a Discriminatory Auction, for almost all θ_i , with a bidder of type θ_i submitting $K_i(\theta_i) \leq 10$ steps, every step k in the equilibrium bid function $y_i(\cdot|\theta_i)$ has to satisfy:*

(i) $\forall k < K_i(\theta_i)$ such that $v(q, \theta_i)$ is continuous in a neighborhood of q_k for a.e. θ_i :

$$v(q_k, \theta_i) = b_k + \frac{\Pr(b_{k+1} \geq P^c)}{\Pr(b_k > P^c > b_{k+1})} (b_k - b_{k+1}) \quad (\text{A-2})$$

and at $K_i(\theta_i)$:

$$b_K = v(\bar{q}, \theta_i)$$

where $\bar{q} = \sup_{(Q, \theta_{-i})} q_i^c(Q, \theta, \mathbf{y}(\cdot|\theta))$, i.e., the largest quantity allocated to bidder i in equilibrium.

(ii) $\forall k \leq K_i(\theta_i)$ such that $v(q, \theta_i)$ is a step function in q at step k such that $v(q, \theta_i) = v_k \forall q \in (q_{k-1}, q_k]$ for a.e. θ_i and signals are independently distributed:

$$v_k = b_k + \frac{\Pr(b_k > P^c)}{\frac{\partial \Pr(b_k > P^c)}{\partial b_k}} \quad (\text{A-3})$$

In practice, we use equation (A-2) to identify the marginal values at all but last step, and we use equation (A-3) at the last step.⁵⁶ Note that as $K \rightarrow \infty$, (A-2) and (A-3) coincide in the limit.⁵⁷

A.3 Liquidity demand and supply

To put the liquidity auctions of the ECB into perspective and understand the supply policy of the ECB, let us first look at the simplified balance sheet of the Eurosystem, for example on June 29, 2007 (Table 7 and Table 8).

On the Liabilities side the main items are Banknotes and Current Accounts (together represent

⁵⁶Using (A-3) at all steps leads to qualitatively very similar results, but the estimates turn out to be less precise due to the necessity to numerically estimate the derivative of the distribution of the market clearing price.

⁵⁷The formal argument is in Kastl (2008).

Table 7: Balance sheet of the Eurosystem on June 29, 2007

Assets		Liabilities	
1. Net Foreign Assets	325,703	5. Banknotes	630,777
2. Net Assets Denominated in EUR	282,041	6. Current Accounts	194,530
3. Liquidity Providing Open Market Operations	463,501	7. Government Deposits	69,621
4. Marginal Lending Facility	5	8. Deposit Facility	80
		9. Other	176,242
Total Assets	1,071,250	Total Liabilities	1,071,250

* Values in million EUR.

Table 8: Structure of the balance sheet of the Eurosystem on June 29, 2007

Assets	%	Liabilities	%
1. Net Foreign Assets	30	5. Banknotes	59
2. Net Assets Denominated in EUR	26	6. Current Accounts	18
3. Liquidity Providing Open Market Operations	43	7. Government Deposits	6
4. Marginal Lending Facility	0	8. Deposit Facility	0
		9. Other	16
Total Assets	100	Total Liabilities	100

77% of total Liabilities), the latter including the minimum reserve requirement. On the Assets side there are two large items: Net Foreign Assets and Net Assets Denominated in Euro (representing 56% of total Assets). The former relates to foreign exchange reserve holdings of the Eurosystem (in gold and US Dollar) managed by the ECB. The latter reflects the investment portfolio holdings of national central banks (managed in a decentralised manner according to agreed rules). It is important to note that this is not a monetary policy portfolio. Liquidity providing OMO represent 43% of the Assets of the Eurosystem. This is the item that is adjusted/managed by the ECB and relevant for monetary policy implementation.

The liquidity needs of the banking system can be calculated from the balance sheet as follows:

+ Assets (other than 3 and 4) provide liquidity

- Liabilities (other than 8) create liquidity needs.

Thus:

Liquidity Deficit = Autonomous factors (AF) + Current Accounts (CA).

Where:

Autonomous factors (AF) = Net Foreign Assets (NFA) + Net Assets Denominated in Euro (NDA)
 - Banknotes (BN) - Government deposits (GOV) - Other (O).

Current Accounts include the reserve requirement (RR) plus very small excess reserves (XR).

Example 1 From the balance sheet data (Table 7) we can see that $AF = -268,896$ million EUR, and $CA = -194,530$ million EUR. Therefore the aggregate liquidity deficit in the euro area was $AF+CA=-463,426$ million EUR or approximately 463 billion EUR, of which 58% was due to the so-called autonomous factors and 42% was due to the reserve requirement (current accounts).

