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Implicit Intraday Interest Rate in the UK Unsecured Overnight Money Market*

Marius Jurgilas† Filip Žikeš‡

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Abstract

This paper estimates the intraday value of money implicit in the UK unsecured overnight money market. Using transactions data on overnight loans advanced through the UK large value payments system CHAPS in 2003–2009, we find a positive and economically significant intraday interest rate. While the implicit intraday interest rate is quite small pre-crisis, it increases more than tenfold during the financial crisis of 2007-2009. The key interpretation is that an increase in implicit intraday interest rate reflects the increased opportunity cost of pledging collateral intraday and can be used as an indicator to gauge the stress of the payment system. We obtain qualitatively similar estimates of the intraday interest rate by using quoted intraday bid and offer rates and confirm that our results are not driven by the intraday variation in the bid-ask spread.

Keywords: interbank money market, intraday liquidity
JEL classification: E42, E58, G21

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1 Introduction

Almost all central banks differentiate between overnight and intraday liquidity in their monetary frameworks either explicitly, in terms of the interest rates charged, or implicitly, via different eligibility criteria for acceptable collateral. While the overnight market is the most liquid interbank market, there is no explicit private *intraday* money market in which counterparties contract on the delivery of funds at a specific time of the day. This is puzzling since various empirical and theoretical studies show that the participants of the payment systems have incentives to delay the settlement of noncontractual payment obligations. Bech and Garratt (2003) provide the seminal game-theoretic exposition of the problem, while a comprehensive survey of the literature can be found in Manning, Nier, and Schanz (2009).

By delaying customer payments settlement banks can expect to use funds received intraday to fund outgoing payments later in the day. Such an argument also applies for contractual payment flows, like overnight loan advances and repayments. But while payment timing cannot be stipulated for noncontractual settlements, agreeing a precise timing for an advance and repayment of an overnight funding agreement seems to be feasible. Thus it can be expected that early (in terms of the time of the day) overnight advances and late repayments would come at a premium compared to overnight loans that are advanced later in the day or agreed to be repaid early next day. Such intraday price dynamics of the overnight loans, if observed, would be an indication that there is an intraday time value of money.

In this paper we test the hypothesis of a positive intraday interest rate implicit in the UK overnight money market. Our hypothesis is that although there is no explicit intraday money market, pricing of overnight loans of different lengths is consistent with the existence of an implicit intraday money market. We believe that overnight loans provide dual service to the participants of the money market. First, overnight loans allow banks to smooth day-to-day imbalances and achieve targeted end of the day reserve balance positions. Second, managing the timing of overnight loan advances and repayments allows banks to smooth intraday imbalances of payment flows. We show that these two components have different effects on the pricing of the overnight loans.

A pure intraday component of an overnight loan can be explained by the following stylized example. A bank borrowing or lending early in the day can enter in an offsetting position later in the day with the same counterparty. This way a bank can effectively obtain liquidity for an arbitrary period of time intraday with no exposure that extends into the next day. For example, bank A can borrow from bank B at 9am, but lend to bank B at 4pm on the same day, thereby generating intraday liquidity between 9am and 4pm. Similarly a bank that expects to have a net outflow of funds during the day can borrow overnight early, instead of late in the day, as the funds obtained can be used to settle outgoing payments. Thus one manifestation of a positive intraday interest rate would be decreasing overnight interest rates over the course of the trading day.

But achieving the desired end of the day balance position is the primary reason for why banks enter into overnight lending contracts. If the cost of deviations from such a perceived target is asymmetric, so that it is costlier to be below the target than above, then obtaining overnight funding at the end of the day may come at a premium. A similar argument, just at the daily frequency, is made by Quiros and Mendizabal (2006) in terms of explaining why overnight interest rates are expected to be higher towards the end of the reserves holding period. Although, as shown in the empirical study of Prati, Bartolini, and Bertola (2003), the tightness of overnight loans market on the last days of the maintenance period varies from country to country.

Intraday liquidity can also be obtained from the central bank. The Bank of England provides interest free collateralized intraday overdrafts to settlement banks (direct participants of the UK large value payment system CHAPS). But the implicit cost of pledging collateral with the Bank of England should provide the upper bound for the intraday liquidity cost. Since the opportunity cost of pledging collateral is not observed, the difference between interest rates charged for overnight loans at different points during the day can serve as an indicator of the opportunity cost of collateral used to obtain intraday liquidity from the Bank of England.

Bank of England does not specify any caps on the ammount of intraday liquidity that can be obtained in its monetary framework. Still banks may face some natural limits. Availability of eligible securities is one constraint. Bank of England only accepts 'Level A' (narrow collateral) when extending intraday liquidity (see Bank of England (2012) for definition). Thus implicit intraday interest rate also is an indicator on the relative scarcity of intraday liquidity repo eligible securities.

Several recent empirical studies document a positive and significant intraday value of money in other European money markets (see discussion in the literature review).

Our contribution to the existing literature is threefold. First, the UK Sterling Monetary Framework underwent an important structural change in 2006 when reserve averaging was introduced. It allows banks more flexibility in managing their end-of-day balances in their settlement accounts held with the Bank of England. Our results show that the intraday pattern of the overnight loan pricing changed as a result of the change in the Sterling Monetary Framework, thereby shedding light on how the reserve requirements affect the intraday value of money.

Second, like for many important markets for overnight funds, an important feature of the UK market is that there is no contractually binding repayment time for an overnight loan. The existing studies of intraday interest rate are based on the data from countries (i.e. Italy and Switzerland) where repayment of the loan is automated and done immediately the next business day. Our paper and the data from UK, a significant financial center, sheds light on the majority of money markets where overnight funds trading is not automated.

Third, our analysis provides empirical evidence that supports the theoretical implications of the recent work by Ashcraft, McAndrews, and Skeie (2011), but does not find evidence for the implications in Gu, Guzman, and Haslag (2011). Gu, Guzman, and Haslag (2011) ague that there are conditions under which it is socially optimal to have a positive intraday interest rate. The key implication of their model is that higher intraday interest rates will lead to more settlements earlier in the day. We report an opposite relationship using UK data. We also show that there is a positive relationship between the overnight lending activity and the tightness of the reserves market in the last hour of the trading day – a theoretical prediction of Ashcraft, McAndrews, and Skeie (2011).

Anecdotally, it is believed that there is a market convention to return borrowed overnight funds by noon on the next day. Our data, however, show that a non-negligible fraction of overnight loans are repaid late in the afternoon. Thus, in the UK money market, an overnight loan has two intraday components, one for the day when the loan is advanced, and one for the day when the funds are returned. We show that during the 2007-2008 liquidity crisis, the latter component is priced substantially higher than the former.

Using overnight loan transactions data from the UK large-value payment system CHAPS in 2003–2009 period, we investigate whether there is a positive intraday interest rate implicit in the UK overnight money market by estimating the average premium (defined as the interest rate less Official Bank Rate[1]) charged in the overnight money market as a function of the time of the day when the loan is advanced. We split the sample period into three subsamples reflecting the changes in the Sterling Monetary Framework (ie introduction of reserves averaging and voluntary reserves targets) and the global financial crisis of 2007.

The first sample period runs from January 2003 until April 2006. The second starts in May 2006 with the introduction of reserves averaging and ends in June 2007 before the onset of the financial crisis. The last subsample then runs from July 2007, when the first signs of financial distress became apparent, until February 2009, just before the Bank of England introduced (in March 2009) the Asset Purchase Facility commonly known as "quantitative easing". Even before introduction of Asset Purchase Facility the amount of reservers provided by the Bank of England increased substantially. During the last period analyzed the key features of the Sterling Monetary Framework were changed several times in response to financial crisis. For the purposes of this study we do not explicitly account for each individual policy change but focus on the treatment of bank reserves.

In the empirical model, we include a variety of control variables. We allow for a bank-specific component capturing the differences in premiums due to credit risk, day-of-the-week effects and loan size. We also include a variable that captures the distance of actual average reserves from the target. The hypothesis is that a borrower facing an increased pressure to meet their reserves target may be willing to accept less favourable terms than a borrower facing no such concerns, as shown in Beaupain and Durré (2008) and Fecht, Nyborg, and Rocholl (2011). Finally, we include a measure of aggregate reserves available in the settlement system to control for the effects of changing supply of reserves.[2]

Our empirical results lead us to conclude that the pricing of overnight loans in the UK money market is consistent with the existence of an implicit intraday money market. While the average implicit hourly intraday interest rate is quite small in the precrisis period (0.1bps), it increases more than tenfold during the financial crisis (1.56bps). For an average loan of £65 million, advancing the loan one hour earlier in the day increases the interest payment by an estimated £2,778 in the crisis period. This is consistent with banks' precautionary liquidity hoarding during the crisis

[1]The main policy rate of the Bank of England, also called the Bank of England base rate.

[2]Note that not all reserve banks are settlement banks.

documented by Acharya and Merrouche (2012). We also observe an increase in the implied loan rate during the last hour of trading. As expected, the end of the day effect is most pronounced during the period without reserves averaging as the settlement banks had to meet the ‘target’ of a nonnegative overnight reserve balance each day.

As a robustness check, we repeat the estimation using brokers’ quote data. The availability of both bid and offer rates allows us to test an alternative explanation for the intraday interest rate pattern – differences in market liquidity during the day, as measured by the bid-ask spread. Our results indicate that this is not the case, and even when controlling for the bid-ask spread we obtain results qualitatively similar to those obtained from the CHAPS transactions data.

The main policy implication of our work is that opportunity cost of collateral pledged to obtain intraday liquidity from the Bank of England can become significant during market distress. This can provide wrong incentives for banks to delay payments, as the intraday value of liquidity rises substantially. Through this channel the financial system under stress can become subject to further market pressure. To avoid possible payment delay, participants of CHAPS are subject to throughput guidelines that prescribe a percentage of payments that need to be processed before certain thresholds during the day. But the Bank of England’s Payment System Oversight Report (Bank of England, 2009) shows that even with throughput guidelines, CHAPS banks started delaying payments after the collapse of Lehman Brothers. In light of our results, we suggest that the implicit intraday interest rate can be used as an indicator of emerging intraday liquidity concerns in payment systems.

