Liquidity of Financial Markets and the Demand for Reserves*

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Abstract

Tensions in money markets often serve as amplification mechanism for financial crises. In order to avoid this, central banks should accommodate shocks to banks' liquidity demand. This requires an accurate assessment of the aggregate demand for central bank money and its major determinants. Using a unique data set on the liquidity demand of German banks, we apply a three-parameter logistic model to estimate the aggregate liquidity demand and its main determinants. In line with several recent theoretical contributions, we find that a great asymmetric distribution of liquidity in the banking sector, a larger dispersion of credit risk in the interbank market, more volatile asset prices, a higher maturity mismatch, and a larger fraction of banks persistently refinancing though central bank operations increase the demand for central bank money. These findings reveal a mutual interrelation between money market tensions and the stability of the broader financial system that central banks need to take into account when adjusting their liquidity supply.

Keywords: Monetary Policy Instruments, Operational Framework, Liquidity Demand, Liquidity Crises, Financial Crises.

JEL Classification: C12, E41, E58, G01.

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1 Introduction

The availability of funding in money markets has a major impact on the stability of the banking sector and on the liquidity of broader financial markets, see e. g. Brunnermeier (2009) and Nyborg and Östberg (2010). In order to contain the pressure in money markets during the recent financial crisis and avoid a spill-over of those tensions to other segments of the financial system, central banks accommodated shocks to the demand for reserves and heavily adjusted their liquidity supply, see e. g. European Central Bank (2010). Yet, central banks' success in coping with liquidity demand shocks crucially depends on the accurate assessment of the determinants of market's demand for central bank liquidity. Assessing the aggregate demand for reserves is particularly important and essential if the demand itself is determined by financial market liquidity and the stability of the banking sector. To shed more light on the interrelationship between liquidity of different markets, this paper identifies an aggregate liquidity demand function for the German banking sector and investigates how it responds to variables derived from economic theory.

In its weekly-held main refinancing operations (MROs), the European Central Bank (ECB) auctions liquidity for a period of one week. During our sample period from June 27, 2000 to October 15 2008, the MROs were conducted as pay-your-bid auctions, i.e. as multi-unit price-discriminatory auctions.[1] Hence, the price-quantity pairs that financial institutions place in these auctions provide a good indication of bank's actual willingness to pay for liquidity. We have access to the unique record of the demand schedules of all German banks that submitted to the ECB's money market auctions from June 2000 onwards. This allows us to derive an aggregate demand function for the complete German banking sector. Following the methodology of Berg et al. (1998) and Boukai and Landsberger (1999), we identify an aggregated bid curve by applying a three-parameter logistic model to banks' cumulated bidding behavior for each auction within our sample. In a second step, we explore the determinants of the three model parameters that describe the aggregated demand functions. This analysis strongly benefits from our unique data on the daily reserve holdings and the monthly balance sheet statistics of each German financial institution.

We find several factors that affect the level and slope of the aggregate demand for reserves. First, our results suggest that before the crisis a larger dispersion of banks' reserve fulfillment increased German banks' willingness to pay for central bank liquidity and lowered the price elas-

[1] Prior to June 2000 and in the aftermath of the Lehman-collapse, the Eurosystem applied a fixed-rate tender rather than a variable rate tender. For further details, refer to European Central Bank (2011).

ticity of liquidity demand. Also during the crisis, a larger dispersion of banks' reserve fulfillment induces more aggressive bidding behavior. In contrast to the pre-crisis period, however, this effect is observed in all *but* the last MRO of a reserve maintenance period. Second, we find that during the crisis higher volatility of stock prices significantly increased the demand for reserves and banks' willingness to pay. Similarly, only after August 2007 a large dispersion of banks' equity ratio elevates banks' willingness to pay for reserves and induces higher dispersion of bids. A large share of tradable securities on banks' balance sheets decreased the level of the liquidity demand before the crisis. During the crisis, a larger share of tradable assets leads to a lower willingness to pay. Finally, we find that a rise in the ratio of banks that persistently refinance through central bank operations increases both the level of reserve demand as well as its price elasticity. We also test whether liquidity demand is determined by the average maturity mismatch on German banks' balance sheets. Our results suggest that a high level of maturity mismatch increases banks' dependency on the primary money market both before and during the recent financial crisis.

Our findings confirm a number of recent theoretical predictions. The observation that a large dispersion of liquidity holdings in the banking sector leads to an upward shift of the reserve demand in the primary money market implies that frictions in the money markets prevail. The ECB follows a neutral liquidity policy, i.e. its allotment complies with the aggregate amount of reserves that allows banks' smooth fulfillment of reserve requirements, see European Central Bank (2004a). Against this background, a higher dispersion among banks' reserve fulfillments indicates that larger amounts of liquidity need to be reallocated within the banking sector. Thus, our findings show that the larger the need for liquidity reallocation through the secondary money market is, the more willing are banks to pay for funding in the euro area primary market for reserves. In that sense, our study confirms the argument pointed out by Freixas et al. (2010), namely that larger idiosyncratic liquidity shocks in the banking sector partially inhibit the liquidity insurance role of banks and thus lead to higher secondary money market rates. Their argument, though, rests on Bhattacharya and Gale (1987) and Bhattacharya and Fulghieri (1994) on the basis of the assumption that bank-specific liquidity shocks are unobservable and banks therefore tend to free-ride on the secondary market for central bank liquidity. This in turn is argued to result in an under-investment in liquidity and elevate money market rates. Our results could, in addition, also reflect the fear of money market squeezes, as pointed out by Nyborg and Strebulaev (2004). As a result of the ECB's neutral liquidity provision, some banks with excess reserves might gain market power over liquidity-short banks. Thus, the more asymmetric liquidity is distributed in the banking sector, the larger is the fear of such market squeezes and the more banks are willing to pay in the primary money market.[2] In this regard, our paper builds on the findings of Fecht et al. (2011) obtained for the period 2000 to 2001.

Our result regarding the heterogeneity in banks' equity ratios fits very well the predictions of recent theoretical work that highlights the role of asymmetric information about credit risk in the secondary money market. For instance, Freixas and Jorge (2008) point out that a higher dispersion of the credit risk increases the information risk premium in the secondary money market. Furthermore, it might induce higher incentives for liquidity hording and contribute to a market dry-up, as shown by Heider et al. (2010). This, in fact, might explain why we find a significant influence of the dispersion of the equity ratio only in the crisis period.

This paper also relates to the theoretical literature that suggests an interplay between liquidity needs and prices in the broader financial markets, see e. g. Allen and Gale (1994), Acharya et al. (2009), and Brunnermeier and Pedersen (2009). Under cash-in-the-market pricing, liquidity shocks affect asset prices and lead to a higher price volatility. At the same time a higher asset price uncertainty induces banks to hold larger liquidity buffers as pointed out by Allen and Gale (2004). Brunnermeier and Pedersen (2009) find that more volatile asset prices tighten financial institutions' liquidity constraints and thereby elevate the demand for central bank reserves. And vice versa, they also point out that tighter liquidity constraints may also trigger a feedback effect on asset price volatility. Both mutually reinforcing dynamics generate a liquidity spiral where tighter liquidity constraints increase volatility of asset prices which in turn exacerbate liquidity constraints even further. Nyborg and Östberg (2010) provide strong empirical evidence for the former effect, i.e. that tensions in the interbank money market give rise to an increased volatility in asset prices in the broader financial markets. Our analysis refers to the latter channel and shows that a dry-up of asset market liquidity associated with a higher price volatility indeed increases banks' demand for liquidity. Nyborg and Östberg (2010) together with our paper imply that liquidity spirals exist.

Our paper also complements earlier empirical studies that explore banks' bidding behavior in central bank auctions from a bank's individual perspective, see e. g. Linzert et al. (2007), Bindseil et al. (2009), and Cassola et al. (2009). These papers show that money market conditions significantly affect bank's *individual* demand behavior and thus the auction outcome. However, these papers do not intend to explain the determinants of aggregate market demand. To the best of our knowledge, Berg et al. (1998), Boukai and Landsberger (1999) and Preget and Waelbroeck (2005)

[2]See also Acharya et al. (2008) for similar arguments.

are the only empirical studies on aggregate bid functions. But they argue that fluctuations from one auction to the other can be explained by random perturbations on the parameters of the aggregate demand curve.[3] Using Israeli, Norwegian and French data sets, respectively, these authors therefore solely focus on an identification of an econometric model that describes the aggregate behavior of Treasury bill auction participants, observed during the period 1995 - 1997. The current paper is the first study that we are aware of which (i) estimates an aggregate demand function for liquidity for the German banking sector, (ii) captures the period as of March 2004 through October 2008, and most importantly (iii) relates the empirical approach to economic theory to test theoretical predictions.

The remainder of the paper is organized as follows. The next section briefly describes the Eurosystem's operational framework. Section 3 identifies a market demand function for the German banking sector and discusses the results. In Section 4, we elaborate on the theoretical literature to derive testable predictions regarding the determinants of market demand for central bank liquidity. Furthermore, we use our data set to test these hypotheses. Section 5 summarizes our key results and draws some policy conclusions.

2 Eurosystem's Institutional Framework

In the euro area, the demand for liquidity is predominantly driven by reserves that banks are obliged to hold with the Eurosystem. These reserve requirements are specified as an average of the end-of-day reserve balances over a reserve maintenance period (RMP). In our sample a maintenance period is defined as the cycle between the first Governing Council meeting of two consecutive months and might therefore have a duration ranging from 28 to 43 days. Reserve requirements amount to 2% of a bank's short-term liabilities held by private non-banks as reported in the balance sheet of the respective bank, two months prior to the beginning of the maintenance period.[4] While there is an interest rate paid on required reserve holdings, reserves held in excess remain unremunerated.[5]

[3] Even though Preget and Waelbroeck (2005) attempt to attribute the variations of aggregated bid curves across auctions in France to some random economic variables, they also conclude that the bulk of fluctuations are mostly random.

[4] This consists of overnight deposits, deposits with an agreed maturity of up to two years, deposits redeemable at notice up to two years, and issued debt securities with agreed maturity of up to two years held by households, the non-bank corporate sector, and banks from outside the euro area.

[5] The Eurosystem applies a certain discretion on how to penalize under-fulfillments. Nevertheless, the penalty rate imposed on reserve deficiencies is the highest interest rate charged such that under-fulfilling the reserve requirements becomes the costliest option.

However, the sum of the autonomous liquidity factors is larger on the liability side than on the asset side of the Eurosystem's balance sheet. This implies that the euro area banking sector operates in a liquidity deficit vis-a-vis the Eurosystem. That is, banks need to get refinancing from the European Central Bank (ECB) in order to comply with their reserve requirements. The ECB provides liquidity in a neutral fashion, i.e. its liquidity allotment is oriented towards the estimated liquidity needs of the euro area banking sector. Prior to each auction, the ECB publishes its benchmark allotment such that all banks are informed about the amount the ECB deems appropriate to allocate, see European Central Bank (2004b).[6]

During our sample, the ECB mainly allocates liquidity through an auction mechanism to the banking sector. In this respect, a pivotal role has been assigned to ECB's main refinancing operations (MROs). These operations are conducted on a weekly basis. In these auctions, banks bid for reversed repurchase agreements (repos) with a maturity of one week.[7] Unlike the U.S. Federal Reserve System (FED), any bank that holds reserves with the Eurosystem and meets several eligibility requirements may participate in these tender operations. In the first meeting of each month, the Governing Council of the Eurosystem sets a minimum bid rate that serves as the key monetary policy interest rate. Banks that intend to participate in an MRO are required to place their bids higher than this minimum bid rate. The MROs follow a multi-unit pay-your-bid auction format where banks are allowed to submit *multiple* price-quantity bids. That is, each bidder may submit up to 10 bid-quantity pairs where the tick size is 1 basis point and the quantity multiple is 100,000 euros. These bids provide a good indication of bank's willingness to pay for central bank liquidity and thus allow us to study the aggregate demand behavior. But it should be noted that this auction mechanism might induce strategic bidding behavior by means of bid shading, see e. g. Nautz and Wolfstetter (1997). That is, the reported bid-quantity schedules might not reflect the exact willingness to pay. Nevertheless, this is the best information available under a multi-unit discriminatory auction format.

