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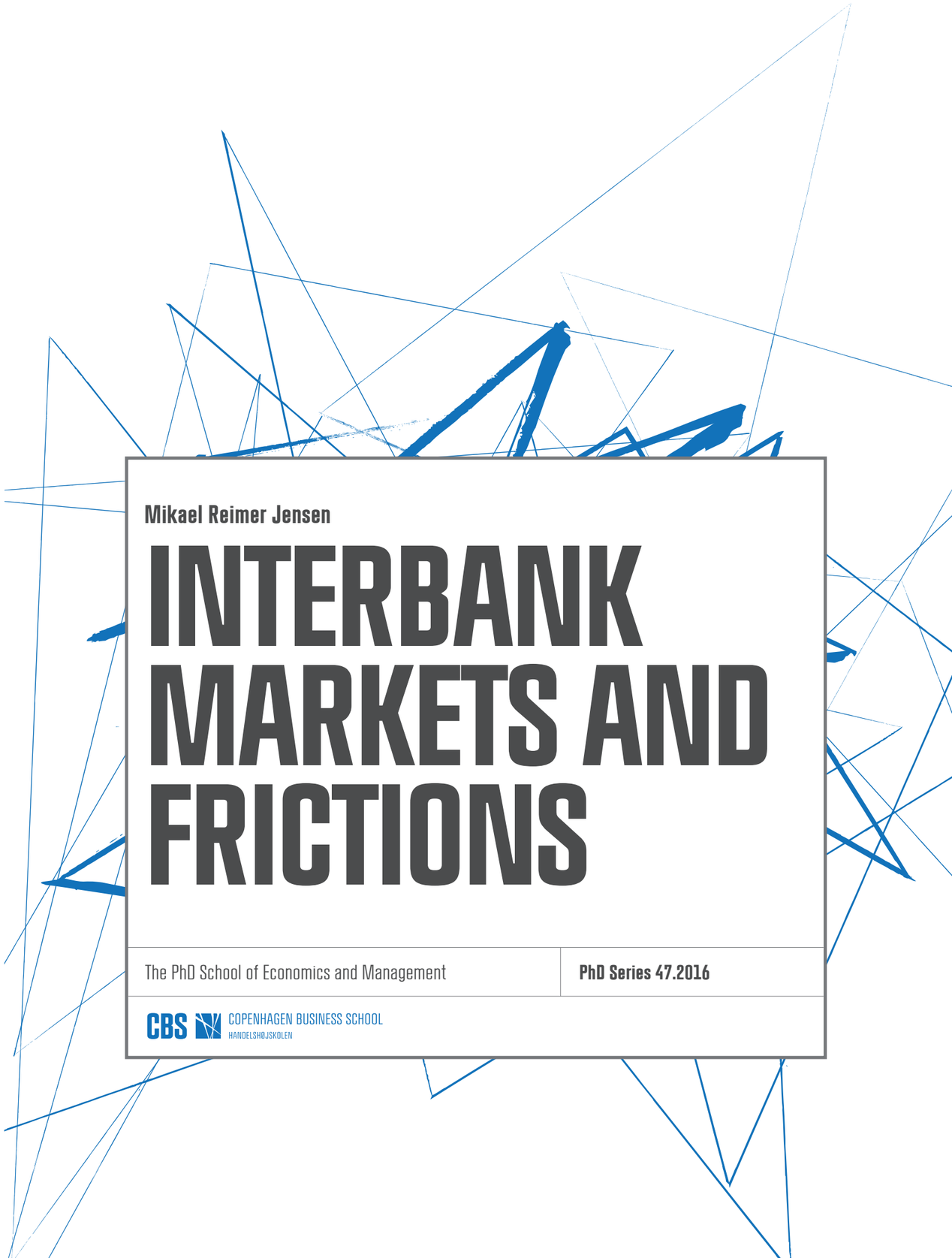
INTERBANK MARKETS AND FRICTIONS



Mikael Reimer Jensen

INTERBANK MARKETS AND FRICTIONS

The PhD School of Economics and Management | **PhD Series 47.2016**

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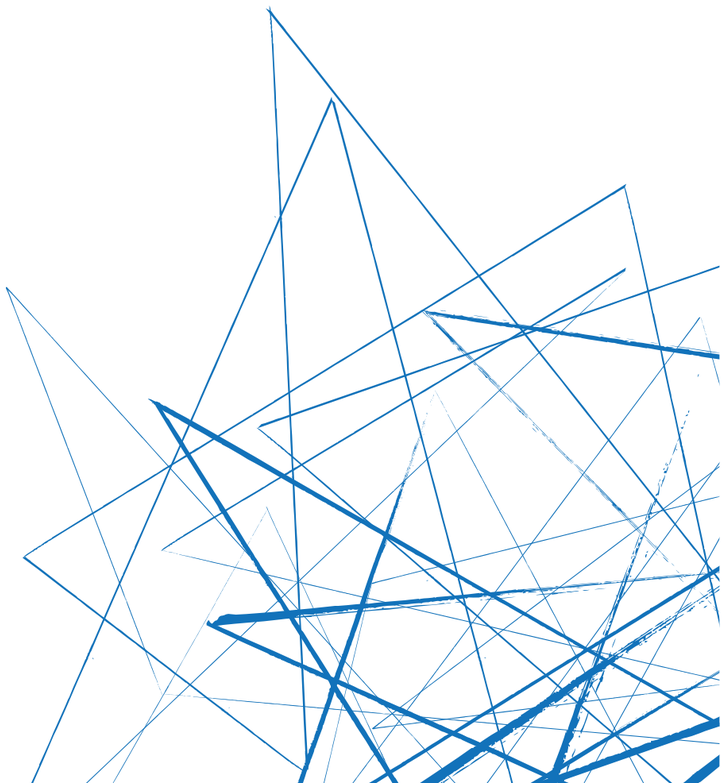

PhD Series 47-2016

Interbank Markets and Frictions

PhD Thesis

by

Mikael Reimer Jensen

Vejleder:

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PhD School in Economics and Management

Copenhagen Business School

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Summary

This section contains English and Danish summaries of the three essays that comprise the thesis.

English Summary

Essay I: Bank Liquidity and the Interbank Market

(co-authored with Søren Korsgaard, CBS)

In the first essay we look at the Danish interbank market and how it functioned during the financial crisis. Prior to the financial crisis the view seemed to be that the money markets were well functioning and capable of handling stress in financial markets. This is the conclusion in Furfine (2001, 2002) who analysis the US money market during the crisis in the autumn of 1998 where Russia effectively defaulted on its sovereign debt. However, the recent financial crisis was a lot more severe than the one in 1998. During the recent crisis we have seen the volatility of money market rates spike and many central banks have conducted unconventional monetary policies. Whether the interbank markets are robust is thus a relevant question again.

A key element in our analysis is that the total amount of liquidity in the interbank market is constant when central bank interventions are absent. A negative shock to one bank's liquidity holdings should correspond with a positive shock for another bank's liquidity holding. In a market with no frictions, banks faced with liquidity shocks should be able to absorb these by borrowing from those with surplus liquidity.

To investigate how well the Danish interbank market functioned during the recent financial crisis we combine two novel data sets. We couple transaction-level data on day-to day interbank loans from 2005 through 2013 with information on Danish banks' liquidity

holdings with the central banks. Using the data on a bank's liquidity holdings we are able to construct a measure that is indicative of a bank's liquidity needs. If the liquidity need affects the rate a bank pays for an interbank loan this is an indication of frictions in the money market.

We find that banks in need of liquidity only pays a small premium relative to those with ample liquidity. The effect is stronger when aggregate liquidity is scare, when liquidity is needed more urgently and payment activity is large.

A concern in our analysis is that the liquidity position and the credit risk of a bank is correlated. Without good measures of credit risk we may thus fail to capture the liquidity effect correctly. To control for this we take an instrumental variable approach where we instrument the liquidity position of a bank by total net payments (excluding interbank payments). The IV-estimate for the liquidity position is substantial higher than the OLS estimates. However, the estimates and economic magnitude are still low enough for a well functioning money market.

Essay II: Identifying Liquidity Risk in the Interbank Market

(co-authored with David Lando, CBS)

The second essay develops a method for extracting a liquidity component in interbank rates. The liquidity component is here the unwillingness for banks to give up liquidity by lending out longer term. A common way to observe stress in the money market is to look at the $LIBOR - OIS$ spread. Here $LIBOR$ is an unsecured term loan and OIS is a swap rate based on overnight loans. The problem with this spread is that it is increasing in both credit risk and banks's unwillingness to give up liquidity. We propose a model that looks at the spread between $EUREPO$ rates and OIS rates. $EUREPO$ rates are secured term loans and should therefore be credit risk free. The advantage is now that while credit and liquidity risk affected the $LIBOR - OIS$ spread in the same direction, credit and liquidity will move the $EUREPO - OIS$ spread in opposite directions. Our model is able to fit a key aspect of the data which is the period around the collapse of Lehman. Here the secured rates given by $EUREPO$ were larger than the comparable OIS rates. This indicates that liquidity risk played an important role during the collapse of Lehman.

We estimate our model using a Kalman filter and we find that liquidity risk was a

significant factor in interbank spreads around the default of Lehman. When we move to the second part of the crisis which is dominated by the European sovereign debt crisis, only credit risk seems to play role. This is consistent with the large liquidity programs conducted by the European Central Bank.

We finally regress our measure of illiquidity on $EURIOBOR-OIS$ spread and find that our measure accounts for the same magnitude of illiquidity in the $EURIBOR-OIS$ spread.

Essay III: How Haircuts Cut the Option Price

The final essay shows how one can price options when certain financial frictions are present. In classic arbitrage free models for derivatives pricing we assume no collateral, free short selling and that the underlying asset is not used in a repurchase contract. This is no longer representative for how modern financial markets work, and a growing literature now looks at adjustments to the traditional pricing models, when we have different funding rates.

We relax the assumptions of no short sell constraints and no repurchase agreement on the underlying asset in the classic binomial model. We derive the pricing formulas in closed form and show how it relates to the traditional formula obtained if we have no short sell constraints and no repurchase agreements in the binomial model. The general result is that when we are able to use the underlying asset for funding, the arbitrage free price is found in the measure where the underlying asset grows at the repurchase rate. We also introduce haircuts and because we are in the binomial model we are again able to find closed form solutions. The way to incorporate haircuts are non-triviel. We describe two different settings that differs on how the haircuts are incorporated. The first case is the most simple and we call this linear haircuts. The second case which we call the symmetric haircut is less simple and it results in a bid-ask spread for the option price.

Finally we look at the put-call parity. The model predicts an adjustment in the classic put-call parity for non-dividend paying stocks. The adjustment is due to the implied dividend you get from owning the underlying asset and obtain cheap funding from this. The model thus implicates a non-symmetric deviation from the classic put-call parity. We test this using data on European style call options on the S&P 500 Index. In general we observe a non-symmetric deviation from the put-call parity and this deviation is greatest in the period where the SEC implemented a short sell ban on certain financial stocks.

Dansk resumé

Essay I: Bank likviditet og Interbankmarkedet

(medforfatter Søren Korsgaard, CBS)

I det første essay ser vi på det danske interbankmarked, og hvordan det fungerede under den finansielle krise. Inden den finansielle krise var det generelle synspunkt, at pengemarkederne fungerede fint, og at de var så robuste, at de var i stand til klare eventuel stress i de finansielle markeder. Dette er konklusionen i Furfine (2001, 2002), som analyserer det amerikanske pengemarked under krisen i efteråret 1998, hvor Rusland defaultede på deres statsgæld. Den seneste finanskrise var dog meget større end krisen i 1998. Under den seneste finanskrise har vi set volatiliteten af interbankmarkedsrenterne stige eksplosivt, og mange centralbanker har indført ukonventionelle pengeprogrammer. Spørgsmålet om robustheden af interbankmarkedet er derfor igen relevant.

Et vigtigt element i vores analyse er, at den totale mængde likviditet, der er i pengemarkedet, er konstant, hvis vi ser bort fra centralbanksinterventioner. Et negativt chok til én banks likviditet vil derfor være modsvaret af et tilsvarende positivt chok til en anden banks likviditet. Hvis vi ikke har nogen friktioner burde banker, der oplever et negativt likviditetschok, absorbere disse ved at låne fra banker, der har overskydende likviditet.

For at undersøge hvor godt det danske interbankmarked fungerede under den seneste finanskrise, kombinerer vi to nye datasæt. Vi kombinerer transaktionsleveldata på dag-til-dag interbanklån i periode 2005-2013 med information om bankernes likviditetsposition hos den danske centralbank. Via informationen om bankernes likviditetsposition er vi i stand til at konstruere et mål, som indikerer, i hvor høj grad en bank har brug for likviditet. Hvis en banks likviditetsbehov påvirker den rente, en bank må betale for et interbanklån, er det en indikation på friktioner i pengemarkedet.

Vi finder, at banker, der har et større behov for likviditet, betaler mere end dem med meget likviditet. Effekten er større, når den samlede likviditet er lav, når behovet for likviditeten er mere præserende og når der er stor betalingsaktivitet.

En bekymring, man kunne have vedrørende vores analyse, er at kreditrisikoen og likviditetspositionen er korreleret. Hvis vi ikke har et godt mål for kreditrisikoen, vil vi også risikere at vi ikke fanger effekten af likviditetspositionen rigtigt. For at kontrollere dette benytter vi os af en instrumentvariable, hvor vi som instrument for likviditetspositionen benytter de

samlede betalinger for en bank (uden interbankbetalinger). IV-estimaterne for likviditetsposition er en del større end de tilsvarende OLS-estimater. Effekterne er dog stadig så små, at det generelt ser ud til, at det danske interbankmarked var velfungerende under krisen.

Essay II: Identificering af Likviditetsrisiko i Interbankmarkedet

(medforfatter David Lando, CBS)

I det andet essay udvikler vi en metode til at identificere likviditetskomponenten i interbankrenter. Likviditetskomponenten er her den uvilje banker har mod at opgive likviditet ved udlån med lang løbetid. En standardmetode til at observere stress i pengemarkedet er at kigge på forskellen mellem $LIBOR$ og OIS. Her er $LIBOR$ en usikret rente af en vis løbetid, mens OIS er en swaprente baseret på renten på dag-til-dag lån. Problemet med denne metode er, at spreaded mellem $LIBOR$ og OIS er stigende i både kreditrisiko, og hvis bankerne er mindre villige til at opgive likviditet. Vi foreslår en model, som ser på spreaded mellem $EUREPO$ og OIS. $EUREPO$ er sikrede renter og skulle derfor være fri for kreditrisiko. Fordelen er nu, at mens kreditrisiko og likviditetsrisiko påvirkede $LIBOR - OIS$ spreaded i den samme retning, vil kredit- og likviditetsrisiko trække $EUREPO - OIS$ spreaded i hver sin retning. Vores model er dermed i stand til at fange et vigtigt element i data, som omfatter perioden omkring Lehmans konkurs. Her er de sikrede renter, givet ved $EUREPO$, større end de sammenlignlige OIS renter. Dette er en indikation på, at likviditetsrisiko spillede en vigtig rolle omkring Lehmans kollaps.

Vi estimerer vores model med et Kalman-filter, og vi finder, at likviditetsrisikoen var en signifikant faktor i forskellen mellem interbankmarkedsrenterne omkring Lehmans konkurs. Når vi ser på perioden efter Lehman og perioden domineret af den europæiske gældskrise, ser det ud til, at kun kreditrisiko spillede en rolle. Dette er konsistent med indførelsen af de store likviditetsprogrammer af den europæiske centralbank.

Til sidst regresserer vi vores mål for illikviditet på spreaded mellem $EURIBOR$ og OIS, og vi finder, at vores mål kan forklare samme mængde illikviditet i $EURIBOR - OIS$ spreaded.

Essay III: Hvordan Haircuts Justerer Optionspriserne

Det sidste essay viser, hvordan man kan prise optioner, når bestemte finansielle friktioner er til stede. I de klassiske nul-arbitrage modeller for derivatsprisning antager vi, at der ikke

er nogen sikkerhedsstillelse, at der er frit kortsalg og at det underliggende aktiv ikke kan benyttes i en genkøbskontrakt. Dette er ikke længere repræsentativt for, hvordan moderne finansielle markeder fungerer, og en stadig større del af litteraturen ser på, hvordan man justerer de traditionelle prisningsmodeller når man har forskellige finansieringsrenter.

Vi relakserer antagelsen omkring ingen kortsalgsbegrænsninger og ingen genkøbskontrakter på det underliggende aktiv i den klassiske binomialmodel. Vi finder prisningsformlen i lukket form, og viser, hvordan den relaterer til den traditionelle prisningsformel, som er givet, når vi ikke har nogen kortsalgsbegrænsninger eller tilbagekøbskontrakter. Det generelle resultat er, at når vi er i stand til bruge det underliggende aktiv til finansiering, da findes den arbitragefrie pris i det mål, hvor det underliggende aktiv vokser med genkøbsrenten. Vi introducerer også haircuts, og fordi vi er i binomialmodellen, er vi i stand til at finde lukkede løsinger. Måden at implementerer haircuts på er ikke triviel. Vi beskriver to forskellige tilgange til at inkorporere haircuts på. Den første metode er den mest simple, og den kalder vi for lineære haircuts. Den anden metode kalder vi for symmetriske haircut, og den er mindre simpel og vil også resultere i et bid-ask spread på optionsprisen.

Til sidst ser vi på put-call pariteten. Modellen forudser en justering af den klassiske put-call paritet for ikke dividendebetalende aktiver. Justeringen skyldes den implicitte dividende man får ved at eje aktien og bruge dette til skaffe sig billig finansiering. Modellen implicerer derfor ikke-symmetriske afvigelser fra den klassiske put-call paritet. Vi benytter os af data på Europæiske optionstyper på S&P 500 indekset. Generelt observerer vi ikke-symmetriske afvigelser fra put-call pariteten, og afvigelserne er størst i den periode hvor SEC forbød kortsalg af bestemte finansielle aktier.

Introduction

This thesis considers different aspects of the financial markets with a special focus on the interbank market. The first two chapters both focus on the interbank market and how it functions. The last chapter may at first glance seem slightly different from the other two. However, one communality is that collateral and credit risk also affect derivatives contracts. In chapter two we look at credit and liquidity risk in the interbank market using repurchase contracts, where we in chapter three look at the effect of being able to repo out the underlying asset on the derivatives pricing. The first two chapters are co-authored papers and the last chapter is my single author paper.

The interbank market is a vital market for banks to manage their liquidity needs. In the interbank market banks are able to borrow and lend money for short maturities. The price of an interbank loan is given by the rate the borrowing bank has to pay. In the two first papers of this thesis we try to shed some light on how this price depends on credit and liquidity risk and how well-functioning these markets were during the crisis. In the papers we will define credit and liquidity risk more precisely, but intuitively credit risk is the risk that the borrowing bank will default on its loan, and liquidity risk is the risk that a bank is unable to obtain funding.

The first chapter which is a co-authored paper with Søren Korsgaard is an empirical study. Here we combine two novel data sets to investigate the functioning of the Danish interbank market. Specifically, we investigate how the distribution of liquidity among banks affects the price of an interbank loan. The investigation period includes the time prior to, during and after the financial crisis. We ask the simple question: do banks with less central bank liquidity pay a higher rate in the interbank market? In other words do the banks in

more need of the money pay more? If banks in great need of liquidity pay a great deal more we take this as a sign of stress in the interbank market.

In order to answer this question we obtain data on interbank loans through transaction level data between banks. We apply the Furfine algorithm Furfine (1999) on the transaction level data to back out interbank loans. Using this algorithm we thus get a data set of plausible interbank transactions between Danish banks. We couple this data set with the liquidity position of the banks with the Danish central bank. This gives us a novel data set where we are able to link the distribution of liquidity across banks with prices given as the rate of the interbank loans.

One of the key challenges of the paper is to separate the effects of credit risk on the rates that are being paid. In the paper we attempt to control for the credit risk effect through several different methods. We find that banks in need of liquidity only pay in average a small premium compared to those with ample liquidity. The effect is greater the more disperse the liquidity is and the more urgent the liquidity is needed. The effects we find are statistically significant but quite small economically. The answer to the more general question about the well-functioning of the interbank market is therefore that the market seemed to be robust during the financial crisis.

Because of the relative opaque nature of the interbank market it is a difficult market to investigate. The paper thus contributes to the growing literature on interbank markets. It also includes a period where the interest rates where negative which may be of interest of its own.

The paper builds on the work by Furfine (1999) and Furfine (2001). In these papers an algorithm to obtain information about interbank loans from transaction level data is developed and the papers also look at the money market. More recent papers as Fecht, Nyborg, and Rocholl (2011) and Afonso and Lagos (2012) have also looked at the interbank market. Fecht, Nyborg, and Rocholl (2011) look at the ECB refinancing auctions and also conclude that more liquidity constrained banks are willing to pay a higher price.

The second chapter is a paper co-authored with David Lando and it also investigates the interbank market. The outline of the paper is more theoretical but it does attempt to explain a curious empirical finding during the financial crisis.

The general idea of the paper is to split the cost of an interbank loan into a credit risk component and a liquidity risk component. To do this we build a model where banks are willing to pay a premium to obtain term funding. The intuition behind the model in chapter two is the following: If a bank wants to borrow money for a year it could follow one of the following two strategies. The first, and most simple strategy would be to find a counterpart who is able to lend the money for the whole duration of the period i.e. borrow the money from the same bank for a year. The other, and slightly more complicated, strategy would be to each day borrow the money from a bank and use an OIS (overnight index swap) contract to fix the rate. In the paper we will go into more detail about how to construct the two strategies. Both strategies result in a one year loan but they also have notable differences. In paper two we highlight these differences and use this to construct a model in which we are able to identify a measure of illiquidity in the interbank market. Specifically, if we take out credit risk from the two strategies, the interest rate difference between the two should be an estimate of illiquidity.

For the empirical part we use $EUREPO$ rates and OIS rates. Using a Kalman filter approach we are able to obtain a measure of banks' liquidity hoarding during the financial crisis. The estimation period covers the financial crisis; both the beginning and the period with the European debt crisis. We find liquidity risk to be a significant part of interbank rates around the collapse of Lehman but it vanishes after the announcement of the SMP program by the ECB. One key empirical finding which the model is able to fit, is that secured rates spiked above comparable unsecured rates during the financial crisis.

The paper closely relates to Filipović and Trolle (2013). They also investigate the interbank market and we use a similar model for the credit risk component in our model. The paper builds upon a large literature (Taylor and Williams (2009), Ashcraft, McAndrews, and Skeie (2011), Michaud and Upper (2008) and Schwarz (2014)) which have all looked at the $LIBOR - OIS$ spread before, during and after the financial crisis.

The spread between $LIBOR - OIS$ has been viewed as a gauge of the well-functioning of the interbank market and the key question has been whether the increase in spreads was caused by credit risk or liquidity risk. We add to this literature and provide further insight towards an answer. We find that liquidity did play a role during the period around the

collapse of Lehman, but the effect seems to vanish hereafter.

The final chapter is a paper that looks at option pricing when we introduce frictions. The paper includes both a theoretical part and an empirical part.

Traditional arbitrage free option pricing models assume no collateral, free short-selling and that the underlying asset is not used in a repurchase contract. In the paper I alter these assumptions and price simple options in a classic binomial tree model. The simple model makes it possible to calculate the option prices in closed form and see how the different assumptions affect the option prices. The main finding is that we can incorporate the repurchase opportunity in the option price if we adjust the risk-neutral measure. The adjusted risk-neutral measure will depend on both the repo rate, the haircut and the funding rate. The model implies that if the ability to use the underlying for funding is not a part of the dividend rate, then the classic put-call parity will no longer hold. The intuition is that having a strike 0 call is not equal to owning the stock. We test this using European style options on the S&P 500 Index. Consistent with our theory we observe deviations from the put-call parity. If we focus on the period where the SEC implemented a ban on shorting certain stocks (some of which were part of the index) the put-call deviations were even greater. This finding is consistent with the findings in Ofek, Richardson, and Whitelaw (2004). However, they look at American style options and thus have to correct for the early exercise premium present in these kind of options. The paper also relates to the work by Piterbarg (2010), Castagna (2013) and Lou (2015) who all look at how to calculate option prices when we incorporate different financial frictions.

References

Afonso, Gara and Ricardo Lagos (2012). "An Empirical Study of Trade Dynamics in the Fed Funds Market". In: *Federal Reserve Bank of New York Staff Reports* No. 550.

Ashcraft, Adam, James McAndrews, and David Skeie (2011). "Precautionary Reserves and the Interbank Market". In: *Journal of Money, Credit and Banking* 43.Supplement s2, pp. 311–348.

Castagna, Antonio (2013). "Pricing of derivatives contracts under collateral agreements: Liquidity and funding value adjustments". In: *Available at SSRN 1974479*.

Fecht, Falko, K.G. Nyborg, and Jörg Rocholl (2011). "The Price of Liquidity: The Effects of Market Conditions and Bank Characteristics". In: *Journal of Financial Economics* 102, pp. 344–362.

Filipović, Damir and Anders B Trolle (2013). "The term structure of interbank risk". In: *Journal of Financial Economics* 109.3, pp. 707–733.

Furfine, Craig H. (1999). "The Microstructure of the Federal Funds Market". In: *Financial Markets, Institutions and Instruments* 46.5, pp. 535–553.

— (2001). "Banks as Monitors of Other Banks: Evidence from the Overnight Federal Funds Market". In: *Journal of Business* 74.1, pp. 33–58.

Lou, Wujiang (2015). "Funding in Option Pricing: the Black-Scholes Framework Extended". In: *Risk*, pp. 56–61.

Michaud, Franşois-Louis and Christian Upper (2008). "What Drives Interbank Rates? Evidence from the Libor Panel". In: *BIS Quarterly Review, March*.

Ofek, Eli, Matthew Richardson, and Robert F Whitelaw (2004). "Limited arbitrage and short sales restrictions: Evidence from the options markets". In: *Journal of Financial Economics* 74.2, pp. 305–342.

Piterbarg, Vladimir (2010). "Funding beyond discounting: collateral agreements and derivatives pricing". In: *Risk*.

Schwarz, Krista (2014). "Mind the gap: Disentangling credit and liquidity in risk spreads". In: *Available at SSRN 1486240*.

Taylor, John B and John C Williams (2009). "A Black Swan in the Money Market". In: *American Economic Journal. Macroeconomics* 1.1, p. 58.

Bank Liquidity and the Interbank Market*

Mikael Reimer Jensen & Søren Korsgaard†

September, 2015

ABSTRACT

Banks exchange liquidity in the money market to absorb payment shocks. In a well-functioning market, banks in need of liquidity should not pay a premium when borrowing. We combine data on bank reserves at the central bank and interest rates paid in the money market to study how bank liquidity affects interbank rates. Banks with scarce liquidity pay only marginally higher rates than do those with ample liquidity. However, during times of financial stress and when the need for liquidity is more pronounced, those short of liquidity pay a higher cost.

Keywords: Financial regulation; Interchange fees; Payments

JEL-classification: E42; G21; G28

I.1. Introduction

The financial crisis has spawned a considerable literature on the functioning of interbank markets. A common theme in this literature is whether the market allows banks to absorb liquidity shocks and allocate liquidity efficiently amongst themselves. Prior to the crisis, the

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†Mikael Reimer Jensen and Søren Korsgaard are at Copenhagen Business School and Center for Financial Frictions (FRIC) and Danmarks Nationalbank

view seems to have been that the money market functioned well. Analyzing the interbank money market during the crisis in the autumn of 1998, when Russia effectively defaulted on its sovereign debt and a rescue of the hedge fund Long-Term Capital Management took place, Furfine (2001) and Furfine (2002) concludes that the market was robust. Rates did not stray from target or increased in variability, market volume actually increased, and there was little evidence of greater credit spreads due to heightened financial uncertainty. The crisis of 1998, however, was minor compared to the financial crisis which unfolded in 2007. In the 2007-2008 financial crisis and its aftermath, interest rate volatility spiked, and many banks resorted to using central bank facilities. The market, while not completely frozen, was stressed (Afonso, Kovner, and Schoar, 2011).

This paper examines the functioning of the money market in a novel way. Now, there is a certain vagueness about what it means for a market to "function well". The nature of the interbank market, however, suggests a natural benchmark, namely whether a bank in need of liquidity pays a premium for liquidity when borrowing. To use an analogy from basic microeconomics, if there is no price discrimination, all individuals pay the same amount independent of their willingness to pay. The analogy is imperfect, however, because a loan is not standardized good: prices (interest rates) should differ across borrowers to reflect their credit risk. When trying to assess whether banks in need of liquidity pay higher rates, one must therefore control for credit risk.

The total amount of liquidity to be distributed in the interbank market is essentially fixed, at least in the absence of central bank intervention. A positive liquidity flow for one bank is a negative flow for another. Liquidity shocks thus affect the liquidity of individual banks, i.e. the distribution of liquidity, but not the total amount of liquidity available to banks. Hence, in the absence of frictions, banks faced with liquidity shocks should be able to absorb these by borrowing from those with surplus liquidity. Competition among the latter should push down interest rates until they equal the opportunity cost of lending funds. A bank faced with a liquidity shock therefore should not, controlling for other characteristics, pay a premium.

Our analysis couples transaction-level data on day-to-day interbank loans in the period from 2005 to 2013 with information on Danish banks' liquidity holdings with the central bank. A key element in our analysis is that, due to lower and upper bounds on bank liquidity

holdings set by the central bank, we are able to define a meaningful measure of a bank's need for liquidity. We call this measure a bank's *liquidity position* and analyze whether it affects the rate a bank pays in the money market. To the extent that a bank's liquidity position affects rates, it is indicative of frictions in the money market. These could be related to e.g. imperfect competition or search.

A cursory glance at the data shows that banks with ample liquidity pay lower rates than do those with less liquidity, see Figure I.1. At the end of each day, all banks must maintain a positive liquidity position, equivalent to a positive account balance at the central bank. A negative liquidity position indicates that a bank strictly needed a loan to satisfy this requirement. A liquidity position of one corresponds to the maximal amount of liquidity which a bank is permitted to hold at the end of the day. Most borrowing banks typically have much less liquidity; otherwise they would not be borrowing. Figure I.1 shows that a bank with sufficient liquidity, say a liquidity position greater than 0.4, on average pays 6 to 7 basis points [bps] more than does a bank which requires liquidity. In comparison, the average daily standard deviation of rates is about 15 bps. However, the rate differential could be due to other factors that affect the liquidity position. Perhaps banks are individually liquidity constrained when aggregate liquidity is scarce, in which case the average effect overstates the true effect of a bank's liquidity position on rates. Or perhaps riskier banks choose to hold more liquidity for precautionary reasons, in which case the averages underestimate the effect of liquidity imbalances.

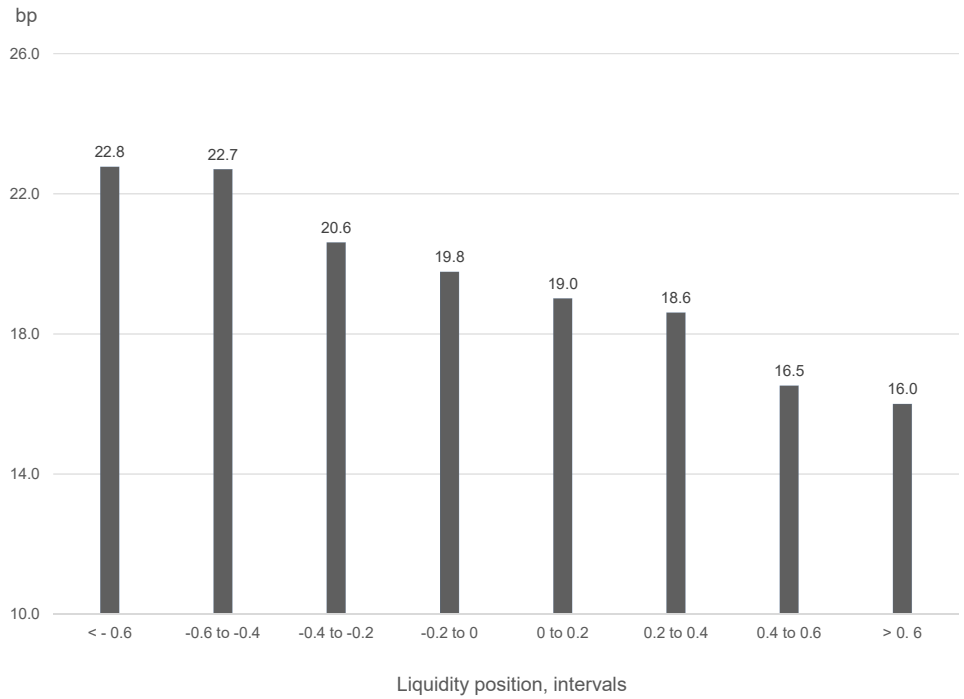

Figure I.1: Average money market rate less the central bank current account rate, by liquidity position.
The table shows the average interest rate paid by borrowers less the central bank current account rate. Banks are grouped by their liquidity position at the time of borrowing. A bank's liquidity position is defined as its pre-loan current account balance divided by its current account limit, which is a limit on how much liquidity the bank is permitted to hold at the end of the day. The table is based on observations of money market loans (N = 40,103) during the period 2005 to June 2013. Loans between the two largest money market participants have been excluded.

Overall, our analysis indicates that the money market functions well. Banks in need of liquidity pay only marginally higher rates than other banks. On average, a one standard deviation decrease in a bank's liquidity position "costs" less than a single basis point. In some circumstances, though, the liquidity premium is larger. Many money market loans are agreed upon a day in advance of the exchange of liquidity, and so banks have time to find counterparties and need not scramble for liquidity. Since such loans are typically settled early in the day, we look at whether loans for which liquidity is exchanged later in the day are different. These are more likely to reflect a sudden liquidity need due to an unexpected payments, and the distribution of liquidity matters more for such loans. The price of liquidity likewise rises when aggregate payment volumes are large. Interbank markets are also characterized by tiering, with most loans involving at least one top tier bank. We find that the liquidity position matters more for rates when a top tier bank is involved in a loan than when when two lower tier banks agree on a loan, though the difference is economically

small. A possible explanation in our setting is that large banks face tighter limits on their liquidity holdings than small banks relative to their payment volume.

There are notable differences in estimates across subsamples. The liquidity position is insignificant in the pre-crisis period, but significant in the period encompassing the early stages of the financial crisis and culminating in the default of Lehman Brothers. Following Lehman there is a period in which all interbank loans were explicitly covered by a government guarantee, essentially removing credit risk, and in that period the liquidity position is again insignificant. It again becomes significant after the expiration of the government guarantee, suggesting a link between credit risk and the role of bank liquidity.

We address the role of credit risk and its relationship to bank liquidity in some detail. There is no clear, discernible link between regulatory measures of credit risk such as the capital ratio and observed interest rates. One possibility is that banks participating in the money market are of such quality that credit risk is of secondary importance. Another is that credit risk affects the interest rate indirectly via the liquidity position as riskier banks choose to hold more liquidity. In that case, the liquidity position would be a bad control and removing it should alter the estimates of credit risk variables. We do not find any evidence that this is the case. Finally, capital ratios and other ratios based on balance-sheet information may fail to measure time variation in credit risk (we control for time-invariant risk through bank fixed effects).

Endogeneity is a concern if unobserved variation in credit risk affects the liquidity position. We take multiple approaches to deal with this issue. First, we estimate the model interacting bank and month fixed effects. This does not substantially alter our estimates. To control for higher-frequency changes in credit risk, we first apply a differencing strategy. If a bank has a target level of liquidity, the credit risk component of the liquidity position might be removed by identifying a proxy for the target (such as the bank's typical end-of-day liquidity level) and subtracting it from the actual amount of liquidity the bank holds at the end of the day. Implementation of this strategy produces estimates that are quantitatively similar to those obtained by simply including the liquidity position directly. The differenced liquidity position is statistically significant, and the estimates remain economically small, less than a single basis point. An alternative approach is to use an instrument which is correlated with the liquidity position, but not credit risk.

Since many bank payment flows are initiated by customers rather than banks themselves, certain payment flows might have these characteristics, and we find larger parameter estimates using an instrumental variables approach. In subsamples such as the crisis period the cost of having a liquidity position of zero (the required end-of-day position) rather than one (a bank's upper end-of-day limit) exceeds 10 basis points. Instrument validity is a concern, however. Moreover, while this approach yields larger estimates than the other estimates in the paper, it does not alter the conclusion that the money market functions in a relatively efficient manner. It should still be low enough to ensure that banks prefer to use the money market rather than e.g. resorting to borrowing from the central bank against collateral.

Finally, we examine the decision to borrow or lend. Among the key determinants of banks' decision to borrow and lend are past behavior - today's decision is strongly affected by yesterday's - and access to central bank facilities. When banks can borrow from or lend to the central bank, the money market is less active. Unlike in the case of the interest rate regressions, credit risk (or regulatory measures thereof) affect outcomes. As a bank's capital ratio increases, it is more likely to borrow and less likely to lend. The effect is amplified if the liquidity position is excluded from the model, suggesting that safer banks choose to hold less liquidity and then turn to the money market to absorb liquidity shocks. Riskier banks, in contrast, hold more liquidity and provide short-term funds to the better-capitalized banks.