The rest of the paper is structured as follows. We overview relevant literature in the next section. We describe the institutional features of the UK overnight money market in Section 3. Empirical methodology is described in Section 5 while we describe the data used in Section 4. We discuss the empirical results in Section 6 while Section 7 concludes.

2 Literature

The theoretical literature on the intraday money markets is scarce. On one hand, Martin and McAndrews (2010) argue that, based on the efficiency arguments, there should not be any private intraday money markets. To achieve a socially efficient outcome the central bank should provide free intraday liquidity, which would therefore preclude any private intraday money market.

On the other hand Gu, Guzman, and Haslag (2011) show that there are conditions under which it is socially optimal to have a positive intraday interest rate and thus an active intraday (resale) market. If late-in-the-day production technology is more productive, while some agents have an intrinsic reason to consume early in the day, efficient allocation is implementable only if the intraday interest rate is positive. Positive capital gain on holding private debt during the day (positive intraday interest rate) is necessary to induce debtors to produce in the morning. But if the intraday interest rate is zero, it leads to debtors choosing to produce according to a more productive late in the day technology and thus debts are settled at the end of the day. Therefore, the model has an implication that higher intraday interest rates shift settlement activity towards the beginning of the day. Our study provides an indirect empirical evidence (high intraday interest rate and relatively low throughput in crisis) that points against the theoretical implication of Gu, Guzman, and Haslag (2011).

When providing free intraday liquidity to market participants the central bank faces a trade-off between enhancing the efficiency of the system and dealing with the moral hazard associated with such a policy. A socially efficient outcome is achieved when the private opportunity cost of borrowing funds intraday is equal to the social opportunity cost of providing these funds. Apart from the possible credit loss the central bank faces almost no cost to supply intraday liquidity. Thus expansion of the central bank balance sheet intraday is costless (apart from the operational costs of running the intraday facility).

Private agents, on the other hand, experience a positive opportunity cost when providing intraday liquidity. For example, some of their liabilities need to be settled with finality at a specific time of the day (a classic example being CLS[3] settlements). But since finality of settlement is generally achieved by settling in central bank liabilities, when lending funds intraday private agents take into consideration the possibility of finding themselves in shortage of the ultimate settlement asset later in the day. In a theoretical model Bhattacharya, Haslag, and Martin (2009) show that central bank provided intraday liquidity is essential to achieve efficiency as private markets for intraday liquidity cannot achieve a socially optimal outcome.

[3] Continuous Linked Settlement, a settlement system for foreign currency transactions that requires members to make payments at specific points during the day.

Martin (2004) shows that the key policy concern is that free unrestricted intraday liquidity can lead to large credit losses for the central bank. More importantly, banks could fund the purchase of risky assets by accessing free intraday facility at the central bank - the usual risk shifting argument. Therefore a fee or some other measure that limits access to intraday liquidity is needed to reduce the extent of such moral hazard, while collateralisation is desired to mitigate the credit risk. It is not clear, however, how exactly the mechanics of asset transformation at this ultra short maturity can take place. Indeed, it has been argued by Bhattacharya, Haslag, and Martin (2008) that intraday funds are not substitutable with productive assets due to the extra short funding horizon and the fact that intraday funding cannot be rolled over.

Martin and McAndrews (2010) show that if moral hazard is of concern, then collateralisation of the intraday liquidity facility does address the moral hazard issue and has the potential to achieve a socially efficient outcome. The key parameter turns out to be the private opportunity cost of collateral. On one hand, if the collateral pledged with the central bank has a zero opportunity cost, collateralization policy leads to the first best outcome. Such an intraday liquidity policy neither provides incentives to engage in excessive risk taking nor does it provide incentives for a strategic default. On the other hand, if collateral is costly, the amount of central bank eligible assets that banks choose to hold can be insufficient to meet their peak intraday liquidity needs. Thus collateralization of intraday overdrafts is distortionary, as it effectively becomes a binding intraday credit constraint. A good overview of various issues arising in payment and settlement systems is provided by Manning, Nier, and Schanz (2009).

This paper provides empirical evidence that pricing of overnight money market contracts in the UK interbank market is consistent with the existence of an implicit market for intraday liquidity. While early empirical work by Angelini (2000) finds no evidence of a positive price of intraday liquidity, several more recent contributions point invariably to the existence of a positive intraday interest rate implied by overnight loans rates. Furfine (2001) estimates the hourly intraday interest rate at 0.9bps using data on overnight loans settled in the U.S. Fedwire system in the first quarter of 1998. Bartolini, Gudell, Hilton, and Schwarz (2005) find a similar pattern in the difference between the overnight unsecured federal funds rate and the target rate for the period between February 2002 and September 2004. Baglioni and Monticini (2008) focus on the Italian e-MID interbank market 2003–2004 and show that the intraday interest rate is positive but economically small. Baglioni and Monticini (2010) repeat the same analysis with a more recent sample period including the financial crisis and show a ten-fold jump in the intraday interest rate during the crisis relative to the precrisis period. Finally, Kraenzlin and Nellen (2010) study the Swiss secured overnight loan market 1999-2008 and estimate the hourly intraday interest rate at 0.43bps.

The key methodological difference of this paper compared to the previously mentioned empirical studies is the treatment of the repayment time of the overnight loans. Previous studies use overnight lending data from trading platforms which ensure automatic repayment of the loans at a predetermined time the next morning (ie 7:50am in Swiss franc repo market). In this paper we allow for the repayment time to be endogenously determined. That is a counterparty borrowing funds overnight in an environment of a high (low) intraday interest rate may be willing to repay the overnight loan later (earlier) the next day.

Our analysis also relates to Hamilton (1996), who finds that overnight interest rates exhibit a U-shaped pattern over the reserve maintenance period in the US. Credit limits and transaction costs are believed to be the key factor contributing to the overnight rates being larger at the beginning and the end of the reserve holding period. We believe that a similar U-shaped pattern of the intraday interest rates found by us is an indication of market frictions and bilateral limits in place intraday.

3 The UK overnight money market

In this section we describe the UK money market and the details of CHAPS, the UK large value payment system. Before we proceed it is important to clarify some of the terminology that is frequently used interchangeably in the literature, in particular liquidity and reserves. Each settlement bank holds a reserves account with the central bank. The reserves account balances at the end of the day are generally referred to as 'central bank reserves'. The amount of funds available to the settlement bank to settle payments intraday is usually referred to as 'intraday liquidity' which effectively is a lower bound (it can be negative) on the reserves account.

An important determinant of the overnight money market activity is the requirement for banks to hold minimum balances at the central bank, the so called reserve requirement.[4] With the money market reform of the 2006 the Bank of England introduced reserves averaging and each participant is free to set a self-imposed reserves target. Within a symmetric narrow range of self imposed required reserves average reserves balances are remunerated at the Bank of England policy rate.

Most central banks operate the so called standing facilities, which offer an opportunity for the eligible set of institutions to deposit or borrow funds overnight at the predetermined spread from the policy rate. The unique element of the UK money market arrangement over the period analyzed is time varying aspect of the standing facility rates[5], which set a narrower band for market interest rates at the end of the reserves holding period. Further, in response to the financial crisis the average reserves range has been widened gradually and the reserve averaging framework has been subsequently suspended, with effectively all reserves balances being remunerated. At the same time the standing facility rates, formerly providing a ± 100bp channel around the policy rate (and ± 25bp on the last day of the reserves holding period) were narrowed and fixed to ± 25bp at all times. For the purposes of our study, these policy changes may have had differential effect on concerns banks have had to achieve specific reserves balances each day. The Sterling Monetary Framework operational during the period of our analysis is laid out in Bank of England (2010) publication also know as the Red Book.

As mentioned above, settlement banks can obtain collateralized intraday overdrafts from the Bank of England in addition to the reserves carried over from the previous day. Usually banks manage their overnight reserves balance by borrowing or lending funds overnight in the interbank money market.[6] The market for overnight reserves is largely an OTC market (due to counterparty risk) where parties to each transaction negotiate the terms bilaterally. Funds are delivered and repaid via CHAPS thus effectively increasing or decreasing each counterparty's reserves balances. While it is understood that the repayment of funds should happen the next day, usually there is no legally binding condition as to when the funds should be repaid. There is anecdotal evidence of a market convention for funds to be returned before noon the next day, but our data show this is not necessarily the case. Absent

[4]See Bank of England (2008a) for a detailed discussion. See also Clews, Salmon, and Weeken (2010) for the latest developments.

[5]Uniform standing facility rates of ± 25bp have been introduced in October 2008.

[6]Banks can also access a deposit and an operational lending facility which are intended to prevent market interest rates from deviating significantly from the Bank of England policy rate.

a legally binding time limit to return the funds on the next day it may be possible that the timing of repaying the overnight loans is a function of the terms of the loan agreement. Therefore in our empirical analysis we allow for endogenous repayment time.

CHAPS, a real time gross settlement system, plays an important role in determining intraday liquidity demand of the settlement banks that are direct members of this system[7]. Before the opening of a settlement day at 6am banks preposition eligible securities with the Bank of England, against which intraday liquidity is provided. Alternatively, settlement banks can carry over larger reserves balances or borrow funds on the interbank market if such a need arises during the day. Yet another alternative to obtain intraday liquidity is to delay outgoing payments in anticipation of incoming payments.

Ball, Denbee, Manning, and Wetherilt (2011) provide a detailed discussion as to why payment delay is an important issue in the real time gross settlement systems. To address these concerns CHAPS settlement banks are required to submit on average 50% of payments by value by noon and 75% of payments by 2:30pm. All settlement members of CHAPS have the technical capability to manage their payment flow intraday by using internal payment schedulers or by utilizing the scheduling functionality of the central payment queue.[8] Historical throughput averages are very close to prescribed threshold values, which is an indirect evidence that banks tightly manage their intraday liquidity.

