**Price discovery on traded inflation expectations: Does the financial crisis matter?**

by

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**Abstract:**

We analyze contributions of different markets, related by an approximate arbitrage relationship, to price discovery on traded inflation expectations and how it changed during the financial crisis. We use a new high frequency data set on inflation-indexed and nominal government bonds as well as inflation swaps to calculate information shares of break-even inflation rates in the euro area and the US. In the euro area, for maturities up to 5 years new information comes from both the swap and the bond markets. For longer maturities the swap market provides less and less information in the euro area. In the US the bond market dominates the price discovery process for all maturities. The severe financial crisis that spread out in Autumn 2008 drove a wedge between bond and swap break-even inflation rates in both currencies. Price discovery ceased to take place on the swap market. Disruptions coming from the short-end of the market even separated price formation on both segments for maturities of up to 6 years in the US. Against the backdrop of the most severe financial crisis in decades contributions to price formation concentrated a lot more on the presumably safest financial instrument: government bonds.

**Keywords:** inflation, bond markets, swaps, price discovery, financial crisis
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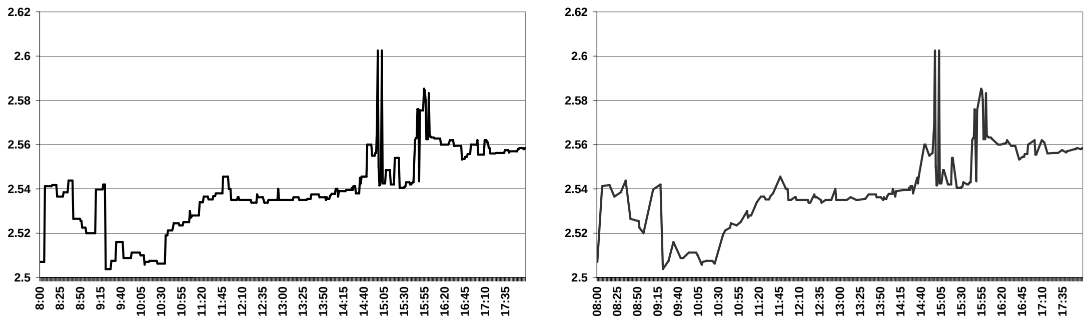
# 1 Introduction

For a central bank to fulfill its price stability mandate assessing inflation expectations is of crucial importance. Market participants gauging long-term investments have similar concerns about inflation. Traditionally, inflation expectations have been derived from models or through surveys of market participants' opinions. In the mid to late 1990s financial markets started to trade claims on inflation actively. Analyzing this source of information has become standard by now. However, there are two main categories in which inflation claims are traded: inflation-linked bonds and inflation swaps. Which market processes information about inflation more quickly and with more impact on long run equilibrium prices or inflation rates? Is it the size of the respective market that drives the lead in processing inflation information? Has the financial crisis changed the price discovery process and bent it more towards one instrument? These are the key questions of the paper. There exists a huge body of literature on how to extract inflation expectations out of financial market data. However, to the extent of our knowledge price discovery for inflation has not been analyzed previously on an intra-day basis. This paper fills the gap.

We find, that information shares are large for central government bonds especially with longer maturities. The larger size of the inflation-indexed bond market in the US compared to the euro area bend the price discovery process even more to the bond market. Whereas in times of financial crisis a heightened risk aversion generally obstructed trades on financial markets, contributions to price formation concentrated a lot more on the presumably safest financial instrument: government bonds.

The standard measurement concept is the break-even inflation rate (BEIR), that is inflation expectations plus risk and liquidity premia. We make use of the approximate arbitrage relationship that exists between bond BEIR and swap BEIR. Figure 1 shows that these instruments do indeed react on news concerning actual and future inflation rates and serves as a first illustration of the close relationship between them. Whereas in practice inflation swaps and nominal and real government bonds are different instruments and therefore differ in prices, the inflation information embedded in these instruments is the same. By means of arbitrage this restricts large price deviations between both instruments. The classical price discovery measures as developed by Hasbrouck (1995) and Gonzalo and Granger (1995) have been applied to the same instrument, eg a share trading in different local markets. We follow the approach used by Blanco, Brennan, and Marsh (2005) and explore price discovery for a claim traded with different instruments on different markets, in our case BEIR.




(a) Bond BEIR

(b) Swap BEIR

Figure 1: Close relation of markets: 4 year break-even inflation rates from bonds and swap on 5 June 2008. President Trichet's remarks in the ECB press conference starting 2:30 p.m. were widely regarded as the turn in the euro interest rate cycle.

We measure the contribution of each markets price innovation to a common efficient price. We use a high frequency data set of the respective bonds and swaps at one-minute intervals. Our sample periods range from May to December 2008. The considered period contains both rising and declining inflation expectations, a turning point of monetary policy and the spread of a severe financial crisis.

The euro area index-linked bond market is rather partitioned, with different credit ratings of issuers and two relevant inflation indices. Thus liquidity is dispersed. Against this backdrop, the euro inflation swap market developed very well in recent years (Hurd and Relleen (2006), Deacon, Derry, and Mirfendereski (2004)). On the other side of the Atlantic, the US maintains a well established issuance program of Treasury Inflation Protected Securities (TIPS) and exhibit only a small inflation swap market. Therefore, we expect the swap market to lead price discovery in the euro area and the bond market in the US. However, these priors do not stand fully up to empirical evidence. In the euro area for shorter maturities up to 5 years new information comes from both markets, whereas for horizons of 7 years and above the bond market increasingly leads the price discovery process. In the US the bond market dominates the price discovery process for all maturities. Only for the shortest time horizon one third of price innovations comes from the swap market. Especially with longer maturities central government bonds are the benchmark for hedging inflation risk and for pricing inflation expectations in both currency areas.

The severe financial crisis that spread out in Autumn 2008 drove a wedge between bond BEIR and swap BEIR in both currencies. Price discovery ceased to take place on the swap market. Disruptions coming from the short-end of the market even separated price formation on both segments for maturities of up to 6 years in the US. Thus even though the swap curve exhibits at times a smoother pattern than its bond derived equivalent it is not adequate to shun bonds from inflation expectation analysis.

The remainder of the paper is organized as follows: The next Section gives an introduction of the respective markets where inflation expectations trade. It also shows how arbitrage guarantees price proximity. Section three contains a description of our data set. In Section four we explain the econometric method used and Section five shows the results of our analysis of price discovery for euro area and US data. The last Section concludes.

# 2 Two markets for trading inflation expectations

Inflation has become a standard commodity on financial markets, or put differently, a well accepted index to link financial claims to. In the following we briefly describe the two most relevant markets for inflation-indexed claims: bonds and swaps.

## 2.1 The inflation-indexed bond market

The UK pioneered the use of inflation-protected bonds. Inflation-linked gilts (gilt-edged securities) were first sold in 1981.[1] But only the start of the US TIPS program in 1997 led the way for several other countries. The US market is the largest for inflation-protected bonds. It has an amount outstanding worth US-$ 516 billion, which is more than 9% of overall Treasury notes, bonds and bills issuance.[2] TIPS are linked to the US city average all items consumer price index for all urban consumers (CPI-U). Within the euro area France, Greece, Italy and Germany have indexed bonds outstanding. France is by far the most active issuer here, sponsoring two programmes linked to the national CPI (ex tobacco, first issue in 1998) and the euro area harmonized index of consumer prices (HICP, again ex tobacco - HICPxT, first issue in 2001), respectively. The combined amount outstanding is €137 billion. Germany issued linkers in 2006 and has built up a volume outstanding of €22 billion. While German

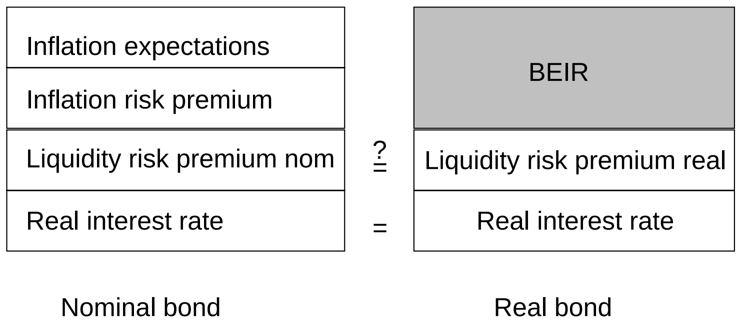



Figure 2: The BEIR derived from nominal and real bonds contains inflation expectations as well as the inflation risk premium and the difference of the respective bonds liquidity premia.

and French bonds enjoy a AAA rating status, Italian government paper (€81 billion outstanding, start in 2003) and Greek government bonds (€15 billion outstanding, 2003) are lower rated. They trade at a spread to German and French bonds.

We infer inflation compensation by subtracting real yields derived from inflation-linked bonds from nominal bond yields using the Fisher equation. Yet, bond yields not only incorporate inflation and real yields or growth expectations. Investors require in addition compensation for unexpected future inflation rate changes in nominal bonds and for illiquidity, default risk and other risk in nominal and inflation-protected bonds. Hence, the bond BEIR comprises everything that is not uniformly priced or not compensated on both, nominal and inflation-linked bond markets (see Figure 2). To begin with, the BEIR contains inflation expectations among financial market participants. Secondly, an inflation risk premium reflects compensation the nominal bond holders require for unexpected inflation rate changes whereas the inflation-indexed bond holder is not exposed to that risk. Liquidity might be different on both markets. Nominal bond markets are larger in volume and might therefore be more liquid. The bond BEIR is the difference of a nominal and a real yield. The cost of carry for both bonds is different and has therefore implications for the level of the BEIR. Repo specialness, delivery options for futures and other institutional features might drive bond yields on both markets further apart.[3] Since we use pairwise government bonds from the same issuer, default risk is not an issue here.