Our main contribution is to address the functioning of the money market in a novel way. Our paper also pertains to the question of whether the distribution of liquidity among agents affects outcomes (Allen and Gale, 2000; Bindseil, K. G. Nyborg, and Strebulaev, 2009). The idea of analyzing the effects of the distribution of liquidity on interest rates is not unique to our paper. Fecht, K. Nyborg, and Rocholl (2011), the paper most closely related to ours, address a related issue by looking at data from ECB refinancing auctions. Their focus is therefore on how the distribution of liquidity affects the demand, or willingness-to-pay, for liquidity. Our focus is different, since we are examining a market characterized by competition among lenders. To get a sense of the magnitudes involved, the average difference between the highest and the lowest rate paid on a given day is about 80 basis points in our data set, and these are overnight loans.[1] This compares to a difference of 11.5 bps between the highest and lowest paying banks in the auctions studied by Fecht,

[1]This average is based on a longer data sample from 2 January 2003 to 17 January 2014.

K. Nyborg, and Rocholl (2011). Nevertheless, we find that in spite of the large differences in interest rates paid by different banks on a given day, only a negligible part of those differences can be attributed to the distribution of liquidity.

While not the primary object of our analysis, we also touch upon the issue of liquidity hoarding (Acharya and Merrouche, 2013; Acharya and Skeie, 2011; Ashcraft, McAndrews, and Skeie, 2011) and the role of credit risk in the money market (Afonso, Kovner, and Schoar, 2011; Heider, Hoerova, and Holthausen, 2015; Bruche and Suarez, 2010). Specifically, our results indicate that riskier banks choose to hold more liquidity, presumably to avoid having to resort to money market borrowing. We do not directly examine the role of banking relationships (Cocco, Gomes, and Martins, 2009; Afonso, Kovner, and Schoar, 2013), but do find that the decision to borrow or lend is closely related to whether a bank participated in the market the previous day, likely reflecting rollover behavior.[2] Finally, there are a number of network analyses of the money market (e.g. Bech, Chapman, and Garratt (2010), Craig and Peter (2014), and Iori et al. (2008)). Our focus is not on network structure, but from these we take the observation that the money market is tiered and may function differently depending on which type of bank is involved in a transaction. Another recent strand of literature attempts to build structural models of the money market (Afonso and Lagos, 2015; Blasques, Bräuning, and Lelyveld, 2014). Such models might prove useful for e.g. studying the effects of alternative central bank policies.

The money market is also of interest in its own right due to its role in the sharing of liquidity among banks. Indeed, the inability to access liquidity from other banks is a potential cause of bank failures. In addition, the overnight rate (Bernanke and Blinder, 1992; Hamilton, 1996) and stress in the money market (Hagen and Ho, 2007) are viewed as important indicators of the stance of monetary policy and financial stability. The inability of market participants to access money market funding could adversely affect asset prices (Pedersen and Brunnermeier, 2009). Perhaps most importantly, the risk of being rationed could affect banks' ability or willingness to extend credit to individuals and corporations (Ivashina and Scharfstein, 2010; Puri, Rocholl, and Steffen, 2011), with possible consequences for the real economy. Finally, the money market is an interesting example of an over-the-counter market

[2]In an earlier version of the paper we computed a number of relationship variables and included in our regressions, but found that these variables had little explanatory power. Indeed, their sign often disagreed among measures and across sub-samples, and they were rarely statistically significant.

characterized by bargaining and search frictions (Ashcraft and Duffie, 2007).

Our analysis has potential implications for policy. We document that central bank policy and payment flows affect interest rates and money market participation. On days with large payment flows, for example, money market rates are more volatile, and banks in need of liquidity pay more dearly for it. Payment activity, moreover, is affected by policy. The days with greatest payment activity tend to those where the government concentrates certain types of payment, e.g. taxes such as VAT. Likewise, bond issues and interest payments are typically made around the end and beginning of the quarter, and so money market activity is particularly pronounced on such days. This exposes banks to liquidity risk on those days, and banks may find themselves forced to rely on e.g. collateralized borrowing in such times, even though collateral may be in scarce supply.

Finally, some words on data. Our study relies on data from the Danish interbank market. A natural concern is that the results are particular to this market. To mitigate this concern we look at whether patterns in the money market found in other countries are also evident in our data set. Bech and Monnet (2013) document a set of stylized money market facts that hold across six important currencies in the period from 2006-2013, and in section 3 we show that these stylized facts are mostly also observed in the Danish market. Moreover, a simple comparison of the money market volumes in Denmark and the US (Afonso and Lagos, 2012) shows a similar time series pattern.[3]

There are, in fact, features of the institutional setup which make the data useful, especially the fact that banks face strong incentives to use the money market due to the institutional setup. Over the period from January 2003 to January 2014, the algorithm used to identify loans finds on average 56 loans per day. This is more than the daily number of loans found in the German market (Bräuning and Fecht, 2012). We also examine a much longer period than other studies of the money market, which have tended to focus solely on the crisis period. Our analysis, which covers the period from April 2005 to June 2013, includes the pre-crisis, crisis, post-crisis and even forays into negative interest rate territory. Also of interest is the fact that we can include sub-period in which interbank loans were guaranteed by the Danish state and a sub-period with negative interest rates.

The rest of the paper is organized as follows. Section 2 contains a description of the

[3]To see this, compare figure 4 in that paper to our figure I.4.

data and the institutional setting. In section 3 we provide an overview of the activity in the money market during the sample period. Section 4 analyzes the determinants of the interest rate. Section 5 studies the decision of individual pairs of banks to borrow from and lend to each other. Section 6 concludes.

I.2. Data and Institutional Setting

The interest rate data is derived from a proprietary transaction-level data set consisting of all payments made by institutions in Kronos, the real-time gross settlement system operated by the Danish central bank. Information on loans between pairs of banks, i.e. loan sizes, rates, counterparties, timing, etc., has been obtained using an algorithm akin to that used by Furfine (1999). The algorithm seeks to identify interbank loans based on payments data. It searches for payments from one bank to another which exceed 1 million in amount and are divisible by 100 thousand, and then pairs these with payments in the opposite direction of the same amount plus a likely interest rate. For instance, if the interest rate is 5%, and there is a payment from Bank A to Bank B of 100 million on day t, then the algorithm will identify an interbank loan if there is a payment of close to 100.0139 (with $0.0139 = 5/360$) on date t+1 from Bank B to Bank A.

The interest rate used by the algorithm is obtained as follows: Each day a panel of banks[4] report on their activity in the interbank market, including the rates at which they lend overnight and tomorrow-next. The algorithm first selects the minimum and maximum among the rates reported.[5] It then searches for loans within a band of the minimum reported rate minus 100 bps and the maximum reported rate plus 100 bps. It makes little difference if a narrower band such as e.g. +/- 50 bps is used instead, as the majority of loans fall within a narrow rate band. This method risks both identifying non-loans as loans and failing to identify loans. Arceiro et al. (2014) perform a detailed analysis of the errors associated with using the Furfine (1999) algorithm based on data from TARGET2, the real-time gross settlement payment system used by banks in the Euro Area, and their analysis suggests

[4]The composition of the panel changes over time. At the time of writing it consists of eight banks, which are among the most active in the money market.

[5]More specifically, it looks at the rates reported on the day in question in the case of overnight rates and the previous business day in the case of the tomorrow-next rates.

that the errors involved in the procedure are negligible.[6]

While we have data on loans from January 2003, the data set we analyze runs from April 2005 to the end of June 2013 as quarterly balance sheet data for the banks is only available for that period. In order to have comparable financial information on banks, loans involving foreign counterparties are excluded. We also remove loans between related parties (e.g. banks and associated mortgage lenders). We also exclude failed banks. This is partly motivated by our question of interest. In attempting to determine whether the money market functions, the key issue is whether relatively healthy banks can obtain loans at reasonable rates, not whether any bank can do so. A more practical reason is that the failed banks cannot be correctly identified backwards in time.[7]

In regressions we use as dependent variable the interest on a loan less a reference rate. We discuss the merits of various candidate reference rates at the beginning of Section I.4. In subsequent analyses, the decision to borrow or lend is the dependent variable. We include three types of controls: (1) bank liquidity variables, (2) bank balance sheet data, and (3) time-series variables. In tables, we report t-statistics based on robust standard errors. However, we have also performed the same inferences using cluster-robust errors and arrive at the same conclusions. For example, in what may be considered the our main regression specification (see Table III, column 1), using cluster-robust standard errors, clustered at the level of borrower-lender pairs, reduces to the t-statistic to 3.07 from 3.32.

The liquidity variables are specific to each bank and are observed at a daily frequency. The most important variable in our analysis is the bank's *liquidity position*. Each bank must have a positive current account balance by the end of the day, and it should not have a balance exceeding a limit set by the central bank. The positive account balance is a hard limit whereas the upper limit can in principle be exceeded (as explained more fully in the following section on institutional details). For the same reason, we emphasize the borrower's liquidity position more than that of lenders since a bank in need liquidity faces a more pressing problem than does a bank with too much liquidity.

[6] A different perspective is provided by Armantier and Copeland (2012) who, based on US (Fedwire) data, argue that the errors can be quite large.

[7] A number of failed banks have been taken over by a government entity that liquidates failed banks. Upon this takeover, the names of the failed banks have been changed backwards in time in the database from which our data is drawn. This implies that the failed banks cannot be distinguished from each other; we can only tell that they were banks which were subsequently taken over.

The liquidity position is computed as follows: For each loan in the sample we first calculate the bank's end-of-day balance minus/plus the loan amount (for the borrower/lender), and then divide this by the bank's current account limit. To illustrate with a simple example, suppose a borrower which has borrowed 50 has end-of-day current account balance of 70. If the bank's current account limit is 100, the liquidity position is then 0.2 $(= (70 - 50)/100)$. This is intended to convey how the bank's end-of-day liquidity would have been *in the absence of the loan*. We make a slight alteration to this definition when analyzing the decision to borrow or lend. In that case we subtract a bank's daily net borrowing from its end-of-day liquidity position.

We also define a broader measure of liquidity, a bank's net position, which is defined as the bank's net claim on the central bank scaled by its current account limit. For example, a bank may have a large holdings of certificates-of-deposit, an asset of the bank and a liability of the central bank. These are not immediately available as a means of making payment, but will become current account holdings at the end of a week. In that sense, a large, positive net position is close to immediately available liquidity. Conversely, a negative net position means that banks are net borrowers with the central bank. To borrow they must post collateral, and so obtaining extra liquidity will be costly when the net position is negative.

In order to control for credit risk, or at least examine whether regulatory measures thereof help explain money market rates and market participation, we use quarterly data for each bank's tier 1 and tier 2 capital ratios as well as information on the bank's profits, writedowns, and ratio of deposits to assets. We assign the past quarter's values of these variables to the loan counterparties. One could argue that it is the relative rather than absolute strength of banks that matters in the money market. A bank with a liquidity surplus may be forced to lend, and will require a higher rate when lending to banks that are worse relative to others. To capture this idea, we also define a relative credit risk measure (RCRM). It is computed by first ranking banks based on their core capital ratio, result/weighted-assets, writedowns/core capital and deposit-to-asset ratio (that is, we compute a ranking for each variable) each quarter. We then scale the ranking from 0 to 1 (1 being worst), and finally take a simple average of the scaled rankings.

As controls we include a number of time series variables. One such variable is the aggregate payment volume, and we include not only the current value, but also that of

the past and following day. The logic is that if there are many payments, there is also more liquidity which needs to be distributed among banks. Since this distribution may happen with some time lag, we include the value of the previous day's payments; and since banks may borrow or lend in anticipation of tomorrow's payment activity, it is likewise of relevance. We also control for government payment flows. The government's money is held in an account of the central bank, and so a flow to the government represents a drain of liquidity from the banks. Finally, we include the aggregate current account balance of all banks at the beginning of the day and the aggregate net position of the banks. These are again narrow and broad measures of liquidity, only at the aggregate level rather than at the bank-specific level. All payment variables are quoted in billions unless otherwise stated.

We also employ as controls log loan size (in billions) and bank size, defined as the log of total bank assets (in billions). An overview of these descriptive statistics relating to these variables is provided in Table I.

Finally, we include the CDS premium for the Danish government as a measure of aggregate credit risk. These are not particularly informative the earliest part of the sample due to stale CDS-prices.[8]

I.2.1. Institutional Setting

This section provides some background information on the monetary policy framework and the payment system as these affect the functioning of the money market.

The Danish central bank is responsible for maintaining a fixed exchange rate against the euro. In practice, this is done by setting monetary policy interest rates and via interventions in the foreign exchange rates. The key interest rates are the current-account rate, the (7-day) lending rate, and the (7-day) certificate-of-deposit rate. In addition, a so-called "discount rate" akin to federal funds target rate is published. Before May 2007, the lending and certificate-of-deposit rates were set on a 14-day basis.

Each day at 3:30 pm banks are required to maintain a positive balance on their current account. Their balance, however, is subject to a cap. The total amount of current account

[8]Subsequent to performing these analysis we also attempted using the time series of CDS premium for Danske Bank, the largest Danish bank by assets. While there is a longer series of liquid prices for Danske Bank, including this series does not alter any conclusions. Moreover, the correlation between the two CDS series is about 0.9 so whether one includes one or the other makes little difference in the period where both are liquid.

Table I: Descriptive statistics
Descriptive statistics on the interest on loans less a reference rate (references: CA = rate on current account balances, CD = certificate-of-deposit rate, avg = average daily rate), lender and borrower liquidity variables, bank characteristics such as financial ratios, and time series variables. The data is from the sample period January 2005 to June 2013. The liquidity variable, liquidity position (B=borrower/L=lender), is calculated for each loan, and the net position (B=borrower/L=lender) is calculated daily for each bank. A bank's liquidity position is defined as its pre-loan current account balance divided by its current account limit, which is a limit on how much liquidity the bank is permitted to hold at the end of the day. A bank's net position is calculated similarly, only with the bank's net assets with the central bank replacing the current account balance. The bank characteristics are based on quarterly data. For example, Result/RW-assets refers to the quarterly result scaled by risk-weighted assets. The write-offs represented changes in a bank's account of impaired assets. The other data is based on daily observations. Total payments refer to the total amount of payments in the RTGS-system operated by Danmarks Nationalbank. Gov't payments are the net daily payments made from banks to the government. The aggregate current balance is the sum of all bank's end-of-day balances with the central bank. The aggregate net position is all banks' total claims on the central bank. All data has been obtained from Danmarks Nationalbank.

	Mean	Median	Std. dev.	1st perc.	5th perc.	95th perc.	99th perc.
Loan variables							
$r_{loan} - r_{CA}$ [bps]	15	10	28	-45	-15	60	115
$r_{loan} - r_{CD}$ [bps]	-4	-5	25	-75	-35	35	70
$r_{loan} - r_{avg}$ [bps]	0	0	17	-53	-25	22	54
Loan size [millions]	297	70	654	1	3	1,500	3,500
Liquidity variables							
Liquidity position (B)	0.03	0.01	0.84	-2.31	-1.18	1.23	2.04
Net position (B)	0.88	1.51	14.68	-53.73	-16.68	17	29.02
Liquidity position (L)	0.82	0.52	1.12	0.01	0.02	2.53	5.34
Net position (L)	2.84	4.07	17.55	-97.04	-15.99	19.97	31.02
Bank characteristics							
Assets [billions]	10.8	6.7	35.1	0.6	1.1	602	2,307
Tier I capital ratio [percent]	14.5	13.7	8.1	6	7.7	21.8	42.3
Tier II capital ratio [percent]	16.7	15.7	8.1	9.4	10.3	24.1	44.9
Result/RW-assets [percent]	0.3	0.8	4.3	-14.5	-4.2	2.8	8.3
Write-offs/core capital [percent]	2.8	1.0	14.6	-3.2	-0.9	8.5	32.5
Time series variables							
Total payments [billions]	130.5	125	42.8	59.4	82.5	195.3	269.3
Gov't payments [billions]	0.1	0.2	9	-26.1	-12.9	16.6	29.9
Agg. CA balance [billions]	19.6	12	23.1	3.1	4.8	89.4	100
Agg. net position [billions]	88.8	92.6	70.1	-104.9	-29.5	202.9	228.8

holdings is capped, with each bank assigned an individual limit. Exceeding the individual limit does not necessarily have consequence. The central bank reacts only if the total current account holdings exceed the cap. In that case current account holdings in excess of the individual limits will be converted into certificates of deposit. Since banks can have neither too much nor too little liquidity, the institutional setup gives the banks an incentive to reallocate liquidity from those with a high supply to those with a demand for liquidity. On Fridays, banks can borrow from the central bank against a list of eligible collateral or invest funds in certificates of deposit, but within the week they must source money from other banks (or, to the extent their limit permits it, hold precautionary reserves). The central bank also maintains an account for the government. On days where there are large payments to or from the government, banks are typically permitted to either borrow from the central bank or place funds in certificates of deposits depending on whether liquidity is drained from or added to the system.

The policy regime facing banks changes during the sample. From the beginning of the sample period until June 2009 the lending rate and the certificate of deposit rate were the same. In June 2009, a spread was introduced, strengthening banks' incentives to reallocate funds among themselves in the money market instead of using central bank facilities. For most of the sample period the current account rate is lower than the rate on certificates of deposits. This changed in July 2012 when negative rates were introduced on certificates of deposits while current account rates were kept at zero; at the same time the cap on current account holdings was substantially increased.

Practically all banks maintain their own accounts with the central bank. This contrasts with the system in some countries (e.g. the UK, see Acharya and Merrouche (2013)) where direct membership in the payment system is restricted to a small subset of banks. This structure provides for a richer data set and also lessens concerns that the ultimate beneficiaries of a money market loan might not be the banks identified by the loan algorithm. In most analyses we exclude the two largest banks, which lessens concerns about loans made on behalf of others.

The timing pattern of payments in the Danish payment system is noticeably different from that observed in e.g. the US (Afonso and Lagos, 2012) where most payment activity takes place at the end of the day. In Denmark, most payments are made in the morning,

hours before banks are required to have a positive account balance. This pattern is perhaps due to intra-day credit not bearing interest charge in Denmark, though it must be collateralized. This could make early payment an equilibrium as long as collateral is not too costly (Bech and Garratt, 2003). Securities transactions and the previous' days retail payments are settled during the night and are typically paid for using intra-day credit obtained from the central bank. Foreign exchange transactions are settled early in the morning. Some of these payments are known in advance, e.g. securities transactions which are mostly settled on a $T + 2$ or $T + 3$ basis, whereas others, e.g. retail transactions, cannot be perfectly forecast. The upshot is that banks often experience payment shocks in the morning. Most money market loans are settled early in the day, some already when the payment system opens. These can e.g. be overnight loans agreed a day in advance ("tomorrow/next") due to predictable payment flows. The data does not permit one to infer when a loan was agreed.

In the remainder of the paper we report results for subsamples corresponding to different regimes. We divide the time series into five sub-periods. The first is the pre-crisis period, which we define to be the period from April 2005 (the beginning of our sample) to July 2007. The next subsample runs from August 2007 when there were beginning signs of liquidity shortages to 9 October 2008.[9] This end-date is chosen to coincide with the introduction of a government guarantee on 10 October 2008 which specifically covered money market loans. The government guarantee expired at the end of September 2010. We therefore refer to the third subsample as the period of the government guarantee. The fourth subsample runs from October 2010 to 5 July 2012. We refer to this period as the debt crisis period as it coincides with the European sovereign debt crisis. Finally, on 6 July 2012 the Danish central bank introduced negative interest rates and the permitted current account holdings of banks also roughly trebled. We refer to this final period as the negative interest rate regime.

[9]It is not clear how to date the start of the crisis. We rely on the information from ECB's timeline of the financial crisis, available at the ECB's website, which dates the beginning of liquidity shortages in August 2007.

I.3. An Overview of the Money Market

In this section we describe the activity in the Danish money market during the sample period. A more thorough description of the Danish interbank market before, during, and after the financial crisis can be found in Abildgren et al. (2015). Here we mainly consider whether the stylized facts documented in other interbank markets (Bech and Monnet, 2013; Afonso and Lagos, 2012) are also observed in the Danish market.[10] The stylized facts identified by Bech and Monnet (2013) pertain to the expansion of reserves observed in many countries. Such an expansion also took place in Denmark, especially following the European Sovereign Debt Crisis, as the central bank had to print (Danish) currency and purchase foreign currency to maintain a fixed exchange rate. Bech and Monnet find that as reserves expand, 1) overnight rates tend to the central bank rate, 2) market volume decreases, and 3) the volatility of the overnight volume declines.

We first look at how the average (value-weighted) money market rate compares to central bank rates over time. Figure I.2 depicts the central bank rates together with the daily value weighted average rate from our sample.

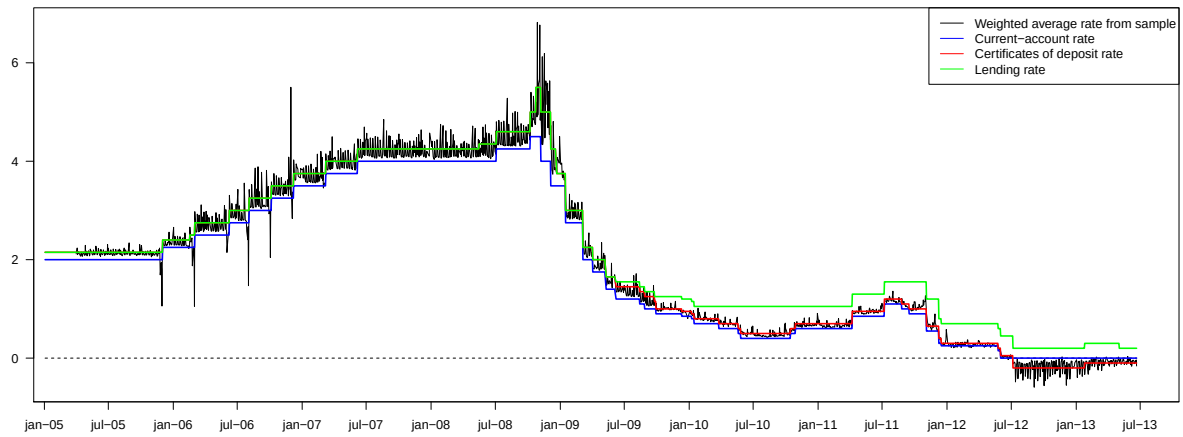

Figure I.2: Money market versus central bank rates.
This figure shows the evolution of average money m arket rates (value-weighted) and three central bank rates through the sample period. The current account rate is the rate at which banks' current account balances are remunerated. Prior to May 2007 banks could either borrow at the lending rate or place surplus liquidity in certificates-of-deposits for two weeks. After May 2007 these became weekly operations. The lending and certificate-of-deposit rates were identical until June 2009.

Figure I.2 shows that the value weighted average interest rate from our sample tracks the central bank rates. In the early parts of our sample the average rate hovers in the middle of

[10]In this section we use the full data set, i.e before removing transactions with banks for which we do not have accounting data.

the corridor between the current-account rate and the lending rate, with occasional spikes outside the corridor. Most of the spikes above the lending rate occur on Fridays where banks can borrow and lend from the central bank and money market activity is low. From 2010 and until the introduction of negative rates on certificates of deposits the value weighted average rate is at the floor of the corridor and the volatility of the rate decreases, with only few spikes outside the corridor. During the period of negative rates, the value weighted average rate is below the current account rate, and we likewise observe many spikes below the certificates of deposit rate.

The daily intraday standard deviation of the rates is shown in Figure I.3. Volatility peaks in late 2008 at the height of the financial crisis. Aside from the surge in late 2008, the intraday standard deviation of the rates have been relatively stable over the sample period. There has perhaps not be a decline in volatility as observed in other markets, but this likely is certain special features of the institutional setup. As in other countries, there was also ample liquidity (central bank reserves) in Denmark following the crisis and especially towards the end of our sample, but the requirement that banks cannot have *too much* liquidity may have contributed to continued volatility.

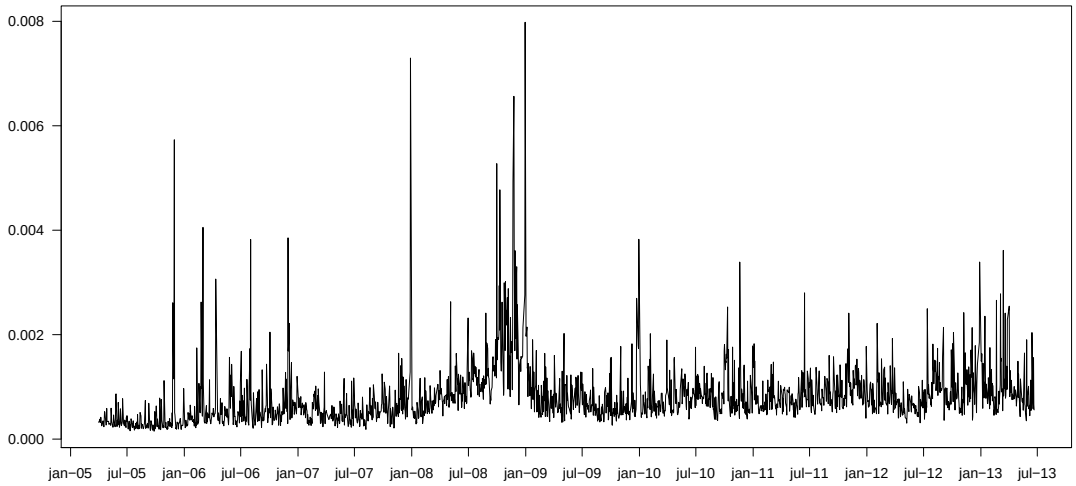

Figure I.3: Standard deviation of interest rates.
This figure shows the standard deviation of daily interest rates (value-weighted by loan size) during the sample period.

The daily number of loans are given in Figure I.4. There is a mean of 67 transactions in the pre-crisis period. For the crisis period (August 2007 - 9 October 2008) the average number of transactions is slightly higher at 74. After the onset of the government guarantee,

we observe a decline in the daily number of transactions. During the government guarantee period the mean is 57, and during the debt crisis period the figure is 47. The most dramatic decline happens in the period with negative interest rates when the mean number of daily transactions is 23. This can be explained by an increase in the cap on current account holdings which decreased the need for reallocation of liquidity.

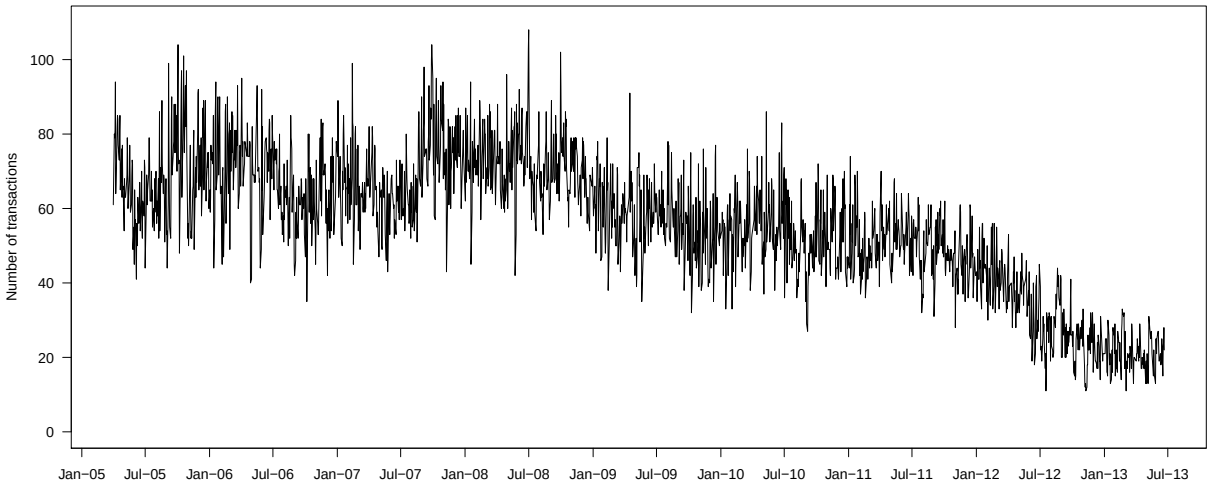

Figure I.4: The daily number of interbank loans during the sample period.

Looking at the daily number of distinct lenders and borrowers (Figure I.5) one observes a declining trend through the sample period. The decline in the number of lenders is even greater. The market becomes more tight in the sense that there are the ratio of borrowers to lenders increases. In this sense, the market is least tight during the beginning of 2009 when the number of unique lenders exceeds the number of borrowers, perhaps because lenders can lend with the knowledge that their loans are guaranteed by the state.

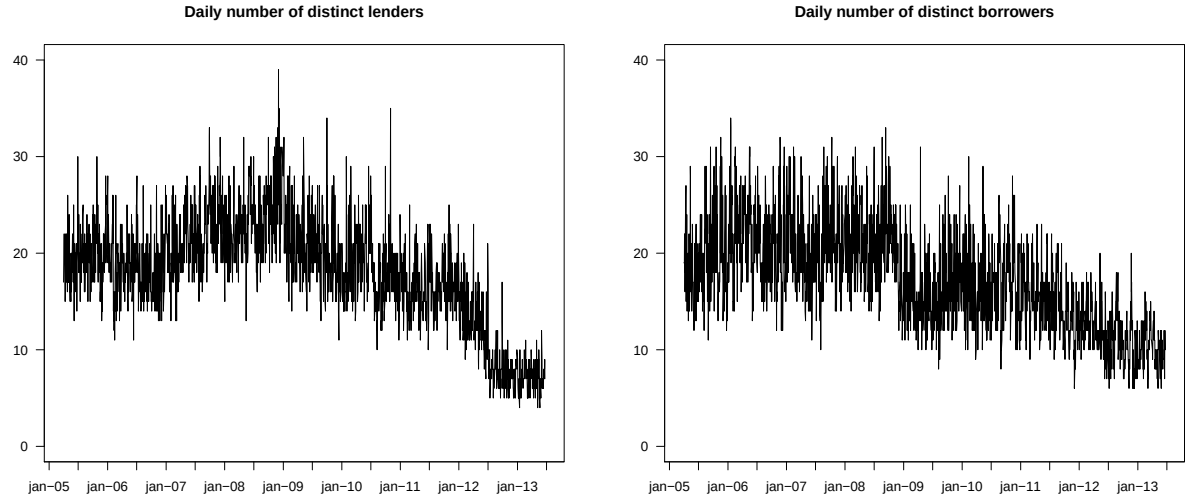

Figure I.5: Unique lenders and borrowers.
The left panel shows the daily number of unique lenders during the sample period and the right panel shows the daily number of unique borrowers.

Next we look at how many times a bank is lending given that it is lending that particular day. The mean across the entire sample period is 3.21 times. However, the distribution is skewed, with the median between one and two. This finding is similar to what Afonso and Lagos (2012) observe; they likewise find that a few banks lend many times in the US data. Afonso and Lagos (2012) also find a decline in the daily total amount of borrowing. This is in line with a decline in the number of transactions. There is a declining trend in the total amount. However, the trend is less visible in our data. The drop is in the number of transactions, not as much in the total amount.

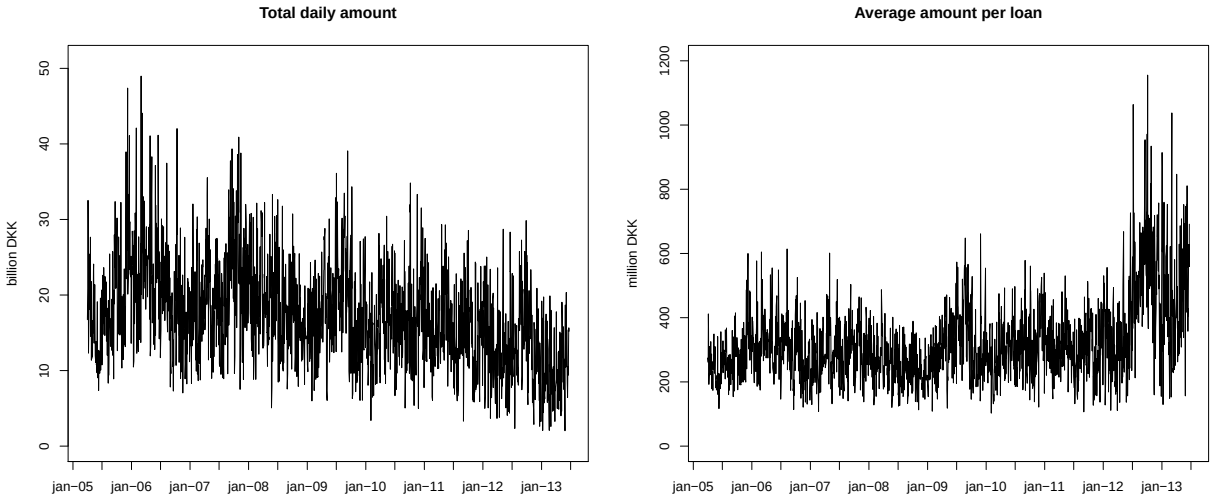

Figure I.6: Total and average loan amounts.
In the left panel, the daily total amount of overnight loans in our sample and in the right panel the average amount per loan.

Finally, we look at when interbank loans are distributed during the day. Recall, though, that he timing of the payments may not be the same as to the point in time of when the loan has been agreed upon. The "tomorrow/next"-loans are examples of loans which are agreed upon a day in advance such that the transfer time is notably different from the time the loan was agreed upon. We see from Figure I.7 that the majority of the activity happens during the morning. Especially, most of the loans are repaid at 7.00 AM. This is in contrast to the fed funds market where a significant part of the activity happens end-of-day (Afonso and Lagos, 2012).

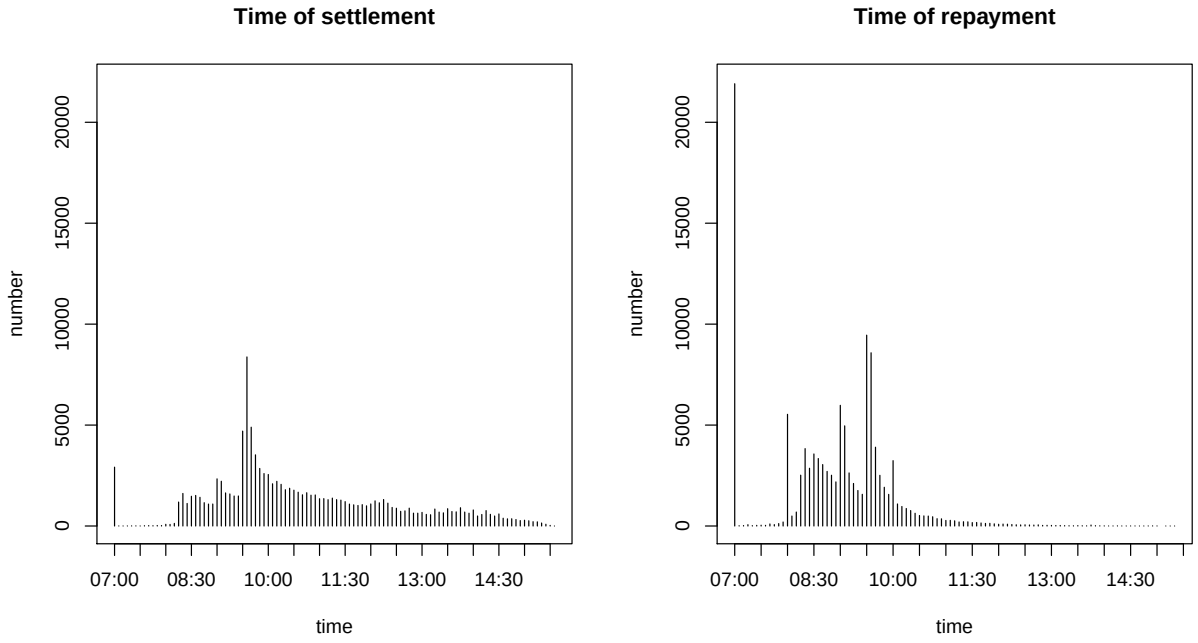

Figure I.7: Timing of loan payments.
In the left panel, the distribution over the day of when the loans have been settled. Each bar represents a 5 minutes interval and the height of the bars is the number of transfers within that 5 minutes period. In the right panel we have the distribution over the day of when the loans have been repaid.

I.4. Determinants of Interbank Rates

In this section we examine the determinants of the interest rate agreed upon between pairs of banks. As in other studies (e.g. Afonso, Kovner, and Schoar (2011) and Bräuning and Fecht (2012)) the dependent variable is the actual rate paid for liquidity less another rate. We first address the question of which other rate to use as a reference rate. From The price of liquidity, the interest rate, should reflect the cost of providing liquidity. A common choice is to use the central bank's policy rate; however, we prefer to use actual rate since

an actual rate and not a policy rate represents banks' alternative to exchanging liquidity in the money market. Our preferred option is to use the rate paid on current account deposits since earning that rate is an immediate available alternative to not lending funds on all days.

There are other rates which could be relevant alternatives. On Fridays - and other occasions when the central bank makes this opportunity available - banks can place funds in certificates of deposit. Another alternative to making a particular money market loan would be to lend surplus funds to another bank. The average rate on a particular day can therefore also be used as a reference rate.

Table II shows a comparison of the same baseline regression model with each of the three reference rates, discussed above, as dependent variable. The baseline model includes the set of controls discussed in section I.2. The results are qualitatively similar across choices of dependent variable. The variable of main interest, the borrower liquidity position variable, has the same sign and is statistically significant in each case. It appears that we are better able, in terms of R^2, to explain the variation in the dependent variable when we use the current account rather than the certificate of deposit rate. It would not be fair to make a similar comparison with the case of the average market rate since we discard much of the information available in the time series variables when subtracting an average.