There are several factors that determine the demand for reserves for each settlement bank. The first one is the agreed reserves targets.[9] Although banks try to reach a self imposed target on average, daily settlement account deviations from the targeted level can accrue and put pressure on the bank over the remainder of the maintenance period. Second, since net payment flows over the day are not known until just before the payment system closing time, banks usually trade in anticipation of any settlement account shocks. To alleviate the last minute rush to square the accounts, settlement banks in CHAPS have a 20 minute period at the end of the day during which only payments initiated by the settlement banks can be settled (as

[7]The securities settlement system CREST, which is not the subject of our study, also generates intraday liquidity demands

[8]See Jurgilas and Martin (2010) for a detailed discussion of the role of liquidity saving mechanisms in CHAPS.

[9]We exclude the period during which excess reserves are remunerated from our analysis.

opposed to payments sent on behalf of the clients). In our data we see that only a small fraction of the overnight loans are settled during this period. This could be an indication that end of the day settlement account balance concern is not the key concern driving overnight borrowing and lending activity, or that banks anticipate their borrowing and lending needs and enter into overnight contracts earlier in the day. The latter explanation is also compatible with the main hypothesis of the paper, that banks time the overnight loan advances and repayments in relation to their intraday liquidity needs. The next section describes the data we use to test this hypothesis.

4 Data

We employ data on payments in the UK's large-value payment system CHAPS for the period running from January 2003 until February 2009. CHAPS is a real time gross settlement system for settling interbank payments. Only a small number of banks (12 or 13 during our sample period) are direct members of CHAPS. Other UK banks have access to the system indirectly through business relationships with direct member institutions.

We extract the overnight loan transactions using a version of the algorithm developed by Furfine (1999) from the raw payments data. The algorithm matches payments on two consecutive days that can be deemed overnight loan advances and repayments. In particular, it searches for all payments in fairly round numbers for which there are payments in the other direction on the following day such that the implied interest rate falls within a reasonable interval around the Bank policy rate. A detailed description of the algorithm is provided by Wetherilt, Zimmerman, and Soramäki (2010), who point out that the robustness checks carried out by Millard and Polenghi (2004) indicate that the data reflect the activity in the unsecured overnight money markets very well.

There are two potential caveats associated with this data set. First, we are not able to distinguish between the direct CHAPS member banks and their clients. Consequently, we cannot control for the credit risk associated with each and every borrower, but only for the average credit risk of the settlement bank and its customers. Second, loan payments between two customers of the same settlement bank, or payments between a settlement bank and its clients, are not included in our data since these payments are settled across the books of the settlement bank and not in CHAPS.

Since the last 20 minutes of the CHAPS settlement day are reserved for interbank payments only[10], we exclude from our data set the loans advanced between 4:00pm and 4:20pm. This amounts to discarding 3.9%, 2.1% and 1.7% of all transactions in the first, second, and third periods respectively. Table 1 reports some summary statistics for the overnight loans data separately for the three subsample periods. The average daily volume of loans advanced through CHAPS grows steadily over time, from £19.5 billion (2003–2006) to about £30 billion (07/2007-02/2009). This is due to an increase in both the average daily number of loans advanced (from 400 to 434) as well as the average loan amount (from £49.2 million to £64.7 million).

Fig. 1 shows the distribution of loan advance time, repayment time and loan duration. The distributions are remarkably stable over time. We observe that the majority of loans are advanced in the afternoon with a peak just shortly before the CHAPS system closes. Repayment usually takes place before noon (about 75%) implying that the average loan duration is less than 24 hours. Interestingly, the distribution of loan duration exhibits two modes, with one at around 19 hours and the other one at 24 hours. The bottom panel of Fig. 1 also shows the implied rate charged on the overnight loans together with the Bank policy rate. As expected, the average loan rate tracks the policy rate very closely, though the loan rate itself fluctuates considerably around it. The variability of the implied overnight rate is lower once reserves averaging is introduced but increases somewhat in the crisis period.

Fig. 2 shows distributions of identified rates. As can be expected, identified overnight interest rates are much more closer to the Bank rate once the reserve averaging was introduced. But the distribution widens a bit during the financial crisis period. There is also a visible asymmetry in the same period with more transactions taking place below the Bank rate than above. This is consistent with an observation that SONIA[11] rates (Sterling overnight index average) for actual transactions was significantly below Bank rate at the peak of the crisis (see Fig. 3). The distributions look identical both by value or by volume indicating that it is not the case that several large transaction are skewing the data.

In addition to the CHAPS payments data, we use data on intraday reserves ac-

[10]Banks can use the last 20min to square off their balances with no uncertainty regarding settlement balances due to customer payments.

[11]SONIA is the weighted average rate to four decimal places of all unsecured sterling overnight cash transactions brokered in London by Wholesale Markets Brokers' Association member firms between midnight and 4.15pm with all counterparties in a minimum deal size of 25 million.

count balances held by settlement banks at the Bank of England. The data are available at a ten minute frequency. For each ten minute period, we calculate the aggregate amount of reserves in the system by summing up the reserves account balances of the settlement banks.[12] We then match the regularly spaced reserves data with the irregularly spaced loans data by taking the most recent value of aggregate reserves for each loan. The reason why we do not use contemporaneous reserves as a control variable is because contemporaneous reserves are potentially endogenous due to market operations to keep market rates closer to the policy rate.

For the two subsample periods characterized by reserves averaging, we also construct a bank-specific variable capturing the distance of the current average reserves from the target the bank set for the maintenance period. In the first subsample period with no reserves remuneration we assume that banks try to end the day with a nonnegative reserves balance. Thus we set the target for this period to be zero. Confidentiality issues prevent us from reporting summary statistics for these variables.

5 Methodology

Let $r_{t,\tau}$ denote the rate of return on some overnight loan advanced at time τ on day t and let d denote the realized duration of that loan in hours. Let's assume that per-hour interest rate charged during the day differs from the per-hour interest rate charged overnight and denote these by i_D and $i_{O/N}$, respectively. Further denote by $d^{(\tau)}$ the time between the advance of the loan and the market closing time, i.e. between τ and 4:00pm. Denote by $d_{O/N}$ the overnight period in hours (4:00pm - 6:00am) and by $d^{(\tau')}$ the time elapsed between 6:00am on $t+1$ and the repayment time of the loan, τ'. Thus $d = d^{(\tau)} + d_{O/N} + d^{(\tau')}$. At time τ, both $d^{(\tau)}$ and $d_{O/N}$ are known but $d^{(\tau')}$ is not. The random nature of the repayment time makes our analysis distinct from Baglioni and Monticini (2008) and Kraenzlin and Nellen (2010) who study overnight money markets with fixed and known maturity.

Assuming continuous compounding and same intraday interest rate on the day of loan advance and repayment, the rate of return on the overnight loan can be written as

$$r_{t,\tau} = i_D d^{(\tau)} + i_{O/N} d_{O/N} + i_D d^{(\tau')}. \tag{1}$$

[12] Note that this does not reflect all reserves available to the banks as not all reserves banks are settlement banks.

If intraday liquidity has no value, $i_D = 0$, and the rate of return on an overnight loan only depends on the interest rate charged for the overnight period, $i_{O/N}$. In other words, it does not matter when the loan is advanced and when it is repayed – the rate of return will not be affected. On the contrary, when intraday liquidity is priced, $i_D > 0$, every additional hour of the duration of the loan increases the rate of return by i_D.

To test if there is a positive intraday interest rate, we propose the following empirical model:

$$\text{Model 1:} \qquad r_{t,\tau} - br_t = c + \sum_{k=1}^{9} \alpha_k D_k^{\tau} + \delta d^{(\tau')} + \sum_{l=1}^{n_s-1} \gamma_l D_l^b + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau} \tag{2}$$

where

$r_{t,\tau}$	rate of return on loan advanced at time τ on day t,
br_t	the Bank rate prevailing on day t,
D_k^{τ}	dummy variable for hour of the day, $k = 1, 2, ..., 9$
D_l^b	dummy variable for borrower b, $l = 1, 2, ..., n_s$
$d^{(\tau')}$	duration in hours between 6:00am and loan repayment time
$\mathbf{x}_{t,\tau}$	vector of control variables

and n_s is the number of settlement banks. The key parameters of interest are the coefficients on the dummy variables for the time of day when the loan is advanced. We split the day into ten hourly intervals, starting with 6:00am - 7:00am and ending with 3:00pm - 4:00pm. The dummy variable for 11:00 - 12:00 is omitted for identification reasons. If, on one hand, the intraday interest rate is zero, so are all the α_k's. It is irrelevant at what time of the day a loan is advanced and only the overnight period is rewarded by a non-zero interest rate. If, on the other hand, the intraday interest rate is positive, the α_k's should exhibit a decreasing pattern in k as the intraday time value of money implies higher rate of return on loans advanced earlier during the day or repayed later the next day. Note that in this specification we alow for differential intraday effects on the day of the loan advance and repayment.

To capture the intraday interest rate charged on the repayment duration component of the loan, $d^{(\tau')}$, we add it into the regression model. We avoid using dummies for repayment time for the following reason. The repayment time of the loan is not known at the time when the loan is advanced and there is no legally binding obligation of the debtor to repay the loan before any given point in time. The duration of the loan, $d^{(\tau')}$, could thus be endogenous. The debtor, in response to being charged an above average rate on the loan, can delay repayment. This hypothesis can be tested by finding a suitable instrument for $d^{(\tau')}$ and comparing the OLS estimates of our regression model with those obtained by running instrumental variable estimation. Needless to say, instrumenting for the dummy variables associated with the repayment time would be difficult.

We instrument for the duration of the loan on the repayment day, $d^{(\tau')}$, using the average repayment duration of a given borrower over the past five business days. Intuitively, a lender can form opinions on when to expect a repayment of the overnight loan, based on the past behavior of the borrower, while such behavior cannot be affected by intraday interest rate prevailing at some future date. Alternatively, the borrower can establish a reputation of being a late payer or an early payer. By construction, this variable is predetermined and hence uncorrelated with the innovations in the loan interest rates. This instrument passes the Steiger and Stock (1997) test for weak instruments, i.e. it possess significant predictive power for the actual repayment duration $d^{(\tau')}$.

As well as repayment time, the advance time of the loan is not explicitly stipulated in the overnight loan contract. Based on anecdotal evidence and market intelligence it is 'as soon as possible' after the trade takes place. Still we cannot rule out the possibility that loan advances may be delayed. But if transfer of funds for an overnight loan is delayed, it would bias our measures of d^{τ} downwards. If delay in sending leg of overnight loan covaries with loan rates, similar to the repayment time of the loan, measurement error potentially can bias our intraday interest rate estimates downwards - loans with high rates (more likely to be delayed) would appear to have small durations, d^{τ}.