## 2.2 The inflation swap market

Markets for inflation-linked derivatives have grown quickly in recent years. Their development has been complementary to those of inflation-indexed bonds. The most important segment of the inflation derivatives market are inflation swaps. These are traded in the over the counter market (OTC) by financial institutions, fund managers and corporate treasurers. The inflation swap is a bilateral contract which requires one party to the contract (the inflation receiver) to make predetermined fixed-rate payments in exchange for floating-rate payments linked to inflation from a second party (the inflation payer). The basic building block of inflation swap structures is the zero coupon inflation swap, where payments are exchanged only on maturity. Typical maturities range from one year to over 30 years.

Euro zero coupon swaps are in general linked to the same index as most bonds in the associated market. They pay the initially published non seasonally adjusted euro zone HICPxT, possible later revisions have no effect. The inflation index is subject to a lag of three month. This ensures, that both swap parties know the reference price level at the start of the contract. Unlike inflation-linked bonds the reference price level for each day is not interpolated between two neighboring months but changes at the end of the month. This involves jumps at the day of the change of the month especially for shorter maturities but has the advantage that a swap can be traded and unwound in the same month without incurring future inflation risk (an interpolated swap would in contrast retain some inflation risk). US zero coupon swaps are linked to the non seasonal adjusted CPI-U and have an interpolated reference price level for each day as base as well as an indexation lag of three month. This closely aligns the swap market with the bond market in the US.

Although a modest amount of inflation-linked trades have taken place in continental Europe since the early 1990s euro inflation swap volumes boomed not before the early years of the new millennium. The issuance of bonds linked to the euro zone HICPxT from the French and Italian government in 2001 and 2003 respectively supported the proliferation of the euro swap market. In 2007 the monthly notional amount traded was estimated at a two digit number of billion euro. Euro inflation swaps were regarded as one of the fastest growing OTC derivative contracts. In contrast to the euro area, the inflation swap market in the US developed while the inflation-linked bond market had already been in existence for some years. In 2004 when TIPS issuance picked up US-CPI swaps became more popular as well. Yet, an estimated trading volume of

US-$ 11 billion in 2007 is only minor compared to that of the inflation-indexed bond market (Peat and Segregeti 2008).

Inflation swaps explicitly target the change of the price level. Thus the swap BEIR is simply the quoted fixed rate agents are willing to pay in order to receive the cumulative rate of realized inflation during the life of a zero coupon swap. The swap BEIR depends on expected inflation over the life of the swap as well as on various risk premia. Again, these premia comprise compensation for unexpected inflation rate changes and liquidity.[4]

Inflation swaps are - compared to bonds - a new instrument, which hints to an illiquid market. However, market reports indicate that the trading volume of swaps clearly exceeds those of indexed bonds, which is of course partly due to the fact, that entering a swap does not involve funding costs. That notwithstanding, market intelligence states a lack of inflation payers resulting in inflation paid via swaps having a higher price than via bonds (Armann, Benaben, and Lambert (2005) and ECB (2006b)).

The swap BEIR may involve in addition a premium for counterparty risk. Payments are typically exchanged between two private corporations, mostly banks and broker firms but also hedge funds, insurers and non-financial corporations. Therefore the degree of creditworthiness attached to that payments is typically lower than that of bonds issued by governments. Since the market trade mostly zero coupon swaps with payments only exchanged on maturity the counterparty risk especially for long term swaps could be prohibitively high. Collateralization tackles that problem and has become increasingly popular among OTC derivatives during the last years. The international swaps and derivatives association (ISDA) states that 66% of fixed income OTC derivatives were collateralized in 2008 compared to 48% in 2003 (ISDA 2005 and 2008). However, a special kind of counterparty risk remains even for fully collateralized swaps: the default-to-replacement risk. It has come to the attention of a broader audience with the collapse of the investment bank Lehman Brothers in September 2008 and contains two related risks. Firstly, collateral is valued at the margin. This means that in case of default the creditor who seeks a replacement has only a marginal price impact. Yet, when Lehman collapsed a huge number of swaps needed to be replaced at the same time. This obviously had more than a marginal impact. A shift in risk aversion might put additional stress on prices. Furthermore, especially in an one-sided market it will take some time to close open positions. This exposes the creditor to general market risk (eg a monetary policy shock that could move inflation expectations) on top of the direct effect of the default. Again, this risk occurring after the default is not covered by collateral.

## 2.3 Pricing and arbitrage

There exists a huge body of literature on how to extract inflation expectations out of financial market data. The literature is largely driven by staff members of investment banks and central banks. Whereas the former are more concerned with pricing and valuation of inflation-indexed bonds and derivatives for trading reasons (Peat and Segregeti (2008) and Kerkhof (2005)) the latter focus more on pure long-term inflation expectations as indicator of credibility of their monetary policy (ECB (2006a), Hurd and Relleen (2006), Wright (2008) and Kim and Wright (2005)). Over the last fifteen years especially the search for measures of inflation risk premia, liquidity and other risk which cloud inflation expectations proliferated. However, the price discovery process on traded inflation expectations has been ignored so far.

Following Blanco, Brennan, and Marsh (2005) and Doetz (2007) we assume that if different instruments spanning the same economic concept or payments, eg credit risk in their case and BEIR in our case, arbitrage will tie the prices of these instruments together. Otherwise the same claim, credit protection in their case and inflation protection in our case, can be bought cheaper on one market than on the other. Taking into account that we compare prices of related but not identical instruments we are geared to the literature in speaking of an approximate arbitrage relationship. Yet, we also take into account the finding that derivative markets have shifted trading away from spot markets - mostly due to lower funding costs - and are increasingly recognized to take the lead in price formation, especially in financial crisis (Upper and Werner 2007).

In practice, an asset swap is the instrument that links bond and swap prices. An asset swap exchanges a fixed investment, such as a bond with coupon payments, for a floating investment, such as Euribor plus a spread. While nominal asset swaps have been established for some time, real or inflation-linked asset swaps have become popular only during the mid 2000s. Like in a standard asset swap the proceeds of a bond are exchanged against a floating rate interest payment, only that the proceeds are not fixed but inflation-linked. Thus, a dealer might buy an indexed bond via a repo, provide an inflation-indexed cash flow to the market via an inflation swap and hedge its position with a standard interest rate swap (Figure 3).[5] Fact is that financing constraints of dealers, maturity mismatches stemming from the low number of available indexed bonds and other transaction costs will hamper arbitrage. Differences in market liq-

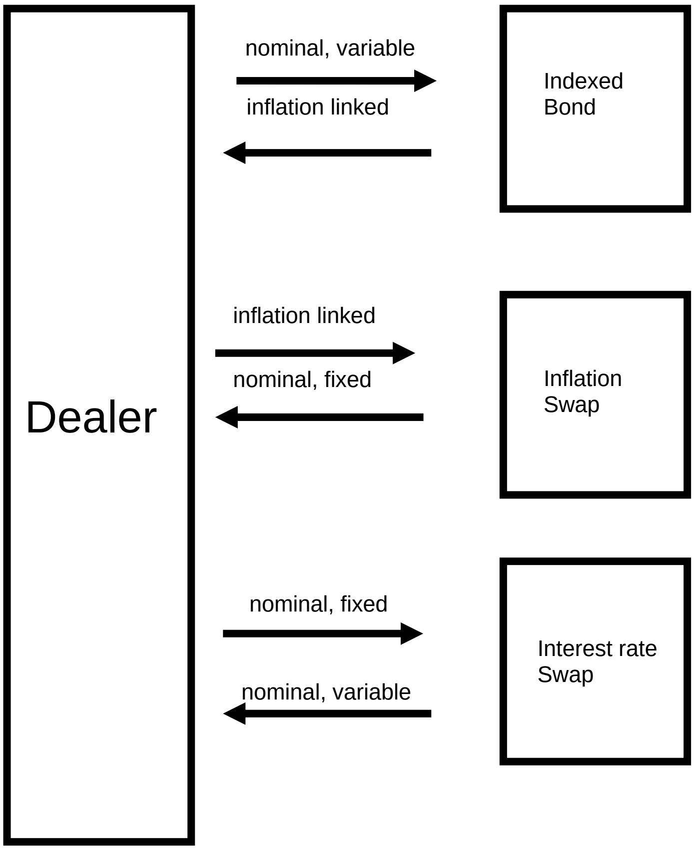



Figure 3: Stylized trading strategy linking inflation-indexed bonds and inflation swaps. Dealer buys inflation-indexed bonds, funds the purchase with a repo and sells inflation protection into the swap market. The nominal swaps closes the position.

uidity both within the bond market and between bond and swap market as well as variations in credit exposure impede price equality. Regulatory barriers preventing investors to engage in derivative instruments or shorten bonds affect the balance of prices furthermore. Thus a constant spread between the two break-even rates can - and does - prevail. However, markets prove to be sufficiently liquid to keep up the arbitrage relationship between bond and swap BEIR in most cases.

# 3 Data

Our data-set consists of real and nominal bonds, as well as inflation swaps. To avoid a credit bias, we concentrate on French and German bonds which all have a AAA rating in the euro area. Furthermore, we focus on the HICPxT as a reference for both inflation swaps and bonds, hence we remove bonds linked to the French national CPI from our sample.[6] The US sample contains TIPS with residual maturities from 2 to 10 years as well as Treasury Notes and inflation swaps with equal maturities. We use two sample periods ranging from May/June to August and from September to December 2008 which we label Summer and Autumn 2008 respectively.

All bonds are capital indexed, ie their notional is inflated with the change of the price index. Coupon and redemption payments are made on the adjusted notional. There is some protection against severe and persistent deflation, as redemption is never below the initial notional. In addition, we restrict the euro area sample to bonds with maturities of up to twelve years, as these are tenors for which inflation swaps are actively traded.[7] Altogether, we keep six linkers in our sample covering maturities of 2, 4, 5, 7, 8 and 12 years. We select six adequate nominal bonds to compute the BEIR (see Table 5 in the Appendix for a list of bonds used). The US operates the world's most active issuing programme; thus we are able to investigate the term structure of bond BEIRs from 2 to 10 years for whole year tenors (see Table 6 in the Appendix).[8] Inflation swaps with corresponding tenors are forming the alternative market.