An conclusion that also emerges is that controlling for borrower and lender fixed effects mainly affects the results for bank-specific variables such as the capital ratio and bank size. As an example, the parameter estimate for the capital ratio decreases when fixed effects are included, meaning that with fixed effects there is more evidence that better capitalized banks pay lower rates, though the result in insignificant here. A possible explanation is that unobserved factors related to a bank's quality simultaneously permits it to hold less equity and borrow at lower rates.

Our primary interest is in the liquidity position variables, especially the borrower liquidity position. While the liquidity positions are statistically significant, the parameter estimates are small from an economic perspective. Using our preferred reference rate, the parameter estimate is -0.55. This implies that covering a one standard deviation decrease in the liquidity position would cost only an additional 0.46 basis points. Such a figure suggests that the money market functions well in general. With the cost of finding liquidity being

Table II: Interest rate regressions - different targets
Cross sectional regressions of loan rates minus reference rates on bank liquidity variables, bank characteristics as well as time-series variables. The columns contain separate regressions for different choices of reference rate, respectively the central bank current account rate, the certificate-of-deposit rate, and the average rate on money market loans on the particular day. Excluded from the sample are loans between the two banks involved in the most money market loans. t-statistics, calculated based on robust standard errors, are in brackets. The dependent variable is quoted in basis points. Details on the computation and measurement units of the independent variables is provided in section I.2.

	Current account rate		Certificate-of-deposit rate		Avg. daily rate	
Liquidity position (B)	-0.70 (-3.97)	-0.55 (-3.32)	-0.58 (-4.88)	-0.43 (-3.56)	-0.51 (-7.71)	-0.26 (-4.28)
Net position (B)	0.02 (2.77)	0.00 (-0.37)	0.02 (2.8)	-0.01 (-1.03)	0.02 (7.33)	0.02 (4.27)
Size (B)	-1.85 (-25.00)	1.04 (1.36)	-1.83 (-28.48)	1.19 (1.35)	-2.01 (-57.22)	1.35 (3.04)
Basiscap (B)	8.21 (3.94)	-11.20 (-2.32)	7.54 (3.26)	-11.59 (-2.39)	11.92 (9.42)	-1.58 (-0.65)
Liquidity position (L)	-0.59 (-7.33)	-0.47 (-5.56)	-0.63 (-8.06)	-0.50 (-5.98)	-0.42 (-9.85)	-0.15 (-3.60)
Net position (L)	-0.02 (-2.95)	0.02 (2.46)	-0.02 (-4.55)	0.01 (1.71)	-0.02 (-8.02)	0.00 (1.78)
Size (L)	-0.06 (-1.13)	1.46 (2.09)	-0.05 (-0.88)	1.68 (1.96)	0.23 (7.99)	0.10 (0.22)
Basiscap (L)	-23.95 (-9.10)	11.14 (2.55)	-22.86 (-8.28)	12.2 (2.51)	-34.19 (-22.62)	5.56 (2.27)
Loan size	-0.86 (-7.43)	-0.14 (-1.14)	-0.87 (-8.22)	-0.16 (-1.35)	-0.39 (-6.76)	0.21 (3.64)
Agg. CA balance	-0.45 (-14.78)	-0.44 (-15.33)	-0.39 (-17.64)	-0.38 (-18.10)	0.03 (2.74)	0.02 (2.13)
Agg. net position	-0.18 (-17.01)	-0.17 (-16.48)	-0.12 (-14.54)	-0.11 (-13.89)	-0.01 (-2.00)	0.00 (-0.55)
Friday	10.93 (38.84)	10.67 (38.46)	10.81 (39.65)	10.54 (39.55)	0.31 (2.08)	0.46 (3.44)
Gov't payment flow	0.08 (4.48)	0.09 (4.86)	0.12 (10.24)	0.13 (11.05)	-0.02 (-3.64)	-0.02 (-3.44)
Total payments (t)	0.04 (13.82)	0.04 (13.19)	0.04 (15.5)	0.04 (14.92)	0.01 (7.00)	0.01 (6.93)
Total payments (t-1)	0.02 (9.31)	0.02 (9.05)	0.02 (8.88)	0.02 (8.67)	0.00 (0.97)	0.00 (0.75)
Total payments (t+1)	-0.01 (-2.44)	-0.01 (-3.25)	0.00 (1.36)	0.00 (0.07)	0.01 (5.53)	0.01 (4.19)
CDS (gov't)	0.05 (1.93)	0.06 (2.06)	-0.13 (-7.35)	-0.12 (-7.36)	-0.04 (-3.93)	-0.04 (-4.36)
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Bank FE	No	Yes	No	Yes	No	Yes
R^2	0.46	0.50	0.19	0.25	0.20	0.37
N	40103					

low, banks have an incentive to keep their current account balances low and use money market transactions to absorb liquidity shocks.

The signs of the other regression coefficients are largely as expected. Borrowers with less liquidity pay higher rates. Larger banks pay substantially lower rates when fixed effects are not included, but the effect vanishes once included. Interestingly, banks with more equity (tier 2 capital) appear to be paying higher rates once fixed effects are accounted for.

The time series variables likewise behave in accordance with expectations. When aggregate liquidity is ample, whether in the form of immediately available liquidity (current account balances) or other assets with the central bank (net position), money market rates are lower. Rates are higher when liquidity is drained from the system due to the government receiving money from banks. On Fridays, or other days where lenders can place their money with a central bank for a week at a higher rate, they also receive a rate that is about 11 basis points higher. In comparison, the certificate of deposit rate has on average been about 15 basis points above the current account rate in the sample period. As expected, rates are also higher when current or past payment activity is large, though the opposite is true in the case of tomorrow's payment activity. If the time fixed effects are excluded, the regression coefficients barely change, but the overall fit declines somewhat. For example, without time fixed effects the R^2 in the third column of Table II would drop to 0.35 from 0.50, but the estimate of the liquidity position would be virtually unchanged, decreasing slightly from -0.55 to -0.58.

In the above we have excluded the two largest banks. Network analyses in the money market emphasize the presence of different tiers of banks, and the Danish market is no exception. Two banks in particular play a vital role in the distribution of liquidity. Of the 75,722 loans we analyze, only 25,738 involve neither one of the banks (either directly or as correspondent for some other financial institution). We generally exclude these banks from regressions, one reason being that these banks function as correspondents for other banks which means that many of the loans we observe between these banks really involve other banks for which we do not have data. In Table III, we show results with these banks included.

Table III shows how the parameter estimates vary for different subsets of banks. One might expect that the largest banks, due to greater diversification and better ability to

Table III: Interest rate regressions - tiering
Cross sectional regressions of loan rates minus reference rates on bank liquidity variables and characteristics as well as time-series variables. The columns represent separate regressions depending on the subsample: (1) includes all loans except loans between the largest two banks, (2) includes only loans to which neither of the largest two banks is a counterparty, (3) includes loans where one the two largest banks is a borrower, and (4) includes loans where one of the two largest banks is a lender. t-statistics are in brackets, and are calculated using robust standard errors. The dependent variable is quoted in basis points. For details on the computation and measurement units of the independent variables, see section I.2. Bank and month fixed effects are included in the regressions.

Reference rate	(1)	(2)	(3)	(4)
Liquidity position (B)	-0.55 (3.32)	-0.47 (2.86)	-2.10 (3.30)	0.37 (0.66)
Net position (B)	-0.00 (0.37)	0.00 (0.64)	-0.02 (0.27)	-0.05 (1.33)
Size (B)	1.04 (1.37)	2.59 (2.73)	-3.67 (0.76)	0.28 (0.17)
Basiscap (B)	-11.20 (2.33)	-6.64 (0.97)	35.59 (1.35)	-11.83 (1.64)
Liquidity position (L)	-0.47 (5.57)	-0.57 (6.02)	-0.31 (1.13)	3.01 (6.99)
Net position (L)	0.02 (2.46)	0.01 (2.17)	0.04 (1.25)	0.01 (0.19)
Size (L)	1.46 (2.09)	2.83 (3.59)	4.91 (2.33)	0.45 (0.15)
Basiscap (L)	11.14 (2.55)	7.68 (1.27)	1.53 (0.16)	15.92 (0.98)
Loan size	-0.14 (1.15)	0.16 (0.97)	-1.15 (3.45)	0.16 (0.49)
Agg. CA balance	-0.44 (15.37)	-0.33 (8.93)	-0.92 (8.74)	-0.63 (11.65)
Agg. net position	-0.17 (16.53)	-0.18 (14.57)	-0.19 (5.79)	-0.14 (6.66)
Friday	10.67 (38.55)	11.37 (34.69)	11.37 (12.96)	7.39 (12.28)
Gov't payment flow	0.09 (4.87)	0.09 (4.30)	-0.16 (3.15)	0.23 (6.28)
Total payments (t)	0.04 (13.22)	0.04 (10.26)	0.07 (7.76)	0.04 (6.01)
Total payments (t-1)	0.02 (9.07)	0.02 (7.56)	0.01 (1.63)	0.02 (5.53)
Total payments (t+1)	-0.01 (3.26)	-0.00 (1.15)	-0.07 (6.47)	-0.01 (1.23)
CDS (gov't)	0.06 (2.07)	0.06 (1.97)	0.12 (1.87)	-0.04 (0.55)
R^2	0.50	0.52	0.49	0.53
N	40103	25738	4395	9970

forecast liquidity flows, are less affected by liquidity shocks. In that case the liquidity position should matter more when small banks are involved. Yet, if one excludes all loans between the two largest banks (column 1), the parameter estimate for the borrower liquidity position drops. It falls even further when the sample is restricted to loans between smaller banks (column 2).

Another possibility is that results are asymmetric, i.e. that large banks pay low rates as borrowers, but charge high rates as lenders. Large banks may be able to extract rents due to an informational advantage. Perhaps they are better at forecasting liquidity flows than smaller banks and can therefore infer the liquidity positions of other banks and charge accordingly. The results suggest otherwise, however. The large banks pay more when in need of liquidity (column 3).

A possible explanation of this phenomenon is that large banks actually face tighter liquidity constraints than small banks. While their limits on their current account holdings exceed those of small banks, the limits are substantially smaller when measured against magnitude of payments handled by the large banks.[11] When the large banks are lenders, a different picture emerges. The liquidity position of borrowers no longer matters, suggesting that the large banks are not exploiting superior knowledge about the liquidity position of other banks. However, when the large banks themselves have ample liquidity, they charge higher, not lower rates. This could be because they account for such a large share of the market that they know that if they have ample liquidity, potential counterparties must be in the opposite position.

There are further issues involved in estimating the consequences of banks having a particular liquidity position. One concern is that some loans are agreed upon a day in advance (so-called "tomorrow/next"-loans), while others are agreed upon on the day of the loan. We are unable to identify which are which, but there is a market convention that tomorrow/next loans should be settled before noon. We therefore introduce a variable which indicates when a loan has been settled after noon. Our expectation is that the liquidity position matters more for such loans. It also seem plausible that the liquidity position matters more on days with large payment flows where there is more liquidity to be exchanged and therefore e.g. greater search costs involved. Likewise, if aggregate liquidity is scarce - the aggregate

[11] This has been suggested to us by a former liquidity manager at a large bank.

Table IV: Liquidity position - interactions
This table provides regression estimates of the borrower's liquidity position and interactions of other variables with the liquidity position. The set of other controls (not shown) is the same as in the regressions reported in Table II, i.e. controls related to borrower and lender characteristics, payment and time series variables, and time and bank fixed effects. Excluded from the sample are loans between the two banks involved in the most money market loans. t-statistics based on robust standard errors are in parentheses. The sample size is N = 40,103.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Liquidity position (B)	-0.55 (3.32)	-0.40 (2.26)	0.35 (0.81)	-1.27 (5.36)	-1.47 (3.83)	-1.33 (3.38)	-0.55 (0.99)
. * post-noon (1/0)		-0.59 (2.12)					-0.44 (1.72)
. * total payments (t) [100 bn]			-0.69 (2.03)				-0.62 (1.83)
. * agg. CA balances [10 bn]				0.51 (4.32)			0.28 (2.18)
. * agg. Net Position [10 bn]					0.11 (3.39)		0.10 (2.66)
. * Tier 2 capital [%]						0.06 (2.44)	-0.03 (2.80)

current account balance or the aggregate net position is low - the liquidity position may matter more.

These predictions are borne out by the data. If we repeat the regressions from earlier, but include interaction terms between the borrower's liquidity position and these variables, the results are significant. The parameters of interest are reported in table IV.

To put the estimates in perspective, one must consider the amount of variation in the variables with which the liquidity position is being interacted. For instance, in the sample period the aggregate net position changes from less than -100 bn to more than 200 bn, implying a variation in the borrower liquidity position estimate of about 3 basis points throughout the sample period. We also observe that the liquidity effect is stronger for loans settled later in the day, indicating, presumably, more urgency on the part of borrowers. Moreover, when aggregate liquidity is greater, whether in the form of immediate liquidity (current account balances) or other central bank assets (the net position), the liquidity effect is weaker. These findings highlight that liquidity premia are higher when liquidity is needed the most. Nevertheless, the economic magnitudes remain small. It does not seem too costly, though, as the cost will rarely exceed a few basis points.

I.4.1. Credit Risk and Liquidity

In the preceding section only a single variable directly related to credit risk, the tier 2 capital ratio, was included as an explanatory variable. In this section we examine the role of credit risk in more detail. Initially, we consider the inclusion of other credit risk measures. The upshot of that analysis is that there is no strong evidence of a clear, direct relationship between money market rates and credit risk measures based on bank balance

sheet information.

One possibility is that credit risk simply does not affect money market rates. Perhaps banks choose which banks they are willing to lend to but, once a bank is considered safe enough to be a counterparty, there is no further price adjustment. Another possibility is that credit risk does matter, albeit in a way not captured by our regression. There might be an indirect relationship if riskier banks choose to hold more liquidity than less risky banks. Or maybe our measures of credit risk, imperfect as they are, fail to measure credit risk.

To motivate these concerns further, suppose that the interest rate on money market loans is determined by the following stylized model with both direct and indirect effects of credit risk, the indirect effect being via the liquidity position:

$$\begin{aligned}
r_{i,t} &= r_f + \alpha_i + \beta_1 \times Liquidity_{i,t} + \beta_2 \times Risk_{i,t} + \epsilon_{i,t} \\
Liquidity_{i,t} &= Liquidity_{i,t}^{EOD} - Borrowing_{i,t} \\
Liquidity_{i,t}^{EOD} &= Liquidity_{i,t-1}^{EOD} + Borrowing_{i,t} + Liquidity_{i,t}^{Shock} \\
Borrowing_{i,t} &= \rho \times (Target_{i,t} - Liquidity_{i,t-1}^{EOD} - Liquidity_{i,t}^{Shock}) \\
Target_{i,t} &= \theta_0 + \theta_1 * Risk_{i,t}
\end{aligned}$$

The stylized model says that the interest rate paid by a bank on a given day is determined by bank-specific factors, the bank's liquidity position, and bank credit risk. The second and third equations are identities. The first links a bank's liquidity position to its end-of-day-liquidity and the net borrowing undertaken by the bank. The second defines links the end-of-day position to the previous days end-of-day position and liquidity flows. The two final equations are behavioral equations, the first expressing the amount of borrowing as a function of deviations between actual and target liquidity, the second saying that riskier banks prefer to hold more liquidity.

In the case of $\rho = 1$, implying that banks fully offset liquidity shocks by borrowing, the expression for the liquidity position is $Liquidity_{i,t} = Target_{i,t} - \theta_1 \times \Delta Risk_{i,t} + Liquidity_{i,t}^{Shock}$. If $\rho < 1$, the expression still includes the current liquidity shock, but also a geometrically weighted sum of past liquidity targets and shocks.

The above points to some of the econometric difficulties when regressing loan rates - and suggests solutions. If we have a variable that actually measures credit risk, we will be estimating β_1, the liquidity position coefficient, correctly. We will, however, be overestimating the effect of credit risk on loan rates. When $\rho = 1$, for instance, the actual credit risk effect

is $\beta_2 + \beta_1 * \theta_1$, and we expect a negative value of β_1. In other words, if we are interested in credit risk, the liquidity position is a bad control, and we would do better by excluding it from our regressions.

A different econometric issue appears if our problem is a failure to measure the credit risk of banks. In that case, credit risk is part of the error term and correlated with the liquidity position. We are thus faced with an endogeneity issue, suggesting that we search a valid instrument for the liquidity position. To be sure, the above model is intended only to illustrate potential econometric difficulties, and there is no suggestion of it being a an accurate representation of how rates are set. Indeed, minor variations to the model could change the interpretation of the results: If the interest rate were to depend directly on the liquidity shock, say, and one estimated the model using liquidity position and credit risk as covariates, β_1 would still be properly estimates, but the credit risk effect would be underestimated.

We first address the issue of bad controls. Table V reports the regression results for the full sample and each of the five subsamples, we examine. It includes estimates of the liquidity position with just the tier 2 capital ratio as a control and with a broader set of credit risk controls and parameter estimates for each of the credit risk controls with and without the liquidity controls.

The liquidity position estimates (here we focus on the borrower) are of the expected sign, though only statistically significant in the period encompassing the crisis and the period during which the European debt crisis took place. It does not matter pre-crisis, in the period of government guarantees, or in the negative interest rate regime when liquidity was generally ample. Moreover, the estimates do not depend on whether more credit risk controls are included. There is no evidence of a problem of bad controls. The parameter estimates for the credit controls likewise do not depend on whether liquidity controls are included.

Table V shows that the parameter estimates for the credit risk are sometimes insignificant, inconsistent over time, and in some cases of unexpected sign. For instance, the results indicate that banks with more write-offs and worse results pay lower rates. Moreover, even the variables are statistically significant, their economic significance is limited. As an example, consider the core capital ratio in the fourth subperiod from October 2010 to early

Table V: Credit risk and the liquidity position
This table shows regression estimates of the liquidity position as well as credit risk measures based on balance sheet data. Estimates are reported for five subsamples. They relate to the borrower in a transaction, not the lender. The set of other controls includes the same payment and time series variables as in Table II. Time and bank fixed effects are also included. In the base specification the only credit risk variable included is the tier 2 capital ratio; the set of full controls include the tier 2 capital ratio, write-offs, the deposit-to-assets-ratio and the relative credit risk measure (RCRM). t-statistics based on robust standard errors are in parentheses.

	Liq. controls	Pre-crisis	Crisis	Gov't guarantee	Debt crisis	Neg. interest rates
Liquidity Position (base spec.)	-	-0.06 (0.21)	-2.30 (5.04)	-0.31 (1.43)	-0.30 (1.98)	-0.41 (0.53)
Liquidity Position (full controls)	-	-0.07 (0.24)	-2.27 (4.90)	-0.30 (1.40)	-0.30 (2.00)	-0.41 (0.52)
Tier 1 capital ratio	Yes	28.28 (2.18)	-24.39 (1.25)	23.92 (1.49)	-29.21 (4.41)	2.18 (0.41)
	No	28.09 (2.16)	-24.03 (1.23)	27.09 (1.69)	-28.19 (4.29)	-3.52 (0.15)
Tier 2 capital ratio	Yes	36.12 (3.32)	-13.26 (0.89)	3.06 (0.22)	-30.50 (4.77)	23.93 (1.10)
	No	35.67 (3.27)	-11.95 (0.81)	5.37 (0.38)	-30.78 (4.82)	12.21 (0.59)
Write-offs	Yes	-30.82 (1.53)	-22.66 (0.52)	-5.25 (1.96)	-7.33 (1.93)	6.31 (0.40)
	No	-31.96 (1.53)	-16.83 (0.39)	-5.19 (1.93)	-7.22 (1.90)	20.31 (1.31)
Result	Yes	-7.48 (0.31)	184.53 (3.19)	34.40 (1.49)	14.57 (0.61)	48.30 (1.33)
	No	-7.07 (0.29)	181.95 (3.16)	37.03 (1.62)	18.71 (0.79)	5.46 (0.16)
RCRM	Yes	-2.51 (1.13)	-9.38 (2.06)	-2.12 (0.82)	0.58 (0.49)	0.41 (0.12)
	No	-2.64 (1.19)	-9.40 (2.06)	-2.56 (1.00)	0.21 (0.18)	2.74 (0.81)
N		11,800	6,408	11,534	8,299	2,062

July 2012 where we find a parameter estimate of -29.21. In economic terms, this means that a bank should experience a decrease in money market rates of 0.3 basis points for a percentage point increase in the core capital ratio.

If we are faced with an endogeneity problem rather than a problem of bad controls, more possible solutions present themselves. One solution might be to control for credit risk at a higher frequency, not by using specific measures of credit risk, but by taking interactions of time (month) and bank fixed effects. This should be sufficient to the extent that we are not concerned by even higher frequency variation in unobserved credit risk. This is a real concern, however, and we attempt to address it in two ways. The first is to identify a direct measure of the liquidity shock and include that rather than the liquidity position, while the second is to identify a suitable instrument (or instruments) for the liquidity position.

Table VI shows the estimates of the liquidity position effect when interactions of time and bank fixed effects are included. We observe the same pattern across subsamples as in Table V; however, the estimated magnitudes are even smaller, indicating that banks in need of liquidity do not pay substantial liquidity premia.

In order to identify a liquidity shock measure, a natural choice seems to be to subtract the target liquidity position of the bank from its liquidity position since that can be thought of as a shortfall relative to target. A bank's target liquidity is not observable, however. As

Table VI: Liquidity position estimates with interactions of fixed effects
This table shows regression estimate of the borrower's liquidity position when controls, bank fixed effects, time effects and interactions of bank and time fixed effects are included in the regression. Estimates are reported for the full sample as well as five subsamples. t-statistics based on robust standard errors are in parentheses.

	Full sample	Pre-crisis	Crisis	Gov't guarantee	Debt crisis	Neg. interest rates
Liquidity Position	-0.37 (3.01)	-0.06 (0.27)	-1.29 (3.52)	-0.13 (0.39)	-0.55 (3.38)	0.41 (0.47)
N	40,103	11,800	6,408	11,534	8,299	2,062

a proxy for the bank's target we use the bank's actual end-of-day-liquidity on the previous day (and examine averages using more days as well). Incidentally, the difference between the liquidity position and the end-of-day position of the previous day equals the liquidity shock in the stylized model discussed at the beginning of the section, though it presumably would not in a more realistic model of the money market. In the stylized model, for instance, the liquidity shock is identical to the net payment activity, much of which certainly is predictable and therefore cannot be though of as a shock, and banks might obtain longer-term (e.g. central bank) loans to offset predictable outflows. The same sort of behavior might lead the actual liquidity position to deviate from the target in a systematic fashion.

Using this differencing approach does not result in markedly different estimates. If we use the past day's end-of-day liquidity as a measure of target liquidity, the resulting parameter estimates for the borrower liquidity position and the lender liquidity position are -0.31 ($t = 2.47$), close to the estimate found when including fixed effect interactions, and -0.17 ($t = 2.43$) respectively. These estimates are based on the same specification as in Table III, column 1. The estimates are less negative than the estimates based on the liquidity position.

If we use the average of the past five days as a measure of the target instead, the estimates are close to the earlier estimates. Using the liquidity shock, we obtain an estimate of -0.57 ($t = 3.73$) for the borrower compared to -0.55 when using the liquidity position. For the lender, the corresponding estimates are -0.44 (5.26) versus -0.47. Extending the averages based on which the liquidity shocks are calculated to e.g. 10 or 20 days does not materially change the figures.

A second solution to the endogeneity problem is to use an instrument for the liquidity position. A possibility is that our credit risk proxies, based on accounting data as they are, simply are not good measures of credit risk. To provide some further motivation we note that there is some simple, but suggestive evidence in the data of a link between credit risk and banks' liquidity holdings. Specifically, there are indications that riskier banks do choose

Table VII: Liquidity and interest rates The table shows the interest rate differential between the loan rate and the central bank current account rate as a function of borrowers' and lenders' liquidity position. Results are reported for the full sample, September 2008, and the period with negative interest rates respectively. The figures are based on all loans except those between the two most active money market participants.

	Full sample		September 2008		Neg. interest rates	
Rate paid - CA rate (BP)	Lender: Liq. pos. > 1	Lender: Liq. pos. < 1	Lender: Liq. pos. > 1	Lender: Liq. pos. < 1	Lender: Liq. pos. > 1	Lender: Liq. pos. < 1
Borrower: Liq. pos. > 0	12.2	20.7	39.4	43.4	-11.5	2.1
Borrower: Liq. pos. < 0	16.9	23.5	37.4	40.0	-6.5	5.1

to hold more liquidity at the peak of the crisis. This can be seen by comparing the rates paid by banks as a function of their liquidity position. In general, we would expect that banks with more liquidity to pay lower rates when they borrow and to require lower rates when they lend.

A means of illustrating this is to compare the rates paid with borrowers for which the liquidity position variable is either positive or negative and for lenders for which it is either larger or smaller than one. For a borrower, a negative value of the variable means that the borrower would have had a negative end-of-day current account balance if the borrower had not obtained the loan. For a lender, a value of the variable above one indicates that the lender would have exceeded its limit if it had not. In table VII we divide the loans into four categories based on borrowers' and lenders' liquidity position and compare the interest rates agreed upon by borrowers and loans.

In the full sample the pattern is as expected: Borrowers and lenders with ample liquidity pay and receive lower rates. That pattern is not reproduced in the September 2008. While all rates are higher than in the full sample, the more interesting fact is that borrowers who are in less need of liquidity actually face the highest rates. This pattern is consistent with liquidity hoarding, since the worst banks may also be those who for precautionary reasons choose to hold the most liquidity.

Interestingly, all banks except the very smallest do borrow occasionally, even at the peak of the crisis. In the data set on which we perform our regressions, the average number of distinct borrowers per month in the period from April 2005 to December 2007 is 27.2. In July, August, and September of 2008 there are 30, 27, and 28 distinct borrowers respectively.

While this pattern is curious, it is not entirely unique to September 2008. In the pre-crisis period, when the liquidity position of banks appeared to matter little, it is common to find no discernible relation between borrowers' need of liquidity and the rates they pay. In the period after the expiration of the government guarantee (that ran from October 2008 to October 2010), however, such a pattern is rarely observed. On average, borrowers with

a negative liquidity position pay 4.3 bps more than those with a positive liquidity position in that period. In only 3 out of 33 months do we observe the opposite sign. This occurs in December 2010 (-1.6 bps), December 2012 (-0.1 bps), and June 2012 (-0.3 bps). This compares to a difference -3.0 bps in September 2008.

Since it might be of interest, we also include results for the period of negative interest. The qualitative pattern is the same as in the sample as a whole, but we also observe that lenders are willing to accept lower rates than they would earn by simply keeping money in their account. This could be because they fear exceeding their current account limit and having their current account holdings converted to certificates-of-deposits which earn even lower rates.

When looking for instruments we are hoping to find variables which themselves are irrelevant to the determination of money market rates when other factors have been controlled for, which are correlated with the liquidity position of banks and uncorrelated with credit risk. Certain payment flows seem promising candidates. For example, daily variation in retail payments (such as consumers' card payments at retail stores) is outside the control of the bank and presumably unrelated to bank credit risk, at least as long as that consumers do not withdraw funds in a bank run.[12] Unfortunately, retail payments constitute a negligible part of total payments and turns out to be a weak instrument. The F-statistic from the first-stage regression of the borrower liquidity position on the instrument is 4.0, while a rule-of-thumb suggests that a value in excess of 10 is required. The resulting estimate of borrower liquidity position coefficient is about -8.7, but the figure is not remotely significant ($t = 0.08$).

An alternative is to use a broader set of payments such as payments resulting from securities trading. We therefore attempt to use total net payments (excluding interbank payments) as an instrument. Total net payments is certainly more strongly correlated with the liquidity position than net retail payments, but its validity as an instrument, however, is also more questionable. For example, banks both handle securities transaction on behalf of customers and for themselves. One could imagine a liquidity constrained bank selling securities to raise cash, creating a link between credit risk and the instrument.

[12]In fairness, there could be sources of correlation between consumer payment behavior and bank risk. As an example, a regional bank might be located in a region in a decline, which might be associated with both risk to the bank and particular payment patterns. However, one might correct for trends in net retail payments, if any.

Table VIII: Failed banks and money flows
For 11 banks which failed in the period 2007-2013, the table reports average standardized liquidity flows and the fraction of days with negative standardized flows in the calender month preceding the failure of each bank. The standardized liquidity flows are calculated for each bank and day in the month by taking a bank's daily net payment, subtracting the average daily net payment of the bank over the period 2005-failure, and then dividing by the average absolute value of the daily net payment of the bank over the period 2005-failure.

Bank	1	2	3	4	5	6	7	8	9	10	11	Total
Avg. liquidity flow	-0.96	-0.09	0.31	0.19	0.39	0.41	0.84	-0.06	0.13	-0.89	0.07	0.01
Outflow days (fraction)	0.67	0.72	0.56	0.37	0.29	0.25	0.50	0.48	0.36	0.59	0.65	0.50

To mitigate concerns about instrument validity, we have collected data on daily total net payments for 11 failed banks for the calendar month preceding the bank failure. We calculate the daily total net payments for each bank and day in the month, subtract the average daily net payment (over the period 2005 until the end of the bank's life) and then scale by the average absolute value (over the same period). This produces a standardized score and helps us understand whether these banks, which were arguably in difficulties, experience unusual payment flows such as outflows due to customers taking their business elsewhere. No such pattern is observed; the scores seem quite random, see Table VIII. Only on half of all days, 104 of 210, do these banks experience larger than normal outflows.

Unlike retail payments, total net payments turn out to be a strong instrument for borrowers' and lenders' liquidity positions. In figure IX, we include the output of the first-stage regressions since they are informative not only about the strength of our instruments, but also show how other covariates relate to the liquidity position. As an example, we observe a link between the capital ratio and the liquidity position, especially of lenders. It appears that banks with more capital are willing to lend from a position of holding less liquidity than banks with less capital. We examine this further in the next section.

The estimates of main interest are those of the liquidity positions. The estimate for the borrower liquidity position is -6.00, implying that a borrower with a liquidity position of 1 would pay fully 6 basis points less than a borrower with a liquidity position of 0. Another way of putting the figures in perspective is to note that a one standard deviation decrease in the liquidity position "costs" about 5 bp for a borrower who wants to cover the shortfall in the money market. The estimate is much larger than the corresponding OLS estimate. Likewise, the estimate of the lender liquidity position, at -1.73, is greater than the OLS estimate. It is in line with expectations that the effect is greater for borrowers than for lenders since those in need of liquidity face a hard limit while those with surplus liquidity face a soft limit.

Table IX: 2SLS-estimates
This table shows the results from a two-stage least squares estimation where the borrower's and lender's net payment flows on the day of the loan are used as instruments for the liquidity positions. Both first- and second-stage result are reported. The dependent variable in the second-stage regression is quoted in basis points. For details on the computation and measurement units of the independent variables, see section I.2. t-statistics based on robust standard errors are in parentheses.

	1st stage: Liquidity position (B)	1st stage: Liquidity position (L)	2nd stage: interest rate
Liquidity position (B) - fitted	. (.)	. (.)	-6.00 (2.65)
Liquidity position (L) - fitted	. (.)	. (.)	-1.73 (5.39)
Net position (B) [10 bn]	0.02 (4.09)	0.01 (2.70)	0.1 (1.11)
Size (B)	0.27 (6.55)	-0.06 (1.33)	2.39 (2.44)
Tier 1 capital (B)	-0.42 (-2.34)	-0.22 (0.93)	-12.71 (2.52)
Net position (L) [10 bn]	0.00 (1.04)	0.03 (4.67)	0.2 (3.24)
Size (L)	-0.16 (5.17)	0.68 (14.60)	1.66 (2.05)
Tier 2 capital (L)	-0.31 (1.88)	-1.73 (6.74)	10.66 (2.34)
Loan size	-0.38 (69.13)	0.37 (53.42)	-1.70 (1.99)
Friday	0.04 (3.12)	-0.02 (1.08)	10.87 (35.69)
Total payments (t) [100 bn]	-0.01 (1.15)	0.07 (4.07)	3.6 (12.03)
Total payments (t-1) [100 bn]	0.00 (0.33)	0.00 (0.21)	1.84 (9.11)
Total payments (t+1) [100 bn]	0.02 (1.73)	0.08 (5.57)	-1.09 (2.98)
Gov't payment flow [100 bn]	0.11 (2.83)	0.3 (4.19)	9.70 (5.42)
Agg. CA balance [100 bn]	0.62 (11.59)	2.04 (22.92)	-21.01 (7.44)
Agg. net position [100 bn]	-0.04 (1.49)	0.17 (3.89)	-18.19 (17.52)
CDS (gov't)	-0.00 (2.06)	0.01 (18.77)	-0.08 (4.28)
Net payments (B, t) [10 bn]	0.25 (10.29)	0.02 (0.71)	()
Net payments (L, t) [10 bn]	-0.04 (2.51)	1.51 (18.31)	()
R^2	0.34	0.44	0.44
1st stage F-statistic	58.3	168.1	
N		40103	

Still, while these figures suggest that finding liquidity is a less than frictionless process, they seem low enough for the money market to function well. A money market loan will still be an attractive source of funding relative to alternatives such as e.g. borrowing from the central bank against collateral. In the sample period (2005 to mid-2013) the rate at which banks could borrow from the central bank was on average 33 bp greater than the current account rate. In comparison, the average rate paid on money market loans, which do not require the posting of collateral, was 15 bp greater than the current account rate (see Table I).

Finally, we examine estimates across subsamples. As was this case with the OLS-estimates, the IV-estimation produces results that vary considerably. The estimates are given in Table X. As before, the borrower liquidity position is significant in the crisis-period and in the period encompassing the European debt crisis, and now also in the period of negative interest rates.

The instrumental variables estimates are generally greater in magnitude than the corresponding OLS-estimates, and especially the estimates found in the financial and debt crises

Table X: 2SLS vs. OLS estimates - subsamples
The table compares parameter estimates of the borrower liquidity position across subsamples when estimated using OLS and 2SLS. The pre-crisis period is dated from January 2005 to June 2007, the crisis period from August 2007- 9 October 2008, the period of government guarantees from 10 October 2008 to September 2010, the period encompassing the European sovereign debt crisis from October 2010 to 5 July 2012, and finally the period of negative interest is dated from 6 July 2012 to the end of the sample in June 2013. The OLS-estimates are based on the same model specification as in Table III, column 1. The 2SLS-estimates are based on the same specification as in Table IX. t-statistics based on robust standard errors are in parentheses.

	Pre-crisis	Crisis	Gov't guarantee	Debt crisis	Neg. interest rates
			IV-estimates		
Liquidity position (B)	1.91 (0.70)	-14.11 (3.82)	1.02 (0.17)	-11.36 (3.99)	-14.27 (4.20)
Liquidity position (L)	-0.52 (0.55)	-3.83 (2.31)	-2.55 (3.42)	-0.22 (0.57)	0.39 (0.34)
			OLS-estimates		
Liquidity position (B)	-0.06 (0.21)	-2.30 (5.04)	-0.31 (1.43)	-0.30 (1.98)	-0.41 (0.53)
Liquidity position (L)	-0.39 (2.41)	-1.25 (4.21)	-0.26 (1.65)	-0.05 (0.66)	0.96 (1.91)
N	11,800	6,408	11,534	8,299	2,062

are large from an economic perspective. The figure for the negative interest rate period is not entirely comparable, because banks' current account limits were greatly increased during that period. In terms of actual liquidity, therefore, a change in the liquidity position during that period corresponds to a much greater change in liquidity.

I.5. The Decision to Borrow or Lend

In our analysis of the interest rate, we did not find evidence that credit risk, or at least regulatory measures thereof, directly affect rates for banks that are able to borrow, nor that there was an indirect effect via the liquidity positions. Perhaps, though, credit risk affects the decision to borrow or lend in the first place. For precautionary motives, riskier banks may choose to hold more liquidity and therefore have less need to borrow; and perhaps, holding more liquidity, they are more likely to supply it as lenders. These considerations suggest that we may again face a potential problem of bad controls if we include both the liquidity position of banks and credit risk variables.

The analysis in this section indicates that credit risk does influence the decisions to borrow and lend via the liquidity position. Unlike before our interest is not in the liquidity position itself. It is self-evident that the liquidity position must be a key determinant of borrowing and lending, since it is exactly to adjust their liquidity position that banks borrow and lend.

We first analyze probit models for each subsample and for both borrowers and lenders

to get a sense of the determinants of the borrowing and lending decisions. In that analysis we simultaneously include the liquidity position and the tier II capital ratio of banks in the analysis. Subsequently, we examine how a broader set of credit risk variables work when the liquidity position is included and excluded.

One issue is whether to include fixed effects. If included, one can perfectly predict the participation decisions of the two largest banks, at least in most subsamples, since they participate virtually every single day. These banks must therefore be taken out of the analysis. If fixed effects are excluded, however, the model is likely to be misspecified. Excluding fixed effects may result in a misspecification. In the case of interest rate regressions we saw, for instance, that one would obtain different estimates for the effect of the capital ratio depending on whether fixed effects were included or not. This could be explained if some unobservable heterogeneity, e.g. the quality of bank systems or management, would permit stronger banks to hold less equity. We thus prefer to include fixed effects, but also show results without fixed effects for comparison.