The liquidity obtained through the ECB is redistributed in the secondary money market. That is, instead of refinancing in the ECB's repo auctions, an individual bank may also obtain central bank money from the secondary money market. In fact, between two consecutive MROs, the ECB

[6]The benchmark allotment is the amount normally required to establish balanced conditions in the short-term money market, given the ECB's complete liquidity forecast. Balanced liquidity conditions should normally result in an overnight rate close to the ECB's policy rate, see European Central Bank (2003)

[7]Beyond the MROs, the Eurosystem also facilitates liquidity through long-term refinancing operations (LTROs). But these operations are beyond the scope of this chapter.

is usually not actively managing liquidity supply. In contrast to the U.S. FED, the ECB makes only very infrequent use of its so called fine-tuning operations, which are usually conducted with a small preselected group of large banks at very short maturities. Thus, between two consecutive MROs, banks generally need to resort to the secondary money market to satisfy their funding needs. This creates some (imperfect) arbitrage opportunities. For instance, instead of bidding for a reversed repo in an MRO, a bank can also borrow with a one week maturity in the Eurepo market.[8] The quality of collateral required in the Eurepo market is higher than what is needed in the MROs. Alternatively, a bank can also buy a one week Eonia-swap which guarantees a bank the payment of a Eonia-swap interest rate in exchange for receiving the result of capitalizing the Eonia rate for a life span of one week.[9] Thus, it permits a bank to borrow in the overnight market a certain amount without incurring any further interest rate risk. However, this constitutes only an imperfect arbitrage, because (i) banks are not necessarily able to borrow at the Eonia, and (ii) the involved credit, collateral and auction risk differ in an Eonia-swap compared to borrowing in an MRO auction.

In order to contain interest rate fluctuations in the secondary money market within a reasonable range, the ECB provides banks with two additional standing facilities. The marginal lending facility grants banks unlimited access to overnight liquidity at a penalty rate that was 100 basis points above the minimum bid rate in our sample period.[10] When drawing on the marginal lending facility, banks have to provide sufficient collateral meeting the general eligibility criteria for open market operations. At the deposit facility, banks can deposit excess liquidity at a rate which was 100 basis points below the minimum bid rate. Arbitrage opportunities prevent banks from trading central bank liquidity outside the corridor set by these two standing facilities.

[8] The Eurepo market refers to the collateralized segment of the euro area money market and constitutes one of the highest trading platforms within the euro area. For further details see http://www.eurepo.org.

[9] In this interest rate swap, as with most swaps, there is no initial or final exchange of principal. The notional principal amount is solely used to determine the two interest rate flows, which in any case are settled via a single net payment at maturity. The European Over-Night Index Average (Eonia) is a reference rate for the overnight segment of the unsecured money market. The Eonia swap market covers roughly 40% of the overall OTC derivatives market, see e. g. European Central Bank (2007).

[10] Note that although the marginal lending rate is well above the key interest rate, it is well below the penalty rate applied to the reserve deficiencies.

3 Identification of a Market Demand Function

3.1 Data Description: Banks' Bidding Behavior

We have a record of all price-quantity pairs that each German registered financial institution placed in the Eurosystem's MROs during the period June 27, 2000 to October 15, 2008. This data is provided by Deutsche Bundesbank and covers on average 48% of the MROs' aggregate bid and total allotment volume. Among all MRO participants, 67% are German banks. Thus, we have a relatively large snapshot of overall bid-quantity pairs submitted in Eurosystem's MROs.

Until March 2004, banks anticipated future rate cuts of the ECB on several occasions and, therefore, simply refrained from bidding in the MROs, see e. g. Bindseil (2004). As a result, the ECB could not allot the intended volume of reserves needed for a smooth fulfillment of reserve requirements in the period until the subsequent MRO. This caused severe reserve imbalances in the short-term money market. In order to stop the disturbing strategic bidding behavior of banks, the ECB adjusted its operational framework in March 2004. The MRO maturity was reduced from two to one week and ECB's interest rate decisions were synchronized with the reserve maintenance period, see e. g. European Central Bank (2003). Additionally, the ECB facilitated counterparties' anticipation of its liquidity allotment in the MROs by publishing its assessment of the banking system's liquidity needs that serves as the basis for its allotment policy. As a result of the exacerbated crisis in the post-Lehman period, the ECB switched its MRO auction format from a variable rate tender to a fixed rate auction design with full allotment as of October 2008. In a fixed rate tender with full allotment, every information about the MRO-related refinancing conditions is already pre-announced. This new auction format reveals no information on the banks' willingness to pay as it requires only the submission of the liquidity amount. The interest rate at which liquidity will be provided to MRO participant is pre-announced by the ECB. To account for the structural change stirred by both reforms of the ECB's operational framework as of March 2004 and October 2008, respectively, we select the sample period from March 09, 2004 to October 09, 2008 for our analysis. Furthermore, we will divide the sample into a pre-crisis and crisis period as of August 2007.[11] Within this sample period, we have a total of 240 MRO auctions, i.e. 178 for the pre-crisis and 62 for the crisis period, respectively.

[11] Structural breakpoint tests support this date as the start of the financial crisis, see Section F in the appendix.

3.2 An Empirical Model for Aggregate Liquidity Demand

Some Preliminary Considerations

Before we suggest an appropriate econometric model to derive a market demand function, we first order the reported bids for each auction t. Recall that the tick size is 1 basis point. This allows a discrete and ascending ordering for $i = 1, \ldots, n$ distinct rounded yields that emerged from all $j = 1, \ldots, m_i$ submissions such that $r_1 \leq r_2 \leq \ldots \leq r_n$. Second, we aggregate the liquidity demand of all participants within each ordered yield class i of the respective auction. In a last step, we cumulate this sum of quantities in a way that for each auction t, the collection of i yield classes with the corresponding cumulated quantities, $\sum_{i=1}^{n} \sum_{j=1}^{m_i} L_{ij}^d \geq \sum_{i=2}^{n} \sum_{j=1}^{m_i} L_{ij}^d \geq \ldots \geq \sum_{j=1}^{m_1} L_{nj}^d$ form our aggregated bid curve.

To control for the effect of (imperfect) arbitrage opportunities with respect to the secondary money market, we normalize the ordered auction bid classes, r_i, by the one-week Eonia swap rate, $swap^{1w}$. This normalization follows Bindseil et al. (2009) and allows us also to compare bids over time. We use the one-week swap rate as it corresponds to the average short-term interest rate that is expected to prevail over the maturity of the MROs. It is therefore less affected by outliers than the daily Eonia. Because MROs are conducted only once a week, the one-week Eonia swap rate prevailing at the auction's announcement day cannot be affected by expectations about future auction outcomes.[12] The timing of the MROs suggests to use Eonia swap rates prior to the auction day. Hence, we normalize the submitted bids for each auction t as follows:

$$\widetilde{r}_{it} = r_{it} - swap_t^{1w}, \quad t = 1, \ldots, T \tag{1}$$

where we use the index t to account for the auctions and i for each ordered yield class along the market demand function. $swap_t^{1w}$ refers to the one-week swap rate that we have observed at the announcement day of auction t, i.e. one day before the repo auction.

For an intertemporal comparison of auctions with different volumes, we will also normalize the aggregate liquidity demand in a way that enables a unified and unit free re-scaling:

$$l_{it}^d = \frac{\text{aggregate liquidity demand}_{it}}{\tilde{L}_t^s}, \tag{2}$$

where for each auction t, aggregate liquidity demand at each ordered yield class i is expressed relative to the ECB's aggregate liquidity supply ($\tilde{L}_t^s$). The ECB's total allotment, however, reflects

[12] Alternatively, we used the one-week Eurepo rate. Refer to Section C of the appendix to see that the results remain qualitatively similar.

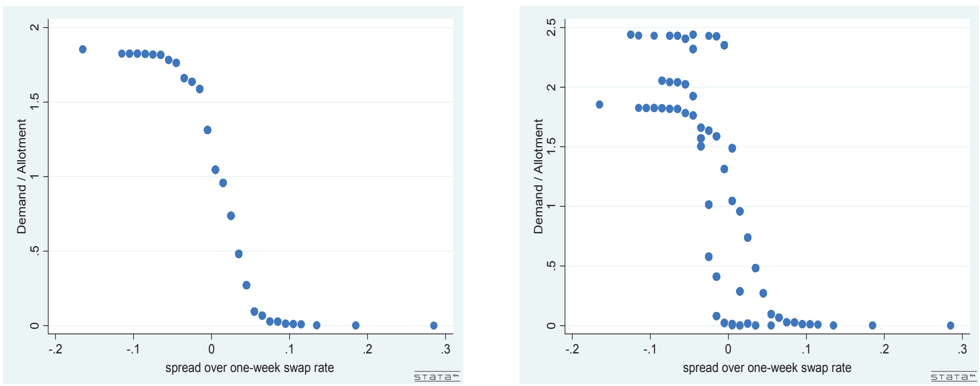
its aggregate liquidity supply to all banks within the euro area (EU). Therefore, we adjust the total allotment for the fraction of German banks (GE) as follows:

$$\tilde{L}_t^s = L_t^s \cdot \frac{\text{cumulative required reserves}_{\text{p}}^{\text{GE}}}{\text{cumulative required reserves}_{\text{p}}^{\text{EU}}} \tag{3}$$

with *p* denoting the respective reserve maintenance period. Note that l_{it}^d is thus a measure for the *excess liquidity demand* or the *disproportional recourse* to Eurosystem's credit.

Figure 1 plots the collection of i price-quantity pairs for one MRO (left figure) and several MRO auctions (right graph) in our sample. Consider the aggregated bid curve for a single MRO auction depicted in the left graph. Each circle represents the cumulative sum of liquidity demand as a fraction of total allotment at the respective yield class in the respective auction.

Figure 1: Some Observed Aggregated Bid Curves



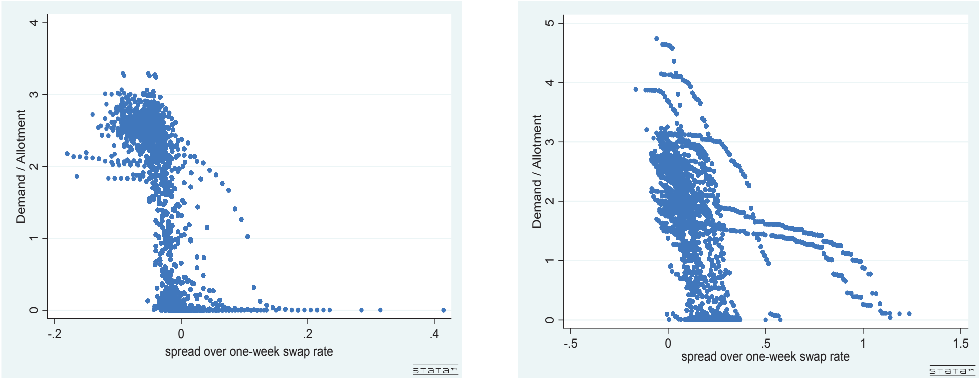
(a) An aggregate bid curve for one MRO (b) The aggregate bid curves for four MROs

Notes: While the left graph reflects the aggregate bid function of one MRO auction, the right panel shows the bid curves for all MROs conducted in December 2005. Each dot on the respective aggregate bid curve represents the cumulated sum of liquidity demand as a fraction of total liquidity supply for the respective bid rate.