We obtained bid and ask prices for bonds as well as for swaps, all on one minute intervals. Furthermore we received the number of quote changes (ticks) in each minute. This gives us an indication on the liquidity of the market. As we do not have transaction data, we use the midpoint of bid and ask quotes as the hypothetical transaction price.[9] For the euro area, we use quotes between 8 a.m. and 6 p.m. as trading hardly takes place in the interim time. The Summer and Autumn data sets range from 5 May to 8 August 2008 and from

2 September to 8 December 2008 respectively. Each set spans 70 trading days. Given the adjustments described above 439,000 swap midpoints remain in our sample as well as about 315,000 observations of nominal bond prices and 185,000 of indexed bonds. Claims on US inflation are traded between 9 a.m. and midnight European Central Time. We obtained data for the Summer sample from 12 June 2008 to 13 August 2008 and for the Autumn period from 3 September 2008 to 9 December 2008. This makes a total of approximately 520,000 quotes for the nine nominal bonds, 324,000 for the inflation-indexed bonds and 858,000 quotes for the matching inflation swaps. Prices are carried forward until a new quote comes to pass. All data are taken from Bloomberg.

Bond prices are transformed into yields. We use the yield to maturity or redemption yield concept to calculate bond yields from our price data. The bond yields are therefore systematically slightly undervalued compared to the zero coupon yields coming from our inflation swap data.[10] The prices for the bond data reflect a decreasing time to maturity whereas the inflation swaps are daily quoted whole year tenors. To establish comparability we adjust the yields of the bond to whole year tenors as well. We use daily estimates of term structures of nominal and real bonds to increase (decrease) the yields of our bonds from the remaining time to maturity to whole year tenors.

Furthermore, we need to correct real bond yields for seasonality effects. These occur because bonds are linked to non-seasonally adjusted inflation indices and yields can be biased especially for shorter maturities.[11] For example, in the euro area consumer prices are typically low in January (high in April). January (April) is indeed the reference month for inflation compensation of German (French) bonds. Investors buying bonds at any other time during the year adjust the price according to the higher (lower) actual non-seasonally adjusted inflation rates and therefore under- (over)estimate the bond yield and the BEIR respectively. We corect for seasonality via daily seasonal factors extrapolated from monthly seasonally adjusted and non-seasonally adjusted CPI data.[12] The same adjustments are performed on US data. Yet, due to the semiannual coupon payments of US bonds the issue of seasonality is less virulent.

The respective competitive market comprises of six inflation swaps for the euro area and nine for the US with tenors equivalent to the bond BEIR. Since we consider only swaps with full year tenors we neither need to correct for maturity nor seasonality.

## 4 Price discovery: Measurement method

If both the swap and the bond market price inflation expectation plus risk premia equally, swap and bond BEIR of the same maturity should be identical. Subject to the arbitrage imperfections noted above the difference between the two measures - here called the basis - should be nonzero. Nevertheless a positive mean of the basis as defined in (1) would imply that there are irrevocable costs attached to the investment that makes the hedging of inflation exposure more costly in the swap market.

The basis for a given tenor, $t$, is defined as:

$$basis_t = swapBEIR_t - bondBEIR_t, \tag{1}$$

where:

$$bondBEIR_t = \left[ \left( \frac{1+y_t^n}{1+y_t^r} - 1 \right) * 100 \right], \tag{2}$$

and $y_t^n$ and $y_t^r$ are the yields of the nominal respectively real bond.

In the BEIR implicit inflation expectations are traded in the swap and the bond market. Price discovery is the process by which prices embed new information in either one or both of the two markets. Arbitrage implies that prices cannot deviate too far. In econometric terms, prices are cointegrated I(1) variables which means that the price series have one or more common stochastic factors. If we assume that there is one cointegration relation only and therefore one common factor, we can thus term this factor the implicit efficient price. It is this price driven by new information which is the source of the permanent movement in the prices of both markets. The price discovery can be analyzed with two alternative concepts: Hasbrouck's information shares (Hasbrouck 1995) and Gonzalo and Granger's contributions to the common factor (Gonzalo and Granger 1995).[13] Hasbrouck defines price discovery in terms of the variance of all innovations in a vector error correction model (VECM) to the common factor. Gonzalo and Granger involves only permanent shocks where each markets contribution to the common factor is defined to be a function of only the error correction coefficient in a VECM. Hasbrouck information shares use contemporaneous correlations between price innovations in both markets as much as the variance of these innovations whereas Gonzalo and Granger does not. In the following we compute both measures.

If the two prices are $I(1)$, cointegrated and have the $r^{th}$ order vector autoregression representation:

$$p_t = \Theta_1 p_{t-1} + \cdots + \Theta_r p_{t-r} + \varepsilon_t, \tag{3}$$

where $p_t = (p_{1,t}, p_{2,t})'$. It follows that the returns:

$$\Delta p_t = \begin{bmatrix} p_{1,t} - p_{1,t-1} \\ p_{2,t} - p_{2,t-1} \end{bmatrix}, \quad (4)$$

evolve according to the Engle and Granger (1987) representation theorem in a bivariate equilibrium correction process

$$\Delta p_t = \alpha z_{t-1} + A_1 \Delta p_{t-1} + \cdots + A_r \Delta p_{t-r-1} + \varepsilon_t, \quad (5)$$

where $z_{t-1}$ is the error correction term and $\varepsilon_t$ is a zero-mean vector of serially uncorrelated innovations. $z_t$ is a vector of differences in prices between markets and because swap BEIR are not directly comparable to bond BEIR includes coefficient $\beta_2$, that adjusts for daily changes in the basis and a constant $c$, that captures the average value of the positive basis between the swap and the bond market:

$$z_{t-1} = [p_{1,t-1} - \beta_2 p_{2,t-1} - c], \quad (6)$$

$$z_{t-1} = \beta p_{t-1}.$$

Following the Stock and Watson (1988) permanent-transitory decomposition Hasbrouck (1995) transforms equation (3) into a vector moving average (VMA) representation and its integrated form:

$$p_t = \Psi(1) \sum_{s=1}^{t} \varepsilon_s + \Psi^*(L)\varepsilon_t, \quad (7)$$

where $\Psi^*(L)$ is a matrixpolynomial in the lag operator, $L$. $\Psi(1)$ represents the permanent effect of the shockvector on all the cointegrated security prices, with $\Psi(1)\varepsilon_t$ being the long run impact of an innovation in t. Under the assumption of a single common factor the long run multipliers $\Psi(1)$ can be provided in the error correction framework as Johansen (1991) and Baillie, Bootha, Tse, and Zabotinac (2002) show:

$$\Psi(1) = \beta_\perp \pi \alpha'_\perp, \quad (8)$$

$$\Psi(1) = \pi \begin{bmatrix} \gamma_1 & \gamma_2 \\ \gamma_1 & \gamma_2 \end{bmatrix}.$$

Since we assumed a single common factor, $\pi$ is a scalar and $\beta_\perp$ and $\alpha_\perp$ are the orthogonal complements of the original parameter vectors in (5) and (6).

Because the prices are cointegrated each error term must have the same long run impact on prices. This means that all the rows in (8) are identical. If the covariance matrix $\Omega$ of the residuals $\varepsilon_t$ is diagonal, i.e. the contemporaneous correlation of the residuals is zero, the information share of market 1 is defined by:

$$S_1 = \frac{\gamma_1^2 \sigma_1^2}{\gamma_1^2 \sigma_1^2 + \gamma_2^2 \sigma_2^2}. \tag{9}$$

If there is correlation between the error terms, i.e. $\rho \neq 0$, Hasbrouck (1995) suggest a Choleski factorization of the covariance matrix such that $\Omega = MM'$, where $M$ is a lower triangular matrix.[14] The Hasbrouck information shares for market 1 and 2 are then defined under the assumption that $H_1 + H_2 = 1$ as:

$$H_1 = \frac{(\gamma_1 m_{11} + \gamma_2 m_{12})^2}{(\gamma_1 m_{11} + \gamma_2 m_{12})^2 + (\gamma_2 m_{22})^2}, \tag{10}$$

$$H_2 = \frac{(\gamma_2 m_{22})^2}{(\gamma_1 m_{11} + \gamma_2 m_{12})^2 + (\gamma_2 m_{22})^2}. \tag{11}$$

That is market 1 information share is the proportion of the variance in the common factor that is attributable to shocks in market 1. The factorization imposes a greater information share on the first price (unless $m_{12} = 0$). Therefore upper (lower) bounds of information shares are calculated when market 1 is first (second) in the ordering of the variables for the factorization. In the following we calculate midpoints of the upper and lower bounds of the Hasbrouck shares induced by the different orderings of the variables.