In addition to the time-of-day dummies and loan repayment time, we include a number of other control variables into the model not to confound the intraday interest rate pattern with some bank-specific or market-wide characteristics. The motivation for our specification is as follows.

Dummy variables for borrower We use bank-specific dummy variables to proxy for average credit risk of the settlement bank and its clients. Furfine (2001) shows that banks with different credit risk profiles are indeed paying different interest rates on overnight loans in the U.S.

Day-of-week dummy variables We employ day-of-week dummies to control for various calendar effects.

Loan size Large-value loans can be presumably more costly to obtain.

Aggregate reserves By the simple supply-demand argument, we expect the level of aggregate reserves across all settlement banks to co-vary negatively with the level of short term interest rate. Note that not all banks holding reserve accounts with the central bank are members of the payment system.

Distance from reserves target Separately for lender and borrower, we calculate the difference between the average reserves to date and the target reserves. The idea is that a bank facing pressure to meet its reserves target at the end of the maintenance period will be prepared to accept less favorable terms than a bank facing no such concerns.

Reserves balance We include actual reserves balances for the borrower as well as the lender. The coefficients on these control variables measures[13] the extent to which intraday demand for positive balances is linked to an intraday premium.

The model in Eq. (2) is flexible in that the intraday interest rate is not assumed to be constant on the day of the loan advance. Under the simplifying assumption that the intraday hourly interest rate is indeed constant and equal to α, the model can be written as

$$\text{Model 2:} \qquad r_{t,\tau} - br_t = c + \alpha d^{(\tau)} + \delta d^{(\tau')} + \sum_{l=1}^{n_s - 1} \gamma_l D_l^b + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}, \qquad (3)$$

since the α_k's in Model 1 decline linearly with k, and thus the difference of $\alpha_k - \alpha_{k+1}$ is equal to the hourly intraday interest rate α.

If we further assume that the intraday value of funds on the day of loan advance is the same as on the day of loan repayment (i.e. $\alpha = \delta$), the model simplifies to:

$$\text{Model 3:} \qquad r_{t,\tau} - br_t = c + \alpha (d^{(\tau)} + d^{(\tau')}) + \sum_{l=1}^{n_s - 1} \gamma_l D_l^b + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}, \qquad (4)$$

[13] Many thanks for anonymous referee for suggestion.

Since $d^{(\tau')}$ is uncertain at the time a loan is advanced, it may well be that the interest rate charged for this part of the loan duration is higher. It remains an empirical question whether or not this is the case.

6 Empirical results

Table 2 and Fig. 6 summarize the estimation results separately for the three subsample periods described above. To ease interpretation, we express the left-hand side variable (overnight loan premium) in basis points. All models are estimated by two-stage least squares as the Hausman test (not reported) rejects exogeneity of the repayment time. That is, we find that repayment time is endogenous to the interest rate charged on the loan.

Common to all three sets of results is a clear downward sloping trend in the average premium on overnight loans persisting up to the last hour of CHAPS operation, see Fig. 6. This is consistent with a positive intraday interest rate during this part of the day and an indirect manifestation of an implicit intraday money market. The difference between the premium charged in the morning and afternoon varies considerably across the three subsample periods. In the first period (January 2003 – April 2006) it is about 3.6bps between 6am and 3pm, implying a relatively small hourly intraday interest rate of 0.4bps.[14] The value of the intraday rate decreases further after April 2006 to about 0.1bps per hour. Similar to Baglioni and Monticini (2010), however, we find a sizable increase during the crisis period. The hourly intraday interest rate jumps to about 1.9bps as loans advanced between 6-7am command a premium 18bps higher than loans taken between 2-3pm, as the last panel of Fig. 6 illustrates. Note that only looking at the premiums on overnight loans advanced at the beginning and end of the day masks a clear U-shaped pattern of the overnight interest rates. Thus marginal effect of advancing a loan one hour earlier is estimated to be much stronger at the beginning of the day.

In the period preceding the introduction of reserves averaging (January 2003 – April 2006) we find a significant increase in the average premium charged for overnight loans advanced in the last hour of the trading day (3-4pm). Recall that during this period settlement banks were not remunerated for positive reserve balances, thus

[14] This calculation is made by assuming a linear intraday pattern between 6am and 3pm and continuous compounding over the nine hour interval.

effectively having a zero reserve balance target.[15] The increase in the premium at the end of the day can thus be explained by an increased demand pressure caused by banks aiming to meet their end-of-day nonnegative reserves balance requirement. During the reserves averaging regime, such concerns are only relevant on the last days of the maintenance period and hence the average increase of the premium in the last hour is much smaller and economically insignificant.

Ashcraft, McAndrews, and Skeie (2011) provide an alternative theoretical explanation as to why overnight rates may be higher at the end of the trading day. If interbank market is characterized by a relative shortage of reserves (with overnight rates being high) one should observe more transactions taking place towards the end of the day. Alternatively, in case of abundant reserves, there would not be a need to obtain a precise reserves distribution, and thus less overnight lending transactions should be observed. Fig. 4 shows the relationship in our data between the amount of overnight loans (by value and volume) and overnight loan premium (defined as loan rate minus the Bank rate). Except of the May 2006 - June 2007 period, there is a significant positive relationship between the overnight lending activity and the tightness of the reserves market in the last hour of the trading day. This goes in line with the theoretical results of Ashcraft, McAndrews, and Skeie (2011).

Contributing to the uptick in the premium after 3pm is also the closure of the European payment systems at that time. Many of the settlement banks manage sterling and euro liquidity from the same offices, and manage them on a global basis (i.e. not separately by currency). Once continental Europe closes, banks can no longer access the European money market to boost their end-of-day reserves balances, and the demand for reserves concentrates in the UK money market.

The clear U-shaped intraday loan rate pattern observed for the first subsample period rules out the linear specification (Model 2) where the intraday interest rate is assumed to be constant. In the second and third periods, on the other hand, it can serve as a reasonable first-order approximation, as Fig. 6 illustrates. The estimated intraday interest rate increases from 0.09bps in the second period to 1.56bps during the crisis.

The repayment time comes out highly significant and positive in the first and third sample periods. Based on the estimates of Model 1, each additional hour of loan duration carries a premium of 2bps and 5.2bps in respective period. These

[15] Bank of England (2005) pages 211-20 describe the Sterling Monetary Framework in more detail.

values are higher than the respective estimates of the intraday interest rates and the difference is statistically significant. The restriction that they are equal, implied by Model 3, is soundly rejected at conventional significance levels. This result indicates that lenders value intraday liquidity more on the repayment day, which likely reflects the higher uncertainty regarding the timing and value of non-contractual payments on the next day as opposed to the day of trading.

Turning to the effect of the various control variables, we find that large-value loans are more costly to obtain between January 2003 and June 2007, while the opposite holds during the crisis. We believe that in the crisis period loan size correlates with the creditworthiness of the counterparty. As this was a period of significant credit rationing[16], larger loans are advanced to the counterparties with a higher credit standing thus explaining the observed negative relationship to the premium charged. We include settlement bank dummies to control for bank specific effects, but it is an imperfect measure of the credit risk component, partly because we can only identify the settlement bank group. The magnitude of the estimated coefficients nonetheless indicates that the effect of loan value is economically quite small.

Aggregate reserves covary negatively with the premium in all three sample periods. For example, during the crisis, an increase in aggregate reserves of £1 billion reduces the premium by 1.2bps. The effect of settlement bank-specific distance from reserves target seems to be economically quite small, except for the crisis period, when the borrowing settlement bank is prepared to accept an increase in the premium of 2bps if its average reserves are short £1 billion of the target. The impact of aggregate reserves on the pricing of overnight loans is evidence of a liquidity effect at an intraday frequency. Given the operational framework of the Bank of England (no daily interventions) and very high frequency of the data our estimation does not suffer from the endogeneity issues well documented in studies estimating liquidity effect using daily data (see Hamilton, 1997 and the literature that followed). Finally, most of the counterparty dummy variables, not reported here for confidentiality reasons, are found to be highly statistically significant.

Meeting reserve requirement is an important consideration for a bank when extending or taking an overnight loan. But having a positive reserves balance intraday (ie being able to settle payments immediately) is also of a concern. Thus we estimate Model 1 and Model 2 for the 3 subsample periods introducing an additional control

[16]Bank of England (2008b) provides a detailed discussion of this market episode.

variable of individual bank reserves balance (both for the lender and for the borrower of the identified overnight loan contract). Since no reserves averaging was in place, reserves distance from an assumed reserves target of 0 is equivalent to reserves balance in the first subperiod. Estimation results are reported in Table 3. We find that in the first and last subsamples reserves balances have a negative effect on the loan premium. This is consistent with our estimated significant and large intraday term premia in these subsamples.

Evidence of increasing intraday interest rate during market stress has important policy implications. Recall that the implicit intraday interest rate is a lower bound for the opportunity cost of collateral pledged with the central bank intraday. Thus it is a signal that the intraday opportunity cost of collateral is higher. In response banks could pledge lower amount of collateral intraday and subsequently start delaying payments. In tense market conditions this can put unnecessary pressure on the market participants who may be cautious that difficulty obtaining intraday liquidity does not translate (via reputation effects) into overnight or term liquidity problems. Note that payments activity is probably the only informative signal that settlement banks can get in real time regarding the liquidity conditions of their counterparties.

Our results can be put in parallel with those in Hamilton (1996) who finds that overnight interest rates exhibit a U-shaped pattern over the reserve maintenance period. The key explanation put forward is that market frictions and credit limits do not allow market participants to act on interest rate fluctuations. This seems to apply to our study as well, as it is known that apart from credit limits settlement banks have net sending limits which put a limit on how many payments will be sent for settlement before a counterparty starts sending payments in return.

6.1 Robustness check with brokers' quote data

One of the potential limitations of our data set is that it only includes overnight loans settled through CHAPS. Moreover, only data on actual transactions is available, with no information about the bid and ask prices prevailing in the market at the time the loan is agreed. Fig. 1 shows that the market is fairly inactive in the morning relative to the afternoon, which can suggest that the increased premium in the morning is a symptom of market illiquidity rather than a genuine intraday interest rate.