The form of this observed aggregate bid function shows two horizontal segments at the lower and upper ends and a decreasing part in between. The pattern is initially slightly concave and then convex. These three segments may be interpreted as follows. The upper end shows that above a given quantity the market is not willing to absorb more liquidity even at very low rates. The middle section may imply that due to arbitrage opportunities the vast majority of bids are placed closely around the one-week swap rate.[13] The lower end of the market demand function means that at the auction there is a demand for a certain (small) amount of liquidity, for which some have

[13]Mind the differences for our crisis sample. We will discuss this in more detail in the next section.

Figure 2: All Observed Aggregated Bid Curves



(a) Aggregate bid curves before August 2007 (b) Aggregate bid curves after August 2007

a relatively high willingness to pay. Despite large fluctuations, we observe this general pattern for all aggregate bid curves in our sample, see Figure 2.

Empirical Model

Following Boukai and Landsberger (1999), we apply the following three-parameter logistic function to model the observed aggregated bid curves:

$$l_{it}^{d} = \frac{\alpha_t}{1 + exp(\frac{(\widetilde{r}_{it} - \tau_t)}{\lambda_t})}, \tag{4}$$

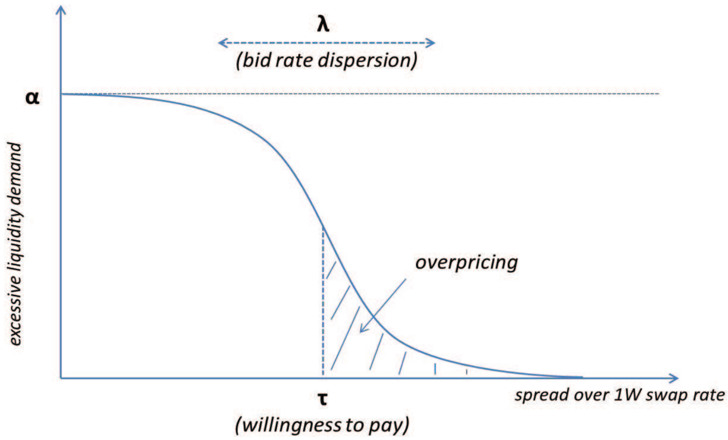
with $\alpha > 0$ and $\lambda > 0$ and where L^d denotes the aggregated liquidity demand (in terms of volume) for each normalized bid rate $\widetilde{r}$. τ may be both negative and positive.[14] The scalars $\widetilde{r}_{it}$ and l_{it}^{d} represent the coordinates of the *i*th observed yield class of auction *t*. The three parameters of our logistic function of auction t are captured by $\theta_t = (\alpha_t, \lambda_t, \tau_t)'$. We do not claim that our specification is the only way to describe the data. In fact, running an *n*th order polynomial may yield better results. However, the usage of the logistic curve has various advantages.[15] First, it is flexible as it captures both the convex and concave features of the demand function observed in our data, see Figure 2. Second, it describes the price-quantity relationship with only three parameters. Third, as will be shown below, the fit is quite astonishing. Fourth and most importantly, however,

[14]Alternatively, we allowed for asymmetries around τ. However, the results remained qualitatively the same (not reported, but available on request). This is intuitive since bidders submit a *schedule* of demand functions. Hence, the quantities demanded for average rates should be higher than for extreme rates. It is reasonable to think that bids are concentrated around a mean and that bids are therefore distributed with a single mode. In other words, this can be interpreted as the integral of a bell-shaped density function of interest rates. This would suggest a rather symmetric distribution of bids around the inflexion point.

[15]The general properties of the logistic curve are well described in Kotz et al. (2006).

these parameters allow for economically highly relevant interpretations. Figure 3 illustrates our three parameters of the market demand function.

Figure 3: Logistic Market Bid Function



α represents the *market satiation level*, beyond which there is no demand for central bank liquidity in the primary market "regardless" of its price. Obviously, potential bids have a lower bound since submissions below the minimum bid rate are not considered. Hence, a is the asymptotic value of L^d as r approaches the lowest bid allowed, i.e. the minimum bid rate. Roughly speaking, it is the height of the almost horizontal segment at the beginning of the curve. Since all volumes are set equal to 1, the parameter $\alpha - 1$ may also be interpreted as the magnitude of unsatisfied liquidity demand.

The parameter τ determines the location of the market demand function and hence measures the position of the bids relative to the secondary money market rate. Due to the logistic specification, τ reflects the (unique) inflexion point of our market demand function that happens to be the value of $\widetilde{r}$ at which the market reaches half of its satiation level, i.e. $\frac{a}{2}$. This parameter may therefore reveal the *willingness to pay* or the *degree of overpricing*.

λ, as the scale parameter, measures the *dispersion of the bids* around τ. A larger amount of uncertainty leads to more dispersed bids and thus to a higher λ. Furthermore, this parameter is closely linked to the price elasticity of reserve demand, see Appendix for further details.

To estimate Equation (4), we apply the method of non-linear least squares that minimizes the sum of squared residuals. As starting values for the iterative algorithm, we use the estimates of a linear transformation of the logistic function in (4). This ensures the convergence of the minimization algorithm to a global minimum. Hence, these preliminary parameter estimates are obtained as follows

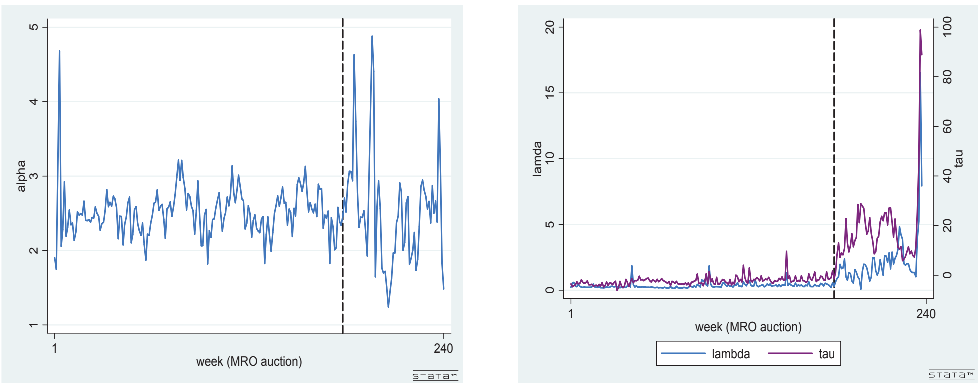
$$log(\alpha_t - 1) \quad = \quad -\frac{\tau_t}{\lambda_t} + \frac{1}{\lambda_t}\widetilde{r}_{it} + \varepsilon_{it}, \qquad (5)$$

To use this specification, however, we must assign a value to α. Following Preget and Waelbroeck (2005), we use the highest observation for each auction. However, to avoid division by zero, we use exactly 101% of this value. We can then estimate parameters $\beta_{1t} = -\frac{\tau_t}{\lambda_t}$ and $\beta_{2t} = \frac{1}{\lambda_t}$ for each auction by the ordinary least squares method. Note that this approach only allows for the determination of the initial values of two parameters of the logistic curve: $\widehat{\lambda_t} = \frac{1}{\widehat{\beta_{2t}}}$ and $\widehat{\tau_t} = -\frac{\widehat{\beta_{1t}}}{\widehat{\beta_{2t}}}$.

3.3 Identification of a Market Demand Function: Empirical Results

Figure 4a presents our estimates of α for each auction as of March 2004. It shows that before August 2007 our point estimates of α vary roughly between 2 and 3, i.e. German banks' satiation is twofold and threefold higher than the level required to fulfill liquidity needs. During the crisis, the span within which excessive liquidity demand fluctuates widens. However, Table 1 reveals that the average factor remains at roughly 2.5. Furthermore, $\hat{\alpha}$ shows large across-auction fluctuations implying that excessive liquidity demand varies across auctions.

Figure 4: Estimation of Model Parameters



(a) Estimation of the excess liquidity demand α

(b) Estimation of the bid rate dispersion λ and the willingness to pay τ

Figure 4b reflects the estimates of λ and τ for all 240 auctions. Prior to the crisis, the estimates for λ show an average dispersion value close to zero.[16] The figure reveals that German banks placed

[16]For illustration reasons we have multiplied λ and τ by 100.

Table 1: Summary Statistics: Parameter Estimates

Parameter estimates	Units	Mean	Std	Min	Max
09 Mar 2004 - 31 Jul 2007: 178 auctions					
$\widehat{\alpha}$		2.49	0.27	1.75	3.21
$\widehat{\lambda}$		0.35	0.22	0.15	1.85
$\widehat{\tau}$	bp	-2.29	1.72	-6.04	9.69
08 Aug 2007 - 09 Oct 2008: 62 auctions					
$\widehat{\alpha}$		2.51	0.75	1.24	4.88
$\widehat{\lambda}$		2.41	2.88	0.07	16.59
$\widehat{\tau}$	bp	18.35	16.43	-1.41	98.63

Notes: The table refers to Equation (4). $\hat{\alpha}$ denotes the estimated aggregate liquidity demand relative to total reserve requirements of the German banking sector such that $\hat{\alpha} - 1$ reflects the estimated magnitude of unsatisfied (excessive) demand. Note that we have multiplied both $\hat{\lambda}$ and $\hat{\tau}$ by 100.

their bids very close around the one-week swap rate. After the onset of the crisis, however, bids became increasingly dispersed around their swap rate counterpart. According to Table 1, there is on average a sevenfold increase of bid rate dispersion relative to the pre-crisis sample.

A similar pattern can be observed for the location parameter τ. Before the crisis, $\hat{\tau}$ moves moderately close to zero. In that sense, the estimates of τ show the close link between the one-week swap rate and the price for liquidity in the primary money market. The average inflexion point of a typical market demand function is at -2 basis points. That is, the typical willingness to pay for liquidity in the ECB's auctions is on average 2 basis points lower than in the secondary money market. During the crisis, however, banks are typically willing to settle for prices that deviate on average more than 18 basis points from secondary money market prices.

3.4 Discussion of Results

The fact that banks demand on average more reserves than they need to smoothly fulfill their requirements may imply that participating German banks bid rather as a buy-and-sell strategy than with the incentive to buy and keep most of their liquidity locked in their portfolios. This conjecture may be derived from the following consideration. To contain the opportunity costs, euro area banks have two alternative strategies to deal with their excess reserves: (i) they may either park their liquidity surplus in the Eurosystem's deposit facility or (ii) lend it in the secondary money market. Before October 2008, however, euro area banks' recourse to the deposit facility was rather of negligible amount, see e. g. Heider et al. (2010). Hence, there is reason to believe that German banks lend their excess funding in the secondary money market.

Larger fluctuations of $\hat{\alpha}$ throughout the crisis period are consistent with anecdotal evidence that German banks had a stronger preference to over-satisfy their liquidity needs at an early stage of the reserve maintenance period. In order to respond to this change in banks' liquidity demand pattern, the ECB started to allot significant excess liquidity at the beginning of the maintenance period during the crisis. This excess liquidity was then gradually reabsorbed over the remaining weeks of the period by reducing the allotment above the benchmark. On average, banks still continued to have a liquidity surplus close to zero at the end of each period as before August 2007, see e. g. European Central Bank (2010). This might explain why both the lower (min) and upper (max) end of the fluctuation range has changed.