An alternative measure for price discovery is based on the Gonzalo and Granger (1995) decomposition of the price vector into a permanent, $g_t$, and a transitory, $f_t$, component:

$$p_t = \theta_1 g_t + \theta_2 f_t, \tag{12}$$

where the permanent component is a linear combination of the prices in the two different markets, $g_t = \Gamma p_t$, i.e. $\Gamma$ is the common factor coefficient vector. The additional identifying restriction that $f_t$ does not Granger-cause $g_t$ implies that $\theta_1 = \beta_\perp \alpha'_\perp = (\gamma_1, \gamma_2)'$. The weights given to price discovery are then defined as:

$$GG_1 = \frac{\gamma_1}{\gamma_1 + \gamma_2}. \tag{13}$$

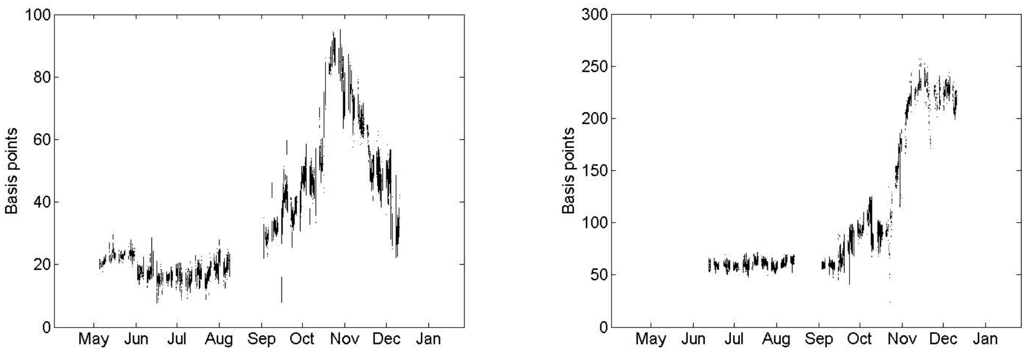
# 5 Price discovery in the Euro Area and the US

We first address the problem implied by the short time horizon of our data set. In the remainder of the Section we lay out price discovery, first in the comparatively calm period of Summer and subsequently in the hot crisis phase of Autumn 2008.

Since our data sets span each only 70 - for the US one only 45 - trading days the use of cointegration techniques which target long run equilibria might appear inappropriate. Yet, we are investigating a (near) arbitrage relationship on a financial market, where corrections to deviations from equilibrium could be effected instantaneously or in our case every minute. Therefore we expect the half live of deviations to be short-lived. Indeed, the average half live of a deviation across all maturities and both markets is around $3\,^1/_2$ hours in the euro area and $7\,^1/_2$ hours in the US in Summer 2008. If we set the length of our data set in relation to this average half life as is proposed by Hakkio and Rush (1991) we get a ratio of 190 or 94 respectively. Studies testing for purchasing power parity where cointegration is routinely applied featuring half lives of three to five years (Rogoff 1996). They would need over 300 years of data to match a ratio of 100. However, the half live of deviations increases to over 40 hours for euro area data and over 120 hours in the US in our extreme crisis sample in Autumn 2008. This implies a ratio of the length of the data set to the average half live of 16 or 6 respectively and gives a first hint that trades and the adjustment to a common efficient price were distinctly slower during the financial turmoil period.

## 5.1 Summer 2008: The baseline scenario

Data for the difference between swaps and bonds, ie the basis, show that it is significantly positive (see Figure 4 and Table 4 in the Appendix). For all maturities - except the shortest in the US - the basis is meaningfully greater than zero implying that the BEIR derived from swaps lies unanimously over the bond BEIR. One part of this difference stems from our use of yields to maturity for bonds versus zero coupon yields for swaps. If the yield curve does not run completely flat, as is the case in our sample, yields to maturity are lower compared to zero coupon yields. The difference makes up to 8 basis points as shows a zero coupon data set with daily frequency for both BEIR. Nevertheless a significant and positive basis persists although it is on average smaller than that of our high frequency data set. This is in line with previous literature assessing the higher swap yield to liquidity considerations and other




(a) Basis euro area

(b) Basis US

Figure 4: Basis: Average of difference between swap and bond BEIR, here: for tenor 7 years.

risk premia (Armann, Benaben, and Lambert (2005), Campbell, Shiller, and Viceira (2009) and Deacon, Derry, and Mirfendereski (2004)).

We performed unit root tests for all time series and could not reject the null at conventional test sizes using the Augmented Dickey Fuller test. We determined the lag order of the unrestricted vector auto regression following the Schwarz information criterion. Since the criterion required at most 15 lags, i.e. 15 minutes, we suspected that overnight returns did not play a prominent role in our estimations. This in contrast would be the case if market prices jumped a lot between market close and opening on the next day.[15] Yet, swaps and bonds are hardly traded outside the peak trading hours ranging from 8 a.m. to 6 p.m. in the euro area and from 9 a.m. to midnight in the US which we fully cover in our sample.

We report Johansen trace statistics for the determination of the number of cointegration vectors in Tables 10 and 11 in the Appendix. The pairs of all swap and bond BEIR for all maturities exhibit one cointegration relation and therefore one common trend. As has been discussed before, markets price BEIR entirely equally only if the unity cointegration vector $[1, -1]$ applies. Yet, swap BEIR nearly always exhibit lower liquidity and higher credit risk than bond BEIR. The difference partly stem from transaction costs. Measured in absolute bid-ask spreads transaction costs for swaps ranges from two and a half basis points to over seven basis points (yield differences) with the lower values attached to the euro area and the higher attached to US markets (see Table 7 in the Appendix). In relative terms to bonds this would mean that bid-ask spreads on swaps are 130 to 400 % of the sum of nominal and real bonds bid-ask spreads, i.e. a kind of round trip costs. To cover this difference, we included a constant in our cointegration vector. In the euro area only shorter maturities, 2 and 4 years, comply with the restriction of a common price up to a constant amount. For the US this is the case for 2, 7, and 8 years. For other (longer) maturities at least one market exhibit time-varying nontransient factors in its price that might be due to nonstationary liquidity differentials on both markets.[16]

Table 1: Contributions to price discovery in the euro area

| | *Hasbrouck inform. shares* | | *Gonzalo and Granger* | |
|---|---|---|---|---|
| | *Summer 08* | *Autumn 08* | *Summer 08* | *Autumn 08* |
| 2 year swap BEIR | 0.46 | 0.09 | 0.29 | 0.09 |
| 2 year bond BEIR | 0.54 | 0.91 | 0.71 | 0.91 |
| 4 year swap BEIR | 0.44 | 0.05 | 0.32 | 0.08 |
| 4 year bond BEIR | 0.56 | 0.95 | 0.68 | 0.92 |
| 5 year swap BEIR | 0.44 | 0.06 | 0.28 | 0.08 |
| 5 year bond BEIR | 0.56 | 0.94 | 0.72 | 0.92 |
| 7 year swap BEIR | 0.30 | 0.05 | 0.22 | 0.07 |
| 7 year bond BEIR | 0.70 | 0.95 | 0.78 | 0.93 |
| 8 year swap BEIR | 0.09 | 0.04 | 0.08 | 0.05 |
| 8 year bond BEIR | 0.91 | 0.96 | 0.92 | 0.95 |
| 12 year swap BEIR | 0.34 | 0.02 | 0.28 | 0.04 |
| 12 year bond BEIR | 0.66 | 0.98 | 0.72 | 0.96 |

*Note: A higher share of the bond market compared to the swap market signals, that new information is revealed to a greater extend in the bond market. Midpoints of Hasbrouck information shares are reported. Lower and upper bounds can be found in Table 12 in the Appendix. Where appropriate according to the results in Table 10 in the Appendix the restriction of an unity vector is imposed.*

The Hasbrouck information share midpoints show that for tenors of 2 to 5 years price discovery on inflation expectations is nearly evenly split in the euro area (see Table 1). Yet, the bond market leads as shares are still significantly different from equality.[17] This changes at longer maturities. Nearly no price discovery takes place in the swap market for 8 year BEIR. This result is confirmed by the Gonzalo and Granger contributions to the common factor which are reported in the same table. For the longest maturity of 12 years the price discovery - although the majority occurs on the bond market - is somewhat more tilted to the swap market. This might be due to the higher ratio of "holdings to maturity" in this issuance segment since investors such as pension funds and insurances are in need of a match for long-term inflation linked liabilities. Lower trading volumes for long-term bonds (one third to one fourth of the yearly volumes of shorter bonds according to EuroMTS data) probably helped the less supply-constrained swap market to gain a higher percentage of price discovery in this segment. Yet, it is still the bond market that dominates the price discovery process. In contrast to what what we see in price discovery studies featuring derivatives and their underlyings (Upper and Werner 2007) it is not the derivative market that dominates price formation in our study.

One interpretation of that result is that especially for longer maturities protection against unexpected inflation rate deviations is virtually only provided by central governments. There is a supply and a demand side to that argument. On the demand side, investors seek long term protection against inflation and want to minimize counterparty risk. This cannot be completely eliminated by posting collateral. The valuation underlying the exchange of collateral is a marginal calculation. However, if a large market participant fails all his counterparties need to hedge their positions. This results in more than a marginal shift in demand or supply and, hence a price movement that is not covered by the collateral posted. Note, that this argument does neither draw on variations in risk-aversion nor on transaction costs. Nevertheless, transaction costs may be relevant as even in a highly developed system it takes some time to negotiate new contracts. After the default of Lehman Brothers some banks needed several weeks to find counterparties to close all their open swap positions. Any price movement during this time is naturally not covered by collateral. This remaining counterparty or default-to-replacement risk may lead market participants to prefer risk free government bonds. On the supply side it is reasonable to assume, that the banking sector's aggregate supply of inflation-indexed claims is zero. This is because banks typically only intermediate between different clients. Yet, inflation supply comes from the private sector, too. Especially for the UK it is well documented that public private partnerships are selling inflation into the market.[18] However, these privately supplied cash flows are very intransparent compared to indexed government bonds. Hence financial institutions, brokers and corporate treasurers which act as inflation takers on the swap market have a reason to be cagey when taking inflation risk in their books that is priced differently to the government bond market.