To address this question, we repeat the same exercise with data on overnight loan quotes extracted from Thompson Reuters. The data is only available to us for the period between May 2006 and February 2009. The first subsample period is therefore omitted from this analysis. We define the premium as the difference between the quoted mid-point, i.e. the simple average of the bid and ask rates, and the Bank rate. We then regress the premium on the time-of-day dummy variables (Model 1') or on the duration to the market close d^q at the time at which the quote was posted (Model 2'), controlling for the level of aggregate reserves and the bid-ask spread:

$$\text{Model 1'}: \qquad r^m_{t,\tau} - br_t = c + \sum_{k=1}^{8} \alpha_k D^\tau_k + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}, \tag{5}$$

$$\text{Model 2'}: \qquad r^m_{t,\tau} - br_t = c + \alpha d^q + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}, \tag{6}$$

where $r^m_{t,\tau}$ is the quoted middle rate at time τ on day t. The bid-ask spread can be viewed as a proxy for market liquidity and allows us to test market illiquidity hypothesis discussed in the previous paragraph. With the exception of aggregate reserves, the other control variables employed before cannot be used here since they are loan-specific, and this has to be taken into consideration when comparing the two sets of results.

The estimation results are reported in Table 4. The intraday term structure implied by the quoted loan rates is qualitatively similar to the one obtained from the CHAPS loan data, especially during the crisis period. The intraday interest rate in the second period at 0.43bps (Model 2') is higher than the rate estimated from the transactions data (0.09bps). The intraday pattern, however, appears to be highly nonlinear (see Model 1') and hence the validity of the linear specification is rather questionable. For the crisis period we obtain very similar estimates across the two data sets ($\approx$ 1.5bps). Including the bid-ask spread into the regression does not significantly alter the results. The effect of the bid-ask spread is positive in the second period and negative and economically small in the crisis period. Aggregate reserves tend to covary negatively with the premium as before.

The robustness of intraday interest rate results using quotes data rules out an alternative explanation of intraday interest rate that we identify. Since we cannot fully control for counterparty risk due to possible indirect trading in CHAPS higher overnight rates could just correspond to higher counterparty risk. But there is no such concern when using quotes data as these are generic quotes that are not counterparty specific.

We also use quotes data to test the validity of identified interest rates based on Furfine algorithm. There could be a concern that Furfine algorithm while picking up overnight loans in good times might not work so well when interest rates are very volatile. In general the validity of Furfine implied data has been tested by the Bank of England by comparing it to the actual short sample of actual overnight loans obtained from several CHAPS banks. Still it does not address the concern that Furfine algorithm performs equally well during volatile market conditions. Therefore we conduct the following exercises.

First, for the crisis period we construct day-by-day and hour-by-hour overnight interest rate average based on Furfine algorithm. Similarly, we construct average bid, ask, and mid-quotes. With 9 observations per day and 422 days in the crisis subsample this gives us 3774 observations that we can compare. We then regress Furfine algorithm based average transaction price on the average mid-quote from quotes data. The regression results are reported in Table 5 column A. The goodness of fit is almost perfect with R^2 of 0.988.

Second, we redo the same exercise averaging quotes and transactions for the day. The regression results for this estimation are reported in Table 5 column B. The goodness of fit is even better.

Third, we zoom in on the worst crisis months of September- November and report bid/ask quotes and Furfine algorithm identified data in Fig. 5. We see that average transaction prices are mostly within bid/ask quotes. The only inference we draw is that in this subperiod transaction price tended to be closer to the bid rather than to the ask quote; this is consistent with the evidence from SONIA rates in Fig. 3.

6.2 Interest rate and throughput

The key empirical results of this paper can be put in parallel with the theoretical implications of Gu, Guzman, and Haslag (2011), who argue that there are conditions under which positive intraday interest rate can be socially efficient. The paper very elegantly shows that if the intrinsic need for settlement is perfectly substitutable between morning and afternoon, the socially optimal allocation is achieved at zero intraday interest rate with all settlements taking place in the evening. In contrast, a positive intraday interest rate can be socially desirable if some agents have an intrinsic need to settle in the morning.

But empirical evidence from CHAPS does not fit very well with the implications of Gu, Guzman, and Haslag (2011). In particular, we find that intraday interest rate increases tenfold during the crisis period, while the Bank of England's Payment System Oversight Report (Bank of England, 2009) reports lower throughput during the same period. That is, larger fraction of settlements took place later in the day, while the implicit intraday interest rate increased.

To further illustrate the implications of the level of interest rate on bank payment behavior, Fig. 7 shows daily time-series of the Bank rate and noncontractual payment throughput. Noncontractual payment throughput is defined as the proportion of all non-contractual payments made made before noon. This therefore excludes the overnight loan advances and repayments which are included for the purposes of evaluating each bank's adherence to CHAPS throughput guidelines.

Fig. 7 shows that there is an inverse relationship between the Bank rate and the noncontractual throughput (throughput thereafter). In the first part of the sample, when interest rates were on the rise, the throughput was gradually decreasing. Note that settlement banks can use their overnight balances to cushion against intraday payment flow imbalance the next day. Ennis and Weinberg (2007) show that overnight reserves and daylight credit act as an alternative means of funding transfers during the day. Thus if there is no shortage of reserves, reflected by a low overnight interest rate, intraday liquidity would come at no cost and hence there would be no incentive for banks to delay payments. This seems to be consistent with our result that an increase in the overnight interest rate makes borrowing as a means of financing outgoing payments more costly and provides incentives for banks to delay payments to smooth intraday liquidity. In the summer of 2007, when the Bank rate reached its peak of 5.75%, throughput fell well below 50%. Following the subsequent interest rate cuts, throughput slowly began to rise again, with the exception of a short spell in the fall of 2008 characterized by market distress brought about by the collapse of Lehman Brothers. In this period, throughput temporarily fell to all time low levels.

7 Conclusion

This paper shows that while there is no explicit interbank intraday money market in the UK, the pricing of overnight loans is consistent with an intraday value for money. We find that the implicit intraday interest rate paid by banks within our sample period varies between 0.09bps and 1.56bps. While the implicit hourly intraday interest rate is quite small in the precrisis period, it increases more than tenfold during the financial crisis. For an average loan of £65 million, advancing the loan one hour earlier in the day increases the estimated average payment by £2,778. We also find that interest premium is not linear throughout the day and is U-shaped. It is higher at the beginning and the very end of the day. We believe that higher interest rates at the end of the day can be attributed to the end of the day settlement balance concerns equivalent to the end of the reserve holding period concerns.

Looking at aggregate (across the settlement banks) and individual bank reserves balances we find that overnight interest rates decrease with the aggregate reserves. This means that the central bank reserves distribution across the settlement banks and other financial institutions with reserves accounts does matter for overnight interest rate determination. It also is an empirical evidence of an intraday liquidity effect.

There are two intraday timing components of the overnight loan, namely the time of the loan advance and the time of loan repayment the next day. While the loan advance time is by definition known at the point of agreeing the overnight loan, the repayment time is uncertain. We find that there is a significant premium on the both intraday components of the loan. That is, overnight loans advanced early or/and expected to be repaid late the next day have a positive premium. The premium is significantly larger for the expected repayment time in the crisis period. Counterparties that delay repaying their overnight loans have to pay on average a premium of 4.3bps per hour of expected delay.

The key policy implication is that implicit intraday liquidity cost can become significant during market stress. This can provide wrong incentives for payments delay and can contribute to financial stress. In parallel to the findings of Hamilton (1996), increased differentials of intraday interest rates can also signal increased market frictions and credit constraints. Thus implicit intraday interest rate can be used as an indicator of intraday liquidity concerns in payment systems.

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A Tables and figures

	Jan '03 - Apr '06	May '06 - Jun '07	Jul '07 - Feb '09
Av. daily volume (£b)	19.3	26.7	30.0
Av. loan amount (£m)	49.2	58.6	64.7
Av. loan duration (hours)	21.2	21.3	21.4
Av. interest rate (%)	4.28	5.01	4.64
Av. premium (bp)	-3.05	5.19	-5.20
No. settlement banks	12	12	12-13
No. days	839	295	422
No. observations	321,945	125,527	193,047

Table 1: Summary statistics for implied overnight loans data in the three subsample periods.

Table 2: Estimation results of different specifications of the regression model for premium (overnight rate minus the Bank rate, $r_{t,\tau} - br_t$) in three subsample periods. All specifications in all subsamples are estimated by two-stage least squares (2SLS) since the Hausman test (not reported) rejects the null hypothesis of exogeneity of repayment time. Robust t statistics are given in parentheses.

$$\text{Model 1:} \quad r_{t,\tau} - br_t = c + \textstyle\sum_{k=1}^{9} \alpha_k D_k^\tau + \sum_{l=1}^{n_s-1} \gamma_l D_l^b + \delta d^{(\tau')} + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}$$
$$\text{Model 2:} \quad r_{t,\tau} - br_t = c + \alpha d^{(\tau)} + \delta d^{(\tau')} + \textstyle\sum_{l=1}^{n_s-1} \gamma_l D_l^b + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}$$
$$\text{Model 3:} \quad r_{t,\tau} - br_t = c + \alpha(d^{(\tau)} + d^{(\tau')}) + \textstyle\sum_{l=1}^{n_s-1} \gamma_l D_l^b + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}$$