Alternatively one could express the liquidity needs as follows (Table 9): *Outright portfolio - Reserve Base - Other* = -463,426 million EUR, where *Reserve Base = Banknotes + Current Accounts* and *Outright Portfolio = NFA + NDA - GOV*.

Table 9: Simplified balance sheet of the Eurosystem on June 29, 2007

Assets	%	Liabilities	%
1. Outright Portfolio	538,125	3. Reserve Base	825,307
2. Repo Operations	463,501	4. Net Standing Facilities	75
		5. Other	176,242
Total Assets	1,001,624	Total Liabilities	1,001,624

* Values in million EUR.

As shown in Table 7 (also Table 9) the ECB provides liquidity to the banking system mainly via its regular *open market operations*, which satisfy: ⁵⁸

$$OMO + ML - DF = AF + CA. \text{ And } OMO = MRO + LTRO.$$

Before the turmoil the MROs represented about 70% of the refinancing and the LTROs only 30%. Thus, the bulk of the liquidity was provided by MROs on a short-term basis (weekly) and was rolled-over every week. For example, on June 29, 2007, the outstanding volumes in OMO consisted of: (i) Main refinancing operations (MROs: 313,499 million EUR) and (ii) Longer-term refinancing operations (LTROs: 150,002 million EUR).

In general, the liquidity policy of the ECB is quantity-oriented even if the objective is to steer the overnight interest rate. It is a rules-based approach where the benchmark allotment plays a central role.

⁵⁸The provision of liquidity via the marginal lending facility is negligible.

The benchmark allotment in a MRO is the allotment amount which allows counterparties to smoothly fulfill their reserve requirements until the day before the settlement of the next MRO, when taking into account the following liquidity needs:

- Liquidity imbalances that have occurred previously in the same reserve maintenance period and which were not anticipated in the preceding MRO
- ECB's forecast of the autonomous factors
- ECB's forecast of excess reserves which are assumed to be the same on each day of the reserve maintenance period

The weekly benchmark allotment is (in simplified terms) given by:

$$MRO^{benchmark} = AF^{forecast} + \underline{RR} + XR^{forecast} + \{Forecast\ error\ of\ previous\ week\}$$

Assuming: $ML - DF = 0$. The reserve requirement is fixed as it is calculated on a lagged accounting basis.

The underlying idea of the benchmark allotment is that if the ECB's forecast errors are unbiased and the forecast error variance is small compared to the reserve requirement, then the overnight rate on the last day in the reserve maintenance period should be expected to be close to the middle of the interest rate corridor defined by the rates on the standing facilities. With a symmetric interest rate corridor this policy should keep the overnight rate close to the policy rate.

In fact, on the last day of the reserve maintenance period we get the aggregate liquidity imbalance equal to the forecast error made by the ECB, the former being either a net recourse to marginal lending (liquidity shortage) or to the deposit facility (liquidity surplus).

$$ML - DF = Forecast\ Error$$

If the overnight rate is expected to be close to the policy rate on the last day of the RMP, then on any other day in the reserve maintenance period it should also be close to the policy rate by

applying the martingale hypothesis.

Empirical evidence before the turmoil matches these predictions very closely (figure 20).

Figure 21 shows that the liquidity needs of the banking system evolved very smoothly before the turmoil between 400 and 450 billion EUR. The MROs had a volume of around 300 billion EUR and the LTROs about 100-150 billion EUR. Deviations from benchmark were negligible as illustrated in figure 22.

Figure 21 further illustrates how the ECB managed liquidity during the turmoil. Four aspects are shown: i) the total volume of refinancing was kept on trend, albeit with somewhat more volatility; there was a significant increase at the end of the year mainly for seasonal reasons; ii) there was an increase in the absolute volume and relative weight of LTROs in total refinancing. However, the volume of MROs declined so that the total volume was kept on trend; iii) the ECB conducted more frequent and sizable fine-tuning operations (FTOs), both providing and draining liquidity; the latter (draining) were more frequent and sizable; A final aspect is illustrated in figure 22: iv) At the MROs deviations from benchmark became very sizable and time-varying (larger at the first MRO in the RMP and somewhat smaller in subsequent MROs in the same RMP).