We motivated our use of an US data set with the different structure of markets for tradable inflation expectations in the euro area and the US. The prior of a larger and more liquid inflation-linked bond market over a less established inflation swap market can be recovered in the results for the US. Hasbrouck

Table 2: Contributions to price discovery in the US

| | *Hasbrouck inform. shares* | | *Gonzalo and Granger* | |
|---|---|---|---|---|
| | *Summer 08* | *Autumn 08* | *Summer 08* | *Autumn 08* |
| 2 year swap BEIR | 0.27 | | 0.14 | |
| 2 year bond BEIR | 0.73 | | 0.86 | |
| 3 year swap BEIR | 0.12 | | 0.06 | |
| 3 year bond BEIR | 0.88 | | 0.94 | |
| 4 year swap BEIR | 0.13 | | 0.06 | |
| 4 year bond BEIR | 0.87 | | 0.94 | |
| 5 year swap BEIR | 0.11 | 0.07 | 0.04 | 0.04 |
| 5 year bond BEIR | 0.89 | 0.93 | 0.96 | 0.96 |
| 6 year swap BEIR | 0.18 | | 0.10 | |
| 6 year bond BEIR | 0.92 | | 0.90 | |
| 7 year swap BEIR | 0.09 | 0.08 | 0.02 | 0.03 |
| 7 year bond BEIR | 0.91 | 0.92 | 0.98 | 0.97 |
| 8 year swap BEIR | 0.04 | 0.04 | 0.00 | 0.03 |
| 8 year bond BEIR | 0.96 | 0.96 | 1.00 | 0.97 |
| 9 year swap BEIR | 0.04 | 0.03 | 0.02 | 0.04 |
| 9 year bond BEIR | 0.96 | 0.97 | 0.98 | 0.96 |
| 10 year swap BEIR | 0.04 | 0.04 | 0.01 | 0.02 |
| 10 year bond BEIR | 0.96 | 0.96 | 0.99 | 0.98 |

*Note: A higher share of the bond market compared to the swap market signals, that new information is revealed to a greater extend in the bond market. Midpoints of Hasbrouck information shares are reported. Lower and upper bounds can be found in Table 13 in the Appendix. Blank spaces indicate no cointegration relation. Where appropriate according to the results in Table 11 in the Appendix the restriction of an unity vector is imposed.*

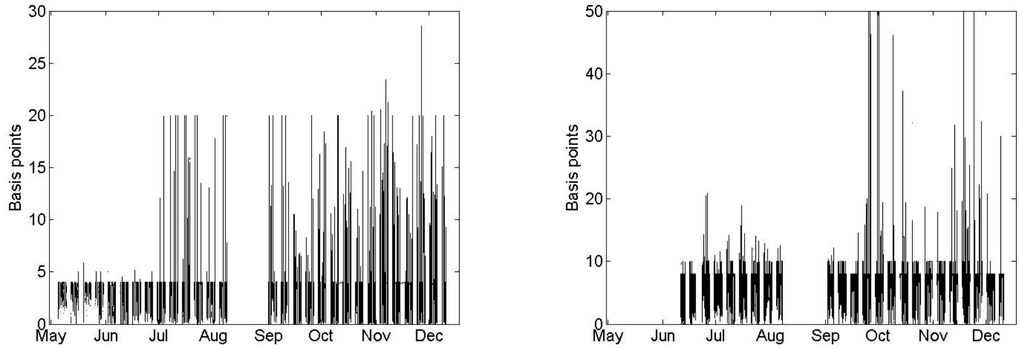
information share midpoints and Gonzalo and Granger contributions show a clear lead of the bond market in our baseline scenario (see Table 2). Only for the shortest maturity the swap market contributes less than one third to the price discovery process. Most likely the volume of the respective market does play a role in determining where price discovery takes place.

## 5.2 Price discovery in times of extreme financial crisis

In Autumn 2008 a fully-fledged financial crisis propagated through the financial system as well as the real economy. It left inter alia the US and the euro area in a recession at the year-end. The turmoil on the financial markets went along with bigger amplitudes for price changes of financial instruments. The increased variability showed up in both, the bond and the swap market (see Tables 8 and 9 in the Appendix). Standard deviations for bond and swap prices nearly quadrupled in the euro area and blew up tenfold in the US. Furthermore, the price distribution exhibited a significant lower kurtosis, eg prices were more splattered away from the mean. The higher variability was more contained for longer maturities as short term markets were firstly and persistently disrupted during the financial crisis. The mean of BEIR decreased considerably for all maturities and it even went negative for some tenors. Again the development was more pronounced in the US. The mean of the BEIR decreased far more in the US from partly over 3 percentage points to negative values of partly over one percentage point for short to medium maturities. The lower inflation expectations incorporated in the BEIR were in line with an upcoming negative economic outlook and falling energy and commodity prices which brought down actual inflation rates and inflation expectations in surveys. Nevertheless it was partly driven by the liquidity drain stemming from the withdrawal of risky assets and the search for highest-quality collateral which affected foremost nominal government bonds. The liquidity differential between nominal and real government bonds widened considerably and bond BEIR fell accordingly.

The crisis involved a significant increase of risk aversion from the part of investors and consequently affected various financial instruments and markets differently. The difference between swap and bond BEIR, the basis, increased considerably since September 2008 (see Table 4 in the Appendix). The estimated value of the coefficient $c$ which should capture the average value of the positive basis ranges from 2 to 66 basis points in the summer and from 51 to 146 basis points in the crisis sample and hence is close to the calculated basis levels. The wedge between the swap and the bond market in the US broadened up to the point where one would expect that both markets do not exhibit a near arbitrage relationship any longer. At that stage, default-to-replacement risk had become manifest for all market participants.

Still, the question remains, why the elevated basis was not arbitraged away. Three factors might have hampered the smoothing out of price differences: increased transaction costs, liquidity constrained dealers and interest rate uncertainty. Firstly, trades have become more costly due to increased bid-ask spreads. The increase was pronounced with inflation swaps in particular (see Figure 5). Even though the mean of the overall tight bid-ask spread was higher by 1 basis point in our US crisis sample and by 4 basis points in the euro area sample, variation picked up dramatically. A bid-ask spread of 20 ba-




(a) Euro area (b) US

Figure 5: Bid-ask spreads for 7 year inflation swaps.

sis points which was not unusual in November and December for some trading hours made relative value trades prohibitively costly. Furthermore, spreads went up for bond trading as well. On the bond market the spread increase was more pronounced for inflation-linked compared to nominal bonds. While the absolute rise of the spread was small in numbers it was twice as high on the inflation-indexed compared to the nominal bond market. In accordance to that trading volumes of inflation-linked bonds on electronic platforms decreased, in the case of the European MTS system by over 60 per cent. For the TIPS market a more than doubled spread as well as a reluctance to trade inflation-linked bonds were reported (Madar, Rodrigues, and Steinberg 2009). This development amplified the liquidity differential between real and nominal bonds. Bond BEIR, the difference between nominal and real bonds, went down further. Secondly, some of the most active traders, eg banks and hedge funds, faced liquidity and financing constraints. With a diminishing capital basis caused by huge write-offs, banks were forced to reduce both portfolio holdings and capital allocated to their trading desks. Hedge funds, a standard class of arbitrageurs, faced significant withdrawals from their customers admit bad performance. Furthermore, banks were less willing to finance highly leveraged operations. Thus, banks, hedge funds and other dealers could hardly invest in buying cheap bonds and reselling the inflation-linked cash flow in a likewise disturbed swap market. Thirdly, increased interest rate uncertainty might also have hampered gap offsetting trades. This is because it became more probable that rates would alter significantly during the transaction time necessary to initiate, calculate, fund and execute an arbitrage deal. Yet, it was not just demand that dried up considerably. The supply side suffered comparably since fewer people were willing to pay inflation or long-end rates.

Table 3: Regressions of bid-ask spreads on price discovery

| | *Euro area* | | |
|---|---|---|---|
| | *Intercept* | *transaction costs* | *adjusted $R^2$ in %* |
| price discovery summer | | bid-ask spreads | |
| | 0.71*** | −12.18*** | 34.92 |
| | (7.99) | (-2.09) | |
| price discovery autumn | | bid-ask spreads | |
| | 1.41*** | −17.74*** | 67.12 |
| | (10.19) | (-7.73) | |
| price discovery (both periods) | | bid-ask spreads | |
| | 0.78*** | −8.25*** | 28.65 |
| | (7.66) | (-4.61) | |
| price discovery (both periods) | | spread ratio | |
| | 0.63*** | −0.06* | 17.58 |
| | (8.78) | (-1.79) | |
| | *US* | | |
| | *Intercept* | *transaction costs* | *adjusted $R^2$ in %* |
| price discovery summer | | bid-ask spreads | |
| | 0.98*** | −13.89*** | 94.15 |
| | (49.95) | (-16.42) | |
| price discovery autumn | | bid-ask spreads | |
| | 1.12*** | −15.57*** | 96.29 |
| | (52.20) | (-19.81) | |
| price discovery (both periods) | | bid-ask spreads | |
| | 1.04*** | −14.48*** | 94.68 |
| | (39.05) | (-26.03) | |
| price discovery (both periods) | | spread ratio | |
| | 0.79*** | −0.06* | 67.69 |
| | (23.85) | (-6.42) | |

*Note: Dependant variable is Hasbrouck information shares (Gonzalo and Granger contributions to common factor yielded similar results). Transaction cost variables are the sum of bid-ask spreads of nominal and inflation-indexed bonds and single spreads for inflation swaps. Spread ratio is the relation spreads of swaps to bonds. Adjusted t-statistics based on the heteroskedasticity and autocorrelation consistent covariance matrix (Newey-West) are in parentheses. Significance at the 1, 5, and 10 % levels is indicated by ***, **, and * respectively. Data on the number of quotes per day proved to be insignificant in most regressions and hence is not reported.*

Not surprisingly the disturbances affected the pricing of different financial market instruments differently.[19] Price discovery changed significantly and nearly ceased to take place on the swap market from September to December 2008 in the euro area (see Table 1).[20] In the shortest maturity segment just under one tenth of information relevant for pricing was firstly processed in the swap market. For all other maturities pricing virtually only occurred on the bond market. Likelihood ratio tests of the variables for the cointegration vector showed weak exogeneity for bond BEIR with maturities above two years. This adds to the interpretation that in the crisis period the swap market has become nearly an appendix to the government bond market when it comes to price inflation expectations.