	Jan '03 - Apr '06			May '06 - Jun '07			Jul '07 - Feb '09		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
A. Time-of-day effects, D_k^τ									
6-7	3.460 (9.88)			0.787 (2.11)			13.98 (16.98)		
7-8	1.825 (5.54)			1.272 (3.23)			13.64 (17.55)		
8-9	0.955 (3.21)			0.038 (0.14)			9.31 (15.55)		
9-10	0.299 (1.26)			0.357 (1.80)			7.94 (17.83)		
10-11	−0.032 (−0.14)			−0.182 (−1.05)			2.82 (6.63)		
12-13	−0.389 (−1.77)			−0.097 (−0.70)			−3.40 (−9.94)		
13-14	−0.835 (−4.07)			−0.433 (−3.43)			−3.94 (−12.44)		
14-15	−0.127 (−0.65)			−0.511 (−4.27)			−4.32 (−14.47)		
15-16	3.046 (15.2)			−0.159 (−1.32)			−2.67 (−9.09)		
B. Same day, $d^{(\tau)}$, and next day, $d^{(\tau')}$, duration ($d^{(\tau)}$ is overall duration in Model 3)									
$d^{(\tau)}$		−0.262 (−9.88)	−0.391 (−17.3)		0.092 (4.30)	0.105 (5.62)		1.563 (33.92)	1.246 (32.2)
$d^{(\tau')}$	1.963 (13.65)	1.079 (7.90)		−0.004 (−0.04)	−0.055 (−0.60)		5.211 (24.05)	4.325 (21.47)	

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	Jan '03 - Apr '06			May '06 - Jun '07			Jul '07 - Feb '09		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
C. Day-of-week effects									
Monday	3.233	3.131	3.133	1.391	1.398	1.412	2.889	2.892	2.776
	(20.1)	(19.5)	(19.7)	(23.1)	(23.1)	(23.8)	(13.52)	(13.78)	(13.7)
Tuesday	0.914	0.930	1.020	1.364	1.354	1.360	2.531	2.479	2.299
	(5.87)	(6.00)	(6.64)	(22.41)	(22.2)	(22.4)	(11.30)	(11.25)	(10.8)
Thursday	0.864	0.861	0.943	1.327	1.332	1.340	1.794	1.817	1.886
	(5.48)	(5.48)	(6.03)	(18.24)	(18.3)	(18.46)	(8.29)	(8.54)	(9.20)
Friday	−4.990	−4.769	−4.420	3.584	3.621	3.603	−0.002	0.091	0.233
	(−31.8)	(−30.6)	(−28.9)	(29.43)	(29.8)	(29.8)	(−0.01)	(0.42)	(1.11)
D. Controls									
Constant	−20.36	−18.54	−14.96	3.17	4.630	3.951	−29.4	−5.70	4.958
	(−32.1)	(−41.9)	(−42.3)	(5.40)	(11.43)	(18.0)	(−24.5)	(−6.35)	(8.10)
Loan size	0.005	0.010	0.019	0.006	0.006	0.005	−0.012	−0.006	0.009
	(4.61)	(9.75)	(30.1)	(10.03)	(11.22)	(18.5)	(−9.05)	(−5.21)	(15.4)
Aggregate reserves	−0.506	−0.388	−0.423	−0.097	−0.080	−0.076	−1.173	−1.157	−1.181
	(−36.1)	(−29.2)	(−32.7)	(−10.02)	(−8.77)	(−8.56)	(−122.2)	(−121.6)	(−129.8)
Reserves lender	−0.180	−0.239	−0.199	0.085	0.077	0.079	0.682	0.622	0.457
	(−8.19)	(−10.9)	(−9.31)	(4.64)	(4.28)	(4.45)	(19.8)	(18.5)	(14.8)
Reserves borrower	−0.804	−0.835	−0.791	0.203	0.191	0.186	−2.068	−2.158	−2.072
	(−29.3)	(−30.5)	(−29.3)	(6.43)	(6.04)	(5.94)	(−33.79)	(−35.6)	(−35.1)
No. observations		321,945			125,527			193,047	

Table 3: Estimation results of different specifications of the regression model for premium (overnight rate minus the Bank rate, $r_{t,\tau} - br_t$) in three subsample periods, controlling for actual reserves. All specifications in all subsamples are estimated by two-stage least squares (2SLS) since the Hausman test (not reported) rejects the null hypothesis of exogeneity of repayment time. Robust t statistics are given in parentheses.

Model 1: $r_{t,\tau} - br_t = c + \sum_{k=1}^{9} \alpha_k D_k^\tau + \sum_{l=1}^{n_s-1} \gamma_l D_l^b + \delta d^{(\tau')} + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}$

Model 2: $r_{t,\tau} - br_t = c + \alpha d^{(\tau)} + \delta d^{(\tau')} + \sum_{l=1}^{n_s-1} \gamma_l D_l^b + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}$

	Jan '03 - Apr '06		May '06 - Jun '07		Jul '07 - Feb '09	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
A. Time-of-day effects, D_k^τ						
6-7	3.460 (9.88)		0.843 (2.26)		12.53 (15.25)	
7-8	1.826 (5.54)		1.295 (3.29)		12.62 (16.25)	
8-9	0.955 (3.21)		0.075 (0.28)		8.68 (14.51)	
9-10	0.299 (1.26)		0.387 (1.95)		7.65 (17.19)	
10-11	−0.032 (−0.14)		−0.162 (−0.94)		2.55 (6.00)	
12-13	−0.389 (−1.77)		−0.115 (−0.83)		−3.31 (−9.71)	
13-14	−0.835 (−4.07)		−0.429 (−3.41)		−3.87 (−12.25)	
14-15	−0.127 (−0.65)		−0.522 (−4.36)		−4.22 (−14.18)	
15-16	3.046 (15.2)		−0.119 (−0.98)		−3.12 (−10.60)	
B. Same day, $d^{(\tau)}$, and next day, $d^{(\tau')}$.						
$d^{(\tau)}$		−0.262 (−9.88)		0.090 (4.22)		1.562 (33.83)
$d^{(\tau')}$	2.027 (14.01)	1.232 (8.91)	−0.004 (−0.04)	−0.066 (−0.72)	5.251 (24.31)	4.590 (22.64)

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	Jan '03 - Apr '06		May '06 - Jun '07		Jul '07 - Feb '09	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
C. Day-of-week effects						
Monday	3.233 (20.1)	3.131 (19.6)	1.349 (22.3)	1.359 (22.3)	3.348 (15.61)	3.391 (16.03)
Tuesday	0.914 (5.87)	0.931 (6.00)	1.328 (21.7)	1.320 (21.5)	2.780 (12.43)	2.761 (12.50)
Thursday	0.864 (5.48)	0.862 (5.48)	1.286 (17.59)	1.294 (17.7)	1.655 (7.66)	1.658 (7.78)
Friday	−4.990 (−31.8)	−4.769 (−30.6)	3.480 (28.51)	3.528 (29.0)	−0.109 (−0.49)	−0.041 (−0.19)
D. Controls						
Constant	−20.36 (−32.1)	−18.54 (−41.9)	2.98 (5.09)	4.514 (11.14)	−27.3 (−22.86)	−4.686 (−5.22)
Loan size	0.005 (4.61)	0.010 (9.75)	0.006 (10.13)	0.006 (11.43)	−0.012 (−8.94)	−0.007 (−6.02)
Aggregate reserves	−0.506 (−36.1)	−0.388 (−29.2)	−0.111 (−11.01)	−0.092 (−9.72)	−1.038 (−100.53)	−1.012 (−98.69)
Reserves lender	−0.181 (−8.19)	−0.239 (−10.9)	0.055 (2.29)	0.053 (2.21)	1.155 (28.65)	1.153 (29.07)
Reserves borrower	−0.805 (−29.3)	−0.836 (−30.6)	0.127 (3.88)	0.116 (3.55)	−1.132 (−16.42)	−1.153 (−16.89)
Reserves 0 lender			0.027 (1.65)	0.020 (1.22)	−0.649 (−20.86)	−0.716 (23.46)
Reserves 0 borrower			0.137 (7.22)	0.133 (7.01)	−0.846 (−24.73)	−0.899 (−26.59)
First stage F-stat	1361.04	1833.85	641.58	876.06	1075.08	1449.59
First stage instrument t-stat	62.38	62.89	51.25	54.09	66.59	70.13
No. observations	320,574		125,527		193,047	

Table 4: Estimation results of different specifications of the regression model for premium (quoted middle rate minus the Bank rate, $r^m_{t,\tau} - br_t$) in three subsample periods based on brokers' quote data. The models are estimated by ordinary least squares. Robust t statistics are given in parentheses.

Model 1': $r^m_{t,\tau} - br_t = c + \sum_{k=1}^{8} \alpha_k D^\tau_k + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}$

Model 2': $r^m_{t,\tau} - br_t = c + \alpha d^q + \beta' \mathbf{x}_{t,\tau} + \epsilon_{t,\tau}$

	May '06 - Jun '07		Jul '07 - Feb '09	
	Model 1'	Model 2'	Model 1'	Model 2'
A. Time-of-day effects, D^τ_k				
7-8	−0.652 (−1.28)		6.131 (4.63)	
8-9	−0.121 (−0.23)		2.911 (1.86)	
9-10	0.399 (0.75)		3.662 (2.27)	
10-11	0.648 (0.96)		2.884 (1.85)	
12-13	−0.615 (−0.97)		−2.380 (−1.67)	
13-14	−0.935 (−1.58)		−3.807 (−2.65)	
14-15	−2.197 (−3.66)		−5.740 (−4.09)	
15-16	−4.229 (−6.76)		−5.015 (−3.74)	
Quote duration, d^q		0.431 (9.55)		1.449 (13.7)
C. Day-of-week effects				
Monday	2.961 (10.2)	2.846 (9.70)	6.093 (6.90)	6.114 (6.92)
Tuesday	2.545 (8.57)	2.537 (8.39)	4.720 (4.24)	4.651 (4.18)
Thursday	2.589 (7.51)	2.606 (7.52)	−0.197 (−0.26)	−0.175 (−0.23)
Friday	4.035 (10.6)	3.976 (10.4)	2.689 (3.44)	2.693 (3.44)
D. Controls				
Constant	−4.733 (−4.74)	−1.709 (−2.20)	−0.771 (−0.52)	15.6 (10.8)
Spread	2.609 (14.0)	2.575 (14.0)	−0.222 (−4.90)	−0.225 (−4.99)
Aggregate reserves	-1.70e-4 (−3.76)	-2.67e-4 (−5.98)	-8.03e-4 (−12.3)	-8.01e-4 (−12.6)
no. obs.	3,718		5,890	

Table 5: Robustness check of Furfine data against quotes data. Column A regresses hourly averages of Furfine algorithm identified overnight loans on mid-quote from Thompson Reuters quotes data. Column B regresses corresponding daily averages of the same. t statistics are given in parentheses.