The estimation results obtained for λ indicate that the secondary money market plays a pivotal role in banks' bidding behavior. Before the crisis, German banks were willing to settle for yields that deviate only slightly from interbank money market rates. In fact, this "rigidity" around zero may imply that the swap market is indeed perceived as a fairly good substitute for the primary money market by German banks. In other words, before August 2007 swap rates represented very well the yields that the German bidders could get if they traded on the secondary money markets instead of at the auction. Therefore, there was no reason for these financial institutions to deviate significantly from secondary money market rates when they bid at the MROs. For the period after August 2007, however, our results change substantially. The lower part of Table 1 shows that not only bids vary among German banks (mean) at each auction but also across banks across auctions (standard deviation). This observation suggests that different German banks faced different funding conditions in the secondary money market.

Similar interpretations may be drawn for our estimations of τ. While we observe an average underpricing of central bank liquidity in the primary money market before August 2007, the German banking sector has a significantly higher willingness to pay during the crisis. The empirical literature identifies the volatility of bond returns as the key driver for bank's bidding behavior and underpricing, see Nyborg et al. (2002), and Keloharju et al. (2005). These papers find that when volatility increases, the typical bidder tends to reduce the average price at which he bids, lowers his total demand, and increases the dispersion of his bids. Their evidence also suggests that the dominating element behind the observed behavior and underpricing is that bidders have private information and adjust rationally for the champion's plague.[17]

However, all these conjectures need a further elaboration. Therefore, we will devote the next part of our exercise to the identification of potential determinants that shape the three parameters of our aggregate liquidity demand. For this purpose, we relate the effects and determinants raised in the literature to specific variables in order to assess the explanatory power of the different theories. Our analysis will substantially benefit from our data set that we obtained from the Deutsche Bundesbank.

4 The Determinants of Market Demand for Liquidity

4.1 Data Description

We have data on reserves from every German registered financial institution in the period January 2004 to October 2008 that was required to hold central bank reserves with the Eurosystem. In total, we are able to capture daily reserve data on 1975 German financial institutions as of January 2004. The reserve data includes (i) each institution's cumulative reserve holdings of each day during the respective maintenance period, (ii) the bank's marginal reserve holdings at the end of each business day, and (iii) each institution's reserve requirements for each maintenance period. We consider each bank that has bid at least once in the ECB's MROs as a bidder. In the same vein, we identify 1067 out of the 1975 German financial institutions as MRO bidders during our sample.

Additionally, we have each bank's end-of-month balance sheet data as it is collected by Deutsche Bundesbank within the scope of its bank balance sheet statistic survey. All German banks are required to contribute to this poll on a monthly basis. For all the banks in our sample, we obtain balance sheet data as of the last calendar day of each month. The data covers each bank's balance sheet position for the period January 1999 through December 2008.[18]

Based on unique bank codes, we are able to merge these data sets with the data on banks' bidding behavior from above. For our analysis we will adopt the same sample period as above. Thus, as of March 2004 we have data on 57 end-of-month balance sheet statistics. Neither the data on reserves nor the results of the balance sheet survey are publicly available. To the best of our

[17] For the discriminatory auction mechanism, Ausubel (2004) has suggested the terminology *champion's plague* instead of the winner's curse, to emphasize that the more units a bidder wins, the worse news it is.

[18] Further details and an overview of the complete balance sheet data is available on `www.bundesbank.de/meldewesen/mw_formbankenstatistik_bilanzmfi.en.php`.

knowledge, this is the first time that these data are jointly used. The variables that we will derive from these data will be motivated by economic theory as we will discuss in the next section.

4.2 Variables and Hypotheses

Interbank Market Frictions

Financial institutions can either seek funding from the primary or the secondary money market to fulfill their liquidity needs. This creates a scope for arbitrage opportunities between these two markets, which in turn may induce frictions.

One major friction is that the interbank money market is not a fully competitive market. Banks might gain market power in the secondary money market because the amount of reserves available in the market is predetermined by the central bank's liquidity allotment.[19] Thus, individual banks can try to corner the market, ration liquidity supply and squeeze liquidity-short banks. The ability of individual banks to follow that strategy depends on the distribution of excess reserve holdings in the banking sector. That is, the more concentrated excess reserve holdings are, the larger is individual banks' market power.[20] As a consequence, banks that rely on the secondary money market to satisfy their liquidity needs run the risk of paying excessive rates, in particular when reserve holdings are asymmetrically distributed. This fear of being squeezed is what Simon (1994) labels the *loser's nightmare*. Nyborg and Strebulaev (2004) show within a theoretical model that the fear of market squeezes leads to more aggressive bidding behavior in the Eurosystem's repo auctions.

Imperfect information in financial markets creates a second interbank money market friction. This is because bank-specific liquidity shocks are unobservable and because banks cannot monitor each other's balance sheets. As pointed out by Bhattacharya and Gale (1987), this informational asymmetry generates an incentive for banks to cover not only their idiosyncratic liquidity shocks, but also to refinance their average liquidity needs in the interbank market. Banks under-invest in reserve holdings because long-term investments usually have a higher expected yield than liquidity holdings. Thus, banks try to save on these opportunity costs by reducing their precautionary

[19] Note that the liquidity neutral allotment policy of the ECB generates a cash-in-the-market constraint. There are a number of theoretical contributions showing that such a cash-in-the-market constraint might induce market power in the secondary money market, see e. g. Hakenes and Fecht (2006) and Acharya et al. (2008).

[20] Recall that this stems from the fact that liquidity is tight in the euro area banking sector. That is, if one bank has more than it needs, another must have less.

liquidity holdings and expect to manage their liquidity needs with excess liquidity offered by other banks in the secondary money market. Among German banks, individual savings banks and cooperatives may free-ride on the efforts of their head institutions, ultimately proving costly for them, see Fecht et al. (2011).[21] In equilibrium, this under-investment in liquidity leads to an excessively high interbank money market rate, i.e. the arbitrage-free interbank rate exceeds the welfare optimal rate.[22] An excessively high secondary money market rate, however, involves particularly large inefficiencies if the need for liquidity reallocation is high.[23] The larger the asymmetry in liquidity holdings in the interbank money market, the larger is the need for a reallocation. This increases the costs of the excessively high secondary money market rate for liquidity-short banks and thereby the costs of this friction. Consequently, if reserves are very unevenly distributed in the banking sector, banks' willingness to pay for reserves in the primary money market should be higher. As a strategy to protect themselves, banks may disperse their bids while bidding aggressively. Both theoretical arguments lead us to the first empirically testable hypothesis:

Hypothesis 1 *A larger dispersion of reserve holdings in the banking sector increases banks' willingness to pay (τ), banks' bid rate dispersion (λ), and their excessive liquidity demand (α).*

In order to test this hypothesis we use our data on banks' reserves. We determine the variable *remaining required reserves* for each bank b in our sample immediately before the auction t, i.e. on the announcement day, such that

$$\text{remaining required reserves}_{btp} = \frac{\text{total required reserved}_{bp} - \text{cumulative holding}_{btp}}{\text{days left of maintenance period}_{btp}}, \tag{6}$$

where p denotes the respective reserve maintenance period. This measure reflects what each bank needs to hold from auction t's perspective on a daily basis to exactly fulfill its requirements within the ongoing maintenance period. To account for the heterogeneity in liquidity needs among all German banks, we further compute the *standard deviation* across all banks' remaining required reserves on the announcement day of auction t within period p.

Intuitively, as the reserve requirements become binding towards the end of the reserve maintenance period, the potential for market squeezes increases and thus the fear of market squeezes should also become more apparent. Moreover, at the beginning of a maintenance period, banks

[21] For an earlier discussion of the free-rider problem within alliances see Olson Jr. and Zeckhauser (1966).

[22] This is, for instance, pointed out by Allen et al. (2009) who argue that it is the central bank's role to correct for that under-investment in liquidity by increasing the supply of reserves through open market operations and bring down the money market rate to its optimal level.

[23] In fact, Freixas et al. (2010) assert that the central bank's need to stabilize interbank money market rates increases under more dispersed liquidity holdings in the banking sector.

might hope for an offsetting liquidity shock in the course of the maintenance period that balances a given under-fulfillment. To see this, consider an event of a positive liquidity shock that causes banks' accounts to exceed the remaining part of their reserve requirements for the respective maintenance period. Any reserves held in excess of the required amount must then be parked at the deposit rate, which is substantially lower than the money market rate. Since this would be more expensive, these banks have an incentive to keep their accounts before the (potential) shock realizes at an appropriate level, see e. g. Pérez Quirós and Rodríguez Mendizábal (2006). Towards the end of the maintenance period such an offsetting liquidity shock becomes rather unlikely and banks need to balance the under-fulfillment through a money market transaction. Thus, during the last days of the maintenance period also the second friction becomes more relevant and banks become more worried about a general mark-up charged in the interbank money market. Therefore, for a given heterogeneity in reserve holdings, banks should bid more aggressively towards the end of the maintenance period. Hence, we expect a higher willingness to pay (τ), higher bid dispersion (λ) and higher quantities demanded (α) as the end of the reserve maintenance period approaches. When banks, however, develop a strong preference to (over-)satisfy their liquidity needs at an early stage in the maintenance period, we would expect that increasing heterogeneity in reserve balances should also affect the shape of aggregated bid curves within the maintenance period.

A third type of friction in the interbank money market results from asymmetric information about counterparties' credit risk. Following Akerlof's path-breaking work, Freixas and Jorge (2008) show that unobservable credit quality of counterparties leads to an adverse selection problem in the unsecured interbank market, i.e. a pooling equilibrium characterized by credit rationing. Thus, the risk premium charged is too high for the default risk of low risk borrowers – they pay an additional lemons premium – while it is too low for high risk borrowers. If the fraction of low quality borrowers increases, the overall risk premium will rise. Hence, the lemons premium paid by high quality borrowers increases as well. Eventually good borrowers drop out of the secondary money market, satisfying their liquidity needs elsewhere, e. g. by liquidation of long-term investments, and leave an adverse selection of low quality borrowers in the money market. Due to this adverse selection effect the default risk in the interbank money market increases further leading to an even higher risk premium being charged. In order to circumvent the negative externalities attached to the adverse selection effect within the interbank money market, banks with excess liquidity in the market will find it beneficial to ration their liquidity supply, in analogy to Stiglitz and Weiss (1981). In any case, liquidity-short banks find it more costly or more difficult to refinance in the secondary money market the more severe the adverse selection problem is. Thus, those banks will use the Eurosystem's repo auctions more intensely and bid more aggressively. Heider et al. (2010), for instance, show that the adverse selection effect worsens when the difference in the default probabilities between high and low quality borrowers in the interbank money market becomes larger or, more generally, the more heterogenous default probabilities are in the banking sector. Consequently, a higher discrepancy in the banks' default probabilities should also increase banks' participation and willingness to pay in the ECB's MROs. This rationale leads us to the second hypothesis we aim to test:

Hypothesis 2 *A larger dispersion of equity ratios in the banking sector raises banks' overall demand (α), the willingness to pay for central bank reserves in the auctions (τ), and encourages bid dispersion (λ).*

In order to test this hypothesis we require a measure for the heterogeneity of banks' default probabilities. As commonly applied, we could use credit default swaps or credit ratings for those banks for which those figures are available. However, those credit risk indicators are publicly available information. Thus the dispersion of these indicators across the banking sector does not measure the severity of adverse selection problems in the interbank money market.