A.4 Long Term Refinancing Operations

We also obtained data on ECB's LTROs. We have 19 auctions covering 10/2006 to 3/2008. As described in the institutional background, these auctions are run only once a month and they are for loans with 3-months maturity. These data are summarized in table 10 and the pre- and post-turmoil means and standard deviation in table 11. The patterns in general correspond to those from the main refinancing operations studied in the main body of this paper. The important differences are (i) the much starker increase the price bid spread against the EONIA rate following the turmoil (from 1 to 47 basis points) which is about five times the increase in the MROs and (ii) the number of participants is less than a half of those in MROs. This is probably mainly due to the overlapping maturities of the loans (monthly auction frequency and 3-month maturity) since the set of banks participating in both types of refinancing operations is very similar. This last observation allows us to perform the same exercise as in the case of MROs and use the estimated values to classify bidders into more and less distressed groups. Doing so, we obtain a similar pattern as in the MROs: only about $\frac{2}{3}$ of bidders experienced an increase in their mean (quantity-weighted) marginal value, while almost all banks significantly increased their bid spreads against EONIA suggesting more aggressive bidding strategy.

Table 10: Data Summary - LTROs

Summary Statistics				
Auctions	19			
	Mean	St.Dev.	Min	Max
Bidders	148	19	96	175
Submitted steps	2.29	1.68	1	10
Price bid	4.20	0.44	3.20	5.05
Price bid spread ^a	0.26	0.26	-0.48	1.02
Quantity bid	0.01	0.02	$1 * 10^{-5}$	0.28
Issued Amount (billions €)	49.74	8.58	40	75

^a Spread against EONIA rate.

Following the same procedure as in MROs, we estimated the marginal values that would rationalize the observed bids in LTROs. We also repeated the same exercise as in the case of MROs to classify the bidders in LTROs into the distressed and not distressed groups. The results are summarized in table 12. Due to less participation frequency (we have only 11 auction pre-turmoil and

Table 11: Data Summary LTROs: Before and After August 2007

Summary Statistics				
	Mean		Std Dev	
	Before	After	Before	After
Bidders	150.6	143.4	10.66	26.53
Submitted steps	1.76	3.04	0.94	2.15
Price bid	3.78	4.55	0.26	0.16
Price bid spread ^a	0.01	0.47	0.02	0.17
Quantity bid	0.009	0.013	0.024	0.023
Issued Amount (billion €)	46.36	54.38	5.05	9.82

^a Spread against EONIA rate.

8 auctions post-turmoil) we were able to classify only 200 bidder identities. Very similar pattern arises for those, however, as in the case of MROs. Virtually all participants significantly increased their bids, but for $\frac{49}{189}$ (or 26%) of those, this does not seem to have been accompanied by an increase in values.

Table 12: Predicting Potential Problems - LTROs

Based on	Bids	
	Yes	No
Values	Yes 140	4
	No 49	7

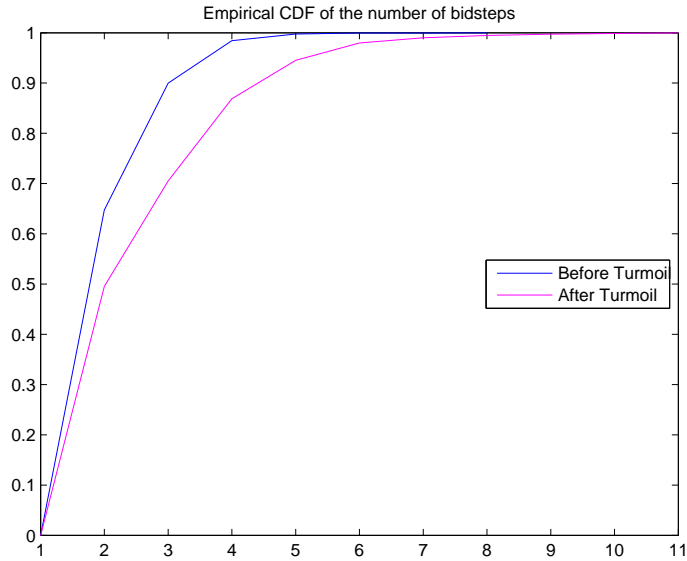


Figure 17: Distribution of the number of steps in a bid before and after the turmoil

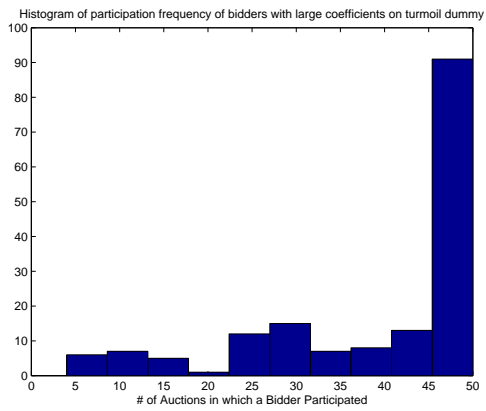


Figure 18: Histogram of Participation by Bidders with Large Significant Turmoil Effects