Overall liquidity premia or liquidity differentials stem from sources such as transaction costs, demand pressure, search frictions or private information (Amihud, Mendelson, and Pederson 2005). Regarding the disturbed arbitrage relationship wider bid-ask spreads are one of the possible proponents. We follow Eun and Sabherwal (2003) and run regressions of the level of bid-ask spreads and the ratio of the spreads on the swap and the bond market on the Hasbrouck information shares (see Table 3). Average bid-ask spreads show a significant negative relation to the respective price discovery measure. The higher the transaction costs the lower the share of price discovery in the respective market. The coefficient becomes even more negative within the crisis period. A higher absolute level of transaction costs discourage the price discovery on the respective market hence even more pronounced. The same holds for the Gonzalo and Granger contributions to the common factor. For the relative spread, i.e. bid-ask spread ratios of swap to bond markets, regression results confirm a negative impact on price discovery and contributions to the common factor. Relative transaction costs does have a negative but only weakly significant effect on price discovery, meaning that it is more absolute levels than relative transaction cost ratios that discourage price discovery. Overall wider bid-ask spreads not only impede arbitrage opportunities which is evidenced in a higher basis but tilted the incorporation of information towards the less affected market, i.e. the bond market, during the crisis.

What happened in the US in Autumn 2008 can be depicted as the collapse of an integrated market for traded inflation expectations. Technically we were not able to find a cointegration relation between the swap and the bond market for maturities of 2, 3, 4, and 6 years (see Table 11 in the Appendix). Economically speaking, arbitrage did not prevent markets from developing in completely different directions. The first explanation for this is the increase in

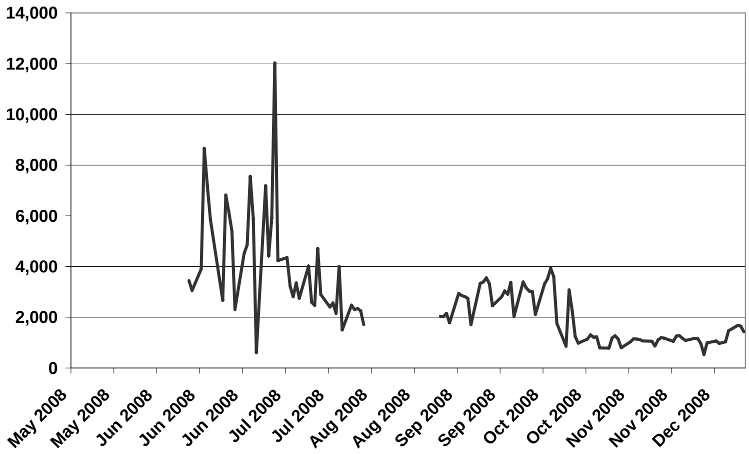



Figure 6: US Inflation Swaps: Number of daily quotes, tenor 2 years.

transaction costs due to liquidity and financial constraints. This led to a downturn in trades and for the inflation swap market even the number of quotes during a day decreased dramatically for shorter maturities (see Figure 6). Interestingly the spread ratio of swaps to bonds did not increase in the US. So it seems to be rather the absolute level of transaction costs that finally prohibited arbitrage between the bond and the swap market. Secondly, a feature that can be seen as unique for the US is that the pronounced deflationary expectations hampered relative value trades in BEIR. Inflation-linked bonds safeguard investors against deflationary deductions which are above the coupon payments since the principle is always repaid at least at 100 percent. This feature only becomes relevant in in the case of extreme deflation since the embedded option is far out of the money in normal times. However, in the extreme crisis period of Autumn 2008 it is not unreasonable to believe that investors actually assigned a positive value to this option. Furthermore, the liquidity differential between nominal and real US bonds also widened substantially and therefore led to lower bond BEIR.

For maturities of 5 years, 7 years, and above we still found a cointegration relation and the information shares showed a complete concentration of the price discovery on the government bond market. Thus declining confidence of investors hindered the trade of financial claims not only on the short term money market segment but on longer-term markets as well. Having this in mind we checked if the idiosyncratic liquidity and market risk and market-specific demand factors that affected the swap and the bond market influence all maturities to the same extent by computing forward rates. Calculations showed an even lower share of price discovery for the swap market. This corroborates our interpretation that the crisis infected the short-term segment of the market differently from long-end rates. Furthermore it shows that apart from idiosyncratic factors prevailing on both markets, the government bond market clearly dominates price discovery for traded long-term inflation expectations.[21] Solely the comparable safest instrument, government bonds, seemed to be still accepted by investors.

# 6 Conclusions

We analyze the price discovery for BEIR by using a high frequency data set on inflation-indexed as well as nominal government bonds and inflation swaps. News affecting inflation expectations incorporated in the BEIR are slightly quicker processed on bond markets for maturities up to 5 years in the euro area. For longer maturities bond markets increasingly lead the price discovery process. These results are somewhat dependent on the structure, that is the volume and liquidity of the respective markets. It is for the US where the TIPS market is large in absolute volume and compared to overall Treasury issuance that the bond market clearly determines the price formation over all time horizons. This is consistent with the notion that even full collateralization does not completely eliminate counterparty risk. The default-to-replacement risk remains: collateral is valued at the margin and does not cover the time to re-enter positions after the default of a contract party.

During Autumn 2008 the turmoil in the financial systems worldwide amplified and pricing on financial markets became seriously disturbed. Price discovery ceased to take place on the swap market. This illustrates the severe dysfunction of the normally smooth working derivative market especially for short to medium maturities. Increased bid-ask spreads hampered arbitrage between the bond and the swap market. BEIR were therefore more driven apart than during our baseline sample in Summer 2008. Disruptions coming from the short-end of the market even led to a collapse of the integration of the two US markets. Whereas a heightened risk aversion generally obstructed trades on financial markets, contributions to price formation concentrated a lot more on the safest financial instrument: government bonds. Thus, even though in times of severe financial stress swap curves often displayed a much smoother picture bond BEIR must not be omitted from economic analysis.

In general, BEIR are priced higher on the swap market. We assign this mostly to liquidity and risk premia. Furthermore the difference between instruments on both markets is not constant but displays time variation. We propose the default-to-replacement risk as well as transaction costs as features driving this time variability. Embedded put options in inflation-linked bonds which safeguard against a loss in an extreme deflationary setting are another explanation for time variable swap and bond BEIR differences. Since idiosyncratic liquidity measures apart from bid-ask spreads and instrument and maturity specific risk premia are difficult to quantify it might be a promising starting point for further research to relate changes in the liquidity premia to aggregate liquidity conditions following Adrian and Shin (2008).

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# Notes

[1]See Campbell and Shiller (1996) for an overview of early linkers, including issues from emerging markets.

[2]As of January 2009. Relative to its outstanding marketable debt the UK is still the largest issuer, with a share of of 28%.

[3]A repo or repurchase transaction is a standard technique to fund purchases of financial instruments, which serve as collateral themselves. See Buraschi and Menini (2002) for a discussion of specialness.

[4]Liu, Longstaff, and Mandell (2006) deal comprehensively with liquidity and default risk in interest rate swaps; to the extend of our knowledge, no similar study exists for inflation swaps.

[5]See Armann, Benaben, and Lambert (2005), p. 94, and Deacon, Derry, and Mirfendereski (2004), chapter 9, for a lucid treatment.

[6]France as a vanguard on issuing inflation-linked debt in the euro area has set the standard of linking claims on an index excluding tobacco products, thus controlling for adminstered prices to some degree.

[7]As reported on Bloomberg. For longer horizons, eg the French bond expiring in 2040, we would need to interpolate between infrequently traded 30 and 40 year inflation swap rates, which is prone to errors.

[8]All bonds except for the 5 year tenors are off-the-run.

[9]Intervals with only either a bid or an ask entry are eliminated.

[10]Calculating true zero coupon yields for our high frequency bond price data is nearly impossible, as necessary interpolations are prone to contaminate the marginal price change of a single bond.

[11]Only on coupon dates, there is no bias as inflation is paid out. For an explanation and visualization of seasonality in CPI see for example Peat and Segregeti 2008, pp. 183.

[12]See Eijsing, Garcia, and Werner (2007) for further explanations of the adjustment method.

[13]See Hasbrouck (1995), Baillie, Bootha, Tse, and Zabotinac (2002), Mizrach and Neely (2005) or Grammig and Peter (2008) for derivations and a discussion of both measures.

[14]The covariance matrix is $\Omega = \begin{bmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{bmatrix}$ and the lower triangular matrix is $M = \begin{bmatrix} m_{11} & 0 \\ m_{12} & m_{22} \end{bmatrix} = \begin{bmatrix} \sigma_1 & 0 \\ \rho\sigma_2 & \sigma_2(1-\rho^2)^{1/2} \end{bmatrix}$

[15]Reestimation of the VECM and the Hasbrouck information shares with the overnight returns substituted with the mean return of the following day showed virtually no influence on the parameters. We thank Franziska Peter and Joachim Grammig for performing the estimation using their Gauss procedures.

[16]Since not all time series showed linear trends we did not include them in our cointegration analysis. Nevertheless, once included the results did not change qualitatively.

[17]Wald tests on the equality of the ratio of adjustment coefficients or the ratio of the $\gamma$ respectively are rejected at conventional test sizes.

[18]This could be traffic infrastructure projects or hospitals. Many are regulated to adjust their prices by the inflation rate or receive a share of their contract payments directly inflation linked, typically the remuneration for operating expenses. See Grath and Windle (2006).

[19]We performed unit root tests for all series. The number of lags recommended by the Schwarz information criterion did not exceed 15 or 22 lags where a number of intermediate lags were excluded.

[20]Wald tests on the equality of the information shares or the ratio of the $\gamma$ for the summer and autumn period respectively are rejected for both currency areas.

[21] Numbers and more information can be found in Schulz and Stapf (2009).