We rather use our access to the monthly balance sheet statistic to derive a measure for bank's credit risk.[24] Equity, in general, meets the most straightforward, narrow definition of capital as funds cannot easily be withdrawn. The sum of total assets denotes the simplest measure of bank size, even though it excludes off-balance sheet activities. The ratio between both measures, i.e. the *equity ratio*, captures a component of individual bank's solvency risk that is subject to asymmetric information. Additionally, the equity ratio plays a crucial role in the bank's credit rating and is also related to each bank's cost of raising funding in the secondary money market. In contrast to other proxies for credit risk, the equity ratio is a completely transparent measure. For our analysis, we classify the sum of subscribed capital and reserves less published losses from each bank's balance sheet as the bank specific equity variable.[25]

It is reasonable to assume that money market participants have some notion whether the dispersion of the equity ratio and thus the solvency risk in the banking sector increased or decreased. Thus, we will use the *standard deviation* of the equity ratio across German banks to capture whether adverse selection in the interbank money market became more or less severe from the

[24] Recall that on an individual bank basis, this end-of-month information is only available to the Deutsche Bundesbank.

[25] The capital of foreign subsidiaries of domestic banks is also included in this measure.

perspective of market participants.

Banks that are rationed in the interbank money market rely to a larger extent on the primary money market to cover their liquidity needs to balance out liquidity shocks. A persistent recourse to the primary money market might also be seen as an indication that a bank cannot refinance in the secondary money market. Thus, a higher fraction of banks that persistently participate in the ECB's MROs might reflect rationing in the interbank money market. According to this argument a higher fraction of persistent bidders in the MROs should also be accompanied by a higher level of reserve demand combined with a more aggressive bidding behavior observed in the ECB's repo auctions. This idea yields to a further testable hypothesis:

Hypothesis 3 *A larger share of persistent bidders in the MROs shifts banks' overall reserve demand (α) upward and increases their willingness to pay for central bank reserves in the auctions (τ).*

In order to test this hypothesis we define a bank to be a persistent bidder if it participated in more than 90% of the preceding auctions from auction t's perspective. In particular, we use an updating approach to determine the fraction of persistent bidders such that at auction t, our variable "persistent banks" refers to all auctions up to $t-1$. Our variable "persistent banks" then denotes the fraction of those banks persistently bidding in MRO's relative to all participating banks.

Market Liquidity and Funding Liquidity

Banks may use the general financial market as an alternative liquidity source. Selling off assets also allows banks to cover their liquidity needs. But under asymmetric information, long-term assets can only be liquidated at a discount.[26] The extent of this discount depends on the ability of market makers and informed traders to absorb these asset sales. The more liquidity constrained market makers are, the higher is their bid-ask spread as for instance argued by Brunnermeier and Pedersen (2009).[27] The more financially constrained informed traders (e.g. institutional investors) are, the lower is the price elasticity of asset demand, the stronger is the effect of a cash-in-the-market pricing, and the larger are price fluctuations from given asset sales as pointed out e. g. by Allen and Gale (1994). In any case, the expected loss incurred by a bank that aims to cover its

[26]When banks sell off their assets in need for reserves they act as liquidity traders in the market. Therefore, they bear on average a loss when selling off their assets to informed market participants, see e. g. Freixas and Jorge (2008).

[27]See e. g. Benston and Hagerman (1974), Grossman and Miller (1988), Glosten and Milgrom (1985), and Kyle (1985) for standard references on market micro structure.

liquidity needs through asset sales is higher, the lower asset market liquidity is and thus the higher is asset price volatility. As a consequence, banks' preference to liquidate their assets is lower for highly volatile asset prices. This also means that banks' dependency on the primary money market increases for a higher asset price volatility. We therefore conclude that under the occurrence of high asset price volatility banks should bid for larger amounts and at higher rates in the ECB's repo auctions. Furthermore, as a reallocation of liquidity through the asset market becomes more costly, banks' incentives for precautionary liquidity holdings should increase leading to a higher overall demand for central bank reserves. This, in particular, captures the main reasoning of Allen and Gale (1994). Our fourth empirically testable prediction is therefore as follows:

Hypothesis 4 *In times of low market liquidity and volatile asset prices banks' willingness to pay for reserves (τ) as well as the aggregate reserve demand (α) in the primary money market increase.*

Empirically, we use the log of the Vstoxx as a measure for asset price volatility. The Vstoxx is an index for the Euro Stoxx 50 implied volatility and comprises the largest 50 euro area listed firms. It is derived from the expected volatility for the future Euro Stoxx 50 prices implied by the respective stock option prices and thus captures market participants' expected stock price volatility over the next 30 days rather than the realized volatility.

Apart from financial market liquidity that affects banks' costs when assets are sold under distress, banks' asset structure might also restrain banks' ability to tap financial markets in search for liquidity. The lower the stock of tradable assets that banks hold on the balance sheets, the lower is the ability of banks to sell off these assets on short notice and thereby attract liquidity. As a consequence, banks are again more dependent on the liquidity provision in the primary money market and will bid more aggressively in the ECB's MROs. Moreover, banks might have stronger incentives for precautionary liquidity holdings, which should increase the level of aggregate reserve demand. Similarly, a high share of long-term assets on banks' balance sheets should reduce under asymmetric information banks' ability to refinance liquidity shortages through asset sales. In addition, a high maturity mismatch in the banking sector increases banks' need to roll-over liabilities and thus raises banks' sensitivity to changing market conditions in secondary money markets. A high level of maturity mismatch increases banks' liquidity risk and the vulnerability to potential liquidity shortages, see e. g. Brunnermeier (2009). All in all, a larger maturity risk carried on banks' balance sheets should lead to a more aggressive bidding and a larger aggregate reserve demand in the ECB's open market operations.

Hypothesis 5 *The lower the fraction of marketable assets and the larger the maturity mismatch* *on banks' balance sheets, the more dependent banks are on the primary money market. Hence, banks have a higher liquidity demand (α) in central bank auctions and bid more aggressively (τ).*

To test this hypothesis, we use again items from the balance sheet statistic that we obtained from the Deutsche Bundesbank. As tradable assets, for instance, we classify debt instruments, shares, and other variable-yield securities. To account for the average share of tradable assets in the German banking sector, we compute the ratio between tradable assets and balance sheet total across all banks.

To account for the average maturity mismatch in the German banking sector, we follow the approach of Deep and Schaefer (2004) and Berger and Bouwman (2009). We measure maturity mismatch as the sum of bank's long-term assets and short-term liabilities over its equity. We determine this measure as an average over all financial institutions. We categorize liabilities (both to banks and non-banks) with a maturity of up to one year and savings deposits of non-banks at a period of notice up to 3 months as short-term liabilities. As long-term assets we define loans and advances both to banks and non-banks beyond the one-year maturity. Table 2 summarizes the expected response of our parameter estimates, $\hat{\alpha}, \hat{\lambda}, \hat{\tau}$, to variables derived from economic theory.

Table 2: Theoretical Predictions on the Determinants of Aggregate Liquidity Demand

		$\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$
Remaining Required Reserves	(std)	+	+	+
Equity Ratio	(std)	+	+	+
Persistent Banks	(%)	+	+/−	+
Vstoxx	(log)	+	+/−	+
Maturity Mismatch	(%)	+	+/−	+
Tradable-to-Total-Assets	(%)	−	+/−	−

4.3 Empirical Model

To test the hypotheses derived from the theoretical literature, we apply the following ordinary least square regression[28]:

$$\begin{aligned}\widehat{\theta}_t &= c + \alpha_1 D_t^{lw}\text{Res}_t + \alpha_2(1 - D_t^{lw})\text{Res}_t + \alpha_3 EQR_t + \alpha_4 PB_t \\ &+ \alpha_5 Vstoxx_t + \alpha_6 MatMis_t + \alpha_7 TA_t + \beta' X_t + \upsilon_t \qquad (7)\end{aligned}$$

where $\widehat{\theta}_t$ comprises the estimated parameters $\hat{\alpha}_t$, $\hat{\lambda}_t$, and $\hat{\tau}_t$ for each auction t. We estimate this equation by equation. Note that our analysis refers to MROs that are performed weekly, i.e. t denotes a weekly time structure. υ is assumed to have a zero mean and *i.i.d.* characteristics. As discussed above, our right-hand side variables correspond to the standard deviation across banks' remaining required reserves (Res), the standard deviation across banks' equity ratios (EQR), the share of persistent banks (PB), the log of Vstoxx ($Vstoxx$), the average maturity mismatch prevailing in the banking sector ($MatMis$), and the across banks' mean of tradable assets over balance sheet total (TA) at auction t. D^{lw} refers to a dummy variable that is one for the last MRO conducted during the respective maintenance period and zero otherwise. Furthermore, the vector X includes an end-of-year dummy that is one for the last MRO auction within a year and zero otherwise. In addition, X comprises the autoregressive component of the respective parameter up to the fourth lag.[29]

Generally, we would expect the impact of all our derived variables to be of a non-linear nature. This is in particular the case for the effects stemming from interbank money market frictions and from the illiquidity in financial markets where both influences mutually reinforce each other. Unfortunately, it is not possible to capture each facet of the potentially prevailing (feedback) effects in our empirical analysis. However, by investigating the explanatory power of the different hypotheses before and during the crisis period separately, we aim to catch most of these effects. Since financial market tensions were generally more prevalent during the crisis, we would expect that, due to the presumed non-linearities, our hypotheses should turn out to play an empirically more pronounced role after August 2007.

[28]Following the Gauss-Markov theorem, generalized least square estimation would be more efficient than OLS when the system errors are correlated. This could be accounted for by using Zellner's seemingly unrelated regression model. However, Kruskal's theorem (Kruskal, 1968) describes that this efficiency gain disappears when each equation contains exactly the same set of regressors on the right-hand side as in our case.

[29]Since there are on average four MRO auctions during a reserve maintenance period, a lag order of four auctions seems reasonable. This is also suggested by the AIC information criteria.

Note that all our right-hand side variables are pre-determined. We use the data on the announcement day, i.e. one day before the auction is conducted, to avoid endogeneity problems. For the balance sheet data, we use the end-of-month entries that are valid before the respective MRO auction t. For instance, the entry relevant for all MROs within September 2005 is provided by the balance sheet statistic on August 31, 2005. To make sure that our results are not driven by the Lehman event, we have excluded all MROs conducted after September 15, 2008.

Empirical Results for the Pre-crisis Period

Table 3 presents the results of our estimation. In the pre-crisis sample, the estimates indicate a significant and plausibly signed response of all three parameters to reserve imbalances, only during the last week of the reserve maintenance period. In that sense, our results are in line with Hypothesis 1. According to our estimates, a change in the heterogeneity of reserve balances at the last-week-operation increases $\hat{\alpha}$ by 0.12 ($0.021 \cdot 1.523/0.27$) standard deviations. Our results also suggest that greater asymmetry in remaining required reserves is associated with higher willingness to pay. A change of these reserve imbalances by one standard deviation will increase the typical willingness to pay during the last week by roughly 1.2 basis points ($(0.021 \cdot 0.549)$) further. The bid rate dispersion, $\hat{\lambda}$, appears to rise also with higher degree of reserve imbalances among market participants during the last week. A change of the asymmetry in remaining required reserves by one standard deviation increases bid shading by roughly 0.54 ($0.021 \cdot 0.057/0.0022$) standard deviations, see also Table 1.[30]

[30] Recall that both λ and τ were multiplied by 100. Our estimates presented in Table 3, however, refer to the initial unit of λ and τ.