Table XI shows the results of the probit analysis for the full sample, with and without fixed effects, and for the subsamples with fixed effects.

The capital ratio does not appear to affect the decision to borrow directly. In fact, it is only significant in the sub-period where we would not expect credit risk to matter (and the parameter estimates is negative). Neither is there a clear pattern when we analyze the panel of lenders. If we did not include fixed effects, we would even conclude that banks with less capital are more likely to borrow and lend. The other variables largely behave as expected; we discuss parameter estimates in more detail later in the context of the linear probability model.

Focusing on the full sample, Table XII compare how parameter estimates for different measures of credit risk compare when the liquidity position variable is included and excluded, and a pattern emerges. In the borrower panel, we observe that the credit risk measures are often insignificant, and only in the case of the financial result is the sign as expected. When the liquidity position is not included, in contrast, the variables are generally significant and tell the same story: Healthier banks are more likely to borrow. Only in the case of the relative credit risk measure is the effect insignificant.

Table XI: The borrowing and lending decisions
This table reports estimates from probit models of the decision to borrow (top panel) and the decision to lend (bottom panel). For details on the computation and measurement units of the independent variables, see section I.2. t-statistics based on robust standard errors are in parentheses. The full sample runs from January 2005 to June 2013. The pre-crisis period is dated from January 2005 to June 2007, the crisis period from August 2007- 9 October 2008, the period of government guarantees from 10 October 2008 to September 2010, the period encompassing the European sovereign debt crisis from October 2010 to 5 July 2012, and finally the period of negative interest is dated from 6 July 2012 to the end of the sample.

	Panel of borrowers						
	Full sample	Full sample	Pre-crisis	Crisis	Gov't guarantee	Debt Crisis	Neg. interest rates
Borrower (t-1)	1.48 (101.71)	1.11 (70.16)	0.80 (27.43)	0.84 (19.02)	1.01 (32.98)	1 (25.56)	0.74 (12.8)
Liquidity position	-0.41 (22.18)	-0.45 (22.19)	-0.83 (14.13)	-0.51 (11.49)	-0.30 (11.21)	-0.78 (10.41)	-1.61 (8.32)
Net position	0.23 (4.7)	-0.58 (9.19)	0.04 (0.19)	-0.55 (2.19)	-0.20 (2.45)	-0.95 (1.11)	-2.58 (0.66)
Size	0.23 (56.88)	0.47 (11.07)	-0.25 (1.26)	0.78 (2.25)	-0.34 (1.46)	0.43 (1.49)	-0.39 (0.75)
Tier II capital	-0.91 (6.98)	-0.13 (0.61)	1.01 (1.13)	-1.37 (1.47)	-3.84 (4.47)	1.99 (1.61)	-3.86 (1.25)
Agg. CA balance [100 bn]	0.3 (2.34)	0.09 (0.67)	-0.22 (0.63)	-0.51 (0.77)	0.46 (1.27)	0.73 (1.56)	-0.70 (2.37)
Agg. Net position [100 bn]	0.27 (4.94)	0.28 (4.88)	0.16 (1.13)	0.19 (1.1)	0.12 (1.28)	0.72 (5.47)	0.62 (2.84)
Friday	-0.48 (26.68)	-0.50 (26.16)	-0.55 (15.51)	-0.68 (12.11)	-0.62 (15.8)	-0.49 (10.9)	0.21 (2.88)
Gov't payments [100 bn]	0.62 (7.73)	0.68 (7.92)	0.55 (2.77)	0.31 (1.21)	0.66 (4.2)	0.84 (4.42)	0.33 (1.09)
Total payments (t) [100 bn]	-0.03 (1.55)	-0.02 (1.28)	0.01 (0.31)	0.06 (0.86)	-0.04 (1.06)	-0.10 (2.27)	0.15 (2.78)
Total payments (t-1) [100 bn]	0.02 (1.32)	0.01 (0.64)	-0.01 (0.2)	0.02 (0.34)	-0.04 (1.12)	0.11 (2.17)	-0.05 (0.94)
Total payments (t+1) [100 bn]	0.13 (6.71)	0.15 (7.47)	0.22 (4.93)	0.10 (1.49)	0.12 (3.22)	0.23 (4.76)	0.16 (2.35)
CDS (gov't)	0.00 (0.81)	0.00 (0.83)	-0.01 (0.28)	0.01 (1.78)	0 (0.51)	0.00 (0.94)	0.00 (1.24)
Bank fixed effects	No	Yes	Yes	Yes	Yes	Yes	Yes
N	71890	67782	16464	7084	16554	11518	2832
Pseudo R^2	0.49	0.56	0.48	0.41	0.50	0.50	0.67

	Panel of lenders						
	Full sample	Full sample	pre-crisis	early crisis	bank package I	post-BPI	neg. interest rates
Lender (t-1)	1.43 (79.53)	0.8 (37.45)	0.71 (18.2)	0.53 (9.08)	0.75 (18.45)	0.58 (12.02)	0.44 (3.92)
Liquidity position	0.18 (19.6)	0.23 (19.92)	0.26 (13.22)	0.32 (17.18)	0.21 (8.3)	0.32 (11.74)	0.91 (9.16)
Net position	0.67 (16.6)	-0.23 (4.09)	0.29 (1.49)	-0.91 (3.97)	-0.05 (0.63)	0.59 (0.95)	-2.52 (0.35)
Size	0.33 (80.28)	0.07 (1.06)	-0.08 (0.3)	1.79 (3.32)	-0.05 (0.18)	-1.18 (3.61)	-0.19 (0.14)
Tier II capital	-0.72 (3.69)	0.72 (2.07)	0.64 (0.42)	-0.46 (0.29)	-3.53 (3.14)	-0.81 (0.52)	-10.01 (1.98)
Agg. CA balance/100	-0.94 (6.14)	-1.51 (8.02)	-2.67 (5.9)	-2.57 (3.41)	-1.7 (3.58)	-3.14 (5.18)	-1.15 (2.6)
Agg. Net position/100	-0.16 (2.49)	-0.21 (3.01)	-0.1 (0.53)	-0.38 (1.68)	-0.21 (1.95)	0.02 (0.12)	-0.76 (2.13)
Friday	-0.18 (8.37)	-0.19 (7.78)	-0.17 (3.76)	-0.11 (1.73)	-0.28 (5.91)	-0.28 (5.25)	-0.23 (1.93)
Gov't payments/100	0.26 (2.69)	0.26 (2.41)	-0.14 (0.57)	-1.12 (3.57)	0.48 (2.44)	0.95 (4.38)	1.01 (2.28)
Total payments (t)/100	-0.01 (0.56)	0 (0.02)	-0.03 (0.64)	0.14 (1.69)	0.01 (0.33)	0.00 (0.10)	-0.04 (0.50)
Total payments (t-1)/100	0.02 (1.09)	0.02 (0.71)	0.05 (1.07)	0.18 (2.35)	-0.02 (0.39)	0.05 (1.08)	0.05 (0.59)
Total payments (t+1)/100	0.1 (4.93)	0.12 (5.17)	0.15 (2.7)	0.13 (1.58)	0.13 (2.98)	0.16 (3.22)	0.17 (2.09)
Agg. Credit risk	0.00 (1.34)	0.00 (1.56)	0.01 (0.49)	0.01 (1.2)	0.00 (0.7)	0.00 (0.31)	-0.02 (4.79)
Bank fixed effects	No	Yes	Yes	Yes	Yes	Yes	Yes
N	65728	65728	16464	5790	15486	13290	6372
Pseudo R^2	0.44	0.50	0.45	0.47	0.42	0.58	0.57

Table XII: Credit risk and the decision to borrow or lend
The table compares parameter estimates from probit models with and without the liquidity position included. The model specification is the same as in Table XI, but different credit risk measures are included. Estimates are not reported for the other control variables. The sample period is the full sample (January 2005 to June 2013).

Credit risk measure	Liq. position	Borrower panel	Lender panel
Tier 1 capital	Yes	-0.132 (0.61)	0.723 (2.07)
	No	0.869 (4.07)	-0.176 (0.55)
Tier 2 capital	Yes	-0.211 (0.92)	-0.188 (0.53)
	No	0.972 (4.39)	-0.376 (1.1)
Write-offs	Yes	0.123 (0.75)	0.061 (1.73)
	No	-0.322 (1.91)	0.073 (2.07)
Result	Yes	2.491 (3.76)	-0.315 (0.33)
	No	3.6 (5.65)	-0.94 (1.02)
Relative CR measure	Yes	0.242 (3.97)	0.298 (3.68)
	No	-0.079 (1.35)	0.398 (5.12)

A qualitatively similar pattern emerges in the case of the panel of lenders. For each credit risk measure, exclusion of the liquidity position indicates that riskier banks are more likely to be lenders than their less risky counterparts. However, for only two of five variables is there a statistically significant relationship between bank health and the lending decision.

Finally, we estimate linear probability models for the borrower and lender panels. While such models suffer from conceptual problems, such as the possibility of predicting probabilities that are negative or exceed one, the results are easier to interpret than is the case with probit models. The results are reported both including and excluding the liquidity position variable in Table XIII.

The linear probability model generally agrees with the probit model about the determinants of loan decisions, but the quantities are easier to interpret in the linear probability model. Unsurprisingly, the liquidity position is significant: After all, banks who borrow generally do so because they need liquidity, while banks with surplus liquidity are more likely to be lenders. Another key determinant of the borrowing decision is past borrowing. The probability of a bank borrowing today is about a 40 percentage point higher if the bank borrowed the day before. This should not come as a surprise; if a bank is hit by a negative liquidity shock one day, it will, absent a liquidity shock in the reverse direction or borrowing from another source, need to borrow the following day again to remain at the same level of liquidity.

This is also evident when evaluating the "Friday" variable, i.e. whether banks have access to central bank facilities on a given day. When banks have such access, they are about 10 percentage points less likely to borrow from other banks and about 2 percentage points less likely to lend to other banks. One way to put this figures into perspective is to compare to the unconditional probability of a bank in our panels borrowing or lending on a given day. Not counting the two largest money market participants, which borrow and lend essentially every day, the probability of a bank borrowing is 32.4 percent, while the probability of a bank lending is 10.1 percent.

There does appear to be a relationship between the capital ratio and the decision to borrow or lend. Consider the case of borrowers. When not including fixed effects, banks with more capital appear to be less likely to borrow. A possible explanation is the some unobserved feature of the banks, their "quality", say, permit certain "high quality" banks to

Table XIII: The borrowing and lending decisions - linear probability model
This table shows estimates of the decision to borrow and lend in a linear probability model. For both borrower and lenders the model is estimated without and with bank effects and, in the latter case, with and without the liquidity position included. For details on the computation and measurement units of the independent variables, see section I.2. t-statistics based on robust standard errors are in parentheses.

	Borrower panel			Lender panel		
Borrower (t-1) / Lender (t-1)	0.49 (152.12)	0.38 (79.58)	0.44 (97.42)	0.46 (83.12)	0.26 (39.19)	0.3 (45.61)
Liquidity position	-0.06 (72.5)	-0.06 (31.85)	. (.)	0.03 (30.54)	0.05 (34.19)	. (.)
Net position [100 bn]	0.07 (9.17)	-0.05 (5.03)	-0.07 (7.11)	0.14 (17.17)	-0.05 (5.53)	-0.03 (3.05)
Size	0.05 (65.28)	0.04 (5.83)	0.02 (3.65)	0.06 (69.78)	0.00 (0.79)	0.02 (2.93)
Tier II capital	-0.10 (4.20)	0.02 (0.55)	0.15 (3.3)	-0.05 (2.76)	-0.11 (4.06)	-0.21 (7.22)
Agg. CA balance [100 bn]	0.04 (1.58)	0.02 (0.62)	-0.06 (2.59)	-0.08 (4.86)	-0.12 (7.44)	-0.06 (3.45)
Agg. Net position [100 bn]	0.05 (4.58)	0.06 (5.01)	0.07 (5.89)	-0.02 (1.87)	-0.02 (2.4)	-0.02 (3.13)
Friday	-0.11 (29.21)	-0.10 (29.33)	-0.10 (29.14)	-0.03 (10.01)	-0.02 (10.06)	-0.02 (9.69)
Gov't payments [100 bn]	0.13 (8.05)	0.14 (8.53)	0.17 (10.03)	0.05 (3.94)	0.05 (4.20)	0.03 (2.33)
Total payments (t) [100 bn]	-0.01 (1.72)	-0.01 (1.94)	-0.02 (4.24)	-0.01 (2.42)	-0.01 (2.46)	0.00 (0.13)
Total payments (t-1) [100 bn]	0.00 (1.26)	0.00 (0.19)	0.00 (0.75)	0.00 (0.01)	0.00 (0.35)	0.00 (1.02)
Total payments (t+1) [100 bn]	0.03 (7.39)	0.03 (7.56)	0.02 (5.37)	0.01 (4.4)	0.01 (4.38)	0.02 (5.97)
Agg. Credit risk	0.00 (0.66)	0.00 (0.61)	0.00 (0.8)	0.00 (0.88)	0.00 (1.34)	0.00 (1.19)
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Bank fixed effects	No	Yes	Yes	No	Yes	Yes
N	65728			71890		
R^2	0.48	0.52	0.48	0.48	0.56	0.53

hold less capital. At least, the negative relationship vanishes when fixed effects are included. As in the probit model, the sign changes when the liquidity position is excluded from the analysis, implying (more in line with prior expectations) that healthier banks are more likely to borrow. Our interpretation is that this is due to healthier banks choose, or can afford, to hold less liquidity since they will be able to obtain loans when faced with liquidity shocks.

Better capitalized banks tend to be borrowers, and less well-capitalized banks lend more. Moreover, this result is amplified, in the same direction as in the probit model, when the liquidity position is excluded from the model. A reasonable interpretation is that healthy banks choose, or can afford, to hold less liquidity. When the liquidity position is included, therefore, there is no significant relationship between the capital ratio and the decision to borrow.

I.6. Event Study Evidence

In this final section we briefly consider some event study evidence. There were two major events which seem especially likely to have affected the Danish interbank market during the financial crisis. The first was the default of Roskilde Bank, the 8th largest bank

in Denmark at the time, and the second was the bankruptcy filing by Lehman Brothers on 15 September 2008. Roskilde Bank was taken over by the Danish Central Bank and an association of banks on 24 August 2008[13], but Roskilde Bank had already begun receiving emergency funding on 10 July 2008.

We consider these three dates as event dates and consider the behavior of the money market around these dates. When performing regressions considering dates around these events, there are clear spikes in interest rates only for loans beginning on July 11 and August 26th, perhaps because many of these loans are agreed a day in advance, corresponding to the actual default dates. There are no significant effects around Lehman's default. We therefore focus on the dates following the two Roskilde events.

We are naturally interested in questions such as whether riskier banks pay premia in times of stress. However, as we have argued in previous sections, our measures of credit risk based on bank balance sheet information may not be particularly good measures of credit risk. In this section we therefore take a slightly different approach. Supposing that banks which are perceived to be riskier do, in fact, pay higher rates, we should be able to capture this through the estimates of bank fixed effects. We therefore estimate the bank fixed effects using data from period from March 2007, roughly corresponding to earliest stage at which problems in the financial system became widely evident, to February 2008. These estimates are then used a measures of credit risk in regressions encompassing the period March 2008 to February 2009, placing the event dates of interest close to the middle of this period.

The results of the event study are reported in Table XIV. Banks which pay higher rates before the event period also pay rater higher in the event period. To put the numbers in perspective, the standard deviation in the credit risk measure is about 10 basis points, implying that a one standard deviation change in the credit risk measure changes rates by 11.2 basis points in the event period. We are more interested in the effects on the particular event dates, however. Average rates are substantially higher than normal on these dates, especially following the actual takeover of Roskilde Bank. The interaction effects all go in the expected direction - the credit risk measure and the effect of being short on liquidity are amplified - but the effects cannot be measured precisely. We do not observe strong effects on banks' access to the market. These findings are somewhat similar to these in Afonso,

[13]This was during the weekend. We look at the following days.

Table XIV: Event study evidence
This table shows the effects of credit risk and the liquidity position on respectively interest rates and access to the interbank market on 11 July 2008 and 26 August 2008, the days after news about difficulties and default at Roskilde Bank. The credit risk of each bank is defined as the individual bank fixed effect found from a regression on interest rates, including other controls, in the period from March 2007 to February 2008. The results in the "Interest rates"-column are based on regressions in which the dependent variable is the money market rate less the central bank current account rate. Also included in the regression, in addition to the reported variables, are the same controls as in the base specification (except the tier 2 capital ratio) and time fixed effects. The "Access"-column shows the result of a panel probit model in which the dependent variable is whether a bank accesses the money market on a particular day. The control variables are the same as in the base specification of the probit model (except the tier 2 capital ratio) used elsewhere in the paper. The sample period runs from March 2008 to February 2009. t-statistics based on robust standard errors are in parentheses.

	Interest rates	Access
Credit risk	1.12 (17.97)	0.01 (3.11)
Liquidity position	-1.72 (-2.63)	
July 11	21.89 (3.27)	0.92 (1.09)
* Credit risk	0.66 (1.11)	0.07 (1.7)
* Liq. Position	-16.18 (-1.35)	
August 26	50.75 (11.62)	-0.64 (1.02)
* Credit risk	0.22 (1.14)	-0.03 (1.22)
* Liq. Position	-11.38 (-2.56)	
Time FE	Yes	Yes
N	7,200	5,580
R^2 / pseudo R^2	0.48	0.49

Kovner, and Schoar (2011) who find that banks mainly adjust interest rates around the major event in the US, the Lehman default.

I.7. Conclusion

Banks turn to the overnight interbank market to absorb liquidity shocks. We assess the efficiency of this market by analyzing how a bank's liquidity position affects the interest rate it must pay. Since a liquidity inflow to one bank is an outflow to another bank, a healthy bank faced with a liquidity need should be able to find liquidity and, due to competition among banks with excess liquidity, pay a rate equal or close to the opportunity cost of holding liquidity for those with liquidity to spare.

On average, banks in need of liquidity pay only a small premium relative to those with ample liquidity. For instance, a bank with a liquidity position of zero, the amount of liquidity the bank must hold at a minimum, pays less than a single basis point more than a bank with a liquidity position of one, the amount it is permitted to hold. Yet, while banks short on liquidity may not pay higher in many cases, they do so in certain circumstances. When aggregate liquidity scarce, when liquidity is needed more urgently, and payment activity is large, the effects of having little liquidity are more pronounced, and the magnitudes are in

the order of a few basis points. These are still relatively low figures when compared to the observed variation in money market rates. To give some perspective, the standard deviation of the interest paid on a loan less the average rate paid on the day of the loan is 17 basis points.

A concern is that liquidity and credit effects are being confounded. For instance, riskier banks may choose to hold more liquidity for precautionary reasons. An implication would be that excluding the liquidity position from regressions should produce different estimates for variables related to credit risk. We do not find any evidence of such an effect when using regulatory measures of credit risk such as bank capital ratios. Another possibility is that we fail to adequately measure credit risk because capital ratios (and other measures based on financial statements) are imperfect and are only sampled on a quarterly basis. To address this concern we take an instrumental variables approach to estimating the effect of the liquidity position. The IV-estimate of the borrower's liquidity position is about 9 basis points, substantially higher than a regular OLS-estimate of less than a single basis point. This estimate further masks differences across sub-samples. The liquidity position mainly appears to matter in the crisis period and in the period encompassing the European sovereign debt crisis. Pre-crisis and during the period in which money market loans were covered by a government guarantee, banks did not pay significantly higher rates when they were in need of liquidity.

While regulatory measures of credit risk do not affect money market rates, there is some evidence to suggest that they influence participation. At first glance it appears that banks with more capital are less likely to borrow than those with less capital. If one controls for bank heterogeneity by including fixed effects, however, this effect vanishes. In that case we show that an increase in the capital ratio is associated with an increase in the likelihood of being a borrower while a decrease is associated with an increase in the likelihood of being a lender. This mainly reflects an indirect effect. Banks with higher capital ratios choose to hold less liquidity and therefore more frequently need to access market; conversely, banks with less equity capital hold more liquidity and therefore tend to have liquidity to lend.

Our analysis contributes to an understanding of - and thereby potentially have implications for - how institutional details such as the monetary policy rules set by the central bank affect money market activity. As an example, we observe that money market rates

are about 10 basis points higher on days when lenders can place money in certificates of deposits (which typically yield 10 basis points more than money deposited in a bank's current account), while borrowing and lending activity is dampened. Also, we show throughout the paper that aggregate liquidity and payment activity affects the functioning of the money market, and these are factors over which the central bank and the government can exert influence.

References

Abildgren, Kim et al. (2015). "The Short-Term Danish Interbank Market Before, During, and After the Financial Crisis". In: *Danmarks National Bank Working Paper* October.

Acharya, Viral V. and Ouarda Merrouche (2013). "Precautionary Hoarding of Liquidity and Interbank Markets: Evidence from the Subprime Crisis". In: *Review of Finance* 17, pp. 107–160.

Acharya, Viral V. and David Skeie (2011). "A Model of Liquidity Hoarding and Term Premia in Inter-Bank Markets". In: *Journal of Monetary Economics* 58.5, pp. 436–447.

Afonso, Gara, Anna Kovner, and Antoinette Schoar (2011). "Stressed, Not Frozen: The Federal Funds Market in the Financial Crisis". In: *Journal of Finance* 66.4, pp. 1109–1139.

— (2013). "Trading Partners in the Interbank Lending Market". In: *Federal Reserve Bank of New York Staff Reports* No. 620.

Afonso, Gara and Ricardo Lagos (2012). "An Empirical Study of Trade Dynamics in the Fed Funds Market". In: *Federal Reserve Bank of New York Staff Reports* No. 550.

— (2015). "Trade Dynamics in the Market for Federal Funds". In: *Forthcoming Econometrica*.

Allen, Franklin and Douglas Gale (2000). "Financial contagion". In: *Journal of Political Economy* 108, pp. 1–33.

Arceiro, Luca et al. (2014). "How To Measure the Unsecured Money Market? The Eurosystem's Implementation and Validation Using Target2 Data". In: *Bank of Italy Occasional Paper* 215.

Armantier, Olivier and Adam Copeland (2012). "Assessing the Quality of "Furfine-based" Algorithms". In: *Federal Reserve Bank of New York Staff Reports* 575.

Ashcraft, Adam and Darrell Duffie (2007). "Systemic Illiquidity in the Federal Funds Market". In: *American Economic Review* 97.2, pp. 221–225.

Ashcraft, Adam, James McAndrews, and David Skeie (2011). "Precautionary Reserves and the Interbank Market". In: *Journal of Money, Credit and Banking* 43.Supplement s2, pp. 311–348.

Bech, Morten L., James T.E. Chapman, and Rodney J. Garratt (2010). "Which Bank is the "Central" Bank?" In: *Journal of Monetary Economics* 57.3, pp. 352–363.

Bech, Morten L. and Rodney J. Garratt (2003). "The Intraday Liquidity Management Game". In: *Journal of Economic Theory* 109.2, pp. 198–219.

Bech, Morten L. and Cyril Monnet (2013). "The Impact of Unconventional Monetary Policy on the Overnight Interbank Market". In: *Reserve Bank of Australia Annual Conference Volume: Liquidity and Funding Markets (eds. Alexandra Heath, Matthew Lilley and Mark Manning)*, pp. 147–177.

Bernanke, Ben and Alan S. Blinder (1992). "The Federal Funds Rate and the Channels of Monetary Transmission". In: *American Economic Review* 82.4, pp. 901–921.

Bindseil, Ulrich, Kjell G. Nyborg, and Ilya Strebulaev (2009). "Repo Auctions and the Market for Liquidity". In: *Journal of Money, Credit, and Banking* 41, pp. 1391–1421.

Blasques, Francisco, Falk Bräuning, and Iman van Lelyveld (2014). "A Dynamic Stochastic Network Model of the Unsecured Interbank Lending Market". In: *SWIFT Institute Working Paper* 2012-007.

Bräuning, Falk and Falko Fecht (2012). "Relationship Lending in the Interbank Market and the Price of Liquidity". In: *Deutsche Bundesbank Discussion Papers* 22.

Bruche, Max and Javier Suarez (2010). "Deposit Insurance and Money Market Freezes". In: *Journal of Monetary Economics* 57.1, pp. 45–61.

Cocco, João F., Francisco J. Gomes, and Nuno C. Martins (2009). "Lending Relationships in the Interbank Market". In: *Journal of Financial Intermediation* 18.1, pp. 24–48.

Craig, Ben and Goetz von Peter (2014). "Interbank Tiering and Money Center Banks". In: *Journal of Financial Intermediation* 23.

Fecht, Falko, K.G. Nyborg, and Jörg Rocholl (2011). "The Price of Liquidity: The Effects of Market Conditions and Bank Characteristics". In: *Journal of Financial Economics* 102, pp. 344–362.

Furfine, Craig H. (1999). "The Microstructure of the Federal Funds Market". In: *Financial Markets, Institutions and Instruments* 46.5, pp. 535–553.

— (2001). "Banks as Monitors of Other Banks: Evidence from the Overnight Federal Funds Market". In: *Journal of Business* 74.1, pp. 33–58.

— (2002). "The Interbank Market During a Crisis". In: *European Economic Review* 46.4-5, pp. 809–8.

Hagen, Jürgen von and Tai-Kuang Ho (2007). "Money Market Pressure and the Determinants of Banking Crisis". In: *Journal of Money, Credit and Banking* 39.5, pp. 1037–1066.

Hamilton, James D. (1996). "The Daily Market for Federal Funds". In: *Journal of Political Economy* 104.1, pp. 26–56.

Heider, Florian, Maria Hoerova, and Cornelia Holthausen (2015). "Liquidity Hoarding and Interbank Market Spreads: The Role of Counterparty Risk". In: *Journal Financial Economics*.

Iori, Giulia et al. (2008). "A Network Analysis of the Italian Overnight Money Market". In: *Journal of Economic Dynamics and Control* 32, pp. 259–278.

Ivashina, Victoria and David Scharfstein (2010). "Bank Lending During the Financial Crisis of 2008". In: *Journal of Financial Economics* 97.3, pp. 319–338.

Pedersen, Lasse H. and Markus Brunnermeier (2009). "Market Liquidity and Funding Liquidity". In: *Review of Financial Studies* 22.6, pp. 2201–2238.

Puri, Manja, Jörg Rocholl, and Sascha Steffen (2011). "Global Retail Lending in the Aftermath of the US Financial Crisis: Distinguishing Between Supply and Demand Effects". In: *Journal of Financial Economics* 100.3, pp. 556–578.

Identifying Liquidity Risk in the European Interbank Market*

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ABSTRACT

We use the spread between secured repurchase rates ($EUREPO$) and $EONIA$ swap rates (OIS rates) to obtain a measure of banks' liquidity hoarding during the financial crisis. Our model involves secured and unsecured money market rates over different maturities and it captures the observed phenomenon that the secured rates may exceed unsecured rates when liquidity hoarding dominates the credit risk in overnight rates. We find liquidity risk to be a significant factor in interbank spreads around the Lehman crisis, but it vanishes after the announcement of the SMP programme by the ECB. We regress $EURIBOR-OIS$ spreads on our measure of illiquidity and find the contribution from illiquidity to be of the same order of magnitude as in $EUREPO - OIS$ spreads.

II.1. Introduction

The interbank markets are critical for bank funding and liquidity management, and the financial crisis was in part caused by severe frictions in this market. While some of these frictions were clearly related to concerns about counterparty credit risk, banks were also reluctant to give up cash simply because of worries that large shocks to funding would cause problems with liquidity, or with meeting capital requirements. Banks in search of interbank

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funding therefore increasingly had to resort to secured borrowing. The increasing demand for secured borrowing exerted upward pressure on secured loans, and we argue in this paper that in European markets the increase that took place during the crisis can be used to assess a funding liquidity premium, i.e., an extra interest rate that a bank was willing to pay to obtain term funding.

Our estimation of the liquidity premium relies on the observation that – except for a small credit risk component – it is the risk of a dry-up in funding that prevents $EONIA$ swap rates from being equal to a repo rate ($EUREPO$) of the same maturity. Thus the difference in these two rates reflects the risk of a shock to a bank's funding liquidity. We will explain the arbitrage argument in more detail below.

To get a clean measure of the liquidity premium, we must take into account that there is a small element of credit risk in the $EONIA$ rates underlying the $EONIA$ swap rates. Our model proposes a way to control for this small credit risk component. We argue that the contamination from credit risk is much smaller than when trying to infer illiquidity from, say, $EURIBOR-OIS$ spreads. These spreads contain both a component that is related to credit risk (because the $EURIBOR$ loan is unsecured) and a funding liquidity component because the $EURIBOR$ loan provides term funding. However, the largest part of the spread during the crisis stems from the credit risk component. Therefore, identifying the liquidity premium as the residual that remains after removing an estimate of the credit spread gives considerable uncertainty in the estimate of the liquidity premium, simply because it is a small quantity measured as the difference of two large quantities one of which has considerable uncertainty.

To identify liquidity risk we use the spread between $EUREPO$ and $EONIA$ swap rates, which we also refer to simply as OIS rates. To the extent that $EUREPO$ rates contain no credit risk component, this spread has the advantage that it is increasing in the premium we are trying to measure but decreasing in counterparty credit risk. This is in contrast with the $EURIBOR-OIS$ spread which is sensitive to both credit risk and liquidity. The more counterparty credit risk, the larger is the $EURIBOR-OIS$ spread because of the credit risk of $LIBOR$ banks, and the more liquidity hoarding the more compensation do banks require to give up liquidity lending at $LIBOR$.

Lending overnight in the $EONIA$ market, that underlies the European OIS market,

does not tie up liquidity. It does involve a small credit risk component that we need to remove to get a clean estimate for the liquidity component. For this purpose, we use the difference between $EURONIA$ and $EONIA$ rates which differ mainly due to panel bank composition.

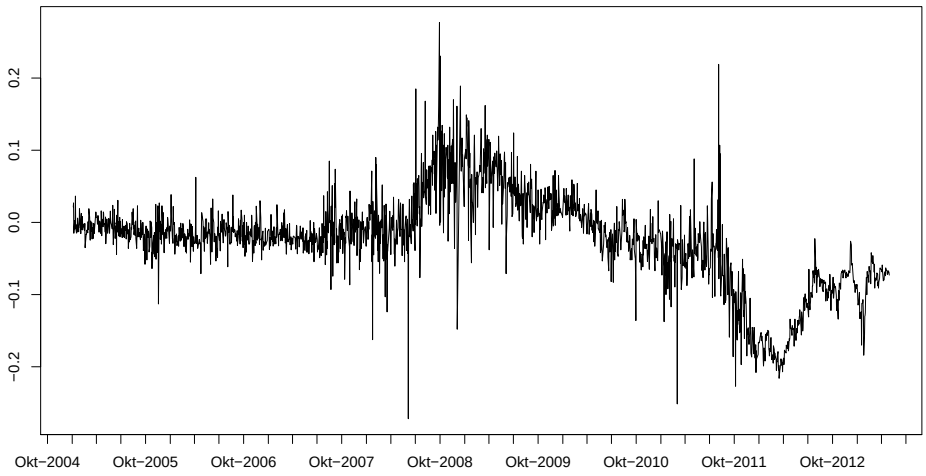

Figure II.8: *The spread between the 1 year EUREPO rate and the 12 month OIS rate*

Our model is able to capture the remarkable feature that, during the crisis secured rates became higher than comparable unsecured rates for longer periods of time. Prior to the financial crisis this was never the case. Unsecured rates were consistently a little higher than the comparable secured rates as we would expect since they should differ due to counterparty credit risk. In the period around the collapse of Lehman brothers, the fact that OIS rates are higher than similar maturity $EUREPO$ rates is a clear sign that the liquidity component is playing an important role.

The model is closely related to Filipović and Trolle (2013). In their paper they distinguish between the default intensity of the $LIBOR$ panel and the default intensity of specific bank initially within the panel. We will also apply a common rate for the panel of $EONIA$ banks, but since the only credit risk component that we model is related to the risk of rolling over in the overnight market, we do not need a model for the risk that a bank leaves the panel. In the empirical part Filipović and Trolle (2013) decompose the $LIBOR - OIS$ spread into a credit component and a non-default component where the non-default component is given as the residual spread after identifying credit risk through CDS spreads. Our goal is to try to identify the liquidity risk directly using interbank spreads on secured term loans.

In Acharya and Skeie (2011) banks hoard liquidity because of their own rollover risk. The key insight is that banks' willingness to provide term lending depends on their own ability to roll over debt. When unsecured markets break down, secured markets take over as an important means of obtaining liquidity. The combination of pressure from banks seeking to obtain liquidity through repo markets combined with banks' reluctance to give up liquidity leads to upward pressure on repo rates. According to Hördahl and King (2008), this was particularly true in Europe and the UK which did not experience the same degree of collateral shortage as did the US market.

There have been several empirical papers investigating interbank market spreads. The $LIBOR-OIS$ spread is attributed to be mostly credit risk driven by Taylor and Williams (2009). In contrast to this McAndrew, Sarkar, and Wang (2008), Michaud and Upper (2008) and Schwarz (2014) attribute most of the spread to liquidity risk. The literature has therefore yet to arrive at a consensus on whether it is liquidity or counterparty credit risk that is most responsible for the $LIBOR-OIS$ spread. Dubecq et al. (2014) propose a quadratic term structure model for decomposing credit and liquidity risk in the $EURIBOR-OIS$ spread. Heider and Hoerova (2009) propose a theoretical model explaining the decoupling between secured and unsecured interbank rates.

Gorton and Metrick (2012) includes the spread between repo rates and OIS rates in their analysis regressing the change of the spread between repo rates and OIS rates on the change of the spread between $LIBOR$ and OIS rates. They have also other control variables but the change of the $LIBOR-OIS$ spread is the only significant variable. They attribute the $LIBOR-OIS$ spread to be mostly a proxy of counterparty risk. In contrast to this paper they thus argue that most of the dynamics of the repo-OIS spread can be explained by counterparty default risk. In contrast, Mancini, Ranaldo, and Wrampelmeyer (2015) document a great resilience of the European repo market during the crisis, and Boissel et al. (2015) find little evidence of an effect of GC collateral credit quality and GC repo rates.

II.2. The Model

To highlight the distinction between spreads due to illiquidity and spreads due to credit risk, it is useful to first describe two different ways in which a bank can obtain a fixed

interest rate loan in in the interbank market over a period of time, say one year. One strategy is to borrow for one year at an unsecured interbank rate which we think of as the $EURIBOR$ rate. A second strategy consists of two parts. One part is to borrow overnight in the interbank market and rolling over the loan every day for a year, and the second part is to enter into a 1-yr $EONIA$ swap (i.e., an OIS contract) as a fixed rate payer. In the second strategy, the amount cumulated in the overnight account will exactly cancel the receiving leg from the floating payment on the OIS, and the net result is a rate of interest equal to the 1-yr OIS rate. Both strategies, therefore, result in a one year loan with a fixed rate, provided that the positions are not liquidated early or that a counterparty is hit by a credit event.

Before the crisis, there was low credit risk and ample liquidity, and therefore the identical pay-offs of the two strategies was enough to keep the $EURIBOR$ rate and the OIS very close together. But the crisis highlighted two important differences between the trading strategies underlying the pay-offs. Credit risk in the $EURIBOR$ loan is higher than in the rolled-over overnight loan, because the $EURIBOR$ loan is given to a fixed counterparty whose credit quality may decline during the life of the contract. The roll-over strategy allows for the lender to change the bank to which it lends on a daily basis thus ensuring a refreshed credit quality of the borrower. Liquidity risk is different in the two strategies as well in that the $EURIBOR$-lender gives up liquidity for the full duration of the loan and the $EURIBOR$-borrower obtains liquidity for the full duration of the loan, whereas in the overnight strategy, the lender may experience a liquidity dry-up which means he can not roll the loan. Our paper focuses on how much the lender is willing to pay in order to compensate for this risk.

If we were to measure the premium for obtaining liquidity that are reflected in $EURIBOR$ rates, we would ideally look for a secured term loan with no credit risk, which gives up liquidity for the duration of the loan, and a swap rate whose underlying rate is an overnight-rate with no credit risk. This would make credit risk irrelevant for both strategies and we could measure cleanly what the required compensation is for obtaining liquidity[1]. We do not have data for such contracts, but we argue that that $EUREPO$ rates are secured rates that do

[1]Note that we are assuming no counterparty risk in the OIS contract. This is a reasonable assumption due to the very limited effect of counterparty risk on swap rates between banks with netting agreements and symmetric credit risk.

give the borrower liquidity for the full duration of the loan. We also argue that the credit risk component of the OIS rates can be estimated reasonably well, and we can therefore adjust OIS rates downward to obtain a rate that is similar to a rate on a default-free term funding where liquidity is not obtain for the full duration of the loan.