# Appendix

Table 4: Basis

| *Euro Area* | | |
|---|---|---|
| | *Summer 08* | *Autumn 08* |
| | *Basis points* | |
| 2 year swap-bond BEIR | 37.9 | 45.2 |
| 4 year swap-bond BEIR | 30.7 | 49.2 |
| 5 year swap-bond BEIR | 36.7 | 68.5 |
| 7 year swap-bond BEIR | 23.4 | 55.8 |
| 8 year swap-bond BEIR | 24.2 | 61.5 |
| 12 year swap-bond BEIR | 19.8 | 53.9 |
| *US* | | |
| | *Summer 08* | *Autumn 08* |
| | *Basis points* | |
| 2 year swap-bond BEIR | -3.1 | 125.9 |
| 3 year swap-bond BEIR | 14.8 | 147.5 |
| 4 year swap-bond BEIR | 25.0 | 115.6 |
| 5 year swap-bond BEIR | 32.3 | 76.6 |
| 6 year swap-bond BEIR | 64.9 | 147.0 |
| 7 year swap-bond BEIR | 66.2 | 129.7 |
| 8 year swap-bond BEIR | 53.2 | 105.4 |
| 9 year swap-bond BEIR | 48.9 | 92.2 |
| 10 year swap-bond BEIR | 45.5 | 94.9 |

*Note: Basis is defined as average difference between swap and bond BEIR over the sample period.*

Table 5: List of euro area bonds

| Tenor | ISIN | Coupon | Type | First Issue | Maturity |
|---|---|---|---|---|---|
| 2 years | FR0108664055 | 1.25 | real | 20 Apr 2006 | 25 Jul 2010 |
| | FR0107674006 | 2.50 | nominal | 16 Jun 2005 | 12 Jul 2010 |
| 4 years | FR0000188013 | 3.00 | real | 25 Jul 2001 | 25 Jul 2012 |
| | FR0000188328 | 5.00 | nominal | 25 Apr 2001 | 25 Apr 2012 |
| 5 years | DE0001030518 | 2.25 | real | 24 Oct 2007 | 15 Apr 2013 |
| | DE0001135234 | 3.75 | nominal | 04 Jul 2003 | 04 Jul 2013 |
| 7 years | FR0010135525 | 1.60 | real | 25 Jul 2004 | 25 Jul 2015 |
| | FR0010163543 | 3.50 | nominal | 25 Apr 2004 | 25 Apr 2015 |
| 8 years | DE0001030500 | 1.50 | real | 08 Mar 2006 | 15 Apr 2016 |
| | DE0001135291 | 3.50 | nominal | 23 Nov 2005 | 04 Jan 2016 |
| 12 years | FR0010050559 | 2.25 | real | 25 Jul 2003 | 25 Jul 2020 |
| | FR0010192997 | 3.75 | nominal | 04 May 2005 | 25 Apr 2021 |

*Note: Real bonds indexed to the harmonized euro area HICP ex tobacco. Indexation month for French paper is April, for German January. All bonds pay interest annually.*

Table 6: List of US bonds

| | *Nominal bonds* | | | |
|---|---|---|---|---|
| Tenor | ISIN | Coupon | First Issue | Maturity |
| 2 years | US912828CX62 | 3.375 | 10/15/2004 | 10/15/2009 |
| 3 years | US912828FD71 | 4.875 | 5/1/2006 | 4/30/2011 |
| 4 years | US912828GQ75 | 4.5 | 4/30/2007 | 4/30/2012 |
| 5 years | US912828HY90 | 3.125 | 4/30/2008 | 4/30/2013 |
| 6 years | US912828CT50 | 4.25 | 8/16/2004 | 8/15/2014 |
| 7 years | US912828EE63 | 4.25 | 8/15/2005 | 8/15/2015 |
| 8 years | US912828FQ84 | 4.875 | 8/15/2006 | 8/15/2016 |
| 9 years | US912828HA15 | 4.75 | 8/15/2007 | 8/15/2017 |
| 10 years | US912828HR40 | 3.5 | 2/15/2008 | 2/15/2018 |
| | *Inflation-linked bonds, TIPS* | | | |
| Tenor | ISIN | Coupon | First Issue | Maturity |
| 2 years | US912828CZ11 | 0.875 | 10/29/2004 | 4/15/2010 |
| 3 years | US912828FB16 | 2.375 | 4/28/2006 | 4/15/2011 |
| 4 years | US912828GN45 | 2.0 | 4/30/2007 | 4/15/2012 |
| 5 years | US912828HW35 | 0.625 | 4/30/2008 | 4/15/2013 |
| 6 years | US912828CP39 | 2.0 | 7/15/2004 | 7/15/2014 |
| 7 years | US912828EA42 | 1.875 | 7/15/2005 | 7/15/2015 |
| 8 years | US912828FL97 | 2.5 | 7/17/2006 | 7/15/2016 |
| 9 years | US912828GX27 | 2.625 | 7/16/2007 | 7/15/2017 |
| 10 years | US912828HN36 | 1.625 | 1/15/2008 | 1/15/2018 |

*Note: TIPS are indexed to the CPI-U and pay interest semiannually. Nominal bonds pay interest semiannually.*

Table 7: Bid-ask spreads

| | *Euro area* | | | |
|---|---|---|---|---|
| | *Pre-crisis/ Summer 08* | | *Crisis/ Autumn 08* | |
| | *bond spreads* | *swap spreads* | *bond spreads* | *swap spreads* |
| 2 year | 5.40 | 3.57 | 7.34 | 5.70 |
| 4 year | 2.71 | 2.48 | 6.04 | 5.81 |
| 5 year | 0.43 | 2.31 | 2.43 | 5.71 |
| 7 year | 1.33 | 2.21 | 8.00 | 7.35 |
| 8 year | 0.90 | 2.27 | 7.35 | 7.78 |
| 12 year | 0.81 | 2.25 | 9.37 | 9.03 |
| average | 1.93 | 2.56 | 6.75 | 6.90 |

| | *US* | | | |
|---|---|---|---|---|
| | *Pre-crisis/ Summer 08* | | *Crisis/ Autumn 08* | |
| | *bond spreads* | *swap spreads* | *bond spreads* | *swap spreads* |
| 2 year | 3.98 | 6.90 | 8.61 | 9.11 |
| 3 year | 2.38 | 5.59 | 4.97 | 9.53 |
| 4 year | 0.85 | 6.34 | 3.59 | 8.12 |
| 5 year | 0.68 | 5.19 | 2.79 | 6.71 |
| 6 year | 0.57 | 6.21 | 2.39 | 6.37 |
| 7 year | 0.49 | 6.75 | 2.08 | 6.61 |
| 8 year | 0.43 | 6.27 | 1.85 | 6.35 |
| 9 year | 0.37 | 6.66 | 2.50 | 7.80 |
| 10 year | 0.35 | 5.83 | 0.60 | 6.53 |
| average | 1.54 | 6.19 | 3.27 | 7.46 |

*Note: Bond spreads are means of the sum of bid-ask spreads of the nominal and the inflation-indexed bonds. Swap spreads are means of single bid-ask spreads. All spreads are quoted in basis points on yields.*

Table 8: Descriptive statistics of bond and swap BEIR in the euro area

| | *Pre-crisis/ Summer 08* | | | *Crisis/ Autumn 08* | | |
|---|---|---|---|---|---|---|
| | *Mean* | *Std.dev.* | *Kurtosis* | *Mean* | *Std.dev.* | *Kurtosis* |
| 2 year bond BEIR | 2.35 | 0.24 | 2.54 | 0.91 | 0.90 | 1.40 |
| 4 year bond BEIR | 2,34 | 0.17 | 2.58 | 1.17 | 0.75 | 1.36 |
| 5 year bond BEIR | 2.25 | 0.16 | 2.53 | 1.11 | 0.71 | 1.31 |
| 7 year bond BEIR | 2.36 | 0.13 | 2.34 | 1.41 | 0.53 | 1.38 |
| 8 year bond BEIR | 2.34 | 0.12 | 2.58 | 1.43 | 0.53 | 1.41 |
| 12 year bond BEIR | 2.39 | 0.11 | 2.41 | 1.70 | 0.40 | 1.67 |
| 2 year swap BEIR | 2.73 | 0.23 | 2.56 | 1.36 | 0.82 | 1.43 |
| 4 year swap BEIR | 2.65 | 0.16 | 2.69 | 1.67 | 0.67 | 1.52 |
| 5 year swap BEIR | 2.62 | 0.14 | 2.61 | 1.79 | 0.59 | 1.55 |
| 7 year swap BEIR | 2.59 | 0.11 | 2.67 | 1.98 | 0.45 | 1.60 |
| 8 year swap BEIR | 2.58 | 0.10 | 2.61 | 2.05 | 0.39 | 1.62 |
| 12 year swap BEIR | 2.59 | 0.09 | 2.06 | 2.24 | 0.28 | 1.85 |