Table 3: Determinants of the Aggregate Bid Curve

Variable		Hypothesis	Pre-Crisis: 09 Mar 2004 - 31 Jul 2007 $\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$	Crisis: 08 Aug 2007 - 09 Sep 2008 $\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$
			Shape of Aggregate Bid Curve $\hat{\theta}_t = (\hat{\alpha}_t, \hat{\lambda}_t, \hat{\tau}_t)'$					
Remaining Required Reserves	(std)	$\mathcal{H}1$						
*Dummy (last week operation)			1.523^{***} (4.11)	0.057^{***} (4.17)	0.549^{***} (4.55)	-0.989 (0.67)	-0.192 (0.98)	-1.115 (1.05)
*[1 - Dummy (last week operation)]			-0.431 (0.58)	0.010^{**} (2.16)	0.049 (0.89)	1.001 (0.44)	0.008 (0.21)	0.742^{**} (2.27)
Equity Ratio	(std)	$\mathcal{H}2$	-4.056 (0.56)	-0.001 (0.23)	-0.152 (0.54)	-12.119 (0.62)	1.416^{**} (2.10)	8.897^{**} (2.23)
Persistent Banks	(%)	$\mathcal{H}3$	1.480 (1.33)	-0.495 (1.01)	3.221 (1.21)	0.084^{***} (2.91)	-0.012^{**} (2.02)	-6.891 (0.91)
Vstoxx	(log)	$\mathcal{H}4$	-0.22 (1.20)	-0.001 (0.64)	-0.001 (0.37)	0.811^{**} (2.45)	0.041 (1.18)	0.291^{***} (3.63)
Maturity Mismatch	(%)	$\mathcal{H}5$	0.119^{***} (2.81)	0.001 (0.78)	0.005^{**} (2.22)	0.294^{**} (2.31)	-0.001 (0.37)	0.028^{***} (2.76)
Tradable-to-Total Assets	(%)	$\mathcal{H}5$	-0.124^{**} (2.51)	0.001^{**} (2.05)	0.007 (0.54)	0.795 (0.83)	-1.173 (0.74)	-0.031^{***} (3.22)
$\sum_{l=1}^{4} AR(l)$			0.601^{***} (7.92)	0.234^{**} (2.34)	0.553^{***} (6.97)	0.324^{**} (2.01)	0.167^{*} (1.83)	0.910^{***} (4.45)
Dummy (last week operation)			0.797^{***} (2.75)	0.005^{***} (3.28)	-0.031^{***} (2.73)	0.341 (0.86)	0.039 (1.11)	0.250^{**} (2.37)
Dummy (end of year)			-1.101^{***} (7.62)	0.021^{***} (24.38)	0.043^{***} (3.87)	0.840^{***} (2.96)	0.145^{***} (3.07)	0.181^{***} (3.77)
cons			1.682^{**} (1.97)	0.004 (0.92)	-0.032 (1.03)	2.989 (0.53)	0.027 (0.78)	-0.072^{***} (2.98)
R^2			0.68	0.76	0.71	0.70	0.54	0.86
Obs.				178			57	

Notes: $\hat{\alpha}$ denotes the market's satiation level, $\hat{\lambda}$ measures the bid rate dispersion and is closely linked to the price elasticity of demand. $\hat{\tau}$ captures the typical willingness to pay. The estimated model is presented in Equation (7). ***,**,* indicate significance at the 1%, 5%, 10% level. Newey-West HAC consistent t-statistics in parentheses. The index t refers to the weekly MROs during the period March 9, 2004 to September 9, 2008. For this analysis, we have excluded all MROs conducted after September 15, 2008 to make sure that our results are not driven by the Lehman-event. Additionally, we dropped the extraordinary MRO auction (with 2-week maturity and immense liquidity provision) of December 18, 2007. *last week operation* is a dummy variable that is one for the last MRO conducted during the respective maintenance period and zero otherwise. Similarly, we have computed a dummy for end-of-year effects that is always one for the last MRO within a year and zero otherwise. The results presented in the first and second row refer to the interaction of our variable *remaining required reserves* and the dummy(last week operation) and [1-dummy(last week operation)], respectively.

During the rest of the maintenance period, reserve imbalances among banks tend to influence only banks' bid shading behavior. A one standard deviation rise of the asymmetry increases $\hat{\lambda}$ by 0.10 standard deviations. These results indicate that banks' fear of potential market squeezes becomes more apparent as the end of the maintenance period approaches, i.e. when reserve requirements become binding.

The results obtained for the average share of tradable to total assets is also in line with our predictions in Hypothesis 5. According to our estimates, an increase in the ratio between tradable assets and total assets by one percentage point will reduce $\hat{\alpha}$ by 0.46 standard deviations. A further plausible and significant result is obtained for $\hat{\lambda}$. The estimate suggests a rise of 0.5 standard deviations in $\hat{\lambda}$ when the ratio of tradable-to-total-assets increases by one percentage point. Before the crisis, the level of maturity mismatch in the German banking sector affects $\hat{\alpha}$ and $\hat{\tau}$. An increase in the maturity mismatch by one percentage point will increase $\hat{\alpha}$ by 0.16 standard deviations and $\hat{\tau}$ by 0.5 basis points. We find no evidence that further variables affect the shape of a typical aggregated bid curve before August 2007.

Table 4: Summary Statistics: Right-Hand-Side Variables

Before vs. After 08 August 2007

		Mean		Std	
		before	after	before	after
Remaining Required Reserves	(std)	0.104	0.110	0.021	0.044
Equity Ratio	(std)	0.067	0.077	0.002	0.004
Persistent Banks	(%)	35.465	35.557	3.302	8.253
Vstoxx	(log)	2.795	3.223	0.192	0.201
Maturity Mismatch	(%)	141.38	163.24	35.21	40.02
Tradable-to-Total-Assets	(%)	20.43	18.90	0.40	0.36

Empirical Results for the Crisis Period

For the crisis period, our results are shown in the right panel of Table 3. In line with Hypothesis 1, we find that large reserve imbalances increase banks' willingness to pay. However, our estimates for the crisis period differ from those obtained for the pre-crisis period in one important aspect. While the heterogeneity played a significant role only for the last week auction before August 2007, banks' asymmetry in remaining required reserves affects market's willingness to pay, $\hat{\tau}$, in the MRO before the last auction within the respective maintenance period, after August 2007. The impact of a standard deviation change in banks' reserve imbalances increases the typical willingness to pay in these auctions by 3.3 basis points. This finding is consistent with the anecdotal evidence that after the onset of the crisis banks had a strong preference to (over-)satisfy their liquidity needs before the end of the maintenance period approaches. It is, however, puzzling that there is no empirical evidence for an impact on $\hat{\lambda}$ and $\hat{\alpha}$.

During the crisis, a rise of the heterogeneity by the same order of magnitude is also found to induce more dispersed bids around the respective typical inflexion point. For instance, our estimated coefficient suggests that an increase by one standard deviation of the dispersion of bank's equity assets ratio rises $\hat{\lambda}$ by 0.20 standard deviations. A large heterogeneity in banks' equity ratio pushes also $\hat{\tau}$ upward. This result is in favor of our second prediction as it provides evidence for more aggressive bidding behavior as a result of counterparty risk combined with asymmetric information about it. Following our estimates, an increase in the heterogeneity among bank's equity ratio by one standard deviation rises banks' typical willingness to pay by 3.6 basis points.

Additionally, we find that persistent banks affect the shape of the aggregated bid curve in a plausible way. In fact, our results indicate that an increase of the fraction of persistent banks by ten percentage points reduces bid shading behavior by roughly 4.2 standard deviations. The same increase in the fraction of dependant banks increases the disproportional recourse to the primary money market by roughly 1.12 standard deviations. Both findings are revealing. First, banks who are "persistent" to the central bank's liquidity provision may be dependant upon this liquidity channel simply because they will find it more difficult to obtain funding from alternative sources. Second, banks that participate persistently in ECB's MROs may be considered as more "experienced" bidders who know the auction procedure well enough to place their bid-quantity schedules more successfully. Alternatively, the latter finding may indicate that dependant financial institutions have less incentives to perform bid shading as the MROs constitute their main funding source.

According to Hypothesis 4, an overall increase in banks' willingness to pay should follow large adverse price changes in the asset market during crises periods. Our estimate supports this theoretical mechanism. In fact, considering a rise in the log of Vstoxx by one standard deviation (equivalent to a 1.2 percentage point increase) will lead to a rise of $\hat{\tau}$ by 5.8 basis points. Additionally, we find that the stock market volatility influences $\hat{\alpha}$. This is intuitive as the number of alternative funding sources may diminish with increasing market illiquidity. Hence, banks want to make sure that they cover their liquidity needs and thus increase also their (excessive) demand in the primary money market. We find a change in the log of Vstoxx by one standard deviation to elevate $\hat{\alpha}$ by 0.22 standard deviations.

Furthermore, we find that the lower the average share of banks' ratio between tradable assets and their total assets the more aggressive will financial institutions place their bids in the MRO auctions. In fact, a one percentage point decrease of this measure will increase $\hat{\tau}$ by 3.1 basis points. This is in line with Hypothesis 5. In addition, we find that a relatively high level of maturity mismatch in the market has a significant and plausible impact on $\hat{\alpha}$ and $\hat{\tau}$. An increase of the average share by one percentage point increases $\hat{\alpha}$ and $\hat{\tau}$ by 0.39 standard deviations and 2.8 basis points, respectively.

Table 5: Determinants of Aggregate Liquidity Demand: Summary of Results

		Pre-Crisis			Crisis		
		$\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$	$\hat{\alpha}$	$\hat{\lambda}$	$\hat{\tau}$
Remaining Required Reserves	(std)	✓	✓	✓			✓
Equity Ratio	(std)					✓	✓
Persistent Banks	(%)				✓	✓	
Vstoxx	(log)				✓		✓
Maturity Mismatch	(%)	✓		✓	✓		✓
Tradable-to-Total-Assets	(%)	✓	✓				✓

Notes: '✓' denotes that our results presented in Table 3 are in line with our theoretical predictions summarized in Table 2.

5 Conclusion

Banking theory suggests a strong interplay between the way banks raise funding in money markets and the liquidity of broader financial markets. Our understanding of how the banking sector demands liquidity as a whole is, however, hampered by the absent comprehension of the key determinants of aggregate liquidity demand. The first contribution of this paper is to identify an aggregate liquidity demand function for the German banking sector. Our second contribution is to use this demand curve to gain a deeper insight into the demand pattern of the German banking sector before and during the recent crisis period. Our third contribution is to test the predictions of recent theories on the determinants of aggregate liquidity demand. This analysis strongly benefits from a rich and unique data set that we obtained from Deutsche Bundesbank.

Our findings show that the larger the need for liquidity reallocation through the secondary money market, the larger the premium that banks are willing to pay for funding in the euro area primary market for reserves. This might result from a fear that some banks obtain market power in the secondary money market and squeeze liquidity-short banks. Second, our results indicate that during times of low market liquidity more volatile asset prices increase the aggregate demand for central bank reserves. In that sense, we complement Nyborg and Östberg (2010). While they show that tensions in the interbank money market can feed into asset prices of the broader financial system, our paper provides strong evidence that high volatility of asset prices can affect banks' demand for liquidity. The strong evidence for both channels suggests that liquidity spirals (Brunnermeier, 2009) exist. Third, we find that a large dispersion of banks' equity ratios, as a measure of the heterogeneity of credit risk in the banking sector, induces both a more aggressive bidding strategy and a bid shading behavior. Fourth, our analysis reveals that an increase in the ratio of banks that persistently refinance through the primary money market during the financial crisis decreases bid rate dispersion. And fifth, a large stock of tradable assets that banks hold on the balance sheets is shown to reduce banks' refinancing needs through the primary money market. And sixth, our results suggest that a high level of maturity mismatch of the German banking sector increases banks' dependence on the primary money market. Thus in sum, our results show that tensions in financial markets and adverse shocks to the stability of the banking sector increase banks' demand for reserves.