Our modeling framework is that of affine credit risk models which combine standard term structure models with intensity-based models of default and liquidity shocks. For a textbook treatment of this framework, see for example Lando (2004). The essential features of the framework are as follows: Given the dynamics under a risk-neutral pricing measure Q of a short rate process r, the time t price price of a riskless zero-coupon bond paying 1 at the maturity date T is given as

$$p(t,T) = E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T r(s)\mathrm{d}s\right)\right]$$

and with affine dynamics for the short rate we have a representation on the exponential-affine form

$$p(t,T) = \exp\left[A_r(T-t) + B_r(T-t)r_t + B_\gamma(T-t)\gamma_t\right]$$

where the functions A_r and B_r have closed-form solutions. The affine setting is extended to also cover a bond which promises to pay 1 also at a maturity date T but whose actual payment may be diminished due to a shock which could be a default event of the issuer or a liquidity-related event forcing a fire-sale. If the shock has an arrival intensity λ and this results in an immediate reduction of the price by a constant factor w with $0 \leq w < 1$, then the price of this risky bond can be represented in the form

$$v(t,T) = E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T r(s) + w\lambda(s)\mathrm{d}s\right)\right]$$

and with affine dynamics of λ this expression also has an exponential-affine form. In his paper, we use this form to represent the extra interest rate that is added to a term loan because of its liquidity being smaller than a cash position. We cannot separate the components w and λ and we therefore collapse them into one factor η which represents the liquidity adjustment.

We now present the dynamics of all the relevant rates and how they determine prices. The explicit closed-form expressions for prices are given in the Appendix. We use a four-factor model to capture the dynamics of the riskless rate, overnight credit risk and the liquidity discount. Two factors are used to model the risk free rate r and its stochastic mean reversion level γ. The third factor Λ models the recovery-adjusted default intensity on an overnight loan, i.e., the credit spread in $EONIA$ rates. We think of this as an average rate for the banks that are part of the $EONIA$ panel. Our fourth factor η captures the addition to the interest rate on a secured term loan which comes from the combined pressure from liquidity hoarding banks to borrow through the repo market and the reluctance of banks to give up cash liquidity also because of liquidity hoarding. We imagine that the lender may have a small cost of converting an existing term repo loan into cash either because it is costly to settle the repo prematurely, or because the reverse repo may add to risk-weighted assets of the bank and is therefore costly for a bank that is constrained in its capital during a crisis period.

The dynamics for the different factors are as follows. For the short rate we use a Gaussian model with a stochastic mean reversion level as defined by the following SDE's

$$\mathrm{d}r_t = \kappa_r \left(\gamma_t - r_t\right) \mathrm{d}t + \sigma_r \mathrm{d}W_r(t) \tag{II.1}$$

$$\mathrm{d}\gamma_t = \kappa_\gamma \left(\theta_\gamma - \gamma_t\right) \mathrm{d}t + \sigma_\gamma \mathrm{d}W_\gamma(t) \tag{II.2}$$

where W_i for $i \in \{r, \gamma\}$ is a standard Brownian motion. The long run mean of r is given by θ_γ. The reason for using this model for the short rate is its analytical tractability and flexibility. The stochastic mean reversion level is important for capturing the large changes in the level of the short rate which occur in the sample period, and the Gaussian specification is better at capturing a realistic level of volatility of the riskless rate when the rate is close to zero. Furthermore, it allows us to have negative interest rates which has been observed in markets for riskless borrowing. The risk-free rate enters directly into the pricing of all the rates that we observe, but in our estimation we do not use rates that depend on the risk-free rate only.

The recovery-adjusted default intensity for the overnight rate Λ is given by a CIR process

$$\mathrm{d}\Lambda(t) = \kappa_\Lambda(\theta_\Lambda - \Lambda(t))\mathrm{d}t + \sigma_\Lambda\sqrt{\Lambda(t)}\mathrm{d}W_\Lambda(t), \qquad \Lambda(0) = \Lambda_0 \tag{II.3}$$

Recall that this is also thought of as the average recovery-adjusted default intensity of the panel banks at time t. Finally, the dynamics for the liquidity discount is given as

$$\mathrm{d}\eta(t) = \kappa_\eta(\theta_\eta - \eta(t))\mathrm{d}t + \sigma_\eta\sqrt{\eta(t)}\mathrm{d}W_\eta(t), \qquad \eta(0) = \eta_0 \tag{II.4}$$

Using these dynamics, we now turn to pricing the relevant bonds and loans that define the rates we observe. An overnight index swap (OIS) consists of an exchange between a fixed rate and a floating rate. In practice, the floating rate is calculated as the compounded overnight rate over the maturity of the swap. For analytical tractability, we approximate this rate with the continuous compounding counterpart

$$\bar{L}(t,T) = \frac{1}{T-t}\left(\frac{1}{E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T r_{ois}(s)\mathrm{d}s\right)\right]} - 1\right)$$

where we let r_{ois} rate be the sum of the riskless rate and the overnight credit spread

$$r_{ois}(t) = \lim_{T\to t} L(t,T) = r(t) + \Lambda(t)$$

We assume that overnight rates are not subject to any liquidity risk, i.e., the banks do not demand a premium for giving up liquidity in the overnight market.

There is only one payment for an OIS with maturity equal to or less than a year. The OIS rate that makes the swap with maturity date T have 0 value at the inception date t is then given by setting the value of the fixed leg equal to the value of the floating leg

$$(T-t)OIS(t,T)P_{OIS}(t,T) = 1 - P_{OIS}(t,T)$$

which gives us

$$OIS(t,T) = \frac{1}{T-t}\left[\frac{1}{P_{OIS}(t,T)} - 1\right]$$

where $P_{OIS}(t,T)$ is given by

$$P_{OIS}(t,T) = E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T (r(s)+\Lambda(s))\mathrm{d}s\right)\right]$$

We will use term repos to represent loans that have no credit risk, but do command a premium for giving up liquidity. The time t value of a secured loan with notional 1 and maturity T will be

$$P_D(t,T) = E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T (r(s)+\eta(s))\,\mathrm{d}s\right)\right] \tag{II.5}$$

and the corresponding rate is thus

$$L_D(t,T) = \frac{1}{T-t}\left(\frac{1}{P_D(t,T)} - 1\right) \tag{II.6}$$

The rate in (II.6) only differs from the riskless rate because of the liquidity hoarding premium which implies that the lender obtains a spread on the repo rate for giving up and providing the borrower with cash liquidity.

Note that the spread between the repo rate and the OIS can be computed as

$$L_D(t,T) - OIS(t,T) = \frac{1}{T-t}\left[\frac{1}{P_D(t,T)} - \frac{1}{P_{OIS}(t,T)}\right]. \tag{II.7}$$

This spread will depend on overnight credit risk Λ and on the liquidity cost $\omega\eta$. If the liquidity compensation is large, the repo rate may become larger than the OIS rate despite the fact that the repo rate is a rate on a secured loan and the OIS is unsecured (albeit over short periods). When the OIS rate is larger, it is a sign that the overnight default intensity dominates the liquidity hoarding motive. It is this separation which is our key contribution.

It would of course be ideal to have an OIS contract where the reference rate in the floating leg was default-free, such as an overnight repo rate. This would give us a term-loan rate (the OIS swap rate) with no default risk and no illiquidity component. While such contracts do exist, we have not been able to find data on prices. Another possibility would be to use interest rates on German government bonds, but here the special nature of treasury securities becomes an additional issue. In our empirical section, we will introduce so-called $EURONIA$ rates to try and estimate a default-free version of OIS rates.

Since we are using the time-series dynamics of all rates, we need to also specify the dynamics under the physical measure, and this is done by specifying market prices of risk as

$$\Gamma(t) = \left(\Gamma_r, \Gamma_\gamma, \frac{\Gamma_\Lambda}{\sigma_\Lambda}\sqrt{\Lambda_t}, \frac{\Gamma_\eta}{\sigma_\eta}\sqrt{\eta_t}\right)$$

II.3. Data

We use four different types of interest rates, some with several maturities, to estimate the four factors of the model. The rates are $EUREPO$, $EONIA$, $EURONIA$, and OIS which we now describe in turn.

The repo rates are the $EUREPO$ rates published by the EMMI - the European Money Market Institute which also publishes the $EURIBOR$ rates. Formerly, both $EUREPO$ and $EURIBOR$ were published by the EBF (The European Banking Federation) but after June 20 2014 the responsibility of publishing the rates was transferred to EMMI. From the end of 2014 the $EUREPO$ has been discontinued. The $EUREPO$ rate was meant to measure the rates of secured money market transactions in the Euro zone. The construction of the $EUREPO$ rate is similar to the $EURIBOR$ rate. A panel of banks operating in the Euro zone submit quotes for the rate:

> *at which, at 11.00 a.m. Brussels time, one bank offers, in the euro-zone and worldwide, funds in euro to another bank if in exchange the former receives from the latter the best collateral within the most actively traded European repo market.*[2]

The collateral must be government guaranteed bonds or bills from one of the Euro zone countries. It is general collateral in the sense that there is not a particular bond which must be pledged as collateral. The $EUREPO$ rate should therefore not be driven by the demand for a particular government bond.

The quotes from the panel banks are collected and trimmed such that the highest and lowest 15% of the quotes are eliminated. The trimming procedure is meant to help prevent outliers from having too much influence on the fixing. As seen with the $LIBOR$ and

[2] from www.emmi-benchmarks.eu

$EURIBOR$ trials, banks may have colluded their quotes and the final fixing may thus not be an accurate representation of the borrowing cost in the interbank market. This is also a potential issue with $EUREPO$. To our knowledge, there have not yet been any incidents where the $EUREPO$ fixing has been questioned. For our purpose the biggest issue would be if the $EUREPO$ fixing was either too high or too low on a systematic basis. During the height of the financial crisis the allegations against the $LIBOR$ was that it was too low. The banks could have an incentive to submit low quotes in order to convey to the market that they did not have any funding problems. The same logic would apply to $EURIBOR$ and $EUREPO$ even though the questions for these two fixings are slightly different. Here the submitted quote should reflect an average panel banks funding cost and not necessarily the funding cost of the bank which submits the quote. The last panel for $EUREPO$ consisted of 9 banks all from the Euro zone and all the panel banks are also part of the current panel for $EONIA$ and $EURIBOR$.

$EONIA$ (Euro OverNight Index Average) is an overnight rate calculated on actual loans which have been transferred using the Trans-European Automated Real-Time Gross-Settlement Express Transfer System (TARGET). Each day, the panel banks report the weighted average overnight lending rate together with the total volume conducted for loans through TARGET to the ECB. Then the ECB calculates the total value weighted overnight rate and makes the rate public. The panel currently consists of 35 banks which for most of them are large banks from the Euro zone, but also banks from outside of the Euro zone are part of the panel.

In order to estimate the overnight credit risk in unsecured interbank loans we use the spread between $EONIA$ and $EURONIA$. The $EURONIA$ rate is also an overnight unsecured rate for loans brokered in London by members of the Wholesale Market Brokers' Association. The contributing banks for $EURONIA$ are generally regarded as having a higher credit worthiness and the spread between $EONIA$ and $EURONIA$ is then a measure of credit risk in the overnight market. According to Bech and Monnet (2013) the spread between $EONIA$ and $EURONIA$ is used by market analysts as a measure of overnight credit risk.

Finally, we use rates on $EONIA$ swaps, which we refer to as OIS (overnight-index swaps) rates. These data are from Bloomberg. These are composite quotes that Bloomberg

collects from major banks and inter-dealer brokers. We also get the $EUREPO$, $EONIA$ and $EURONIA$ fixings from Bloomberg.

II.4. Estimation

We use daily quotes of the 3, 6, 9 and 12 month maturity $EUREPO$ and OIS rates in order to estimate the model and our sample starts on January 5, 2005 and ends on October 15, 2014. We thus cover the pre-crisis period as well as the crisis period. Table XV shows summary statistics of the data.

We have 4 latent state variables, and for notational convenience we collect the state variables in the 4-dimensional vector X:

$$\mathrm{d}X_t = \begin{pmatrix} \mathrm{d}r_t \\ \mathrm{d}\gamma_t \\ \mathrm{d}\Lambda_t \\ \mathrm{d}\eta_t \end{pmatrix} = \begin{pmatrix} \kappa_r\left(\gamma_t - r_t\right)\mathrm{d}t + \sigma_r \mathrm{d}W_r \\ \kappa_\gamma\left(\theta_\gamma - \gamma_t\right)\mathrm{d}t + \sigma_\gamma \mathrm{d}W_\gamma \\ \kappa_\Lambda(\theta_\Lambda - \Lambda_t)\mathrm{d}t + \sigma_\Lambda\sqrt{\Lambda_t}\mathrm{d}W_\Lambda \\ \kappa_\eta(\theta_\eta - \eta_t)\mathrm{d}t + \sigma_\eta\sqrt{\eta_t}\mathrm{d}W_\eta \end{pmatrix}$$

The spread between $EONIA$ and $EURONIA$, $EUREPO$ rates and OIS rates are functions of X and the parameter vector Θ a but our observed values are subject to a measurement error, i.e.,

$$\begin{pmatrix} EONIA_t - EURONIA_t \\ OIS_t \\ EUREPO_t \end{pmatrix} = Z_t = h(X_t;\Theta) + u_t \qquad u_t \sim N\left(0,\Sigma\right)$$

Here Z_t is 9-dimensional because of the 4 OIS and $EUREPO$ maturities. We assume that the measurement errors are cross-sectionally uncorrelated and that they have the same variance i.e. Σ is a diagonal matrix with σ^2_{err} on the diagonal.

To implement a quasi-maximum likelihood procedure, we approximate the transitions of X with a normal density such that we have

$$X_t = \Phi_0 + \Phi_X X_{t-1} + w_t \qquad w_t \sim N(0, Q_t)$$

The first and second moments of the approximating normal distribution are computed in closed form in Appendix II.7.2, which also contains additional details on the estimation procedure.

II.5. Empirical Results

Table XVI displays our parameter estimates with standard errors in parenthesis. Column I displays the estimates from an unrestricted estimation. In this estimation, there are relatively large standard errors on the estimates of the mean reversion levels and the risk premia. As a robustness check we carry out the estimation in a restricted model in which all parameters that have a t-statistic with an absolute value below 1 are set to zero. The remaining parameters do not change much from the unrestricted estimation. We are primarily interested in the process η that represents the illiquidity premium, and Figure II.9 shows the difference between the estimated values of η using the unrestricted and the restricted model. We note that η has a longer period initially where it is essentially zero, but that its behavior around and during the crises periods is roughly the same using the two specifications.

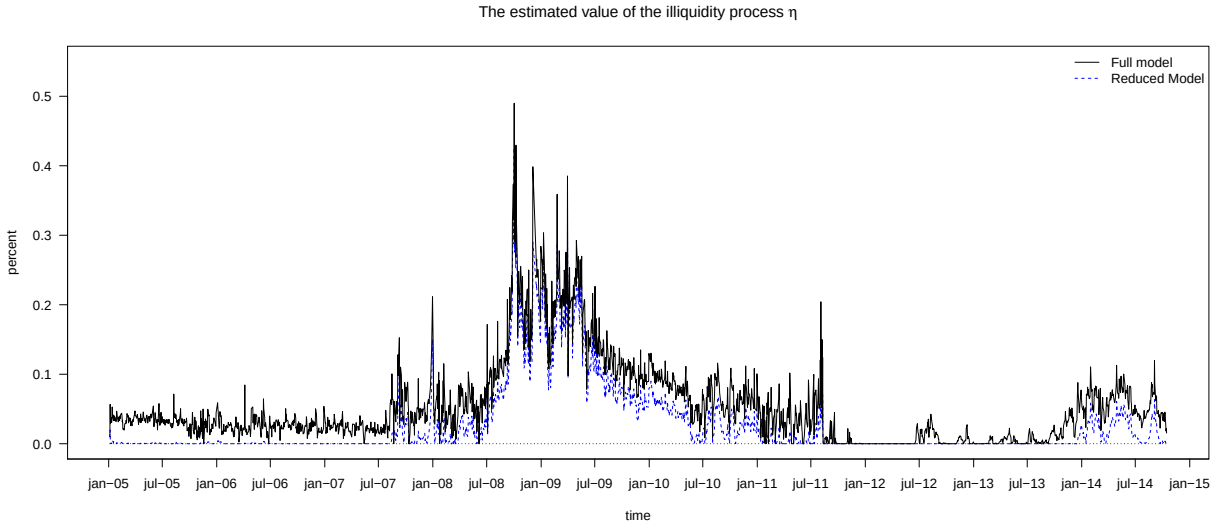

Figure II.9: *Plot of η_t between January 2005 and October 2014 using two different sets of parameters: One set obtained from an unrestricted estimation of the full model and one set of parameters obtained from a reduced specification in which all parameters from the unrestricted estimation with an absolute value of the t-statistic below 1 have been set to 0.*

We therefore continue with the unrestricted model and turn to the liquidity risk factor η and the overnight credit risk process Λ. Recall that η controls the difference in repo rates

and riskless rates that can be attributed to a liquidity impact of lending on repo as opposed to keeping the cash. In Figure II.10 we see that before the crisis η is very close to 0 but it has a sharp increase after the bankruptcy of Lehman Brothers. This is also where the peak of the process is reached. This is consistent with the reluctance to give up liquidity in the aftermath of the Lehman Brothers collapse. Note that it does not reach the same level at any point after this - not even during the European debt crisis.

In Figure II.10 we have highlighted different events during our sample period together with our estimated process for η. The most pronounced effects of ECB interventions seem to be associated with the Securities Market Programme (SMP) announcements on May 10, 2010 and Aug 7, 2011. The first of these announcements explicitly had the goal "to ensure depth and liquidity in those market segments which are dysfunctional", and it involved ECB purchasing Greek, Irish and Portuguese government bonds. The programme expanded after Aug 7, 2011 to include Italian and Spanish bonds. De Pooter et al. (2013) find large announcement effects of the SMP programme and conclude that the main effect of the programme on bond yields was through a confidence channel. To the extent that SMP has indeed built confidence it is plausible that it has lowered the incentive to hoard liquidity.

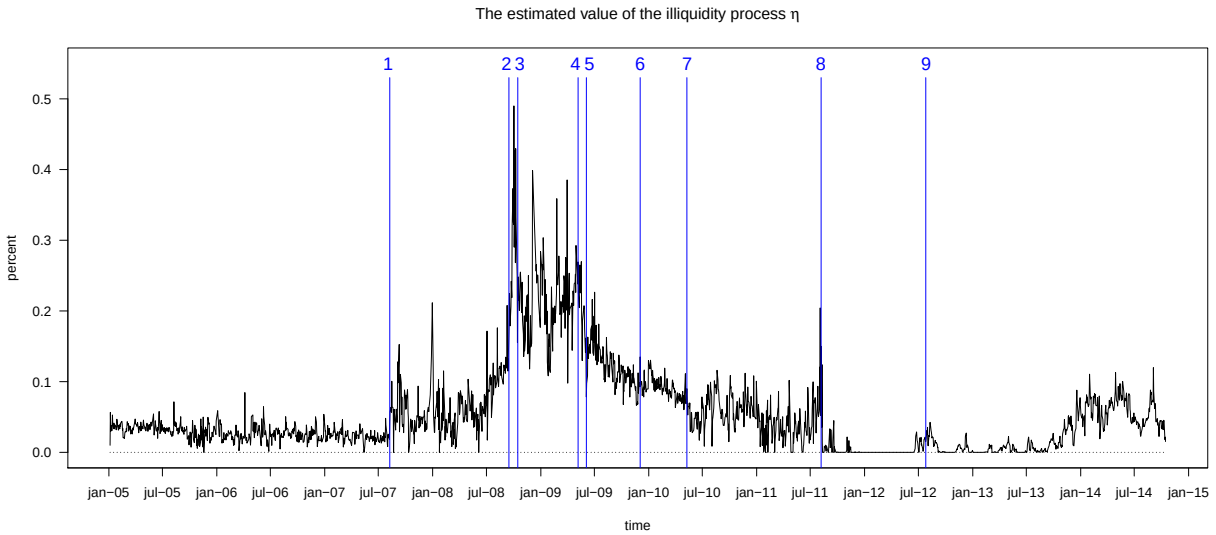

Figure II.10: *Plot of η_t between January 2005 and October 2014. The vertical lines represent different events. From left to right we have: 1) August 9th 2007, the beginning of the financial crisis marked by the date where BNP Paribas freeze three of their funds. 2) September 15th 2008, the default of Lehman Brothers. 3) October 15th 2008, expansion of the list of eligible collateral in the Eurosystem. 4) May 7th 2009, longer-term refinancing operations (LTRO) with maturity of 1 year. 5) June 4th 2009, purchase programme for covered bonds. 6) December 3rd 2009, announcement that the main refinancing operations will continue as fixed rate full allotment as long as needed. 7) May 10th 2010, announcement of the securities market programme (SMP). 8) August 7th 2011, ECB statement that it will "actively implement" its SMP programme after a 4-month pause. 9) July 26th 2012, Draghi's speech "whatever it takes".*

Since the process η which governs the reluctance to give up liquidity is the only factor

that distinguishes the $EUREPO$ rate from the riskless rate, we can obtain an estimate of the part of the $EUREPO$ rate that is due to funding liquidity risk. In Figure II.11 we have used our estimated dynamics for the riskless rate and its mean reversion level (shown in the appendix) to calculate the 1 year risk free rate and compared it with the observed $EUREPO$ rate.

We are interested in the difference between the $EUREPO$ rate and the estimated riskless rate since this gives us an estimate of the increase in $EUREPO$ rates that comes from liquidity hoarding. The spread between the *observed* $EUREPO$ rate and the estimated riskless rate is shown in Figure II.11, and the difference between our *estimated* $EUREPO$ rate and the estimated riskless rate is shown in Figure II.12. The estimated spread and the observed spread are very close, and it makes no difference which of the two graphs we use for our discussion of the behavior of the liquidity spread. For most of the time the observed $EUREPO$ and the model implied risk free rate are very close to each other and the spread therefore close to zero. After the onset of the financial crisis the liquidity component spikes up and reaches its peak of 30 basis points just after the collapse of Lehman. In late 2011 the spread falls close to 0 again until 2014 where we again begin to see some movement and there again seems to be some liquidity risk in the $EUREPO$ rate.

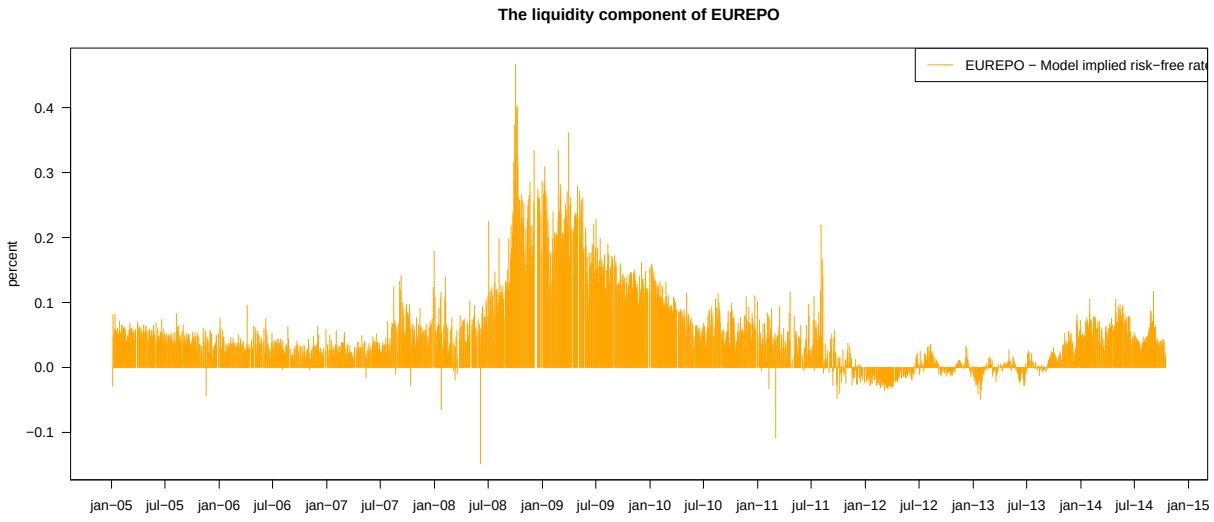

Figure II.11: *The observed 1 year EUREPO rate minus the model implied 1 year risk free rate i.e. the model implied 1 year rate without liquidity and credit risk. This rate is calculated using the dynamics for r and γ given in Figure II.20 and II.21 and the parameter estimates in Tabel XVI*

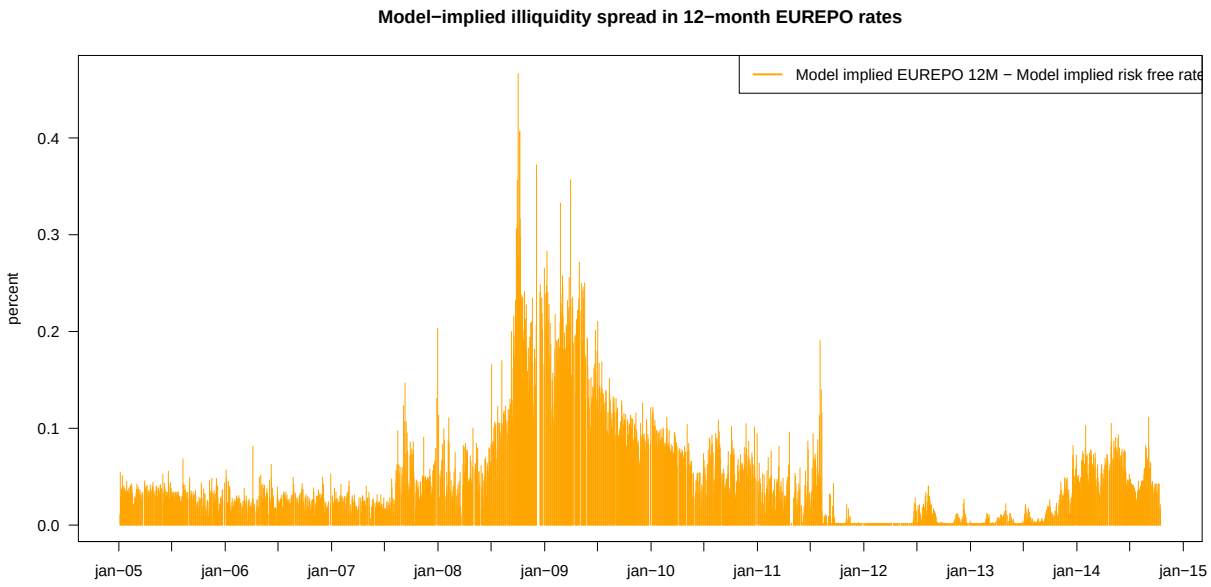

Figure II.12: *The model-implied 1-year EUREPO rate minus the model implied 1-year risk free rate. This rate is calculated using the dynamics for r and γ given in Figure II.20 and II.21 and the parameter estimates in Tabel XVI*

We now turn to our process Λ which measures the recovery-adjusted default intensity of borrowers in the $EONIA$ panel. Consistent with the perception of interbank lending being almost riskless before the crisis, Λ is very close to 0 before the crisis. It shows signs of increases in the summer of 2007 when the initial warnings of a crisis start to appear, and it then shoots up drastically after the bankruptcy filing of Lehman Brothers. It remains elevated compared to pre-crisis levels, even as we move away in time after the Lehman collapse. It then increases again as the European debt crisis worsens. So while the ECB measures seem to lower the illiquidity premium, the fear of bank defaults shoots up again. Around the summer of 2012, Λ begins its decline back towards a lower level but still clearly different from zero. The decline coincides with famous Drahgi statement that *"Within our mandate, the ECB is ready to do whatever it takes to preserve the euro. And believe me, it will be enough."* The liquidity risk factor η was already low when Draghi made this statement ass seen in Figure II.10.

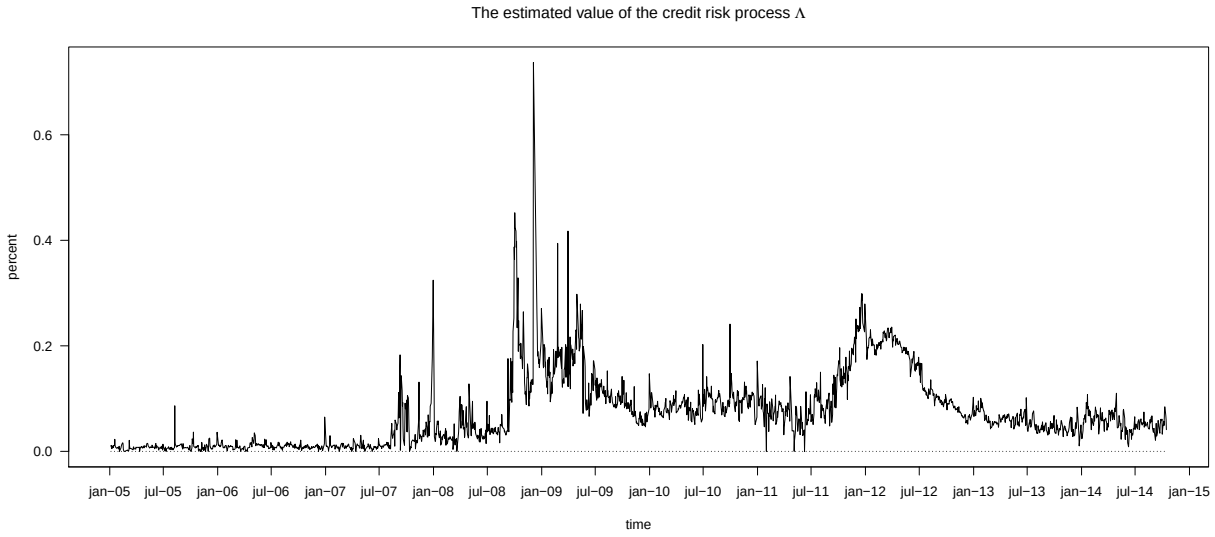

Figure II.13: *Plot of Λ_t estimated through a Kalman filter where we use the 3, 6, 9 and 12 month EUREPO and OIS rates together with the spread between EONIA and EURONIA. The parameter estimates for the dynamics of Λ are given in Table XVI.*

OIS rates include a compensation for the risk embodied in the recovery-adjusted default intensity. This is because the fixed-rate payment in an OIS swap reflects current and anticipated levels of overnight-default risk embedded in the $EONIA$ rates. We can therefore follow the same procedure as above and analyze the difference between OIS rates and the model-implied riskless rate. In Figure II.14 we graph the levels of the observed 1-yr OIS rate and our estimated riskless rate and in II.16 we have shown the spread between the two. From II.16 we see that credit risk makes up around 20 basis points of the 1 year OIS rate at the peak. Before the crisis it is a very small part of the rate. From mid 2011 to mid 2012 the part due to credit risk is high again and accounts for around 20 basis points of the OIS rate, i.e., it is comparable to the level experienced around the collapse of Lehman. Of course, due to the very low level of OIS rates, credit risk accounts for a much larger fraction of the total OIS rate at this point. We also show in Figure II.16 the difference between our *estimated* 1-year OIS rate and the 1-year risklee rate based on the values of our state-variables and the parameter estimates obtained using the Kalman flter. Because of a close model fit, there is very little difference between using the observed or the estimated OIS-rates.

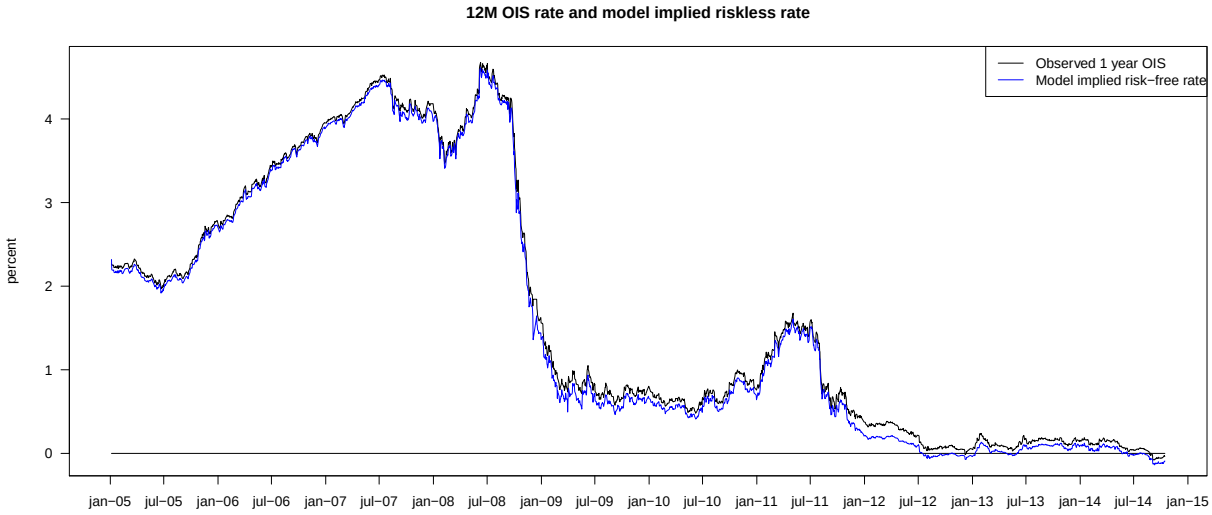

Figure II.14: *The observed 1 year OIS rate and the model implied 1-year risk free rate. The risk-free 1-year rate is calculated using the estimated values for r and γ shown in Figure II.20 and II.21, and the parameter estimates in Tabel XVI.*

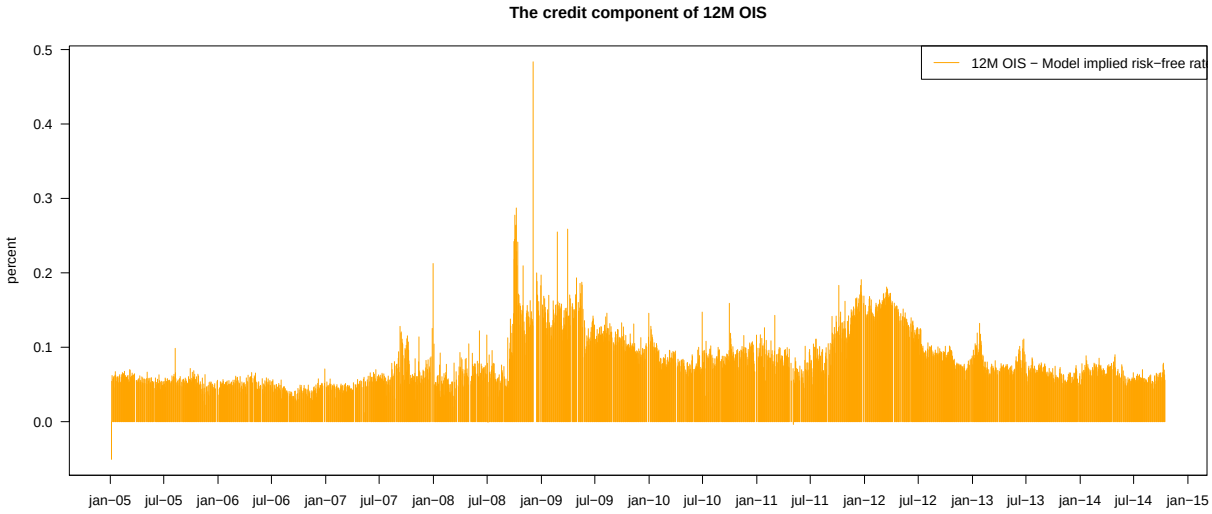

Figure II.15: *The observed 1 year OIS rate minus the model implied 1-year risk free rate. The risk-free 1-year rate is calculated using the estimated values for r and γ shown in Figure II.20 and II.21, and the parameter estimates in Tabel XVI.*

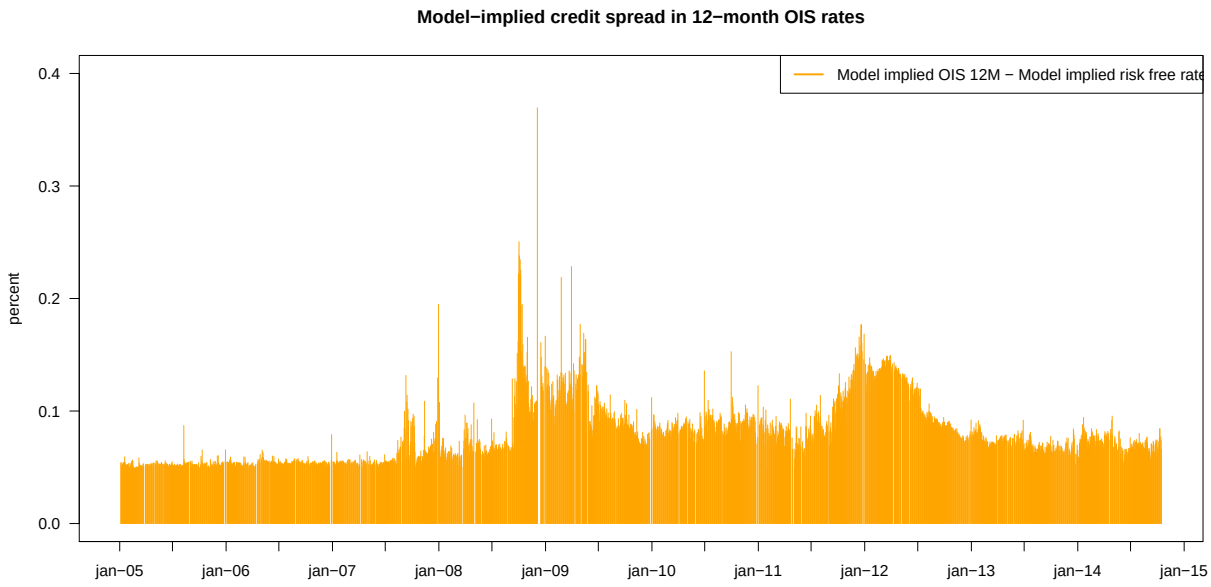

Figure II.16: *The model-implied 1-year OIS rate minus the model implied 1-year risk free rate. This rate is calculated using the dynamics for r and γ given in Figure II.20 and II.21 and the parameter estimates in Tabel XVI*

Until now, our focus has been on $EUREPO$ rates because we wanted a direct measure of funding liquidity risk, i.e., a measure that is not obtained as a residual after having cleaned out credit risk. But is our measure capable of capturing part of the $EURIBOR - OIS$ spread which is a more closely followed measure of stress in the interbank market? Figure II.17 shows the 1-yr $EURIBOR - OIS$ spread which also peaks around the Lehman crisis and during the European sovereign crisis.