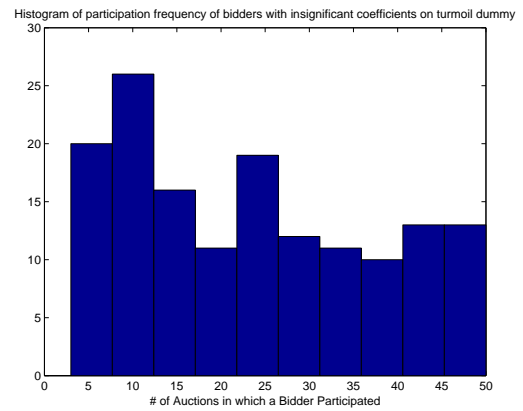


Figure 19: Histogram of Participation by Bidders with Insignificant Turmoil Effects

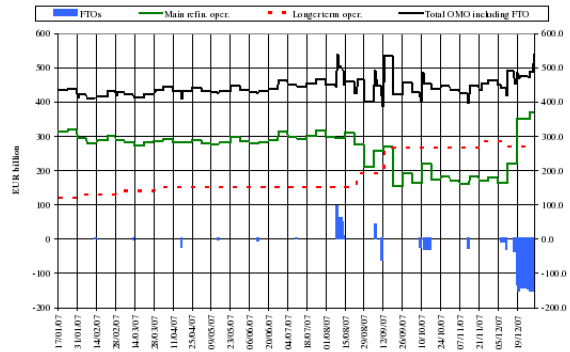
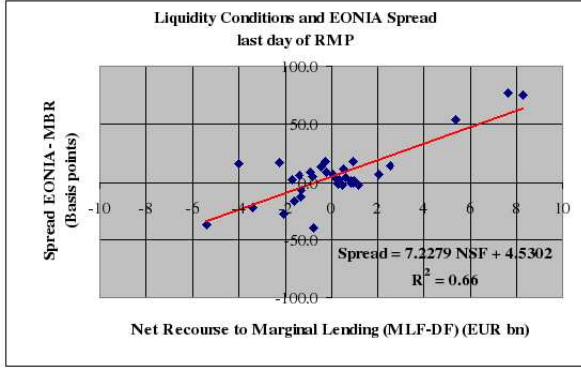


Figure 20: EONIA Spread and Liquidity Conditions on the Last Day of the RMP

Figure 21: Liquidity Provision by the ECB in 2007

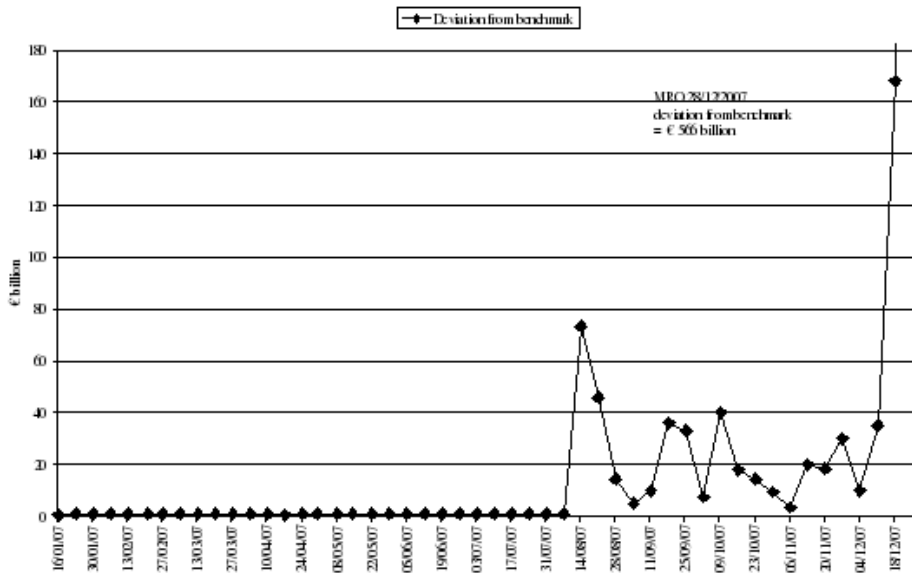


Figure 22: Deviation from Benchmark at the MROs in 2007