Table 9: Descriptive statistics of bond and swap BEIR in the US

| | *Pre-crisis/ Summer 08* | | | *Crisis/ Autumn 08* | | |
|---|---|---|---|---|---|---|
| | *Mean* | *Std.dev.* | *Kurtosis* | *Mean* | *Std.dev.* | *Kurtosis* |
| 2 year bond BEIR | 3.07 | 0.26 | 1.74 | -1.75 | 2.77 | 1.51 |
| 3 year bond BEIR | 2.87 | 0.20 | 1.68 | -1.22 | 2.11 | 1.48 |
| 4 year bond BEIR | 2.75 | 0.20 | 1.68 | -0.26 | 1.46 | 1.48 |
| 5 year bond BEIR | 2.67 | 0.19 | 1.76 | 0.49 | 0.95 | 1.51 |
| 6 year bond BEIR | 2.33 | 0.17 | 1.98 | -0.05 | 1,23 | 1.56 |
| 7 year bond BEIR | 2.30 | 0.15 | 2.56 | 0.26 | 1.08 | 1.60 |
| 8 year bond BEIR | 2.40 | 0.14 | 2.55 | 0.62 | 0.97 | 1.66 |
| 9 year bond BEIR | 2.43 | 0.11 | 2.54 | 0.90 | 0.75 | 1.80 |
| 10 year bond BEIR | 2.47 | 0.12 | 3.00 | 1.01 | 0.60 | 1.97 |
| 2 year swap BEIR | 3.04 | 0.33 | 1.96 | -0.49 | 1.64 | 1.58 |
| 3 year swap BEIR | 3.03 | 0.30 | 1.90 | 0.25 | 1.27 | 1.64 |
| 4 year swap BEIR | 3.00 | 0.26 | 1.88 | 0.89 | 0.90 | 1.92 |
| 5 year swap BEIR | 3.00 | 0.22 | 1.96 | 1.26 | 0.77 | 2.34 |
| 6 year swap BEIR | 2.98 | 0.20 | 2.02 | 1.41 | 0.66 | 2.06 |
| 7 year swap BEIR | 2.96 | 0.17 | 2.07 | 1.56 | 0.58 | 2.03 |
| 8 year swap BEIR | 2.93 | 0.14 | 2.22 | 1.67 | 0.53 | 2.15 |
| 9 year swap BEIR | 2.92 | 0.12 | 2.44 | 1.82 | 0.46 | 2.29 |
| 10 year swap BEIR | 2.93 | 0.10 | 2.36 | 1.96 | 0.38 | 2.38 |

Table 10: Long-run relation between swap and bond BEIR in the euro area

| | *Pre-crisis/ Summer 08* | | |
|---|---|---|---|
| | *# coint. vectors (cv)* | | *Restriction on cv* |
| | *None* | *At most 1* | *(1,-1,c)* |
| 2 year swap-bond BEIR | 66.91*** | 2.59 | 1.18 |
| 4 year swap-bond BEIR | 111.07*** | 3.05 | 2.85* |
| 5 year swap-bond BEIR | 97.61*** | 2.66 | 22.43*** |
| 7 year swap-bond BEIR | 166.85*** | 3.41 | 67.49*** |
| 8 year swap-bond BEIR | 187.65*** | 3.31 | 66.10*** |
| 12 year swap-bond BEIR | 61.64*** | 5.23 | 16.65*** |
| | *Crisis/ Autumn 08* | | |
| | *# coint. vectors (cv)* | | *Restriction on cv* |
| | *None* | *At most 1* | *(1,-1,c)* |
| 2 year swap-bond BEIR | 151.93*** | 2.93 | 60.71*** |
| 4 year swap-bond BEIR | 44.94*** | 3.09 | 11.39*** |
| 5 year swap-bond BEIR | 23.88*** | 3.47 | 7.46*** |
| 7 year swap-bond BEIR | 23.27*** | 2.97 | 5.19** |
| 8 year swap-bond BEIR | 35.19*** | 3.36 | 19.33*** |
| 12 year swap-bond BEIR | 46.67*** | 3.13 | 30.17*** |

Rejections of the null at the 10%, 5%, or 1% level is indicated by a superscript *,**, or *** respectively.

*Note: First two columns show Johanson trace statistics for determination of number of cointegration vectors with specification:* $H_1^*(r)$. *Column three shows* $\chi^2$ *test statistics for LR test for binding restrictions on* $\beta = (1, -1, c)$.

Table 11: Long-run relation between swap BEIR and bond BEIR in the US

| | *Pre-crisis/ Summer 08* | | |
|---|---|---|---|
| | *# coint. vectors (cv)* | | *Restriction on cv* |
| | *None* | *At most 1* | *(1,-1,c)* |
| 2 year swap-bond BEIR | 34.23*** | 0.73 | 1.98 |
| 3 year swap-bond BEIR | 87.77*** | 0.96 | 16.53*** |
| 4 year swap-bond BEIR | 90.90*** | 0.75 | 29.07*** |
| 5 year swap-bond BEIR | 122.79*** | 0.94 | 26.83*** |
| 6 year swap-bond BEIR | 179.55*** | 1.07 | 71.53*** |
| 7 year swap-bond BEIR | 139.04*** | 1.61 | 44.11*** |
| 8 year swap-bond BEIR | 122.31*** | 2.15 | 0.04 |
| 9 year swap-bond BEIR | 128.65*** | 1.56 | 0.48 |
| 10 year swap-bond BEIR | 145.78*** | 2.10 | 19.13*** |
| | *Crisis/ Autumn 08* | | |
| | *# coint. vectors (cv)* | | *Restriction on cv* |
| | *None* | *At most 1* | *(1,-1,c)* |
| 2 year swap-bond BEIR | 119.73*** | 12.05*** | |
| 3 year swap-bond BEIR | 181.45*** | 31.88*** | |
| 4 year swap-bond BEIR | 54.65*** | 9.21** | |
| 5 year swap-bond BEIR | 25.30*** | 7.34 | 4.40** |
| 6 year swap-bond BEIR | 52.28*** | 10.76** | |
| 7 year swap-bond BEIR | 61.18*** | 6.94 | 44.68*** |
| 8 year swap-bond BEIR | 56.14*** | 7.71 | 40.39*** |
| 9 year swap-bond BEIR | 41.20*** | 7.28 | 22.89*** |
| 10 year swap-bond BEIR | 41.89*** | 2.70 | 24.92*** |

Rejections of the null at the 10%, 5%, or 1% level is indicated by a superscript *,**, or *** respectively.

*Note: First two columns show Johanson trace statistics for determination of number of cointegration vectors with specification: $H_1^*(r)$. Column three shows $\chi^2$ test statistics for LR test for binding restrictions on $\beta = (1, -1, c)$.*

Table 12: Bounds on Hasbrouck information shares in the euro area

| | *Summer* | | *Autumn* | |
|---|---|---|---|---|
| | *Lower* | *Upper* | *Lower* | *Upper* |
| 2 year swap BEIR | 0.44 | 0.47 | 0.08 | 0.11 |
| 2 year bond BEIR | 0.53 | 0.56 | 0.89 | 0.92 |
| 4 year swap BEIR | 0.42 | 0.47 | 0.03 | 0.07 |
| 4 year bond BEIR | 0.54 | 0.58 | 0.93 | 0.97 |
| 5 year swap BEIR | 0.41 | 0.46 | 0.04 | 0.08 |
| 5 year bond BEIR | 0.54 | 0.59 | 0.92 | 0.96 |
| 7 year swap BEIR | 0.27 | 0.32 | 0.03 | 0.06 |
| 7 year bond BEIR | 0.68 | 0.73 | 0.93 | 0.97 |
| 8 year swap BEIR | 0.08 | 0.10 | 0.03 | 0.06 |
| 8 year bond BEIR | 0.90 | 0.92 | 0.94 | 0.98 |
| 12 year swap BEIR | 0.29 | 0.37 | 0.01 | 0.03 |
| 12 year bond BEIR | 0.63 | 0.70 | 0.97 | 0.99 |

*Note: Upper and lower bounds of Hasbrouck information shares refer to the ordering, where the upper bound is calculated for the respective market is first in the ordering of the variables for factorization. This puts the most weight to price discovery on the first market. Since the ordering of the two markets can not be unequivocally justified by economic reason ex-ante, reporting upper and lower bounds gives information on the impact of the ordering on the price discovery results for each market. The higher the divergence the higher the impact. Nevertheless the midpoint is not affected by the divergence of the bounds (see Table 1). Where appropriate according to the results in Table 10 the restriction of an unity vector is imposed.*

Table 13: Bounds on Hasbrouck information shares in the US

| | *Summer* | | *Autumn* | |
|---|---|---|---|---|
| | *Lower* | *Upper* | *Lower* | *Upper* |
| 2 year swap BEIR | 0.27 | 0.27 | | |
| 2 year bond BEIR | 0.73 | 0.73 | | |
| 3 year swap BEIR | 0.44 | 0.47 | 0.08 | 0.11 |
| 3 year bond BEIR | 0.11 | 0.12 | | |
| 4 year swap BEIR | 0.88 | 0.89 | | |
| 4 year bond BEIR | 0.13 | 0.13 | | |
| 5 year swap BEIR | 0.86 | 0.87 | 0.03 | 0.04 |
| 5 year bond BEIR | 0.10 | 0.11 | 0.96 | 0.97 |
| 6 year swap BEIR | 0.18 | 0.19 | | |
| 6 year bond BEIR | 0.81 | 0.82 | | |
| 7 year swap BEIR | 0.09 | 0.09 | 0.02 | 0.02 |
| 7 year bond BEIR | 0.91 | 0.91 | 0.98 | 0.98 |
| 8 year swap BEIR | 0.04 | 0.04 | 0.00 | 0.00 |
| 8 year bond BEIR | 0.96 | 0.96 | 1.00 | 1.00 |
| 9 year swap BEIR | 0.04 | 0.04 | 0.01 | 0.02 |
| 9 year bond BEIR | 0.96 | 0.96 | 0.98 | 0.99 |
| 10 year swap BEIR | 0.04 | 0.04 | 0.00 | 0.01 |
| 10 year bond BEIR | 0.96 | 0.96 | 1.00 | 0.99 |

*Note: Upper and lower bounds of Hasbrouck information shares refer to the ordering, where the upper bound is calculated for the respective market is first in the ordering of the variables for factorization. This puts the most weight to price discovery on the first market. Since the ordering of the two markets can not be unequivocally justified by economic reason ex-ante, reporting upper and lower bounds gives information on the impact of the ordering on the price discovery results for each market. The higher the divergence the higher the impact. Nevertheless the midpoint is not affected by the divergence of the bounds (see Table 2). Where appropriate according to the results in Table 11 the restriction of an unity vector is imposed.*