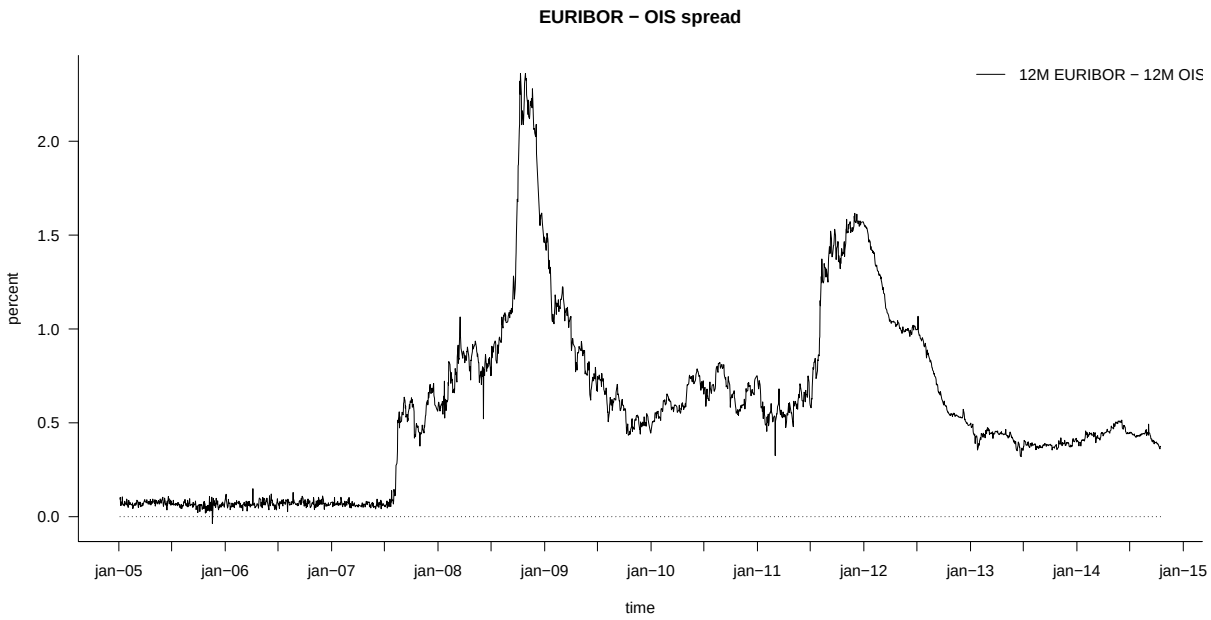

Figure II.17: *12-month EURIBOR - OIS spread.*

We suspect that a significant part of the $EURIBOR-OIS$ spread comes from credit risk because the 1-year $EURIBOR$ loan is a loan made to a fixed counterparty whose credit risk may increase during the time of the loan, whereas the overnight $EONIA$ rate that underlies the OIS contract is based on a panel of banks which would leave out a bank experiencing a severe drop in credit quality. But can some of the spread also be attributed to our illiquidity measure? To investigate this, we perform regressions of the $EURIBOR - OIS$ spread on our measure of illiquidity. We perform two regressions one in which we regress on our illiquidity measure η only, and one in which we control for credit risk in the banking sector using the iTraxx Senior Financials Index. This index is based on CDS contracts referencing senior debt of 25 European financial institutions with liquidly traded CDS contracts. We do not include our overnight default risk factor Λ in the regression since it has essentially been subtracted on the left-hand side in the $EURIBOR - OIS$ spread already. Standard tests for stationarity of all the series involved show significant non-stationarity, and we therefore work with differenced series throughout. Also, because of the clear evidence of different regimes in our sample, we perform rolling regressions in which our parameter estimates are based on 200 daily observations preceding the estimation date. We consider the period between events 1 and 8 in our event window of Figure II.10 because our estimate for η becomes essentially zero after event 8. This means that, except for a few brief periods, we

are unable to attribute any part of the $EURIBOR - OIS$ spreads after the second SMP announcement in August 2011 to illiquidity. Summing up, at each date t between June 2008 (which is 200 days after the Bear Sterns announcements in August 2007) and August 2011, we perform two rolling regressions:

$$\Delta(EURIBOR - OIS)_s = \beta_0(t) + \beta_1(t)\Delta\eta_s + \epsilon_s \text{ for } s = t - 200, \ldots, t \quad \text{(II.8)}$$

$$\Delta(EURIBOR - OIS)_s = \beta_0(t) + \beta_1(t)\Delta\eta_s + \beta_2(t)\Delta iTraxx_s + \epsilon_s \text{ for } s = t - 200, \ldots, t. \quad \text{(II.9)}$$

In Figure II.18 we show the time series of the regression coefficient $\beta_1(t)$ in the univariate regression II.8 and in Figure II.19 we show the time series of our regression coefficient $\beta_1(t)$ in the regression II.9 where we control with the iTraxx index. In both figures we show 95% confidence bands, revealing that our illiquidity measure is significantly different from zero throughout the estimation period.

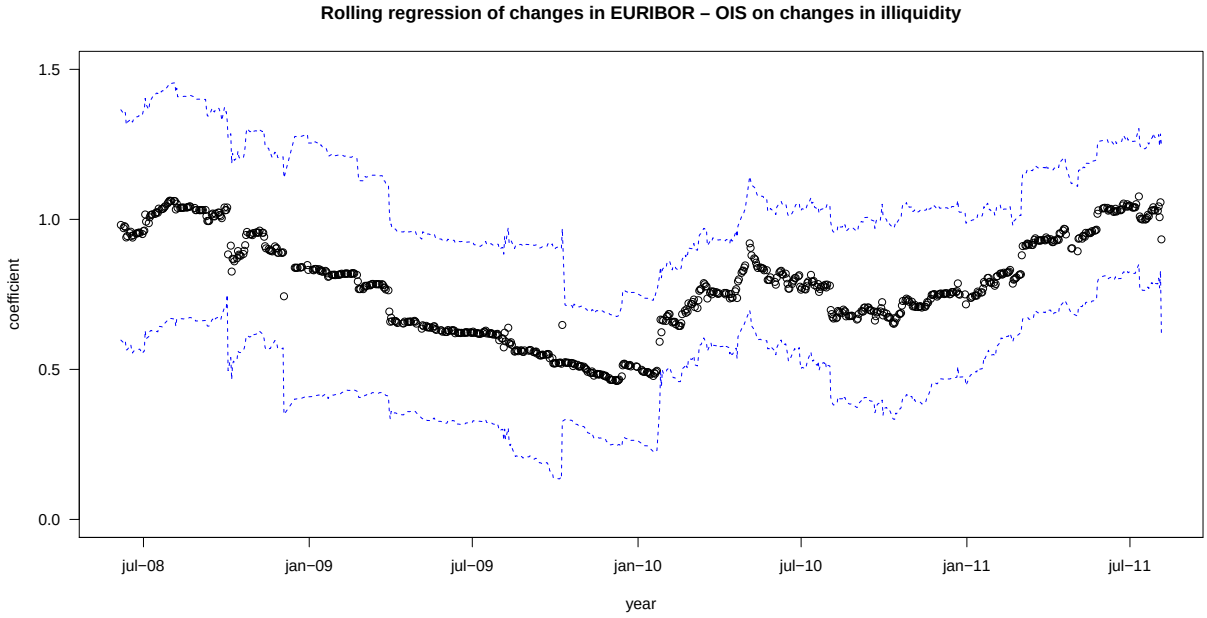

Figure II.18: *The black dots are a time series of the regression coefficient $\beta_1(t)$ estimated from the following rolling regression: $\Delta(EURIBOR - OIS)_s = \beta_0(t) + \beta_1(t)\Delta\eta_s + \epsilon_s$ for $s = t - 200, \ldots, t$. i.e we are regressing the differenced series of the difference between EURIBOR and OIS on the differenced series of our estimated measure of illiquidity using a 200-day window. The blue lines represent 95% confidence bands.*

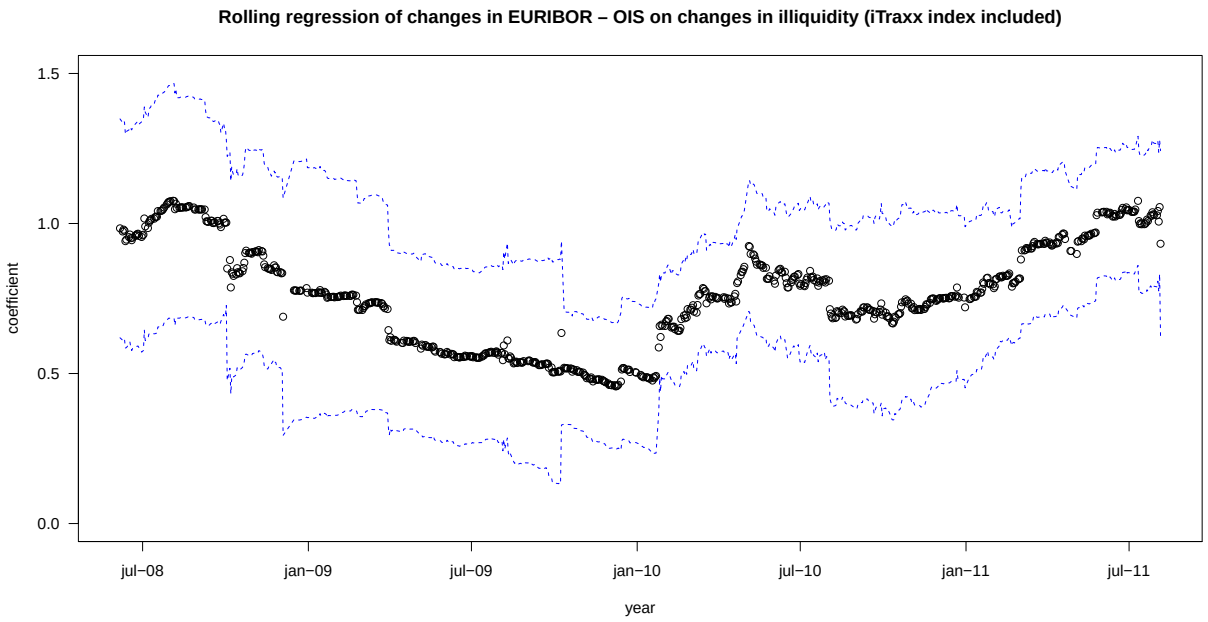

Figure II.19: *The black dots are a time series of the regression coefficient $\beta_1(t)$ estimated from the following rolling regression: $\Delta(EURIBOR - OIS)_s = \beta_0(t) + \beta_1(t)\Delta\eta_s + \beta_2(t)\Delta iTraxx_s + \epsilon_s$ for $s = t - 200, \ldots, t$. i.e we are regressing the differenced series of the difference between $EURIBOR$ and OIS on the differenced series of our estimated measure of illiquidity and the differenced series of the iTraxx Senior Financials Index using a 200-day window. The blue lines represent 95% confidence bands.*

Intuitively, one might have expected the effect of liquidity hoarding on repo rates to be significantly smaller in $EUREPO$ rates than in the unsecured term rates, such as $EURIBOR$, simply because the collateral in the repo contract helps alleviate a liquidity shock to the lender. We had therefore expected our regression coefficient to be larger than one. In our regressions, it is consistently between 0.5 and 1, and hence the size of the illiquidity spread in $EURIBOR$ rates is similar to the spread estimated from $EUREPO$-rates. This would be consistent with a situation in which the use of collateral for rehypothecation in case of a liquidity shock is difficult because of an increased capital requirement. When rehypothecation causes the bank's balance sheet to grow, it has implications for capital, and this means that even a collateralized repo loan is not liquid despite the liquid collateral.

II.6. Conclusion

In this paper we have used rates on $EUREPO$ loans to identify a component of interbank rates which represents reluctance to give up cash ('liquidity hoarding'). The most clear evidence of the existence of a liquidity component is periods in which rates on secured (repo) loans (which have no credit risk) exceed $EONIA$ swap rates. These swap rates

contain a compensation for credit risk arising from credit risk in the overnight rates that define the floating leg of the swap. We rely on a model that incorporates both credit risk in overnight loans and liquidity risk in interbank rates which is able to capture the positive spread between $EUREPO$ and OIS. We find that liquidity risk was a significant part of the secured term rates just after the collapse of Lehman Brothers. The liquidity risk then slowly decreases throughout the crisis. In the first stage of the crisis, both credit and illiquidity risk affect interbank rates, but in the second part associated with the European sovereign debt crisis, only credit risk seems to play a role. This is consistent with the large liquidity-enhancing programme (SMP) carried out by the ECB. We finally consider to what extend our illiquidity measure explains $EURIBOR - OIS$ spreads by performing rolling regressions of $EURUIBOR - OIS$ on our measure. We find that the illiquidity component in $EURIBOR - OIS$ is of the same order of magnitude as the one we have estimated in $EUREPO - OIS$ spreads. This indicates that the lender of cash in repos is being compensated for the liquidity provision.

II.7. Appendix

II.7.1. Prices and rates

For the OIS rate we want to evaluate

$$E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T (r(s)+\Lambda(s))\mathrm{d}s\right)\right] = E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T r(s)\mathrm{d}s\right)\right] E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T \Lambda(s))\mathrm{d}s\right)\right]$$

where we have used the assumption that r and Λ are independent. Both factors on the right-hand side are exponentially affine. The simplest expression is the second factor which is a standard CIR specification under the real-world $\mathbb{P}$-measure. With our definition of the market price of risk the $\mathbb{Q}-$dynamics becomes

$$\begin{aligned}\mathrm{d}\Lambda(t) =& \kappa_\Lambda\left(\theta_\Lambda - \Lambda(t)\right)\mathrm{d}t + \sigma_\Lambda\sqrt{\Lambda(t)}\left(\mathrm{d}W^{\mathbb{Q}}(t) - \Gamma_\Lambda\sqrt{\Lambda(t)}\mathrm{d}t\right)\\ =& \left(\kappa_\Lambda + \sigma_\Lambda\Gamma_\Lambda\right)\left(\frac{\kappa_\Lambda\theta_\Lambda}{\kappa_\Lambda+\sigma_\Lambda\Gamma_\Lambda} - \Lambda(t)\right)\mathrm{d}t + \sigma_\Lambda\sqrt{\Lambda(t)}\mathrm{d}W^{\mathbb{Q}}(t)\end{aligned}$$

The zero-coupon bond price is affine and has the following form according to formula (3.25) in Brigo and Mercurio (2007)

$$E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T \Lambda(s))\mathrm{d}s\right)\right] = \exp[A_\Lambda(T-t) + B_\Lambda(T-t)\Lambda(t)] \tag{II.10}$$

where A_Λ and B_Λ are given by

$$\begin{aligned}A_\Lambda(T-t) &= \frac{2\kappa_\Lambda\theta_\Lambda}{\sigma_\Lambda^2}\log\left[\frac{2\gamma_\Lambda e^{(\kappa_\Lambda+\sigma_\Lambda\Gamma_\Lambda+\gamma_\Lambda)\frac{(T-t)}{2}}}{2\gamma_\Lambda + \left(\kappa_\Lambda+\sigma_\Lambda\Gamma_\Lambda+\gamma_\Lambda\right)\left(1-e^{\gamma_\Lambda(T-t)}\right)}\right]\\ B_\Lambda(T-t) &= \frac{-2\left(1-e^{\gamma_\Lambda(T-t)}\right)}{2\gamma_\Lambda + \left(\kappa_\Lambda+\sigma_\Lambda\Gamma_\Lambda+\gamma_\Lambda\right)\left(1-e^{\gamma_\Lambda(T-t)}\right)}\end{aligned}$$

and

$$\gamma_\Lambda = \sqrt{(\kappa_\Lambda+\sigma_\Lambda\Gamma_\Lambda)^2 + 2\sigma_\Lambda^2}$$

Note that expression for the repo loan is of the exact same form as the OIS loan, i.e.,

$$P_D(t,T) = E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T (r(s)+\eta(s))\,\mathrm{d}s\right)\right]$$

where η here is the liquidity adjustment. Again, we use the fact that r and η are independent such that we can split the expectation and the expression for the term involving η is of the same for as that involving Λ above.

Discounting with the riskless rate is a bit more involved. We still have the affine form, but the stochastic mean-reversion level complicates things. We assume that the market price of risk is given by Γ_r and Γ_γ. Thus, under the pricing measure Q the dynamics of the interest rate process and the mean reversion level are:

$$\begin{aligned}
\mathrm{d}r_t =& \kappa_r\left(\gamma_t - r_t\right)\mathrm{d}t - \sigma_r\Gamma_r\mathrm{d}t + \sigma_r\mathrm{d}W_r^{\mathbb{Q}}(t)\\
\mathrm{d}\gamma_t =& \kappa_\gamma\left(\theta_\gamma - \gamma_t\right)\mathrm{d}t - \sigma_\gamma\Gamma_\gamma\mathrm{d}t + \sigma_\gamma\mathrm{d}W_\gamma^{\mathbb{Q}}(t)
\end{aligned}$$

To obtain the solution

$$E_t^{\mathbb{Q}}\left[\exp\left(-\int_t^T r(s)\mathrm{d}s\right)\right] = \exp\left[A_r(T-t) + B_r(T-t)r_t + B_\gamma(T-t)\gamma_t\right]$$

we follow Lund (1998). The ODE system characterizing A_r, B_r and B_γ is

$$\begin{aligned}
A_r'(T-t) =& \frac{1}{2}\sigma_r^2 B_r^2(T-t) + \frac{1}{2}\sigma_\gamma^2 + \rho\sigma_r\sigma_\gamma B_r(T-t)B_\gamma(T-t) - \Gamma_r\sigma_r B_r(T-t)\\
&+ (\kappa_\gamma\theta_\gamma - \Gamma_\gamma\sigma_\gamma)B_\gamma(T-t)\\
B_r'(T-t) =& -\kappa_r B_r(T-t) - 1\\
B_\gamma'(T-t) =& \kappa_r B_r(T-t) - \kappa_\gamma B_\gamma(T-t)
\end{aligned}$$

with the boundary conditions $A_r(0) = 0$, $B_r(0) = 0$ and $B_\gamma(0) = 0$. Solving the ODE

system yields the following expressions for A_r, B_r and B_γ

$$
\begin{aligned}
A_r(\tau) =& \frac{1}{4}\frac{-4}{(-\kappa_\gamma+\kappa_r)^2(\kappa_\gamma+\kappa_r)\kappa_\gamma{}^3\kappa_r{}^3}\Big\{\kappa_r{}^3\kappa_\gamma{}^2(\kappa_r(\rho\sigma_r-\sigma_\gamma)-\rho\sigma_r\kappa_\gamma)\sigma_\gamma e^{-\tau(\kappa_\gamma+\kappa_r)} \\
&+4\kappa_\gamma{}^2(-\kappa_\gamma+\kappa_r)(\kappa_\gamma+\kappa_r)\left[\left(\theta_\gamma\kappa_r{}^2-\sigma_r\Gamma_r\kappa_r-\sigma_r{}^2\right)\kappa_\gamma{}^2+\left[(-\sigma_\gamma\Gamma_\gamma+\Gamma_r\sigma_r)\kappa_r{}^2\right.\right. \\
&\left.\left.+\left(-2\sigma_r\sigma_\gamma\rho+\sigma_r{}^2\right)\kappa_r\right]\kappa_\gamma+\kappa_r{}^2\sigma_\gamma(\rho\sigma_r-\sigma_\gamma)\right]e^{-\kappa_r\tau} \\
&+4\left(-\theta_\gamma\kappa_r\kappa_\gamma{}^2+\sigma_\gamma(\rho\sigma_r+\kappa_r\Gamma_\gamma)\kappa_\gamma+\sigma_\gamma{}^2\kappa_r\right)\kappa_r{}^3(-\kappa_\gamma+\kappa_r)(\kappa_\gamma+\kappa_r)\mathrm{e}^{-\kappa_\gamma\tau} \\
&+2\kappa_\gamma{}^3\left(-\frac{1}{2}\sigma_r{}^2\kappa_\gamma{}^2-\kappa_r\sigma_r(\rho\sigma_\gamma-\sigma_r)\kappa_\gamma+\kappa_r{}^2\left(\sigma_r\sigma_\gamma\rho-\frac{1}{2}\sigma_r{}^2-\frac{1}{2}\sigma_\gamma{}^2\right)\right)(\kappa_\gamma+\kappa_r)\mathrm{e}^{-2\kappa_r\tau} \\
&-\kappa_r{}^5\sigma_\gamma{}^2(\kappa_\gamma+\kappa_r)\mathrm{e}^{-2\kappa_\gamma\tau} \\
&+4(-\kappa_\gamma+\kappa_r)^2\left[\left(-\tau\kappa_r{}^3\theta_\gamma+(\tau\Gamma_r\sigma_r+\theta_\gamma)\kappa_r{}^2+\left(\frac{1}{2}\tau\sigma_r{}^2-\Gamma_r\sigma_r\right)\kappa_r-\frac{3}{4}\sigma_r{}^2\right)\kappa_\gamma{}^4\right. \\
&+\left[-\tau\kappa_r{}^3\theta_\gamma+(\tau\Gamma_\gamma\sigma_\gamma+\tau\Gamma_r\sigma_r+2\theta_\gamma)\kappa_r{}^2+\left((\tau\rho\sigma_r-\Gamma_\gamma)\sigma_\gamma+\frac{1}{2}\tau\sigma_r{}^2-\Gamma_r\sigma_r\right)\kappa_r\right. \\
&\left.-\frac{3}{2}\left(\rho\sigma_\gamma+\frac{\sigma_r}{2}\right)\sigma_r\right]\kappa_r\kappa_\gamma{}^3+\kappa_r{}^2\left[(\tau\Gamma_\gamma\sigma_\gamma+\theta_\gamma)\kappa_r{}^2+\sigma_\gamma\left(\tau\rho\sigma_r+\frac{1}{2}\tau\sigma_\gamma-2\Gamma_\gamma\right)\kappa_r\right. \\
&\left.\left.-\frac{3}{4}\sigma_\gamma{}^2-2\sigma_r\sigma_\gamma\rho\right]\kappa_\gamma{}^2+\frac{1}{2}\kappa_r{}^3\left((\tau\sigma_\gamma-2\Gamma_\gamma)\kappa_r-2\rho\sigma_r-\frac{5}{2}\sigma_\gamma\right)\sigma_\gamma\kappa_\gamma-\frac{3}{4}\kappa_r{}^4\sigma_\gamma{}^2\right]\Big\}
\end{aligned}
$$

$$
B_r(\tau) = \frac{e^{\kappa_r\tau}-1}{\kappa_r}
$$

$$
B_\gamma(\tau) = \frac{e^{-\kappa_\gamma\tau}-1}{\kappa_\gamma}-\frac{e^{\kappa_r\tau}-e^{\kappa_\gamma\tau}}{\kappa_r-\kappa_\gamma}
$$

II.7.2. Kalman Filter

The dynamics of our model are given as

$$
\mathrm{d}X_t = \begin{pmatrix} \mathrm{d}r_t \\ \mathrm{d}\gamma_t \\ \mathrm{d}\Lambda_t \\ \mathrm{d}\eta_t \end{pmatrix} = \begin{pmatrix} \kappa_r(\gamma_t-r_t)\,\mathrm{d}t+\sigma_r\mathrm{d}W_r \\ \kappa_\gamma(\theta_\gamma-\gamma_t)\,\mathrm{d}t+\sigma_\gamma\mathrm{d}W_\gamma \\ \kappa_\Lambda(\theta_\Lambda-\Lambda_t)\mathrm{d}t+\sigma_\Lambda\sqrt{\Lambda_t}\mathrm{d}W_\Lambda \\ \kappa_\eta(\theta_\eta-\eta_t)\mathrm{d}t+\sigma_\eta\sqrt{\eta_t}\mathrm{d}W_\eta \end{pmatrix}
$$

and to use the Kalman filter, we approximate the transitions of X with a conditional normal density such that we have

$$X_t = \Phi_0 + \Phi_X X_{t-1} + w_t \qquad w_t \sim N(0, Q_t).$$

The conditional means and variances captured by the parameters Φ_0, Φ_X and Q_t are as follows.:

$$\begin{aligned}
\Phi_0^i &= \theta_i(1 - e^{-\kappa_i \Delta t}) \\
\Phi_X^{[i,i]} &= e^{-\kappa_i \Delta t} \\
Q_t^{[i,i]} &= X_{t-1}^i \frac{\sigma_i^2}{\kappa_i}\left(e^{-\kappa_i \Delta t} - e^{-2\kappa_i \Delta t}\right) + \frac{\theta_i \sigma_i^2}{2\kappa_i}\left(1 - e^{-\kappa_i \Delta t}\right)^2 \qquad \text{for } i = \{\Lambda, \eta\}.
\end{aligned}$$

These are standard results when we have CIR dynamics see Brigo and Mercurio (2007). For r and γ we have

$$\begin{aligned}
\Phi_0^r &= \theta_\gamma + \kappa_r \frac{\theta_\gamma}{\kappa_r - \kappa_\gamma} \exp(-\kappa_\gamma t) + \frac{-\kappa_\gamma \theta_\gamma}{\kappa_\gamma - \kappa_r} \exp(-\kappa_r t) \\
\Phi_0^\gamma &= \theta_\gamma \left(1 - \exp\left(-\kappa_\gamma t\right)\right) \\
\Phi_X^{[r,r]} &= \exp(-\kappa_r t) \\
\Phi_X^{[r,\gamma]} &= \frac{\kappa_r}{\kappa_r - \kappa_\gamma} \exp(-\kappa_\gamma t) + \frac{\kappa_r}{\kappa_\gamma - \kappa_r} \exp(-\kappa_r t) \\
\Phi_X^{[\gamma,\gamma]} &= \exp(-\kappa_\gamma t)
\end{aligned}$$

and

$$\begin{aligned}
Q_t^{[r,r]} &= \frac{1}{2} \frac{\left(1 - e^{-2\kappa_r t}\right) \sigma_r^2 - 4\rho\kappa_r\sigma_\gamma \left(1 - e^{-2\kappa_r t}\right)}{\kappa_r} \\
Q_t^{[\gamma,\gamma]} &= \frac{1}{2} \frac{{\sigma_\gamma}^2 \left(-\mathrm{e}^{-2\,\kappa_\gamma\, t} + 1\right)}{\kappa_\gamma}
\end{aligned}$$

These results are derived in II.7.2.

We now follow the extended Kalman filter setup given in Harvey (1990) and Lund (1995).

The prediction step is

$$\begin{aligned}\hat{X}_{t|t-1} =& \Phi_0 + \Phi_X \hat{X}_{t-1} \\ P_{t|t-1} =& \Phi_X P_{t-1} \Phi_X^\top + Q_t\end{aligned}$$

Where we use the conditional moments of X and the normality approximation.
We then set $\hat{Z}_{t|t-1}$ and F_t to

$$\begin{aligned}\hat{Z}_{t|t-1} =& h(\hat{X}_{t|t-1}; \Theta) \\ F_t =& H_t P_{t|t-1} H_t^\top + \Sigma\end{aligned}$$

where H_t is given by

$$H_t = \left.\frac{\partial h}{\partial X}\right|_{\hat{X}_{t|t-1}}$$

and Σ is the measurement errors. Which we assume to be cross-sectional uncorrelated and having the same variance σ_{err}^2 such that Σ is a diagonal matrix with σ_{err}^2 on the diagonal.
The update step then becomes

$$\begin{aligned}\hat{X}_t =& \hat{X}_{t|t-1} + W_t(Z_t - \hat{Z}_{t|t-1}) \\ P_t =& \left(P_{t|t-1}^{-1} + H_t^\top \Sigma^{-1} H_t\right)^{-1}\end{aligned}$$

where

$$W_t = P_{t|t-1} H_t^\top F_t^{-1}$$

With $\hat{Z}_{t|t-1}$ and F_t we can construct the log likelihood function

$$\mathcal{L}(\Theta) = -\frac{1}{2}\sum_{t=1}^{T}\left(n\log(2\pi) + \log|F_t| + \left(Z_t - \hat{Z}_{t|t-1}\right)^\top F_t^{-1}\left(Z_t - \hat{Z}_{t|t-1}\right)\right)$$

where T is the number of observation dates and n is the number of observations at each

date. The maximum likelihood estimator $\hat{\Theta}_{\text{ML}}$ is given as

$$\hat{\Theta}_{\text{ML}} = \arg \min_{\Theta} \mathcal{L}(\Theta)$$

The number of parameters in Θ is 16.

$$\Theta = \{\kappa_r, \kappa_\gamma, \kappa_\Lambda, \kappa_\eta, \theta_\gamma, \theta_\Lambda, \theta_\eta, \sigma_r, \sigma_\gamma, \sigma_\Lambda, \sigma_\eta, \sigma_{err}, \Gamma_r, \Gamma_\gamma, \Gamma_\Lambda, \Gamma_\eta\}$$

To get the asymptotic standard errors of the parameter estimates we follow Harvey (1990) such that a consistent estimator of the information matrix is given by

$$\hat{I}_{ij}(\Theta) = \frac{1}{T}\left\{\frac{1}{2}\sum_{t=1}^{T} \text{tr}\left(F_t^{-1}\frac{\partial F_t}{\partial \Theta_i}F_t^{-1}\frac{\partial F_t}{\partial \Theta_j}\right) + \sum_{t=1}^{T}\left(\frac{\partial v_t}{\partial \Theta_i}\right)^\top F_t^{-1}\frac{\partial v_t}{\partial \Theta_j}\right\} \qquad i,j = 1,...,16$$

where

$$\frac{\partial F_t}{\partial \Theta_i} = \frac{\partial H_t}{\partial \Theta_i}P_{t|t-1}H_t^\top + H_t\frac{\partial P_{t|t-1}}{\partial \Theta_i}H_t^\top + H_t P_{t|t-1}\left(\frac{\partial H_t}{\partial \Theta_i}\right)^\top + \frac{\partial \Omega}{\partial \Theta_i}$$

$$\frac{\partial v_t}{\partial \Theta_i} = - H_t\frac{\partial \hat{X}_{t|t-1}}{\partial \Theta_i} - \frac{\partial H_t}{\partial \Theta_i}$$

$$\frac{\partial \hat{X}_{t|t-1}}{\partial \Theta_i} = \frac{\partial \Phi_0}{\partial \Theta_i} + \frac{\partial \Phi_X}{\partial \Theta_i}\hat{X}_{t-1} + \Phi_X\frac{\partial \hat{X}_{t-1}}{\partial \Theta_i}$$

$$\frac{\partial P_{t|t-1}}{\partial \Theta_i} = \frac{\partial \Phi_X}{\partial \Theta_i}P_{t-1}\Phi_X^\top + \Phi_X\frac{\partial P_{t-1}}{\partial \Theta_i}\Phi_X^\top + \Phi_X P_{t-1}\left(\frac{\partial \Phi_x}{\partial \Theta_i}\right)^\top + \frac{\partial Q_t}{\partial \Theta_i}$$

Here H, Φ_0, Φ_X, Ω and Q are all known functions of the parameters in Θ. The derivatives can thus be found in closed form. However, especially the expressions for $\frac{\partial H_t}{\partial \Theta_i}$ are very long and we thus use symbolic derivation in `R` in order to get the formulas. Finally we use the

following recursive formulas for $\frac{\partial \hat{X}_t}{\partial \Theta_i}$ and $\frac{\partial P_t}{\partial \Theta_i}$ found in Harvey (1990)

$$\begin{aligned}\frac{\partial \hat{X}_t}{\partial \Theta_i} =& \frac{\partial \hat{X}_{t|t-1}}{\partial \Theta_i} + \frac{\partial P_{t|t-1}}{\partial \Theta_i} H_t^\top F_t^{-1} v_t + P_{t|t-1} \left(\frac{\partial H_t}{\partial \Theta_i}\right)^\top F_t^{-1} v_t - P_{t|t-1} H_t^\top F_t^{-1} \frac{\partial F_t}{\partial \Theta_i} F_t^{-1} v_t \\ &+ P_{t|t-1} H_t^\top F_t^{-1} \frac{\partial v_t}{\partial \Theta_i}\end{aligned}$$

$$\begin{aligned}\frac{\partial P_t}{\partial \Theta_i} =& \frac{\partial P_{t|t-1}}{\partial \Theta_i} - \frac{\partial P_{t|t-1}}{\partial \Theta_i} H_t^\top F_t^{-1} H_t P_{t|t-1} - P_{t|t-1} \left(\frac{\partial H_t}{\partial \Theta_i}\right)^\top F_t^{-1} H_t P_{t|t-1} \\ &+ P_{t|t-1} H_t^\top F_t^{-1} \frac{\partial F_t}{\partial \Theta_i} F_t^{-1} H_t P_{t|t-1} - P_{t|t-1} H_t^\top F_t^{-1} \frac{\partial H_t}{\partial \Theta_i} P_{t|t-1} - P_{t|t-1} H_t^\top F_t^{-1} H_t \frac{\partial P_{t|t-1}}{\partial \Theta_i}\end{aligned}$$

where we set $\frac{\partial \hat{X}_0}{\partial \Theta_i} = 0$ and $\frac{\partial P_0}{\partial \Theta_i} = 0$.
The asymptotic standard errors are then

$$\mathrm{SE}\left(\hat{\Theta}\right) = \frac{1}{\sqrt{\hat{I}\left(\widehat{\Theta}_{\mathrm{ML}}\right)}}$$

Expectations in the Gaussian Central Tendency Model

We will here calculate the mean and variance when the short rate follows the Gaussian Central Tendency Model. The Gaussian Central Tendency Model (GCTM) consists of the following two SDEs

$$\begin{aligned}\mathrm{d}r_t =& \kappa_r \left(\gamma_t - r_t\right) \mathrm{d}t + \sigma_r \mathrm{d}W_r(t) \\ \mathrm{d}\gamma_t =& \kappa_\gamma \left(\theta_\gamma - \gamma_t\right) \mathrm{d}t + \sigma_\gamma \mathrm{d}W_\gamma(t)\end{aligned}$$

where W_i for $i \in \{r, \gamma\}$ is a standard Brownian motion. The two Brownian motions may be correlated by ρ.
We will first calculate the mean of γ. First we write γ on integral form

$$\gamma_t = \gamma_0 + \int_0^t \kappa_\gamma \left(\theta_\gamma - \gamma_t\right) \mathrm{d}t + \int_0^t \sigma_\gamma \mathrm{d}W_\gamma(t)$$

We take the mean

$$E\left[\gamma_t\right] = \gamma_0 + \int_0^t \kappa_\gamma \left(\theta_\gamma - E\left[\gamma_t\right]\right) \mathrm{d}t$$

Which then leads to the following ODE for the mean of γ

$$m'(t) = \kappa_\gamma \left(\theta_\gamma - m(t)\right) \qquad m(0) = \gamma_0$$

This can be solved such that we get the following expression for $E[\gamma_t]$

$$E\left[\gamma_t\right] = \gamma_0 \exp\left(-\kappa_\gamma t\right) + \theta_\gamma \left(1 - \exp\left(-\kappa_\gamma t\right)\right)$$

With a similar method we can now find the mean of r_t

$$\begin{aligned} r_t =& r_0 + \int_0^t \kappa_r \left(\gamma_t - r_t\right) \mathrm{d}t + \int_0^t \sigma_r \mathrm{d}W_r(t) \\ E[r_t] =& r_0 + \int_0^t \kappa_r \left(E[\gamma_t] - E[r_t]\right) \mathrm{d}t \end{aligned}$$

such that the ODE for $E[r_t]$ becomes

$$h'(t) = \kappa_r \left(m(t) - h(t)\right) \qquad h(0) = r_0$$

$$E\left[r_t\right] = \theta_\gamma + \kappa_r \frac{\left(\gamma_0 - \theta_\gamma\right)}{\kappa_r - \kappa_\gamma} \exp(-\kappa_\gamma t) + \frac{\gamma_0 \kappa_r - \kappa_\gamma \theta_\gamma}{\kappa_\gamma - \kappa_r} \exp(-\kappa_r t) + r_0 \exp(-\kappa_r t)$$