Column A:	$r_{t,\tau} = c + \beta_{hourly} a\_quote_{t,\tau} + \epsilon_{t,\tau}$
Column B:	$r_t = c + \beta_{daily} a\_quote_t + \epsilon_t$

	A	B
Constant	-0.06 (-6.31)	-0.11 (-8.62)
Average hourly quote	1.01 (547.)	
Average daily quote		1.02 (372.)
R^2	0.988	0.997
Adj. R^2	0.988	0.997
no. obs.	3,774	422

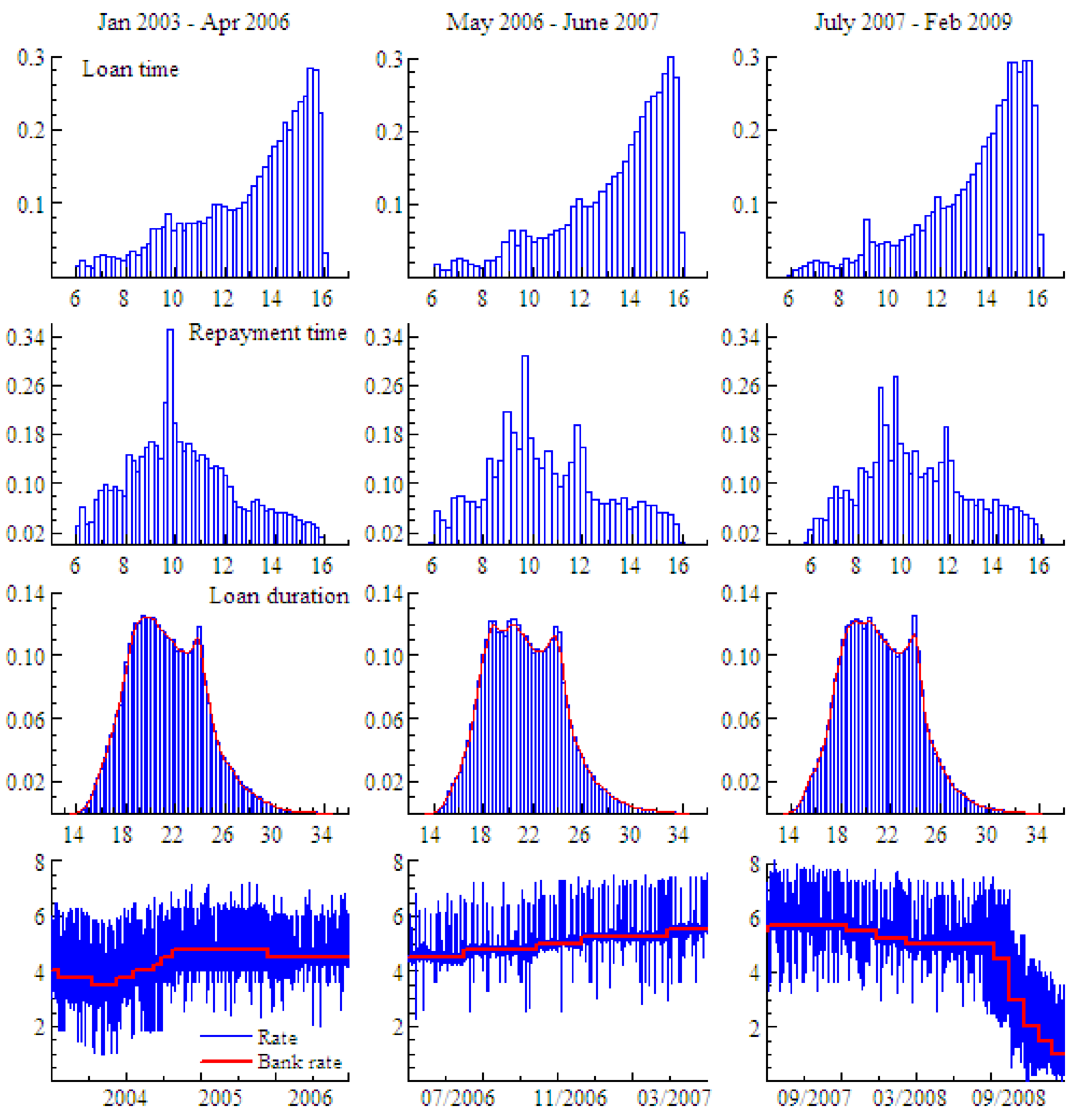

Figure 1: Top three panels show the distribution of loan advance time, repayment time and loan duration (in hours) across the three subsample periods. The bottom three panels show the loan rate of return together with the Bank rate (annualized %).

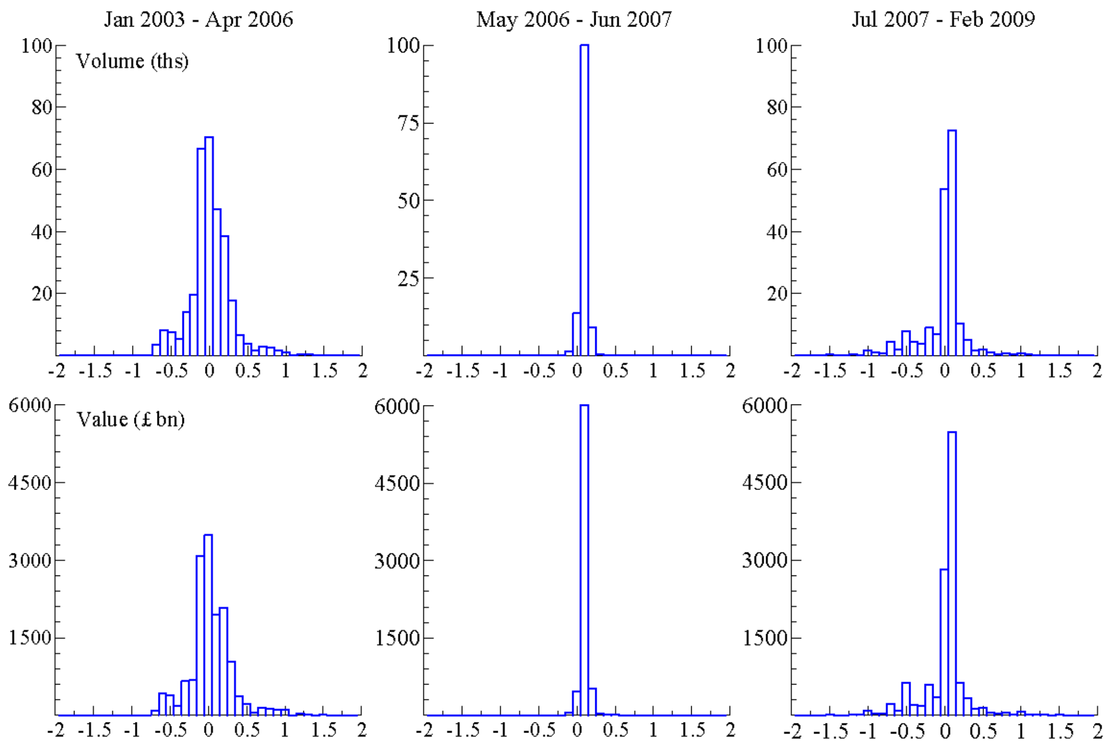

Figure 2: Histograms show period by period distributions (by volume and value) of identified loan rates. The rate of the identified loan relative to the Bank rate is on the horizontal axis.

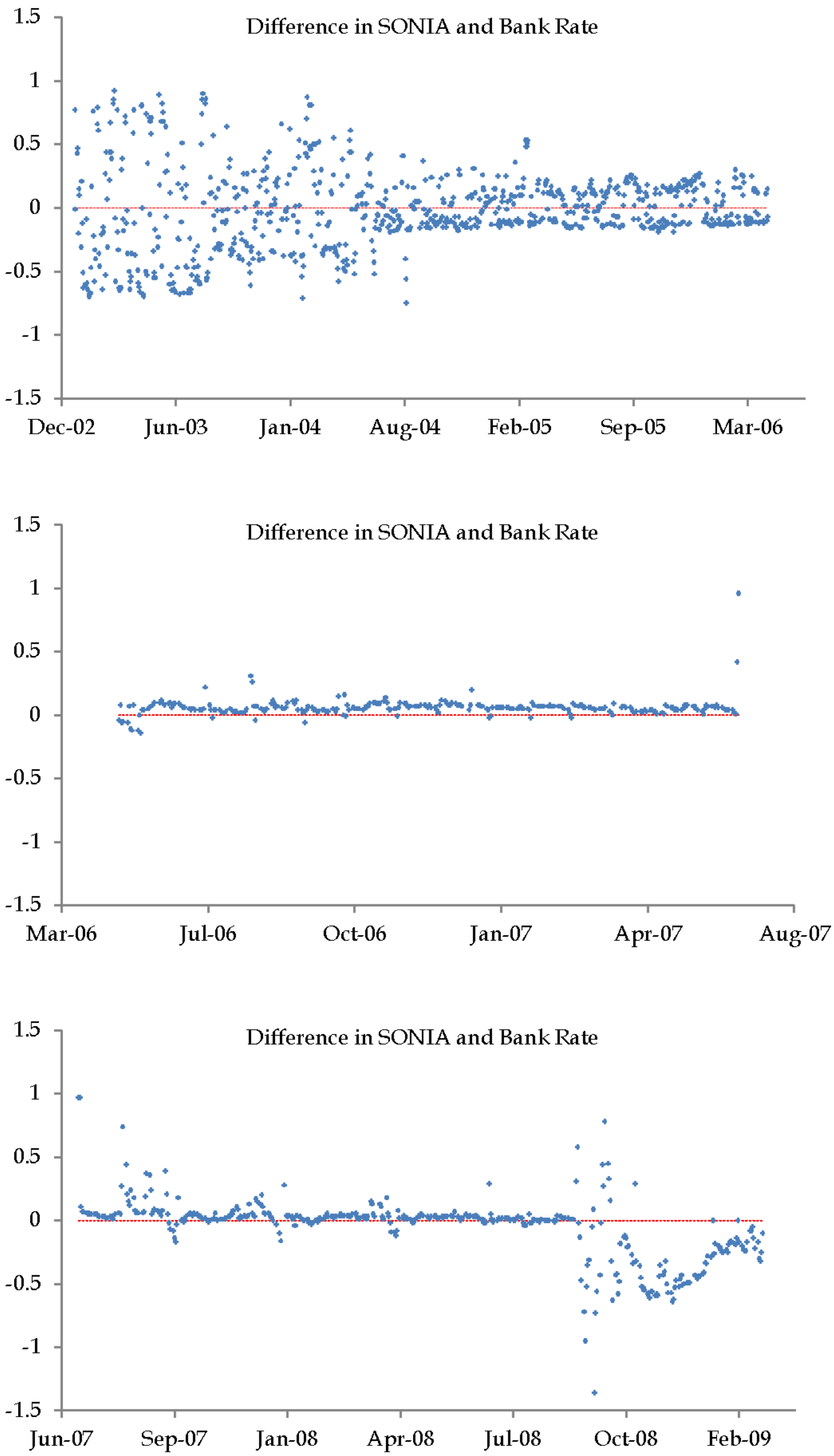

Figure 3: This figure shows the difference between SONIA (Sterling Overnight Index Average) and the Bank rate (% points) for the three subperiods.