Our results strongly support the ECB's decision to abandon its liquidity neutral allotment policy in October 2008. Ever since, the ECB regularly states that this change is only of temporary nature and will be reversed as soon as the strains are mitigated, see European Central Bank (2010). The findings of our analysis, however, challenge the resumption of the neutral liquidity provision policy for the post-crisis monetary policy practice. With such a policy, a central bank does not accommodate shocks to the aggregate reserve demand. Therefore, an increase in aggregate reserve demand resulting from detrimental shocks to the financial systems' stability leads to an increase in the equilibrium rate in the primary money market and supposedly also to higher rates in secondary money markets. This, in turn, may destabilize liquidity-short banks aggravating tensions in the financial system. For instance, if banks' liquidity demand increases in the primary market for reserves because asset markets happen to be illiquid, the equilibrium rate will increase. The resulting tensions in money markets impair the liquidity of financial markets further, raising the demand for central bank reserves. Consequently, a liquidity neutral allotment policy gives rise to self-enforcing liquidity crises. Keeping the aggregate supply of reserves over the reserve maintenance period at the level of the required holdings and only accommodating the banks' desire to front-load the fulfillment of reserve requirements, as the ECB did at the wake of the crisis, is according to our findings just not sufficient to break this vicious circle.

In order to avoid a contribution to adverse liquidity spirals, central banks should accommodate shocks to reserve demand by increasing the supply of reserves, in particular if these shocks result from instabilities in the banking sector or in the general financial system. However, to tackle a liquidity demand shock properly, central banks have to rely on valid estimates of its size. That is, central banks must be aware of the determinants of reserve demand and how changes of those determinants shape the level and slope of market liquidity demand. This is a particularly essential issue, since many of those determinants are themselves affected by tensions in the money market as our results indicate. Therefore, when deciding about the optimal allotment policy the central bank has to take into account the feedback that an accommodative allotment has on tensions in the banking system and ultimately on the demand for reserves.

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A Goodness of Fit

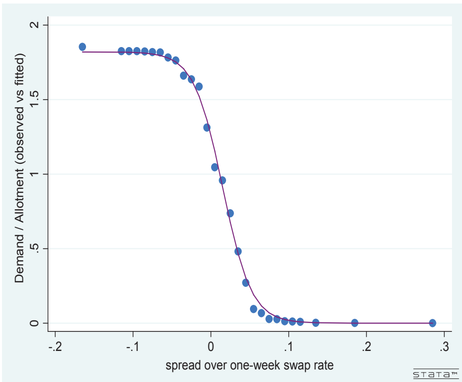
In order to assess the goodness of our model fit, we estimate the excessive liquidity demand per auction by using our parameter estimates ($\hat{\theta}_t = (\hat{\alpha}_t, \hat{\lambda}_t, \hat{\tau}_t)'$) and compare these estimates with the actual observed data. More precisely, we determine for each auction t the fitted quantities, $\hat{l}^d_{it} = f(\widetilde{r}_{it}; \hat{\theta}_t)$, at each ordered yield class $\widetilde{r}_i$, $\forall i = 1, \ldots, n$ and compare these fitted quantities with the observed values of l^d_{it}. Based on this comparison, Table A.1 provides a cross-auction evaluation by the means of mean absolute deviation (MAD) and the median absolute deviation (MEAD). With a value of 0.059 and 0.040, respectively, our model can be considered to fit the observed data astonishing well. Figure A.1 shows exemplarily the fit of our model graphically. It contrasts the observed aggregated bid curves from Figure 1 (dots) with the fitted values using our model with estimates parameters (solid line).

Table A.1: Fitting Evaluation Statistics

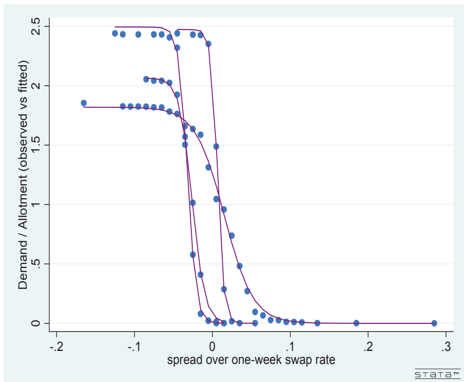
Parameter estimates	mean	std	MAD	MEAD
l^d	1.59	1.23		
$\hat{l}^d$	1.60	1.20	0.06	0.04

Notes: This table provides a cross-auction summary of observed (l^d) and fitted ($\hat{l}^d$) quantities.

Figure A.1: Graphical Illustration of the Goodness of Fit



(a) One aggregate bid curve



(b) Four aggregate bid curves

Notes: The graphs show exemplarily the fitted values (solid line) and the observed quantities (dots) for the aggregate bid curves presented in Figure 1.

B Alternative Illustration of the Goodness of Fit

In this section, we follow Boukai and Landsberger (1999) and compare the fitted and observed yields from a different perspective. Therefore, we consider two particular components of the MRO auction outcome, i.e. (i) the marginal or stop-out rate and the (ii) (quantity-)weighted average rate of all successful bids. The former represents the yield at which the last bidder is still satisfied, i.e. where the total amount to be allotted is exhausted. The latter reflects the quantity-weighted average of all *successful* bids per auction. Both interest rates are published by the ECB on behalf of the Eurosystem. To illustrate the goodness of our model fit, we calculate both the marginal rate and the weighted average rate for each auction using our fitted logistic curve.

To estimate the marginal rate, we use the fact that at this rate liquidity demand equals liquidity supply, such that:

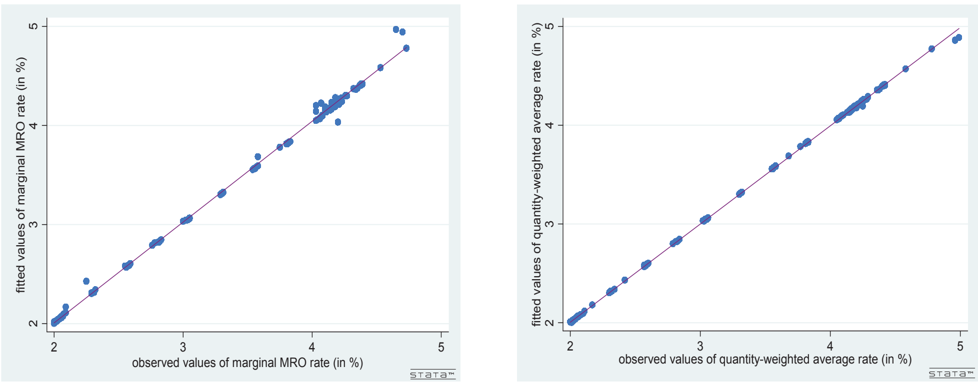
$$L_{it}^{d} = \frac{a_t}{1 + exp(\frac{(\tilde{r}_{it} - \tau_t)}{\lambda_t})} = \tilde{L}_t^s \tag{8}$$

Hence, rearranging Equation (8) allows us to predict the marginal rate by using our parameter estimates as follows:

$$r_t^{\hat{mr}} = \left(\hat{\tau}_t + \hat{\lambda}_t log(\hat{\alpha}_t - 1)\right) + swap1w_t \tag{9}$$

where $\hat{\alpha} = \frac{\hat{a}}{\tilde{L}^s}$. We plot both the fitted marginal MRO rate and the fitted weighted average rates against their respective actual values announced by the ECB immediately after each auction, see Figure B.1. In total, there are 240 pairs of fitted and observed values. As our data follows the 45 degree line, we conclude that our model yields an excellent fit of observed values.

Figure B.1: Alternative Graphical Illustration of the Goodness of Fit

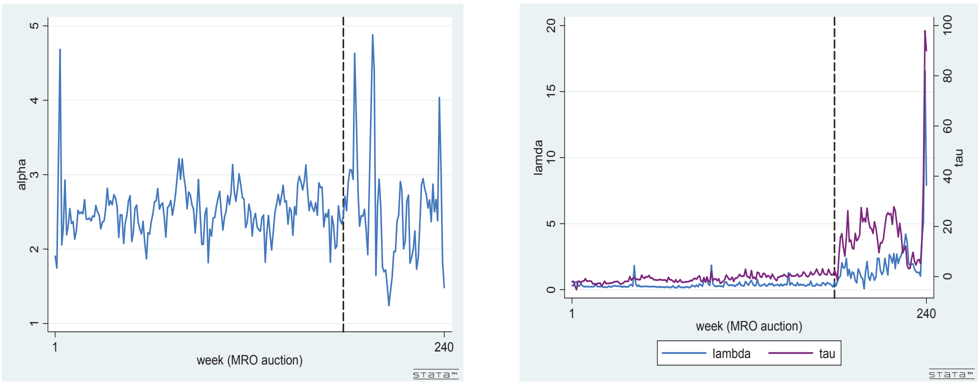


(a) Fitted vs observed marginal MRO rate (b) Fitted vs observed weighted average rate

C Alternative Specification: Results with Repo Rates

This section uses an alternative benchmark yield, i.e. the one-week repo rate, to make individual bids comparable across Eurosystem's MRO auctions. As in Equation (1), we substract the correspondingly dated one-week repo rate and re-estimate Equation (4). The summary statistics are presented in Table C.1. Obviously, $\hat{\alpha}$ remains unaffected. For $\hat{\lambda}$ and $\hat{\tau}$ our results are slightly different, yet qualitatively similar to those presented in Table 1. While before the crisis bid shading is performed rather weakly, the dispersion of bids increase after August 2007. The estimates for τ indicate that before the onset of the crisis the one-week repo rate exceeded the typical willingness to pay on average across auctions. During the crisis, however, banks are willing to pay more than roughly 18 basis points above the respective repo rate. These results are qualitatively the same as presented in Table 1.

Figure C.1: Estimation of Model Parameters with Alternative Specification



(a) Estimation of the excess liquidity demand (α)

(b) Estimation of the bid rate dispersion (λ) and the willingness to pay (τ)

Notes: These graphs show the estimations of the model parameter where the one-week repo rate was used to benchmark the reported bids For further details see Figure 4.

Table C.1: Summary Statistics: Parameter Estimates (with Alternative Specification)

Parameter estimates	units	mean	std	min	max
09 Mar 2004 - 31 Jul 2007: 178 auctions					
$\hat{\alpha}$		2.49	0.27	1.75	3.21
$\hat{\lambda}$		0.34	0.20	0.14	1.85
$\hat{\tau}$	bp	-0.74	1.47	-5.19	3.14
08 Aug 2007 - 09 Oct 2008: 62 auctions					
$\hat{\alpha}$		2.51	0.75	1.24	4.88
$\hat{\lambda}$		2.18	2.42	0.07	16.58
$\hat{\tau}$	bp	18.13	15.99	-1.39	97.93

Notes: For further details, please refer to Table 1.