To find the second moment of r_t and γ_t we use Itô to get the dynamics os r_t^2 and γ_t^2

$$\begin{aligned} \mathrm{d}r_t^2 =& 2 r_t \kappa_r \left(\gamma_t - r_t\right) \mathrm{d}t + 2 r_t \sigma_r \mathrm{d}W_t^r + \sigma_r^2 \mathrm{d}t \\ \mathrm{d}\gamma_t^2 =& 2 \gamma_t \kappa_\gamma \left(\theta_\gamma - \gamma_t\right) \mathrm{d}t + 2 \gamma_t \sigma_\gamma \mathrm{d}W_t^\gamma + \sigma_\gamma^2 \mathrm{d}t \end{aligned}$$

and on integral form

$$\begin{aligned} r_t^2 =& r_0^2 + \int_0^t 2r_t\kappa_r\left(\gamma_t - r_t\right)\mathrm{d}t + \int_0^t 2r_t\sigma_r \mathrm{d}W_t^r + \int_0^t \sigma_r^2 \mathrm{d}t \\ \gamma_t^2 =& \gamma_0^2 + \int_0^t 2\gamma_t\kappa_\gamma\left(\theta_\gamma - \gamma_t\right)\mathrm{d}t + \int_0^t 2\gamma_t\sigma_\gamma \mathrm{d}W_t^\gamma + \int_0^t \sigma_\gamma^2 \mathrm{d}t \end{aligned}$$

If we take the mean and again first look at γ_t^2 we get

$$E\left[\gamma_t^2\right] = \gamma_0^2 + 2\kappa_\gamma \int_0^t \left(E[\gamma_t]\theta_\gamma - E\left[\gamma_t^2\right]\right)\mathrm{d}t + \int_0^t \sigma_\gamma^2 \mathrm{d}t$$

$$n'(t) = 2\kappa_\gamma\left(m(t)\theta_\gamma - n(t)\right) + \sigma_\gamma^2$$

and for r_t^2

$$\begin{aligned} E\left[r_t^2\right] =& r_0^2 + 2\kappa_r \int_0^t \left(E[\gamma_t r_t] - E\left[r_t^2\right]\right)\mathrm{d}t + \int_0^t \sigma_r^2 \mathrm{d}t \\ =& r_0^2 + 2\kappa_r \int_0^t \left(E[\gamma_t]E[r_t] - 2\sigma_r\sigma_\gamma\rho - E\left[r_t^2\right]\right)\mathrm{d}t + \int_0^t \sigma_r^2 \mathrm{d}t \end{aligned}$$

$$l'(t) = 2\kappa_r\left(m(t)h(t) - 2\sigma_r\sigma_\gamma\rho - l(t)\right) + \sigma_r^2$$

Solving these two ODEs yield

$$E[\gamma_t^2] = \theta_\gamma^2 + 2(\gamma_0 - \theta_\gamma)\theta_\gamma \exp(-\kappa_\gamma t) + \frac{\sigma_\gamma^2}{2\kappa_\gamma} + \frac{2\gamma_0^2\kappa_\gamma - 4\gamma_0\kappa_\gamma\theta_\gamma + 2\kappa_\gamma\theta_\gamma^2 - \sigma_\gamma^2}{2\kappa_\gamma}\exp(-2\kappa_\gamma t)$$

$$
\begin{aligned}
E\left[r_t^2\right] = & \frac{2}{\left(-\kappa_\gamma+\kappa_r\right)^2\kappa_r}\mathrm{e}^{-2\,\kappa_r\,t}\left[{\kappa_r}^2\theta_\gamma\,\left(-\kappa_\gamma+\kappa_r\right)\left(\gamma_0-\theta_\gamma\right)\mathrm{e}^{t(-\kappa_\gamma+2\,\kappa_r)}\right.\\
& +\frac{1}{2}\,{\kappa_r}^3\left(\gamma_0-\theta_\gamma\right)^2\mathrm{e}^{-2\,t(\kappa_\gamma-\kappa_r)}+\left(\gamma_0-\theta_\gamma\right)\left(\left(r_0-\gamma_0\right)\kappa_r-\kappa_\gamma\,\left(r_0-\theta_\gamma\right)\right){\kappa_r}^2\mathrm{e}^{t(-\kappa_\gamma+\kappa_r)}\\
& -\left(\left(\sigma_\gamma\,\sigma_r\,\rho-\frac{1}{2}\,{\theta_\gamma}^2\right)\kappa_r-\frac{1}{4}\,{\sigma_r}^2\right)\left(-\kappa_\gamma+\kappa_r\right)^2\mathrm{e}^{2\,\kappa_r\,t}\\
& +\theta_\gamma\,\left(\left(r_0-\gamma_0\right)\kappa_r-\kappa_\gamma\,\left(r_0-\theta_\gamma\right)\right)\left(-\kappa_\gamma+\kappa_r\right)\kappa_r\,\mathrm{e}^{\kappa_r\,t}\\
& +\left(\sigma_\gamma\sigma_r\rho+\frac{{r_0}^2}{2}+\frac{{\gamma_0}^2}{2}-r_0\gamma_0\right){\kappa_r}^3+\left(\left(\left(r_0-\gamma_0\right)\theta_\gamma-2\sigma_\gamma\,\sigma_r\rho-{r_0}^2+r_0\gamma_0\right)\kappa_\gamma-\frac{\sigma_r^2}{4}\right)\\
& \left.+\kappa_\gamma\left(\left(-r_0\,\theta_\gamma+\frac{1}{2}{\theta_\gamma}^2+\frac{1}{2}\,{r_0}^2+\sigma_\gamma\,\sigma_r\,\rho\right)\kappa_\gamma+\frac{1}{2}\,{\sigma_r}^2\right)\kappa_r-\frac{1}{4}\,{\kappa_\gamma}^2{\sigma_r}^2\right]
\end{aligned}
$$

Finally the variance of both r_t and γ_t can be found using the first and second moment. Simplification will lead to the following expressions

$$
\begin{aligned}
Var[r_t] = & -\frac{1}{2}\frac{e^{-2\kappa_r t}\left(4e^{2\kappa_r t}\rho\kappa_r\sigma_\gamma-4\rho\kappa_r\sigma_\gamma-e^{2\kappa_r t}\sigma_r+\sigma_r\right)\sigma_r}{\kappa_r}\\
= & \frac{1}{2}\frac{\left(1-e^{-2\kappa_r t}\right)\sigma_r^2-4\rho\kappa_r\sigma_\gamma\left(1-e^{-2\kappa_r t}\right)}{\kappa_r}
\end{aligned}
$$

$$
Var[\gamma_t] = \frac{1}{2}\,\frac{{\sigma_\gamma}^2\left(-\mathrm{e}^{-2\,\kappa_\gamma\,t}+1\right)}{\kappa_\gamma}
$$

II.7.3. Tables

Rate	Min	Max	Mean	Std.
EONIA	-0.045	4.601	1.53	1.48
EURONIA	-0.102	4.462	1.46	1.50
3M EUREPO	-0.063	4.389	1.53	1.53
6M EUREPO	-0.070	4.483	1.57	1.55
9M EUREPO	-0.080	4.601	1.60	1.56
12M EUREPO	-0.080	4.716	1.64	1.57
3M OIS	-0.065	4.350	1.56	1.51
6M OIS	-0.068	4.453	1.59	1.53
9M OIS	-0.075	4.728	1.63	1.54
12M OIS	-0.078	4.677	1.67	1.55

This table shows min, max, mean and standard deviations. Each time series consists of 2416 daily observations from January 5, 2005 to October 15, 2014

Table XV: Summary statistics

Parameter	Model I	Model II
κ_r	0.2706 (0.02366)	0.2709 (0.0339)
κ_γ	1.0233 (0.1024)	1.025 (0.1862)
κ_Λ	2.015 (0.3378)	2.018 (0.0416)
κ_η	0.1722 (0.1265)	0.190 (0.0212)
θ_γ	0.01719 (3.666)	0
θ_Λ	0.000848 (0.001949)	0
θ_η	0.000197 (0.01367)	0
σ_r	0.0390 (0.01969)	0.0392 (0.01849)
σ_γ	0.164 (0.09044)	0.165 (0.1104)
σ_Λ	0.2899 (0.1409)	0.2904 (0.2002)
σ_η	0.1681 (0.07164)	0.168 (0.1547)
σ_{err}	0.000189 (0.00008198)	0.000857 (0.000354)
Γ_r	-0.0251 (0.1301)	0
Γ_γ	-0.0251 (22.75)	0
Γ_Λ	-0.0251 (1.1609)	0
Γ_η	-0.00992 (0.7587)	0

Table XVI: Maximum likelihood estimates. The sample period is January 5th, 2005 to October 15th, 2014. Model I is our main model where all the parameters are unconstrained. In model II we constrain the parameters to 0 where the absolut t-statistic does not exceed 1. Asymptotic standard errors are in the parentheses.

The estimated process for r_t and γ_t are given in Figure II.20 and II.21. We see here how γ_t is quite volatile, especially before and around the default of Lehman. We also have a negative long run mean rate after 2012. This is consistent with the very low rates observed in this period.

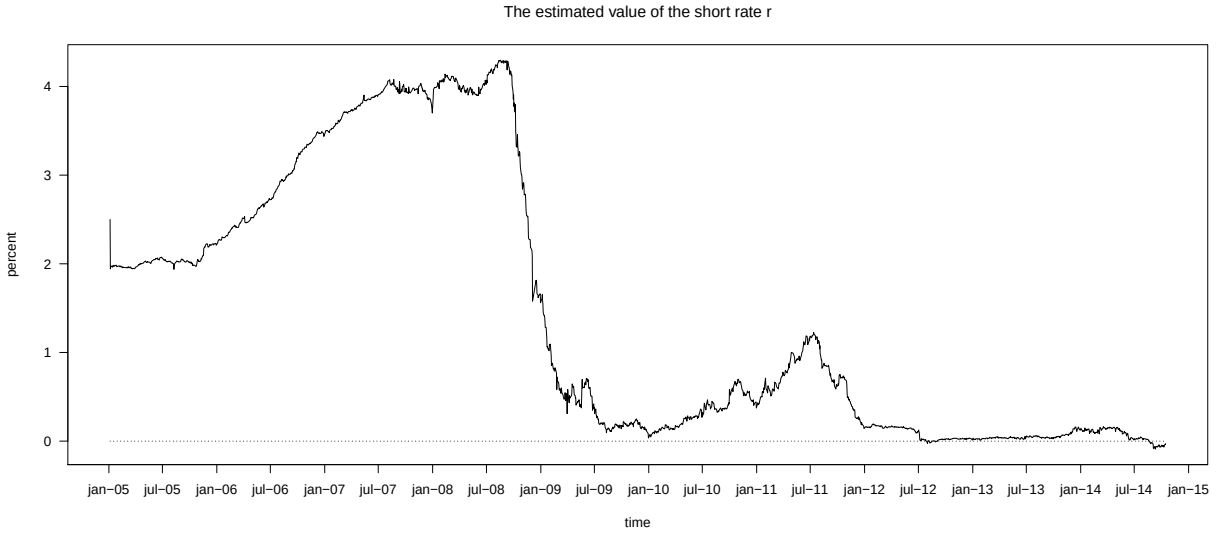

Figure II.20: *Plot of r_t estimated through a Kalman filter where we use the 3, 6, 9 and 12 month EUREPO and OIS rates together with the spread between EONIA and EURONIA. The parameter estimates for the dynamics of r are given in Table XVI.*

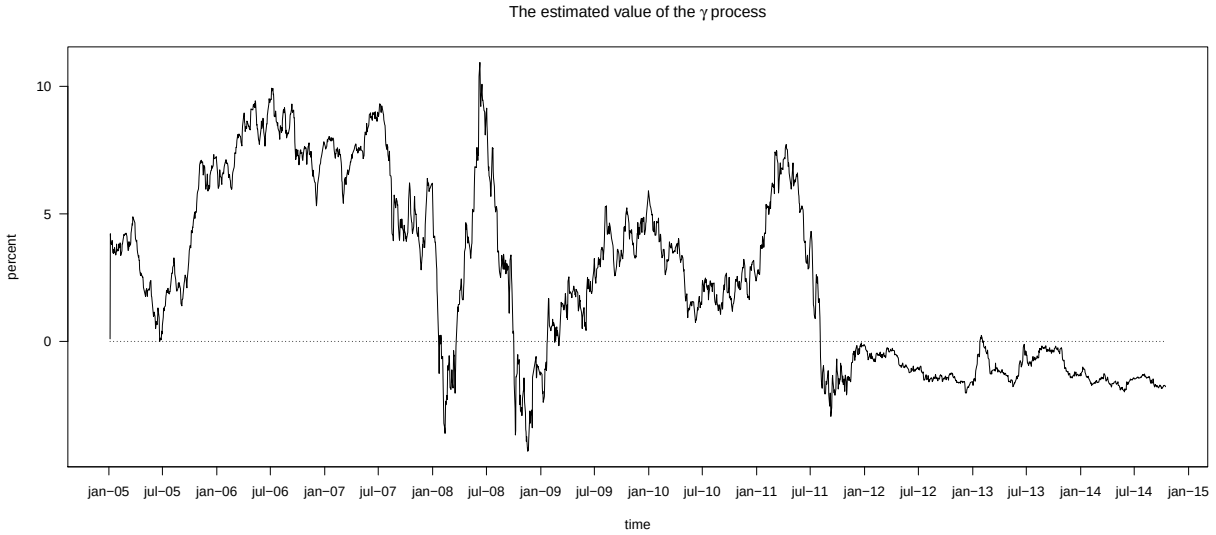

Figure II.21: *Plot of γ_t estimated through a Kalman filter where we use the 3, 6, 9 and 12 month EUREPO and OIS rates together with the spread between EONIA and EURONIA. The parameter estimates for the dynamics of γ are given in Table XVI.*

References

Acharya, Viral V and David Skeie (2011). "A model of liquidity hoarding and term premia in inter-bank markets". In: *Journal of Monetary Economics* 58.5, pp. 436–447.

Bech, M and Cyril Monnet (2013). "The Impact of Unconventional Monetary Policies on the Overnight Interbank Market". In: *Reserve Bank of Australia Conference*.

Boissel, Charles et al. (2015). "Systemic risk in clearing houses: Evidence from the European repo market". In: *Working Paper, HEC Paris*.

Brigo, Damiano and Fabio Mercurio (2007). *Interest rate models-theory and practice: with smile, inflation and credit*. Springer Science & Business Media.

De Pooter, Michiel et al. (2013). "Cheap Talk and the Efficacy of the ECB's Securities Market programme: Did bond purchases matter?" In: *Working paper. Federal Reserve Board*.

Dubecq, Simon et al. (2014). "Credit and liquidity in interbank rates: a quadratic approach". In: *Available at SSRN 2331959*.

Filipović, Damir and Anders B Trolle (2013). "The term structure of interbank risk". In: *Journal of Financial Economics* 109.3, pp. 707–733.

Gorton, Gary and Andrew Metrick (2012). "Securitized banking and the run on repo". In: *Journal of Financial economics* 104.3, pp. 425–451.

Harvey, Andrew C (1990). *Forecasting, structural time series models and the Kalman filter*. Cambridge university press.

Heider, Florian and Marie Hoerova (2009). "Interbank lending, credit risk premia and collateral". In: *International Journal of Central Banking* 4, pp. 5–43.

Hördahl, Peter and Michael King (2008). "Developments in the repo markets during the financial turmoil". In: *BIS Quarterly, December*.

Lando, David (2004). *Credit Risk Modeling - Theory and Applications*. Princeton University Press.

Lund, Jesper (1995). *Econometric analysis of continuous-time: arbitrage-free models of the term structure of interest rates*. Handelshøjskolen i Århus, Institut for informationsbehandling, Anvendt statistik og databehandling.

— (1998). "Review of Continuous-Time Term-Structure Models". In: *working paper*.

Mancini, Loriano, Angelo Ranaldo, and Jan Wrampelmeyer (2015). "The euro interbank repo market". In: *Review of Financial Studies*, doi: 10.1093/rfs/hhv056.

McAndrew, James, Asani Sarkar, and Zhenyu Wang (2008). "The Effect of the Term Auction Facility on the London Inter-Bank Offered Rate". In: *Federal Reserve Bank of New York Staff Reports No. 335*.

Michaud, Franşois-Louis and Christian Upper (2008). "What Drives Interbank Rates? Evidence from the Libor Panel". In: *BIS Quarterly Review, March*.

Schwarz, Krista (2014). "Mind the gap: Disentangling credit and liquidity in risk spreads". In: *Available at SSRN 1486240*.

Taylor, John B and John C Williams (2009). "A Black Swan in the Money Market". In: *American Economic Journal. Macroeconomics* 1.1, p. 58.

How Haircuts Cut the Option Price*

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February, 2016

ABSTRACT

Classical arbitrage free derivatives pricing models assume no collateral, free short selling, and that the underlying asset is not used in a repurchase contract. Recent pricing models have been extended to accommodate the effects of collateralization and short selling constraints. We use a binomial framework to take into account the effect of repo and haircuts. Our main finding is that options can be priced using an adjusted risk-neutral measure where the haircut, the repo rate, and the funding rate enter. We show how symmetric haircuts can create bid-ask spreads for options in the binomial setting, and we derive an explicit formula for this spread.

The model implies an adjustment to the put-call parity if short sell constraints and repurchase opportunities are present, and this is confirmed in the data.

III.1. Introduction

In the seminal paper Black and Scholes (1973) the option prices are found in a continuous time framework by constructing a replicating portfolio using the underlying stock and a bank account. This is also the case in the classic binomial model in Cox, Ross, and Rubinstein (1979). The models derive the value of an option by using the underlying asset and a bank account to form a replicating portfolio i.e., a portfolio that matches the pay-off of the option in all states. The value of the option is the cost of forming the replicating

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portfolio. However, neither of the models capture important frictions which occurs in todays trading environment such as short sell constraints, different funding rates, and collateral posting. In this paper, the frictions we will focus on, are the short sell constraints and different funding rates. In the classic methods the funding mechanism is given by the ability to borrow unsecured through a bank account. This is too simple in a world in which assets can be pledged to obtain funding. In the classic setup we have only one interest rate, namely the risk-free interest rate. Now a growing literature describes how we should adjust the derivative's pricing when we are faced with different funding rates and collateral agreements (see Hull and White (2012)). The nature of these adjustments has proven to be less straightforward than one might think. We attempt to desrcibe the question of different funding rates in a very simple binomial model and we hope that from this simple model we can generate an intuition behind the adjustments.

In this paper we extend the option pricing method in the classic binomial model by including financial frictions modeled by repo agreements of the underlying stock, short selling constraints and different haircuts. We show how these financial frictions alter the price of options, create a modified put-call parity, and induce bid-ask spreads. Because of the binomial setting we are able to get closed form solutions.

The idea behind our approach is to modify the classic model so that a long position in the underlying asset may be used for funding. Piterbarg (2010) and Castagna (2013) show that this changes the option price. They find that in order to get the arbitrage free price, the stock has to grow at the repo rate under the risk neutral measure. We extend this result to include haircuts, i.e. a setting where only a fraction of the value of the underlying asset can be used for funding because of haircuts. We show how different ways of incorporating haircuts will yield different prices and potentially give rise to bid-ask spreads.

First, we show how the results of Piterbarg (2010) and Castagna (2013) can be extended to include haircuts. We implement two different regimes: One with linear haircuts and one with symmetric haircuts. In the symmetric haircut regime we need the same amount of cash to go either long or short in the underlying asset, whereas in the linear case the margin cost is only positive for either a short or a long position. This means that in the linear case long positions can be funded by short positions because the cash needed to go long exactly equals the cash received from going short. It also means that a haircut of 1 will correspond

to no short sell restrictions because it would not cost anything to borrow the underlying asset. These features are prevented by the symmetric haircut. On the positive side the option pricing becomes a lot more simple in the linear case.

For the symmetric case we see how a haircut will create a spread between an option's bid and ask price, and we derive a closed form solution for the spread under constant haircut. This is consistent with Lou (2015), who also derives a bid-ask spread for the option when we have symmetric haircuts in the Black-Scholes framework. With the closed form solution we see how the spread depends on the delta of the option, the spread between the funding and repo rate, and the haircut.

Finally, we show how the put-call parity should be modified in the case of a linear haircut. We test this finding using data on European style options on the S&P 500 Index. Consistent with our theory we observe deviations from the put-call parity. If we focus on the period in 2008 where the SEC implemented a short sell ban on multiple financial stocks, we see an even stronger effect. This is consistent with the findings in Ofek, Richardson, and Whitelaw (2004). Ofek, Richardson, and Whitelaw (2004) investigate the put-call parity when there are short sell restrictions. They document how greater short sell restrictions are associated with larger and more persistent violations of the put-call parity. Ofek, Richardson, and Whitelaw (2004) use American options on single stocks and thus have to correct for the early exercise premium in American options. By using European options on the S&P 500 Index we are able to avoid this issue. We also show how the observed deviation from the put-call parity is positively correlated with the maturity of the options. This is consistent with our theory where the short sell restrictions and repurchase agreements are similar to a positive dividend yield on the underlying asset.

In this paper we model short sell constraints as a requirement to borrow the underlying stock in order to short it. This can be seen as a reverse repo. The repo agreements of the underlying asset and short sell constraints are thus linked. If we have repo agreements, we also have short sell constraints.

Option pricing has come a long way since Black and Scholes (1973) and Merton (1973). It has been documented how several financial frictions affects the option prices. Brenner, Eldor, and Hauser (2001) and Christoffersen et al. (2014) look at transactions cost and Leippold

and Su (2015) and Santa-Clara and Saretto (2009) look at how funding constraints affect the option prices. Bergman (1995), Avellaneda and Lipkin (2009) and Ofek, Richardson, and Whitelaw (2004) all look at pricing models with short sell constraints on the underlying stock. Jensen and Lasse H. Pedersen (2015) document how early exercise of calls on non-dividend paying stocks can be rationalized with short sell constraints, and that early exercise actually occurs. This paper is thus closely related to this litteratur. However, we differ in at least two ways. Firstly, many these papers are set in a continuous-time framework. This allows for an elegant formulation of the problem, but except for very few cases, the resulting equations can only be solved numerically. We use the binomial model to arrive at closed-form solutions which allow for clear comparative statics and intuition. Secondly, we introduce haircuts in the repurchase agreement. In Lou (2015), which is probably the paper most related to ours, haircuts are also introduced. However, we extend this study by including different ways of incorporating haircuts and the ability to get closed-form solutions to the bid-ask spread and the funding value adjustments in the presence of haircuts. This gives theoretical foundation for the empirical results found in Battalio and Schultz (2011). They document how implementation of short sell restrictions in the stock market increased the bid-ask spread for options.

This paper is structured as follows. In section II we describe the frictions and more specifically define how we set the haircut. In section III we derive the main results of the paper. Section IV contains an empirical study using the put-call parity and section V concludes the paper.

III.2. Model and Frictions

The Cox-Ross-Rubinstein binomial model for pricing options (Cox, Ross, and Rubinstein, 1979) has been a workhorse in the financial literature. We will build upon this model to price options in a market where there are short sell costs and repo opportunities when holding the underlying asset.

The basic model is as follows

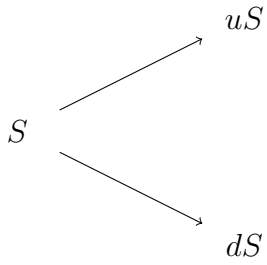

Figure III.22: The dynamics of the underlying asset S

S denotes the underlying asset. In the *up* state S takes the value of uS and in the *down* state S takes the value of dS. Let V_u and V_d be the value of the option contract in the *up* and *down* state, respectively. We have a funding rate r^f and a repo rate r^r. We assume that r^f is both the unsecurred borrowing and lending rate. We will assume $d < 1 + r^r < 1 + r^f < u$. This ordering comes from the fact that r^r is secured by the asset where r^f is the unsecured borrowing and lending rate. The dynamics in Figure III.22 can of course be generalized to multiple periods.

We will now specify how the short sell costs and repo opportunities can be implemented in the model. To do this we will differentiate between a long and a short position in the underlying asset.

In the traditional setting if either the option replicator or hedger has a long position, he is not able to pledge the asset as collateral and get cash back. We will modify this such that he can borrow money using the asset as collateral. The amount of cash he will get from this will then depend on the haircut on the asset. If he has αS worth of the underlying asset he will get $(1 - \omega)\alpha S$ in cash when he borrows against the asset. Here ω is thought to be between 0 and 1 which means that the amount of cash he gets is less than the present value of the position in the underlying asset. At maturity he then gets the pledged assets back and pays back the cash plus interest, where the interest is determined by the repo rate r^r. If r^r is below the funding rate r^f we can intuitively see how this will make it cheaper to have a long position in the stock. This is because the long stock position can be used for funding. The closer the haircut is to 1, the more expensive it becomes to finance the long position since a larger part of the asset has to be funded using r^f. With $\omega = 1$ we are back to the classic case where the asset can not be pledged.

For a short position in the underlying asset the repurchase agreement works a little differently. In the traditional binomial setting the asset could be shorted without any restrictions. In this paper we will assume that in order to enter into a short position, the stock has to be borrowed. This is closer to reality, where there are restrictions on 'naked short selling', which would be to sell the asset without borrowing it in the first place. The question is then, how much cash that needs to be pledged in order to borrow the asset. In this paper, we will look at two different assumptions regarding the amount of cash the stock borrower has to pledge in order to borrow the stock.

In the first setting we assume that borrowing the stock is equivalent to being the opposite part of the transaction in which the stock is used as collateral. In this setup only $(1-\omega)\alpha S$ worth of cash would have to be used in order to borrow αS of the asset. This corresponds to a setting where the borrowing and pledging of collateral is bilateral. In the literature this form of margin is called linear margin constraints. We will see that this linearity will make option pricing simpler. The problem with this setting is that a large portion of stock lending is not bilateral but happens through an intermediary bank like BNY Mellon or State Street according to D'avolio (2002).

In a triparty setting, we have a custodian bank which charges a haircut for lending out the stock. We will therefore also consider a setting in which the stock borrower needs to post a margin in order to borrow the stock. If we let η denote the haircut, the assumption is that when the stock borrower wants to borrow the stock, he would need to pledge $(1+\eta)\alpha S$ in order to borrow αS worth of the stock. If we set $\eta = \omega$, we have a case in which it costs the same margin to go long or short in the underlying asset, and we will refer to this setting as a symmetric haircut setting. This setting is in line with the margin requirements in Garleanu and Lasse Heje Pedersen (2011). In the next section we will price an option in both haircut regimes.

III.3. Pricing options

We will now price options in the binomial model in Figure III.22. At first, we will look at the case of linear margin requirements and derive the adjustment to the price compared to the case with no repurchase opportunities and short selling constraints. After this we

will move on to the case with a symmetric haircut.

Linear case

In the case of linear margin requirements $(1-\omega)\alpha S$ worth of cash can be obtained by pleding αS worth of assets. Therefore $(1-\omega)\alpha S$ worth of cash will be needed to borrow αS worth of the asset in order to short the asset. The intuition is that an option hedger or replicator can position himself as a cash lender, where the collateral must be the asset, if he wants to borrow the asset. In Proposition 1 we will price an option in this setting.

Proposition 1 *Assume a linear margin requirement and let* $0 \leq \omega \leq 1$ *be the haircut on the underlying asset. Let* r^f *denote the funding rate and* r^r *the repo rate where the underlying asset is used as collateral. The option price* V_0 *in the one-period binomial model described in Figure III.22 is then given by*

$$V_0 = \frac{1}{1+r^f} E_0^{\mathbb{Q}^r}\left[V_T\right]$$

where $\mathbb{Q}^r$ *is a probability measure given by* $q^r = \frac{1+r^f-(1-\omega)(r^f-r^r)}{u-d}$

Proof. We form a replicating portfolio consisting of α of the underlying asset and β in the unsecured bank account. The replicating strategy must then satisfy

$$\begin{aligned} \alpha u S + (\beta + (1-\omega)\alpha S)\left(1+r^f\right) - (1-\omega)\alpha S\left(1+r^r\right) &= V_u \\ \alpha d S + (\beta + (1-\omega)\alpha S)\left(1+r^f\right) - (1-\omega)\alpha S\left(1+r^r\right) &= V_d \end{aligned} \tag{III.11}$$

where V_u is the option value in the *up* state and V_d the option value in the down state. Solving these two equations for α and β yields

$$\begin{aligned} \alpha &= \frac{V_u - V_d}{S(u-d)} \\ \beta &= \frac{1}{1+r^f}\frac{uV_d - dV_u - (1-\omega)\left[\left(r^f - r^r\right)(V_u - V_d)\right]}{u-d} \end{aligned} \tag{III.12}$$

We now have a replicating portfolio and the value of this must therefore equal the option price.

$$\begin{aligned} V_0 =& \alpha S + \beta \\ =& \frac{1}{1+r^f}\left[\frac{1+r^f-d-(1-\omega)\left(r^f-r^r\right)}{u-d}V_u + \frac{u-1-r^f+(1-\omega)\left(r^f-r^r\right)}{u-d}V_d\right] \\ =& \frac{1}{1+r^f}E_0^{\mathbb{Q}^r}\left[V_T\right] \end{aligned} \tag{III.13}$$

where $\mathbb{Q}^r$ is given by $q^r = \frac{1+r^f-d-(1-\omega)(r^f-r^r)}{u-d}$ ■

The result in Proposition 1 can be extended to a multi period setting where we have

$$V_t = \frac{1}{(1+r^f)^{T-t}}E_t^{\mathbb{Q}^r}\left[V_T\right] \tag{III.14}$$

In the proof of Proposition 1 we have set up the two equations we must solve in order to replicate the payoff of the option. In these two equations we have two terms which are not present in the traditional derivation. The first term is

$$(1-\omega)\alpha S(1+r^f)$$

This term represents the funding received from pledging the underlying as collateral. If $\alpha > 0$ then αS worth of collateral can be pledged at time 0 and this will provide $(1-\omega)\alpha S$ worth of cash. The cash will grow at the rate r^f and be worth $(1-\omega)\alpha S(1+r^f)$ at time T. The second term

$$-(1-\omega)\alpha S(1+r^r)$$

is then the repaying of the repo contract. Again with $\alpha > 0$ the option hedger or replicator gets $(1-\omega)\alpha S$ worth of cash at time 0 and will then have to pay $(1-\omega)\alpha S(1+r^r)$ back at time T.

There are two things to note from Proposition 1. Firstly, in the proof we did not specify the payoff of the option in the up or the down state. The proof thus also works, if a call has

been bought and a hedger wants to go short the stock. Secondly, we see how similar the result in Proposition 1 is to the standard option pricing. The only thing that has changed is what risk-neutral measure to use. If we set $\omega = 0$, i.e. we have no haircut, we see that instead of the funding rate r^f it is the repo rate r^r which enters the probability measure. This result is identical to the continuous time results from Piterbarg (2010) and Castagna (2013). They also find that when we have a haircut of 0, the expectation which leads to the arbitrage free price is taken in the measure where the underlying asset grows at rate r^r.

We will now split the option price in Proposition 1 into two components. The first component is the traditional option price where r^f is used in the pricing measure. The second part we will then denote FVA. This is the funding value adjustment to the option price originating from the repo or reverse repo of the underlying asset. We describe it as a funding value adjustment because the change in the option price comes from our ability to fund the position in the underlying asset at a different rate than r^f. First, we will look at the 1-period model and then, in Proposition 2, generalize this result to a multi-period model.

If we look at the situation where $\alpha > 0$ in the 1-period model, we would have to borrow at r^f in order to go long the underlying asset in the traditional setup. Now we incorporate our ability to use the long position for funding such that in the case of $\omega = 0$ we can fund the position using $r^r < r^f$.

$$\begin{aligned}
\frac{1}{1+r^f}E^{\mathbb{Q}^r}\left[V_T\right] =& \frac{1}{1+r^f}\left[\frac{1+r^f-d}{u-d}V_u + \frac{u-1-r^f}{u-d}V_d\right] - \frac{r^f-r^r}{1+r^f}\frac{V_u-V_d}{u-d}(1-\omega) \\
=& \frac{1}{1+r^f}E^{\mathbb{Q}}\left[V_T\right] - \frac{r^f-r^r}{1+r^f}\frac{V_u-V_d}{u-d}(1-\omega) \\
=& \frac{1}{1+r^f}E^{\mathbb{Q}}\left[V_T\right] - \frac{r^f-r^r}{1+r^f}\Delta S(1-\omega) \\
\equiv& \frac{1}{1+r^f}E^{\mathbb{Q}}\left[V_T\right] + FVA
\end{aligned} \tag{III.15}$$

The sign of the FVA is given by the sign of Δ. The value of a vanilla call option will thus be lower because $\Delta \geq 0$. The intuition is that it becomes cheaper to replicate the payoff of the call, because we can use the long stock position for funding. Conversely, a call buyer

will find it more expensive to hedge because he now has to borrow the stock in order to short it. The price a call buyer is willing to pay is thus also lower. For put options we have the same intuition. A put becomes more valuable because it will be more expensive to short sell the stock in order to replicate the payoff and the price is thus higher. The put buyer is willing to pay a higher price for the put because it becomes cheaper to hedge it. The result in (III.15) can be extended to a multi-period model and this is done in Proposition 2.

Proposition 2 *Let S evolve according to a multi-period binomial model. Assume linear margin requirement with ω as the haircut on the underlying asset. Let r^f denote the funding rate and r^r the repo rate. The option price V_t of an option with expiry at T can then be represented as*

$$\begin{aligned} V_t =& \frac{1}{(1+r^f)^{T-t}} E_t^{\mathbb{Q}}[V_T] + E_t^{\mathbb{Q}}\left[\sum_{i=t}^{T-1} FVA_i\right] \\ =& \frac{1}{(1+r^f)^{T-t}} E_t^{\mathbb{Q}}[V_T] - E_t^{\mathbb{Q}}\left[\sum_{i=t}^{T-1} \frac{r^f - r^r}{(1+r^f)^{i-t+1}} \Delta_i^r S_i (1-\omega)\right] \end{aligned} \tag{III.16}$$

where Δ^r is the option delta under the $\mathbb{Q}^r$ measure.

Proof. To prove that this holds for an n-period model we first show that this holds the last 1-period models in all states, i.e. standing at time $T-1$ Proposition 2 collapses to

$$V_{T-1} = \frac{1}{1+r^f} E_{T-1}^{\mathbb{Q}}[V_T] - E_{T-1}^{\mathbb{Q}}\left[\frac{r^f - r^r}{1+r^f} \Delta_{T-1}^r t S_{T-1}(1-\omega)\right] \tag{III.17}$$

Everything in the last expectation is then measurable given information at time $T-1$ so we can drop the expectation sign:

$$V_{T-1} = \frac{1}{1+r^f} E_{T-1}^{\mathbb{Q}}[V_T] - \frac{r^f - r^r}{1+r^f} \Delta_{T-1}^r S_{T-1}(1-\omega) \tag{III.18}$$

This is then equal to the expression found in (III.15) which proves the result for all the last 1-period models.

Now assume the result holds for all the k-period models standing at time $T-k$ for $T > k > 1$. We then need to prove that it also holds for all the $k+1$-period models standing at time $T-k-1$.

For each $k+1$-period model we have

$$\begin{aligned}\frac{1}{(1+r^f)^{k+1}}E^{\mathbb{Q}^r}_{T-k-1}\left[V_T\right] &= \frac{1}{(1+r^f)^{k+1}}E^{\mathbb{Q}^r}_{T-k-1}\left[E^{\mathbb{Q}^r}_{T-k}\left[V_T\right]\right] \\ &= \frac{1}{(1+r^f)^{k+1}}E^{\mathbb{Q}}_{T-k-1}\left[E^{\mathbb{Q}^r}_{T-k}\left[V_T\right]\right] + FVA_{T-k-1} \\ &= \frac{1}{(1+r^f)^{k+1}}E^{\mathbb{Q}}_{T-k-1}\left[E^{\mathbb{Q}^r}_{T-k}\left[V_T\right]\right] - \frac{r^f-r^r}{1+r^f}\Delta^r_{T-k-1}S_{T-k-1}(1-\omega) \\ &= \frac{1}{1+r^f}E^{\mathbb{Q}}_{T-k-1}\left[\frac{1}{(1+r^f)^k}E^{\mathbb{Q}^r}_{T-k}\left[V_T\right]\right] - \frac{r^f-r^r}{1+r^f}\Delta^r_{T-k-1}S_{T-k-1}(1-\omega)\end{aligned} \tag{III.19}$$

where we in the second equation use the result for the 1-period model given in (III.15). Now use that we have assumed Proposition 2 to hold for a k-period model on the inner expectation to get

$$\begin{aligned}&\frac{1}{(1+r^f)^{k+1}}E^{\mathbb{Q}^r}_{T-k-1}\left[V_T\right] \\ &\quad= \frac{1}{1+r^f}E^{\mathbb{Q}}_{T-k-1}\left[\frac{1}{(1+r^f)^k}E^{\mathbb{Q}}_{T-k}\left[V_T\right] + E^{\mathbb{Q}}_{T-k}\left[\sum_{i=T-k}^{T-1}FVA_i\right]\right] + FVA_{T-k-1} \\ &\quad= \frac{1}{(1+r^f)^{k+1}}E^{\mathbb{Q}}_{T-k-1}\left[V_T\right] + \frac{1}{1+r^f}E^{\mathbb{Q}}_{T-k-1}\left[\sum_{i=T-k}^{T-1}FVA_i\right] + FVA_{T-k-1} \\ &\quad= \frac{1}{(1+r^f)^{k+1}}E^{\mathbb{Q}}_{T-k-1}\left[V_T\right] + E^{\mathbb{Q}}_{T-k-1}\left[\sum_{i=T-k-1}^{T-1}FVA_i\right]\end{aligned} \tag{III.20}$$

which then proves the result for the $k+1$-period models ■

In the previous two propositions we have priced options assuming linear margin requirements and incorporated a haircut. Finally, before we move to the case of symmetric haircuts, we will in the next proposition see that the exact same option prices can be found if we have 0 haircut but adjust the repo rate r^r. In other words, a model with linear margin requirements and constant haircut is nested in a model with 0 haircut.