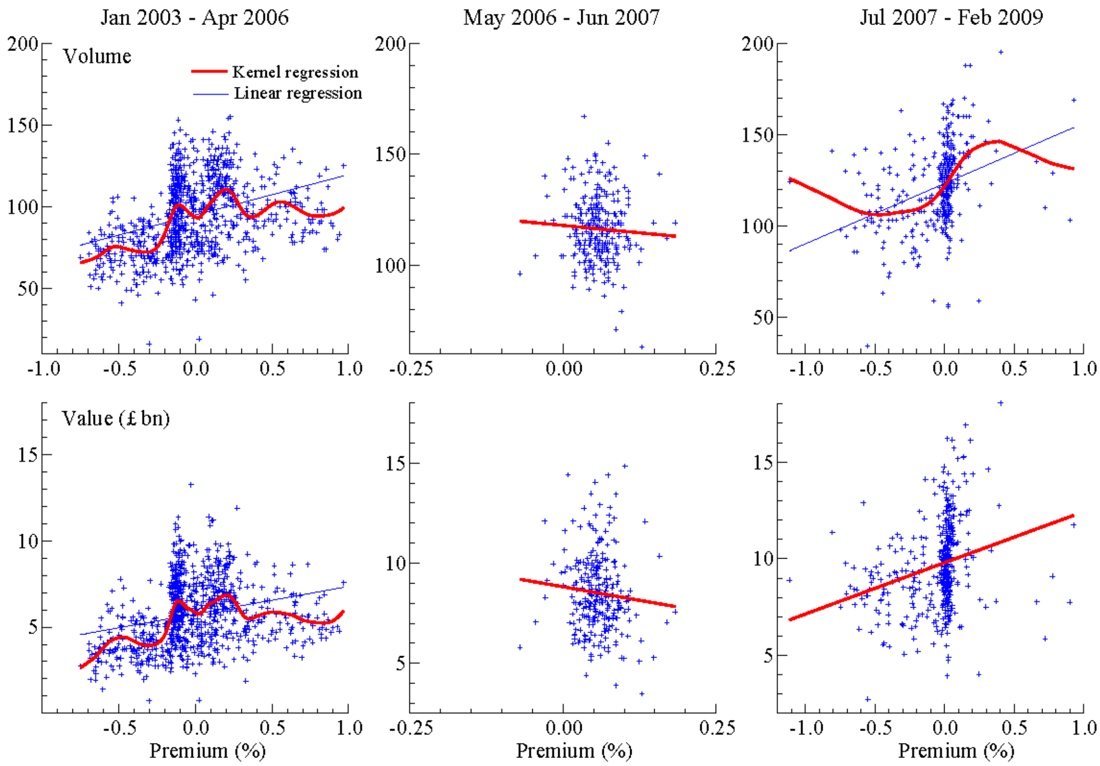

Figure 4: Scatter plots and fitted regressions (kernel & linear) relating the amount (by volume and by value) of overnight lending activity and the overnight loan premium.

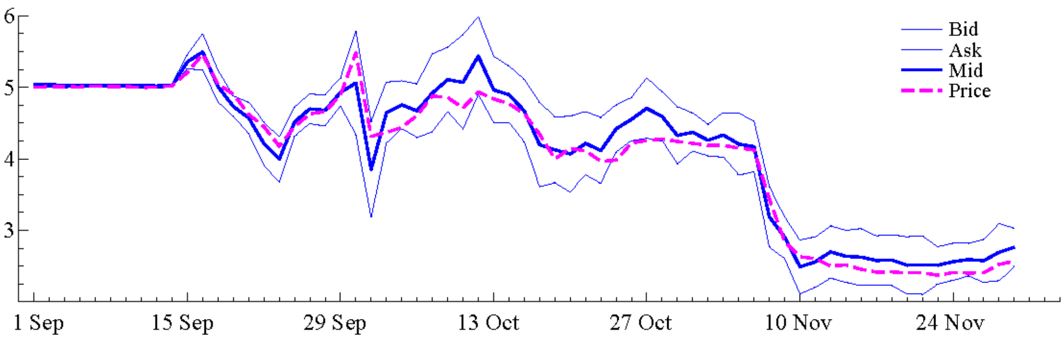

Figure 5: This figure shows bid, ask and mid quote on overnight loans from Thompson Reuters as well as Furfine algorithm identified overnight loan prices (dashed line) over the most severe crisis months of September-November 2008.

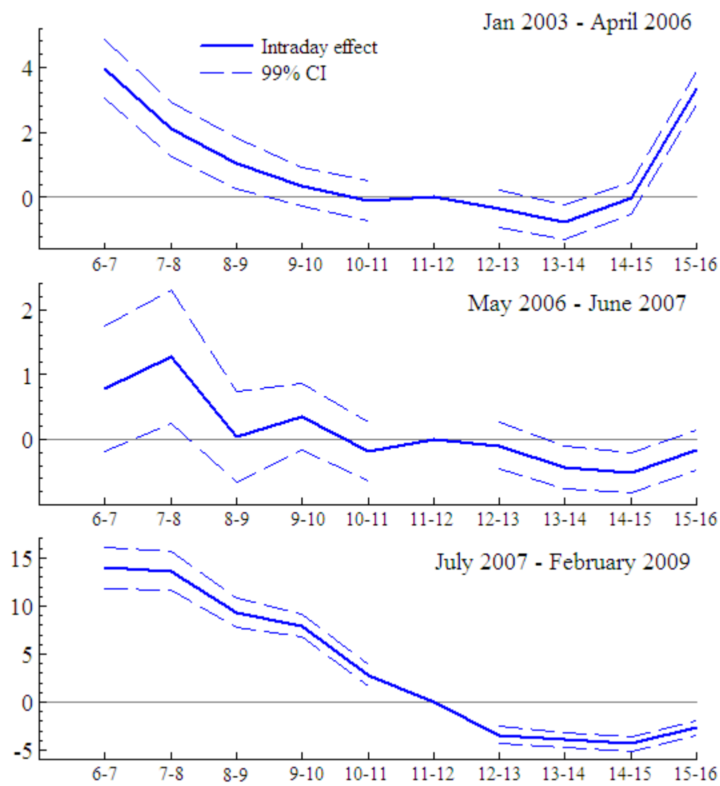

Figure 6: The figure shows estimated intraday effects (in bp) in Eq. (2) with 99% confidence bounds relative to 11am-12pm dummy which is excluded in the three subsample periods.

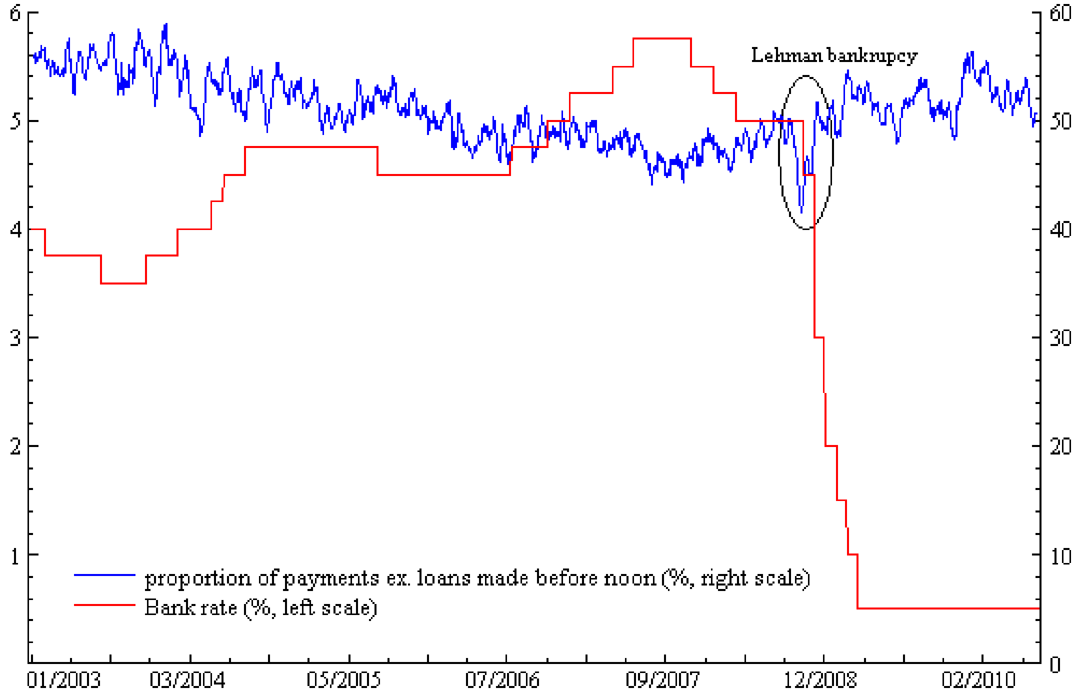

Figure 7: The figure shows the proportion of daily payments excluding overnight loans made through CHAPS before noon (10-day moving average) together with the Bank rate.