D Marginal Demand and Elasticity along a Market Bid Function

This section shows the close relationship between the parameters of the logistic curve and the price elasticity of demand. For this purpose, we consider the general logistic representation:

$$f(\widetilde{r},\vartheta) = \frac{\alpha}{1 + exp\left(\frac{\widetilde{r}-\tau}{\lambda}\right)}, \tag{10}$$

where ϑ is a vector of the parameters, i.e. $\vartheta = (\alpha, \lambda, \tau)'$. To show that this expression is continuously differentiable for any value of $\widetilde{r}$, we define:

$$f(\widetilde{r},\vartheta) = \frac{\alpha}{g(\widetilde{r},\vartheta)} \tag{11}$$

such that

$$f'(\widetilde{r},\vartheta) \equiv \frac{\partial f(\widetilde{r},\vartheta)}{\partial \widetilde{r}} = \frac{-\alpha g'(\cdot)}{g(\cdot)^2} \tag{12}$$

with $g(\cdot) = \left(1 + exp\left(\frac{\widetilde{r}-\tau}{\lambda}\right)\right)$ and $g'(\cdot) = \frac{1}{\lambda}\left(exp\left(\frac{\widetilde{r}-\tau}{\lambda}\right)\right)$. Hence the derivative with respect to $\widetilde{r}$ becomes:

$$f'(\widetilde{r},\vartheta) = \frac{-\alpha\left(exp\left(\frac{\widetilde{r}-\tau}{\lambda}\right)\right)}{\lambda\left(1 + exp\left(\frac{\widetilde{r}-\tau}{\lambda}\right)\right)^2} \tag{13}$$

The marginal normalized rate is therefore unimodal and the minimum is obtained at $\widetilde{r} = \tau$. At this point $f'(\tau,\vartheta) = \frac{\alpha}{4\lambda}$. The elasticity along the complete aggregate bid curve can then be computed as follows:

$$\varepsilon_d(\widetilde{r}) \equiv \frac{\partial log f(\cdot)}{\partial log \widetilde{r}} = \frac{\partial log f(\cdot)}{\partial \widetilde{r}} \cdot \left(\frac{\partial log \widetilde{r}}{\partial \widetilde{r}}\right)^{-1} \tag{14}$$

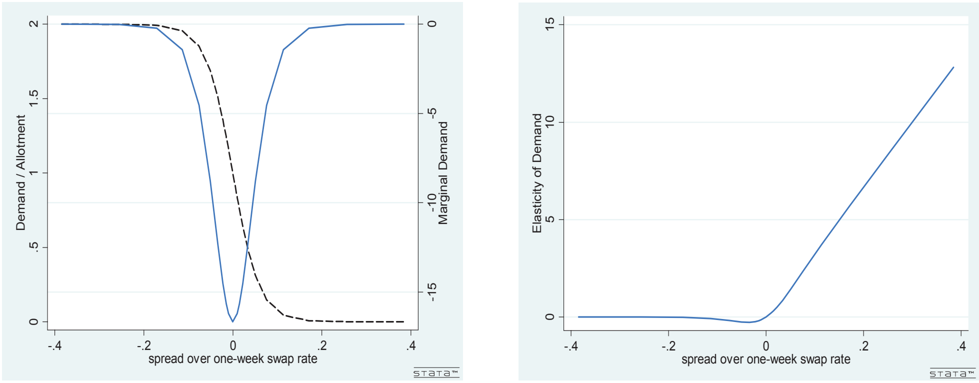
$$= \widetilde{r} \cdot \frac{\partial log f(\cdot)}{\partial \widetilde{r}} = \widetilde{r} \cdot \frac{\partial log f(\cdot)}{\partial f(\cdot)} \cdot \frac{\partial f(\cdot)}{\partial \widetilde{r}} \tag{15}$$

$$= \frac{\widetilde{r}}{f(\cdot)} \cdot \frac{\partial f(\cdot)}{\partial \widetilde{r}} \tag{16}$$

$$= \frac{\widetilde{r} \cdot exp\left(\frac{\widetilde{r}-\tau}{\lambda}\right)}{\lambda\left(1 + exp\left(\frac{\widetilde{r}-\tau}{\lambda}\right)\right)} = \frac{\widetilde{r}}{\lambda\left(1 + exp\left(\frac{\tau-\widetilde{r}}{\lambda}\right)\right)} \tag{17}$$

The elasticity achieves its minimum at $\widetilde{r}^* < \tau$. For any $\widetilde{r} < \widetilde{r}^*$ the elasticity corresponds to $\lim_{\widetilde{r}\to-\infty} \varepsilon_d(\widetilde{r}) = 0$ since $\lim_{\widetilde{r}\to-\infty} exp\left(\frac{\tau-\widetilde{r}}{\lambda}\right) = \infty$. For $\widetilde{r} > \widetilde{r}^*$, the elasticity increases linearly in $\widetilde{r}$ at the constant rate $\frac{1}{\lambda}$ because $\lim_{\widetilde{r}\to\infty} \varepsilon_d(\widetilde{r}) = \frac{\widetilde{r}}{\lambda}$ for $\lim_{\widetilde{r}\to\infty} exp\left(\frac{\tau-\widetilde{r}}{\lambda}\right) = 0$. At $\widetilde{r} = \tau$, the elasticity reaches $\varepsilon_d(\tau) = \frac{\tau}{2\lambda}$. Both marginal demand and the elasticity along the market bid curve are shown in Figure D.1.

Figure D.1: Marginal Demand and Elasticity along an Aggregated Bid Curve



(a) Marginal demand (b) Price elasticity of demand

Notes: These graphs show the marginal demand (dashed line, left graph) and price elasticity (right graph) along an aggregate bid curve with $\alpha = 2$, $\lambda = 0.03$ and $\tau = 0$ using Equation (13) and (14), respectively.

E Times Series Characteristics and Correlation

Table E.1 also reports the time-series characteristics of our three parameter estimates. The augmented Dickey-Fuller test suggests a rejection of the null hypothesis that the parameters have a unit root, i.e. that they are $I(1)$. We test the robustness of these results by applying a KPSS test following Kwiatkowski et al. (1992), that tests whether a series is $I(0)$. Both test statistics confirm that our parameter estimates can be considered as stationary variables.

Table E.1: Unit Root Tests

	ADF	KPSS	ADF	KPSS
Parameter	09 Mar 2004 - 31 Jul 2007		08 Aug 2007 - 09 Oct 2008	
estimates	178 auctions		62 auctions	
$\hat{\alpha}$	-10.28*	0.08	-4.30*	0.12
$\hat{\lambda}$	-18.94*	0.13	-3.62*	0.08
$\hat{\tau}$	-4.71*	0.05	-3.29*	0.16

Notes: We provide the t-statistic and the LM-statistic for the Augmented Dickey-Fuller (ADF) test and the KPSS-test, respectively. The lag length for the ADF-test (with an intercept) is chosen according to the Schwarz Information Criterion while the bandwidth choice for the KPSS-test follows the Newey-West criterion using a Bartlett kernel. * indicate significance at the 5% level.

Table E.2 presents the results from a Pearson covariance analysis. For both the pre-crisis and crisis period, the correlation coefficients $\rho_{\hat{\alpha},\hat{\tau}}$ and $\rho_{\hat{\alpha},\hat{\lambda}}$ are both negative, whereas $\hat{\tau}$ and $\hat{\lambda}$ appear to be positively correlated. These results reflect the stability of the generating process of market demand. For instance, $\rho_{\hat{\tau},\hat{\lambda}}$ shows that banks' aggressive bidding (large values of $\hat{\tau}$) is associated with higher bid shading behavior, i.e. higher $\hat{\lambda}$ and thus decreasing price elasticity of reserve demand. Since aggressive bidding strategy ensures some liquidity allocation, this finding illustrates how German financial institutions protect themselves while bidding aggressively. Not surprisingly, we find this correlation to be higher during the crisis.

Table E.2: Correlation Analysis Among Estimated Parameters

	09 Mar 2004 - 31 Jul 2007	08 Aug 2007 - 09 Oct 2008
$\rho_{\hat{\alpha},\hat{\tau}}$	-0.41 [0.0000]	-0.23 [0.0846]
$\rho_{\hat{\alpha},\hat{\lambda}}$	-0.35 [0.0000]	-0.46 [0.0003]
$\rho_{\hat{\lambda},\hat{\tau}}$	0.47 [0.0000]	0.71 [0.0000]

Notes: p-values are presented in parentheses.

F Structural Break Test

This section uses structural break tests to investigate whether the financial crisis had a significant impact on the relationship between the determinants of the aggregated bid curve and its parameters $\hat{\alpha}$, $\hat{\lambda}$, and $\hat{\tau}$. To that aim, the Quandt-Andrews test for unknown breakpoints is applied to our Equation (7):

$$\begin{aligned} \hat{\theta}_t &= c + \alpha_1 D_t^{lw}\text{Res}_t + \alpha_2(1 - D_t^{lw})\text{Res}_t + \alpha_3 EQR_t + \alpha_4 PB_t \\ &+ \alpha_5 Vstoxx_t + \alpha_6 MatMis_t + \alpha_7 TA_t + \beta' X_t + \upsilon_t \end{aligned} \tag{18}$$

We test whether there has been a break in all the equation parameters for the full sample from April 09, 2004 to October 09, 2008. The Quandt-Andrews test is based on standard F-statistics, see Andrews (1993). $Max\ F$ denotes the maximum of the individual F-statistics while the *Ave* statistic refers to their average.Since the break point is unknown, the asymptotic distribution of both test statistics are non standard and depend on the number of coefficients that are allowed to break and on the fraction of the sample that is examined. Note that the distributions become degenerate as the first period tested approaches the beginning of the equation sample, or the end period approaches the end of the equation sample. To compensate for this behavior it is generally suggested to

Table F.1: Quandt-Andrews Unknown Breakpoint Test

Statistic	Date	Max F	Ave F
$\hat{\alpha}$	Oct 17 2007	31.92 [0.0034]	21.21 [0.0002]
$\hat{\lambda}$	Aug 22 2007	56.41 [0.0000]	18.95 [0.0005]
$\hat{\tau}$	Aug 08 2007	93.82 [0.0000]	17.92 [0.0020]

Notes: Estimated break date and approximate asymptotic p-values in line with Hansen (1997) in parenthesis. Test sample: April 09, 2004 to October 09, 2008 for weekly parameter estimates $\hat{\theta}_t = (\hat{\alpha}_t, \hat{\lambda}_t, \hat{\tau}_t)'$. Number of breaks compared: 177.

exclude the end of the equation sample from the testing procedure. Following Andrews (1993), we apply a symmetric ”trimming” of 10%. Approximate asymptotic *p*-values are calculated in line with Hansen (1997). The results show that the determinants of the aggregate bid curve have significantly changed since the start of the financial crisis. For $\hat{\tau}$, the test statistics choose the first MRO auction after the outbreak of the crisis as the main candidate for a significant break point. For $\hat{\lambda}$ and $\hat{\alpha}$, the statistics point to a breakpoint at August 22 and October 17 2007, respectively. These results imply that the determinants of these two parameter estimates have also undergone a structural change during the second half of 2007.

However, Table F.2 shows the results of a Chow's breakpoint test at a specified date. The idea of this test is to fit the Equation (18) separately for each given subsample and check whether there are significant differences in the estimated equations. These differences are interpreted as structural change in the relationship. The reported *F*-statistic is based on the comparison of the restricted and unrestricted sum of squared residuals. The *log likelihood ratio* statistic is refers to the comparison of the restricted and unrestricted maximum of the (Gaussian) log likelihood function. While the former has an exact finite sample *F*-distribution, the ***LR*** test statistic has an asymptotic χ^2 distribution with k degrees of freedom, where k is the number of parameters in the equation. Both statistics reveal also a structural change for the determinants of $\hat{\alpha}$ and $\hat{\lambda}$ as of August 8, 2007.

Table F.2: Chow's Breakpoint Test

$\mathcal{H}_0$: No (structural) breaks at specified breakpoints			
	Test Date	*F*-statistic likelihood ratio	Log
$\hat{\alpha}$	Aug 08 2007	2.54^{**}	21.65^{***}
$\hat{\lambda}$	Aug 08 2007	3.55^{***}	29.66^{***}

Notes: ***,**,* indicates significance at the 1%, 5%, 10% level. The F-statistic is based on the comparison of the restricted and unrestricted sum of squared residuals. The log likelihood ratio statistic compares the restricted and unrestricted maximum of the (Gaussian) log likelihood function.