Proposition 3 *The option price V_t in a binomial model with constant haircut ω, funding rate r^f and repo rate r^r is equivalent to an option price in a binomial model with 0 haircut,*

funding rate r^f and repo rate r^{r*} given by

$$r^{r*} = r^r + \omega\left(r^f - r^r\right) \tag{III.21}$$

Proof. We note that if we set $r^{r*} = r^r + \omega\left(r^f - r^r\right)$ we will then have that $\mathbb{Q}^{r^{r*}}$ is equal to $\mathbb{Q}^r$ such that

$$\frac{1}{(1+r^f)^{T-t}} E_t^{\mathbb{Q}^r}\left[V_T\right] = \frac{1}{(1+r^f)^{T-t}} E^{\mathbb{Q}^{r^{r*}}}\left[V_T\right]$$

■

The intuition behind Proposition 3 is as follows; paying a lower rate on some of the value of the underlying asset is equivalent to paying a less lower rate on the entire value of the underlying asset.

Symmetric case

We now turn to a model with symmetric haircuts. In this setting the haircut is $(1+\eta)$, when we want to borrow the underlying for a short position. If we set $\eta = \omega$, the cost is the same for a long and a short position in terms of haircut. To price an option in this setup we again need to write up the two equations we should solve as in (III.11). First, we will set the scene for pricing an option in this setting, and then, in Proposition 4, we will derive the option price for simple options.

To set up the two equations we can reuse the old equations from (III.11) where we explicitly write that the haircut will depend on α.

$$\begin{aligned} \alpha u S + (\beta + (1-\omega(\alpha))\alpha S)\left(1+r^f\right) - (1-\omega(\alpha))\alpha S\left(1+r^r\right) &= V_u \\ \alpha d S + (\beta + (1-\omega(\alpha))\alpha S)\left(1+r^f\right) - (1-\omega(\alpha))\alpha S\left(1+r^r\right) &= V_d \end{aligned} \tag{III.22}$$

Solving (III.22) with respect to α will again yield

$$\alpha = \frac{V_u - V_d}{S(u-d)}$$

and for β we get

$$\beta = \frac{1}{1+r^f}\frac{uV_d - dV_u - (1-\omega(\alpha))\left[\left(r^f - r^r\right)(V_u - V_d)\right]}{u-d}$$

The price of the option is then

$$\begin{aligned} V_0 =& \alpha S + \beta \\ =& \frac{1}{1+r^f}\left[\frac{1+r^f-d-(1-\omega(\alpha))\left(r^f-r^r\right)}{u-d}V_u + \frac{u-1-r^f+(1-\omega(\alpha))\left(r^f-r^r\right)}{u-d}V_d\right] \\ =& \frac{1}{1+r^f}E^{\mathbb{Q}^{\omega(\alpha)}}\left[V_T\right] \end{aligned} \tag{III.23}$$

where $\mathbb{Q}^{\omega(\alpha)}$ is given by $q^{\omega(\alpha)} = \frac{1+r^f-d-(1-\omega(\omega(\alpha)))(r^f-r^r)}{u-d}$. In order for $\mathbb{Q}^{\omega(\alpha)}$ to be well-defined we need $0 \leq q^{\omega(\alpha)} \leq 1$. If we have the same capital charge for a long position as for a short position the functional form of ω would be

$$\omega(\alpha) = \begin{cases} \omega & 0 \leq \alpha \\ -\omega & \alpha < 0 \end{cases} \tag{III.24}$$

for $0 \leq \omega \leq 1$. If $\alpha \geq 0$ we see that $\mathbb{Q}^{\omega(\alpha)}$ is well defined as long as $0 < d < 1+r^r < 1+r^f < u$. If $\alpha < 0$ then we need

$$0 \leq \frac{1+r^f-d-(1+\omega)(r^f-r^r)}{u-d} \leq 1 \quad \Rightarrow \tag{III.25}$$

$$\frac{1+r^r-u}{r^f-r^r} \leq \omega \leq \frac{1+r^r-d}{r^f-r^r} \tag{III.26}$$

If we restrict the haircut to be between 0 and 1, the lower bound can be dropped because $0 < d < 1+r^r < 1+r^f < u$ such that

$$0 \leq \omega \leq \min\left(1, \frac{1+r^r-d}{r^f-r^r}\right)$$

An important implication of the derivation in (III.23) is that the price of a claim promising V_T will not be equivalent to minus the price of a claim promising $-V_T$ because the measure by which we would have to evaluate the two claims in would be different. This will result

in a bid-ask spread for options, because replication and hedging will not be equivalent. In Proposition 4 we will state this result for simple options where the sign of the underlying position is constant.

Proposition 4 *In a 1-period model assume the option payoff is a non-decreasing function of the underlying asset. Assume a symmetric haircut of ω as in* (III.24)*, funding rate r^f and repo rate r^r. The replication value of the option will be given by*

$$V_0^{rep} = \frac{1}{1+r^f} E^{\mathbb{Q}^r}[V_T] \tag{III.27}$$

where $\mathbb{Q}^r$ is given by $q^r = \frac{1+r^f-d-(1-\omega)(r^f-r^r)}{u-d}$.
The hedge value is

$$V_0^{hedge} = \frac{1}{1+r^f} E^{\mathbb{Q}^{-\omega}}[V_T] \tag{III.28}$$

where $\mathbb{Q}^{-\omega}$ is given by $q^{-\omega} = \frac{1+r^f-d-(1+\omega)(r^f-r^r)}{u-d}$.
and the bid ask spread will be

$$V_0^{rep} - V_0^{hedge} = 2\frac{r^f - r^r}{1+r^f}\Delta S\omega$$

Proof. When the payoff is a non-decreasing function of the underlying asset we know that α is non-negative. A replicating strategy will then have haircut ω and the price becomes

$$V_0^{rep} = \frac{1}{1+r^f} E^{\mathbb{Q}^r}[V_T]$$

For the hedge we see that if the pay-off is a non-decreasing function of S then the hedge will be a non-increasing function in S and thus a non-positive delta, i.e. a short position in the underlying asset. The haircut then becomes $-\omega$ and the price will be

$$V_0^{hedge} = \frac{1}{1+r^f} E^{\mathbb{Q}^-}[V_T] \tag{III.29}$$

where $q^- = \frac{1+r^f-d-(1+\omega)(r^f-r^r)}{u-d}$

For the bid ask spread we first observe that we can use the representation from (III.15)

to get

$$\begin{aligned} V_0^{rep} =& \frac{1}{1+r^f} E^{\mathbb{Q}}\left[V_T\right] - \frac{r^f - r^r}{1+r^f} \Delta^{rep} S(1-\omega) \\ V_0^{hedge} =& \frac{1}{1+r^f} E^{\mathbb{Q}}\left[V_T\right] - \frac{r^f - r^r}{1+r^f} \Delta^{hedge} S(1+\omega) \end{aligned}$$

Here we have calculated the hedge as a positive function. Thus, the sign of Δ^{hedge} is positive and in the 1-period model $\Delta^{rep} = \Delta^{hedge}$ the bid-ask spread therefore becomes

$$\begin{aligned} SPREAD =& \frac{1}{1+r^f} E^{\mathbb{Q}^r}\left[V_T\right] - \frac{1}{1+r^f} E^{\mathbb{Q}^-}\left[V_T\right] \\ =& \frac{1}{1+r^f} E^{\mathbb{Q}}\left[V_T\right] - \frac{r^f - r^r}{1+r^f} \Delta S(1-\omega) - \frac{1}{1+r^f} E^{\mathbb{Q}}\left[V_T\right] + \frac{r^f - r^r}{1+r^f} \Delta S(1+\omega) \\ =& \frac{r^f - r^r}{1+r^f} S\left(\Delta(1+\omega) - \Delta(1-\omega)\right) \\ & 2\frac{r^f - r^r}{1+r^f} S\Delta\omega \end{aligned}$$

■

From 4 we see that the bid ask spread depends on the haircut ω, the delta of the option, and the spread between the repo rate r^r and the funding rate r^f. If we have 0 haircut the spread is 0. The intuition is here the same as for the linear haircut. When the haircut is 0, the price for an option seller equals the price of an option buyer, where the option seller replicates the option payoff and the option buyer hedges the option payoff. This is because the discount, the option seller is willing to give compared to the traditional setting exactly equals the discount the option buyer requires, because it is now more expensive to hedge the option. It is an important insight that we only have a bid-ask spread for the options when we have a non-zero haircut in the symmetric haircut regime.

In Proposition 4 we simplified the haircut to be symmetric such that going short and going long would cost you the same amount of cash. We did this because it is closer to real market conditions, where there is a capital charge for both long and short positions. However, in reality the haircuts to go short and long are not the same. Veronesi (2010) suggests that if an agent wants to borrow a specific bond then the haircut is 0, but the rate you receive is adjusted downward. The reason for this is that it is a special bond and

not just any bond that is desired. A similar mechanism could work in the market for stock lending. If we implement this, the functional form of ω would be

$$\omega(\alpha) = \begin{cases} \omega & 0 \leq \alpha \\ 0 & \alpha < 0 \end{cases} \tag{III.30}$$

We also have two repo rates. Let r^r be the repo rate you pay when you borrow funds using the stock as collateral, and let r^{r*} be the repo rate you receive on the funds pledged in order to borrow a specific stock. The definition of $\omega(\alpha)$ in (III.30) coincides with the case where it is always possible to pledge the asset and then borrow $(1-\omega)\alpha S$ worth of cash at the rate r^r. r^r can be viewed as the general collateral rate. αS has to be pledged at the rate r^{r*} in order to get the specific asset of interest for the short position. Thus, there is no haircut when a option replicator or hedger wants to borrow the asset in order to short it. As in Duffie (1996) the specialness of the asset can be measured by the difference between r^r and r^{r*} and we also have that $r^f > r^r \geq r^{r*}$. The rate r^{r*} is thus an asset specific rate and may be lower than r^r. The ordering comes from the fact that only the agents who own the asset are able to utilize the cheap funding they are able to get from a low r^{r*}. There is thus no mechanism to drive the rate r^{r*} up if only few agents are able to provide the asset as collateral.

The bid-ask spread for a call option in the 1-period model would then be

$$\begin{aligned} SPREAD =& V_0^{rep} - V_0^{hedge} \\ =& \frac{1}{1+r^f} E^{\mathbb{Q}}[V_T] - \frac{r^f - r^r}{1+r^f}\Delta S(1-\omega) - \frac{1}{1+r^f} E^{\mathbb{Q}}[V_T] + \frac{r^f - r^{r*}}{1+r^f}\Delta S \\ =& \frac{r^r - r^{r*}}{1+r^f} S\Delta + \frac{r^f - r^r}{1+r^f} S\Delta\omega \end{aligned} \tag{III.31}$$

As in Proposition 3 we see that if $r^{r*} = r^r - \omega(r^f - r^r)$ then the spread is the same as the spread in the symmetric haircut case in Proposition 4. If we set the haircut to 0, we see from (III.31) that we will have a spread between the bid and ask if the rates r^r and r^{r*} are different. The bigger the difference is between r^{r*} and r^r the more difficult it is to short the underlying asset. That the bid-ask spreads of options are increasing in the shorting cost is

empirically documented in Battalio and Schultz (2011).

III.4. Put-Call Parity

In this section we will look at the put-call parity when hedging and replication are affected by short sell constraints and repo opportunities. First, we will derive a modified put-call parity for non-dividend paying stocks where we take the financial frictions into account. We will then look at options on the S&P 500 Index to see whether we are able to observe the effects of short sell costs and repurchase agreements. The empirical analysis will follow similar ideas as in Ofek, Richardson, and Whitelaw (2004).

The classic put-call parity for non-dividend paying stocks is

$$C_t(K) - P_t(K) = S_t - K\frac{1}{1+r^f} \tag{III.32}$$

where C_t and P_t are call and put prices for European style options with the same maturity T and strike K. That (III.32) no longer holds can be seen by looking at a strike 0 call. For a strike 0 call we should have that

$$C_t(0) = S_t$$

However, according to Proposition 1 and 4 we have that

$$C_t(0) = \frac{1}{1+r^f}E^{\mathbb{Q}^r}\left[S_T\right] \neq \frac{1}{1+r^f}E^{\mathbb{Q}}\left[S_T\right] = S_t$$

when $\omega < 1$. The intuition behind this result is the following. Having a strike 0 call option is not the same as having the underlying stock, because we can use the underlying stock for funding, whereas this is not possible with the option in our modelling framework. The put-call parity, we should use is therefore one where we correct for the return we can get by using the stock as collateral. This insight is similar to Avellaneda and Lipkin (2009).

Proposition 5 *Assume linear margin requirements with haircut ω. Let r^f be the funding rate and r^r the repo rate. Let $C_t(K)$ be a call option with strike K and expiry T and $P_t(K)$*

a put with similar strike K and expiry. We then have the following put-call parity

$$C_t(K) - P_t(K) = S_t\left(\frac{1 + r^r + \omega(r^f - r^r)}{1 + r^f}\right) - K\frac{1}{1 + r^f} \tag{III.33}$$

Proof. A long call position together with a short put position, where the call and put have the same strike and expiry, is equivalent to getting the stock at expiry at the price K which is the strike of the options. The price of the position of the long call and short put should therefore equal the price of the stock minus the discounted strike. This will give us the traditional put-call parity. However, the stock can be used for funding at the rate r^r which can be invested at the rate r^f. The implied dividends from having the stock with ω as the haircut is thus

$$S_t\left(1 - \left(\frac{1 + r^r + \omega(r^f - r^r)}{1 + r^f}\right)\right)$$

The value of the long call position and the short put position is thus

$$S_t - K\frac{1}{1 + r^f} - S_t\left(1 - \left(\frac{1 + r^r + \omega(r^f - r^r)}{1 + r^f}\right)\right)$$
$$= S_t\left(\frac{1 + r^r + \omega(r^f - r^r)}{1 + r^f}\right) - K\frac{1}{1 + r^f}$$

■

From Proposition 5 it follows immediately that the implied stock price using the classic put-call parity will be below the observed stock price whenever the haircut is less than 1 and $r^r < r^f$. A straightforward way of investigating the put-call parity is to use prices for calls and puts with the same strike and maturity and then calculate the value of the underlying asset that these prices correspond to. If the classic put-call parity holds, the implied prices should equal the observed prices of the underlying asset with no asymmetry in the deviations. However, if the options are affected by repurchase agreements and short sell restrictions, the implied prices of the underlying asset should be below the observed prices, and we should therefore observe an asymmetric deviation from the put-call parity. Therefore, a perfect setting to test Proposition 5 would be to find prices on European style call and put options on non-dividend paying stocks. Then, using the call and put prices we can calculate the implied price of the stock using the put-call parity, i.e. the implied stock

value S_t^* would be

$$S_t^* = C_t(K) - P_t(K) + K\frac{1}{1+r^f} \tag{III.34}$$

According to Proposition 5 we should then observe that $S_t^* \leq S_t$. The higher the implied dividends are from owning the underlying asset, the bigger should the difference also be. Furthermore, if the difference stems from the implied dividend of owning the underlying asset, we should observe a maturity dependence on the difference. This means that the longer the maturity is for the put-call pair used for calculating the price of the underlying asset, the greater should the difference between the observed price and the implied price be. This is true, if we have positive interest rates.

To our knowledge most single stock options are American style options. However, European style options do exist when we look at options on the S&P 500 Index. Our empirical approach is thus to use options on the S&P 500 Index. From these options we will calculate what the index price should be according to the classic put-call parity and compare this with the observed index price. Besides being European style options, there is one more advantage using options on the S&P 500 Index. Garleanu, Lasse Heje Pedersen, and Poteshman (2009) document how end-users have a net long position in S&P 500 Index options. This means, that some options must be hedged by dealers using the underlying index which fits into our model.

We have 5111 put-call option pairs on the S&P 500 Index observed between January 5th 2005 and September 30th 2009 obtained from OptionMetrics. These pairs are obtained through the following strategy: Each Wednesday, from January 5th 2005 through September 30th 2009, we have found all put-call option pairs with the same maturity and strike where also the time to maturity > 30 days, volume > 50, Impl. vol $< 100\%$ and bid price > 0.5. These filters are in place to insure that the option pairs we look at are in fact traded options. We have 248 Wednesdays in the timespan, and we observe an average of 20.6 option pairs each Wednesday.

Table XVII: This table shows some descriptive statistics on the option sample

	Mean	Median	Std. deviation
Time to maturity (days)	143.4	66	177.98
Moneyness $\left[\log\left(\frac{S}{K}\right)\right]$	-0.00367	-0.00327	0.059
Daily volume call	3219.42	1010	5551
Daily volume put	3875.79	1324	6473
Bid-ask spread call	7.02%	4.94%	8.76%
Bid-ask spread put	6.73%	5.36%	5.81%

One caveat from using options on the S&P 500 Index is that the index pays dividends. We therefore have to adjust for these dividends. OptionMetrics does supply a dividend yield for the S&P 500 Index. However, this yield is based on the classic put-call parity. Therefore, we will instead use a dividend yield based on annual realized dividends on the S&P 500 Index. These are obtained from Binsbergen, Brandt, and Koijen (2012) and displayed in Figure III.23. From Figure III.23 we see that realizations of dividends are very persistent. We use these realization of dividends to calculate the dividend yield. This methodology hinges on the assumption that the market participants are able to forecast the dividend realizations, such that the expected dividend realizations equal the actual realizations. For the risk-free rate we use the zero-coupon rates from OptionMetrics. The implied index price S^* is thus given by

$$S^* = \left[C_t(K) - P_t(K) + K\exp\left(-r^f(T-t)\right)\right]\exp\left(q(T-t)\right) \tag{III.35}$$

where q is the annualized dividend yield computed from the dividends realizations in Figure III.23.

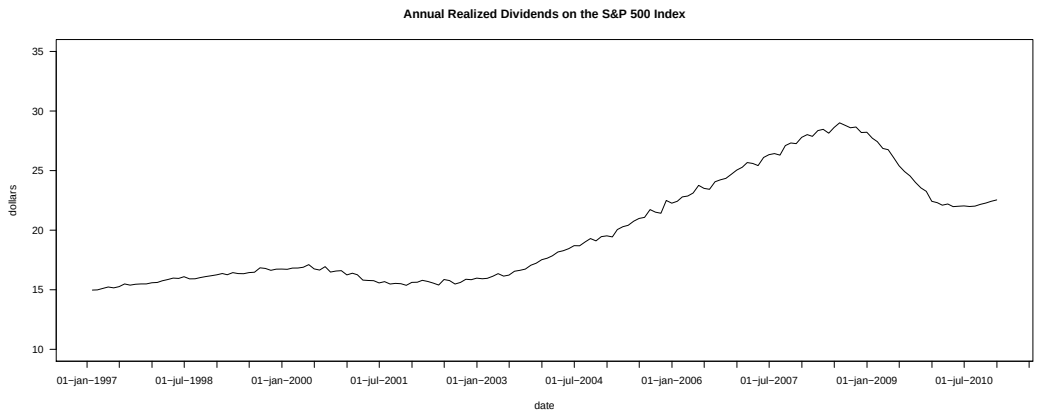

Figure III.23: *Plot of annual realized dividends on the S&P 500 Index. The time period is January 1997 to December 2010 with monthly observations. The data is obtained from Binsbergen, Brandt, and Koijen (2012)*

Each Wednesday equation (III.35) gives us on average around 21 values of the S&P 500 Index. We now follow Ofek, Richardson, and Whitelaw (2004) and calculate the ratio

$$R = 100 \log\left(\frac{S}{S^*}\right) \tag{III.36}$$

If repurchase agreements and short sell restrictions are affecting the put-call parity, we would expect to see positive values of R. This corresponds to a positive implied dividend from owning the index.

Figure III.24 depicts a histogram of the ratio R, and in Table XVIII some summary statistics on R are reported. If repurchase agreements and short sell restrictions affect the put-call parity, we would expect to see larger effects during periods where shorting is more difficult. During our sample period the SEC implemented a ban on shorting different financial stocks (Boehmer, Jones, and Zhang (2013)). Some of these stocks are also part of the S&P 500 Index, and the ban could therefore potentially have an effect on the shorting cost for the index. The ban came into effect September 20th 2008 and lasted until October 8th 2008. Even though this is a short period and the ban only affected a fraction of the stocks in the index, we will try to use this period and to see if we can detect any effect on the deviations from the put-call parity. Therefore, we have divided our sample into 3 different groups in Table XVIII.

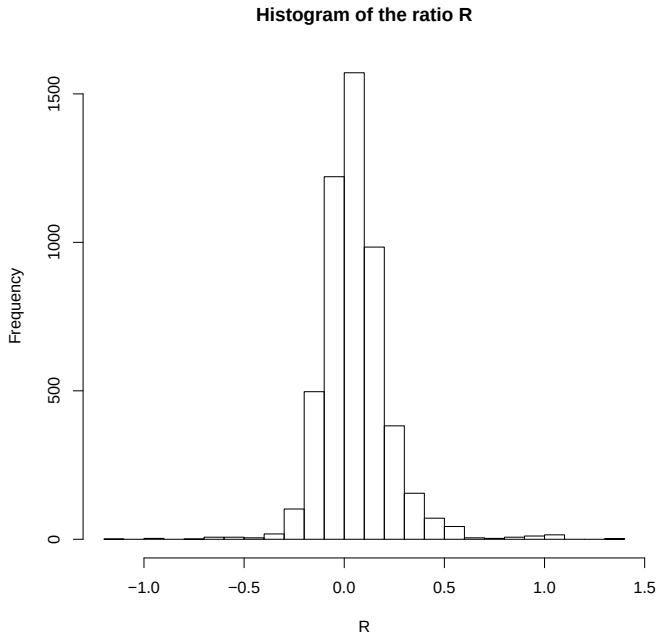

Figure III.24: *Histogram of the ratio R for our full sample. For every put-call pair we calculate the ratio* $R = 100 \log\left(\frac{S}{S^*}\right)$ *where* $S^* = \left[C_t(K) - P_t(K) + K \exp\left(-r^f (T-t)\right)\right] \exp\left(q(T-t)\right)$.

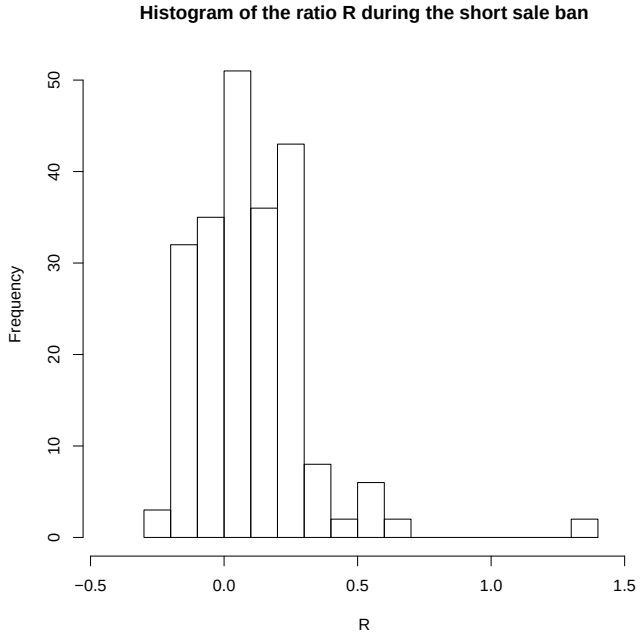

Figure III.25: *Histogram of the ratio R during the short sell ban. For every put-call pair in the period we calculate the ratio* $R = 100 \log\left(\frac{S}{S^*}\right)$ *where* $S^* = \left[C_t(K) - P_t(K) + K \exp\left(-r^f (T-t)\right)\right] \exp\left(q(T-t)\right)$.

Table XVIII: Distribution of the ratio R
This table shows some summary statistics on the ratio R given by $R = 100 \log\left(\frac{S}{S^*}\right)$ where $S^* = \left[C_t(K) - P_t(K) + K \exp\left(-r^f(T-t)\right)\right] \exp\left(q(T-t)\right)$. We have divided the sample into different periods. The first column shows the result using the entire sample. Column II is only using using data during the short sell ban in 2008 and finally column III reports the results using the entire data excluding the short sell ban period.

	Full sample	Ban period	Ex. ban period
Obs	5111	220	4891
Mean	0.0567	0.1033	0.0546
Median	0.0458	0.0731	0.0451
$R < 0$	63.6%	68.2%	63.4%
$R > 0$	36.4%	31.8%	36.6%

It is evident from Table XVIII and Figure III.24 and III.25 that the distribution of R is skewed to the right such that we observe more observations above 0 than below 0. We have that the mean is above the median, which also indicates a right skewed distribution. This asymmetric deviation from the put-call parity is consistent with our theory, that repurchase agreements and short sell restrictions affect the put-call parity. If we look at the period where shorting of certain stocks were banned, we see an even greater asymmetry. Both the mean and the median are above the full sample mean and median in this period, and the number of positive deviations are up from 63.6% to 68.2%. This is consistent with the hypothesis that repurchase agreements and short sell restrictions cause the deviations.

Next, we investigate the maturity effect on the put-call parity violations. If the deviations are caused by repurchase agreements and short sell restrictions, we would expect to see a maturity dependence on the ratio R. This is because the shorting cost must be paid over a longer period or equivalently, the gain from the repurchase agreement is obtained over a longer period of time. The longer the maturity of the option pair is, the larger the deviation therefore should be. Figure III.26 and III.27 plot the relationship between the put-call deviations measured by R and the maturity of the option pairs. This is done both for the full sample and for the period with the short sell ban. For at least the ban period it seems like there is a positive relationship between the put-call parity deviations and the maturity. In order to investigate this relationship more thoroughly, we regress the ratio R on the maturity of the option pair. That is, we look at the following regression

$$R_i = \alpha + \beta_1 \times Maturity_i + \beta \times Controls_i + \varepsilon_i$$

In order to control for the underlying liquidity in the option market we have added some liquidity proxies for the option pairs. We will use the moneyness of the options calculated as $\log\left(\frac{S}{K}\right)$, the option volume calculated as the average volume over the put and call option in the option pair, and finally, the bid-ask spread, which again is calculated as the average percentage bid-ask spread over the put and call option in the option pair. Option pairs observed on the same day are probably correlated. We will control for this by using daily fixed effects and cluster the standard errors by observation day.

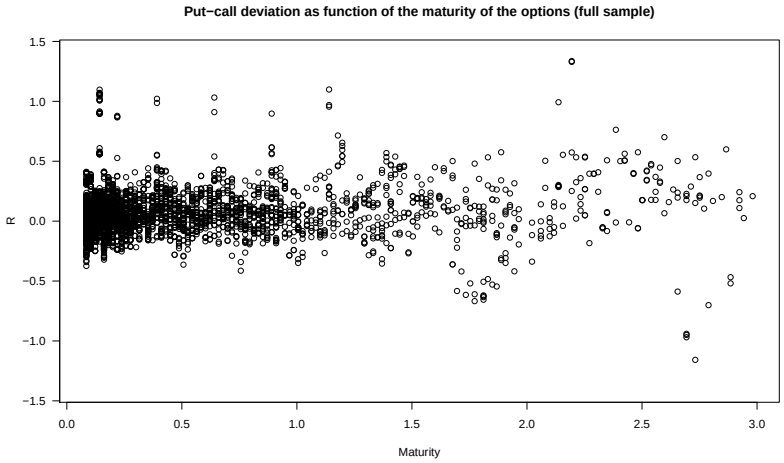

Figure III.26: *Plot of the relationship between the put-call parity deviations measured by R and the maturity of the option pairs using the full sample*

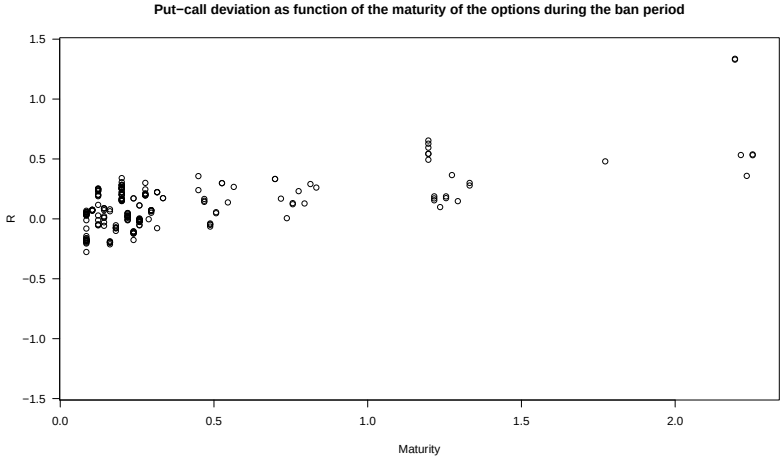

Figure III.27: *Plot of the relationship between the put-call parity deviations measured by R and the maturity of the option pairs where we only look at period during the short sell ban*

Table XIX: Maturity effect
This table shows the results from an OLS regression of the maturity effect on the ratio R. The dependent variable is the ratio R where R is given by $R = 100 \log\left(\frac{S}{S^*}\right)$ and $S^* = \left[C_t(K) - P_t(K) + K \exp\left(-r^f(T-t)\right)\right] \exp\left(q(T-t)\right)$. We look at three different samples. First column shows the result using the full sample i.e. all 5111 option pairs. The second column, labeled 'ban period', only looks at the period between September 20th and October 8th 2008. Finally, the third column uses the residual days i.e. all the days in the sample which are not in the short sell ban period. The maturity for each option pair is measured in years and volume is scaled by a 1000. The t-statistics in the parentheses are based on standard errors that are clustered by observation day.

	Full sample	Ban period	Full Sample ex. ban period
Intercept	0.23 (30.88)	0.025 (0.99)	0.23 (31.7)
Maturity	0.038 (2.51)	0.303 (5.37)	0.0289 (1.96)
Volume	-0.00046 (-1.76)	-0.00054 (-0.71)	-0.00031 (-1.29)
Moneyness	-0.0089 (0.217)	-0.0723 (-1.77)	-0.013 (-0.30)
Bid-ask spread	-0.129 (-2.44)	-0.218 (-1.08)	-0.0789 (-1.97)
Fixed effects	yes	yes	yes
R^2	0.76	0.89	0.77
N	5111	220	4891

The results in Table XIX are quite clear. If we focus on the maturity variable, we see that it is significant in the full sample and in the ban period. The parameter estimate also increases in the ban period. This is consistent with the hypothesis that the deviations from the put-call parity stem from repurchase agreements and short sell constraints where the gain/loss accumulates over time. For the liquidity proxies we see that they are mostly insignificant. The bid-ask spread is the only signigficant variable but with a negative sign. Thus, larger positive values of R are not explained by larger bid-ask spreads in the option market. This is consistent with the findings of Ofek, Richardson, and Whitelaw (2004).

III.5. Conclusion

In the classic frictionless option theory we price options in a setting without short sell constraints where the underlying asset can not be used in a repurchase agreement. We show how the pricing results change when we introduce haircuts and repurchase opportunities. We derive the option price in a simple binomial model when we include 1) short sell constraints 2) repurchase opportunities and 3) haircuts on the underlying asset. In this simple model we are able to get closed form solutions and thus extend the results in the existing literature. We show how the price adjustment depends on the haircut, and especially how a symmetric haircut can generate a bid-ask spread for options. We predict that the bid-ask spread depends on the haircut and the spread between the funding rate and the repo rate.

Finally, our model predicts a modification to the classic put-call parity. We again derive this modification in the simple binomial model. We then use European style options on the S&P 500 Index and find asymmetric deviations from the classic put-call parity, which are consistent with the model predictions. The empirical evidence fit the hypothesis; that short sell constraints and repurchase agreements affect the option prices and in turn also the put-call parity. We also find a correlation between the maturity of the option pairs used in the calculation of the implied index price and the size of the deviation between the implied and observed index price. Again, this is consistent with the story that short sell constraints and repurchase opportunities affect the option price. However, we should note that further studies of the relationship between short sell constraints and repurchase opportunities on the underlying asset and the put-call parity are needed to determine whether these deviations are caused by these particular financial frictions. We use the short sell ban period in 2008 to give some evidence of a causal link, but to provide further evidence it would be relevant to do a formal event study on European options.

References

Avellaneda, Marco and Mike Lipkin (2009). "A dynamic model for hard-to-borrow stocks". In: *Risk, June*, pp. 92–97.

Battalio, Robert and Paul Schultz (2011). "Regulatory Uncertainty and Market Liquidity: The 2008 Short Sale Ban's Impact on Equity Option Markets". In: *The Journal of Finance* LXVI.6.

Bergman, Yaacov Z (1995). "Option pricing with differential interest rates". In: *Review of Financial Studies* 8.2, pp. 475–500.

Binsbergen, Jules van, Michael Brandt, and Ralph Koijen (2012). "On the Timing and Pricing of Dividends". In: *American Economic Review* 102.4, pp. 1596–1618. DOI: 10.1257/aer.102.4.1596. URL: http://www.aeaweb.org/articles.php?doi=10.1257/aer.102.4.1596.

Black, Fischer and Myron Scholes (1973). "The Pricing of Options and Corporate Liabilities". In: *Journal of Political Economy* 81.3, pp. 637–654. ISSN: 00223808, 1537534X.

Boehmer, Ekkehart, Charles M Jones, and Xiaoyan Zhang (2013). "Shackling short sellers: The 2008 shorting ban". In: *Review of Financial Studies* 26.6, pp. 1363–1400.

Brenner, Menachem, Rafi Eldor, and Shmuel Hauser (2001). "The price of options illiquidity". In: *The Journal of Finance* 56.2, pp. 789–805.

Castagna, Antonio (2013). "Pricing of derivatives contracts under collateral agreements: Liquidity and funding value adjustments". In: *Available at SSRN 1974479*.

Christoffersen, Peter et al. (2014). "Illiquidity premia in the equity options market". In: *Available at SSRN 1784868*.

Cox, John C, Stephen A Ross, and Mark Rubinstein (1979). "Option pricing: A simplified approach". In: *Journal of financial Economics* 7.3, pp. 229–263.

D'avolio, Gene (2002). "The market for borrowing stock". In: *Journal of financial economics* 66.2, pp. 271–306.

Duffie, Darrell (1996). "Special repo rates". In: *The Journal of Finance* 51.2, pp. 493–526.

Garleanu, Nicolae and Lasse Heje Pedersen (2011). "Margin-based asset pricing and deviations from the law of one price". In: *Review of Financial Studies* 24.6, pp. 1980–2022.

Garleanu, Nicolae, Lasse Heje Pedersen, and Allen M Poteshman (2009). "Demand-based option pricing". In: *Review of Financial Studies* 22.10, pp. 4259–4299.

Hull, John and Alan White (2012). "The FVA debate". In: *Risk magazine* 25.8, pp. 83–85.

Jensen, Mads V. and Lasse H. Pedersen (2015). "Early Option Exercise: Never Say Never". In: *working paper*.

Leippold, Markus and Lujing Su (2015). "Collateral smile". In: *Journal of Banking & Finance* 58, pp. 15–28.

Lou, Wujiang (2015). "Funding in Option Pricing: the Black-Scholes Framework Extended". In: *Risk*, pp. 56–61.

Merton, Robert C. (1973). "Theory of Rational Option Pricing". In: *The Bell Journal of Economics and Management Science* 4.1, pp. 141–183.

Ofek, Eli, Matthew Richardson, and Robert F Whitelaw (2004). "Limited arbitrage and short sales restrictions: Evidence from the options markets". In: *Journal of Financial Economics* 74.2, pp. 305–342.

Piterbarg, Vladimir (2010). "Funding beyond discounting: collateral agreements and derivatives pricing". In: *Risk* 23.2, p. 97.

Santa-Clara, Pedro and Alessio Saretto (2009). "Option strategies: Good deals and margin calls". In: *Journal of Financial Markets* 12.3, pp. 391–417.

Veronesi, Pietro (2010). *Fixed income securities: Valuation, risk, and risk management*. John Wiley & Sons.

Conclusion

This thesis contains three different papers which consider different aspects of the financial markets with a special focus on the interbank market. The papers are based on both mathematical models and detailed empirical studies.

The first paper is a detailed analysis of the Danish interbank market. Here we first extract plausible interbank loans from a novel data source from the Danish Central Bank. We are able to analyse the effect of a bank's liquidity need on the cost it would pay on an interbank loan. We find that banks in need of liquidity only pay a small premium relative to those with ample liquidity. This effect is greater if the overall liquidity is scarce. In the second paper we develop a model that incorporates banks unwillingness to give up liquidity in the interbank rate. We use this model to identify liquidity risk in interbank rates by looking at the spread between OIS rates and $EUREPOR$ rates. We use a Kalman filter to estimate the model and the model is able to explain the period where we observe that the secure $EUREPO$ rates are higher than the comparable unsecure OIS rates. We also link our measure for the unwillingness to give up liquidity to actions by the ECB. The third and final paper focus on another aspect in finance. Here we extent the classic binomial option pricing model to include financial frictions such as restricted short selling and repurchase opportunity on the underlying asset. We are able to get close form solutions in the simple binomial model under different assumptions. Finally we investigate the put-call parity and find evidence for the model predicted adjustments to the classic put-call parity.

The general theme of this thesis is thus how financial frictions effects financial markets, with a focus on the interbank market. The interbank market is a relative opaque market and this thesis gives some insights both theoretical and empirical in this market.

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