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Arbitrage costs and the persistent non-zero CDS-bond basis: Evidence from intraday euro area sovereign debt markets*

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Abstract

We find evidence that in the market for euro area sovereign credit risk, arbitrageurs engage in basis trades between credit default swap (CDS) and bond markets only when the CDS-bond basis exceeds a certain threshold. This threshold effect is likely to reflect costs that arbitrageurs face when implementing trading strategies, including transaction costs and costs associated with committing balance sheet space for such trades. Using a threshold vector error correction model, we endogenously estimate these unknown trading costs for basis trades in the market for euro area sovereign debt. During the euro sovereign credit crisis, we find very high transaction costs of around 190 basis points, compared to around 80 basis points before the crisis. Our results show, that even when markets in times of stress are liquid, the basis can widen as high market volatility makes arbitrage trades riskier, leading arbitrageurs to demand a higher compensation for increased risk. Our findings help explain the persistent non-zero CDS-bond basis in euro area sovereign debt markets and its increase during the last sovereign crisis.

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1 Introduction

The theoretical no-arbitrage condition between credit default swaps (CDS) and credit-risky bonds based on Duffie (1999) is a cornerstone for empirical research on price discovery in credit risk markets. This condition requires that CDS spreads and (par floating rate) spreads on bonds issued by the entity referenced in the CDS contract must be equal, as any discrepancy would present investors with an arbitrage opportunity. For this no-arbitrage condition to hold, markets must be perfect and frictionless. In practice, however, frictions and imperfections often make such arbitrage trades difficult and costly to varying degree. These imperfections include limited and time-varying liquidity across market segments, unavailability of instruments with identical maturity and payout structures, and the fact that some arbitrage trades require tying up large amounts of capital for extended periods of time. As a result, the difference between the CDS premium and the bond spread, the so-called basis, is typically not zero. Moreover, the basis can become sizeable and persistent in times of market stress. This was particularly evident during the euro area sovereign debt crisis, when the basis widened significantly (see for example Fontana and Scheicher (2016) and Gyntelberg et al. (2013)). This paper adds to the existing literature by analysing the importance of arbitrage trading and arbitrage costs with respect to the size of the CDS-bond basis.

A persistent non-zero CDS-bond basis is likely to reflect the unwillingness of arbitrageurs to try to exploit it, unless the pricing mismatch is greater than the overall transaction costs of undertaking the arbitrage trade. Empirically, we would therefore expect to see such arbitrage forces intensifying as the magnitude of the basis exceeds some level that reflects the overall, average transaction costs for implementing the arbitrage trade. This suggests that the adjustment process towards the long-run equilibrium is nonlinear, in that it differs depending on the level of the basis. In order to capture such behaviour, we extend the vector error correction model (VECM) which has been the convention in existing studies (see for example Blanco et al. (2005) and Zhu (2004) for corporates, Ammer and Cai (2007) for emerging markets, and Fontana and Scheicher (2016), Gyntelberg et al. (2013), Mayordomo et al. (2011) and Palladini and Portes (2011) for euro area sovereigns) to a nonlinear set-up using a threshold VECM (TVECM). This framework will help to answer the question if transaction costs on arbitrage trades were related to the widening of the CDS-bond basis during the sovereign debt crisis period. As it is impossible to disentangle the exact transaction costs for arbitrage trades in sovereign credit risk, our estimated transaction costs comprise overall costs that arbitrageurs face when implementing these trading strategies such as liquidity costs, funding cost, repo costs, risk compensation, search costs, cost associated with committing balance sheet space, etc..

One of the key contributions of our paper to the existing literature on price discovery in credit markets is that, in contrast to all studies mentioned above, we allow for a non-linear adjustment of prices in CDS and bond markets towards the long-run equilibrium. This allows us to determine whether a relationship exists between the overall costs that arbitrageurs face in the market for sovereign risk and the magnitude of the CDS-bond basis. Hence, with this model we can capture the possibility that arbitrageurs step into the market only when the trading opportunity is sufficiently profitable. Our TVECM approach can directly quantify the threshold beyond which such trading opportunities are seen by investors as 'sufficiently profitable'. Furthermore, our results show that even when markets in times of stress are liquid, the basis can widen as high market volatility makes arbitrage trades riskier, leading arbitrageurs to demand higher compensation (suggesting a higher threshold) before stepping into the market. This could explain why the basis reached very high levels during the euro area sovereign debt crisis as it was subject to considerable volatility in a stressed market environment.

Our analysis relies on intraday price data for both CDS and bonds, allowing us to estimate the spread dynamics and the price discovery implications substantially more accurately than existing studies that rely on lower frequency data. Our TVECM approach identifies thresholds in the CDS-bond basis, below which arbitrageurs are reluctant to step in. We also find that once the basis exceeds the estimated transaction costs (given by the threshold and the constant long-run mean of the basis), the adjustment speeds towards the long run equilibrium intensify. This supports our assumption that arbitrageurs only step into the market when the trade becomes profitable. We find that the estimated average transaction cost is around 80 basis points in the pre-crisis period. During the euro area sovereign debt crisis this average increased to around 190 basis points. This increase in the estimated threshold during the crisis period coincided with a higher CDS-bond basis volatility. As arbitrageurs face the risk that the arbitrage trade will go in the wrong direction in the short run, they will demand higher compensation for undertaking the arbitrage trade in volatile markets. Thus, our findings help to explain the persistent non-zero basis in markets for sovereign credit risk.

The remainder of the paper is structured as follows. Section 2 discusses in more detail the relationship between sovereign CDS and bonds. Section 3 explains our data, while Section 4 discusses the set-up and estimation of our TVECM. Section 5 provides the empirical results and Section 6 concludes.

2 Relation between sovereign CDS and bonds

The importance of frictions in credit risk modelling is well-known. However, only few empirical studies analyse the effects of frictions on the price discovery process for credit risk. Several papers conclude that for example liquidity affects corporate bond spreads significantly (eg Chen et al. (2007), Ericsson and Renault (2006), Elton et al. (2001) and Mahanti et al. (2008)). By contrast, other papers argue that CDS spreads reflect pure credit risk, ie that they are not significantly affected by liquidity (eg Longstaff et al. (2005)). However, there are numerous papers reporting that CDS spreads are too high to represent pure credit risk (eg Berndt et al. (2005), Blanco et al. (2005), Pan and Singleton (2005)). Tang and Yan (2007) find that the level of liquidity and liquidity risk are important factors in determining CDS spreads. Hull and White (2000) address the effects of market frictions from a theoretical point of view and determine conditions under which CDS prices are affected. Longstaff et al. (2005) study price differences between CDS and bonds and attribute them to liquidity and counterparty risk. Also Zhu (2004) concludes that liquidity matters in CDS price discovery. Ammer and Cai (2007), Levy (2009) and Mayordomo et al. (2011) find evidence that liquidity (as measured by the bid-ask spread) is a key determinant for price discovery, but without explicitly modelling any market frictions. Tang and Yan (2007) focus on pricing effects in CDS and show that the liquidity effects on CDS premia are comparable to those on treasury and corporate bonds (Tang and Yan; 2007).

2.1 Frictionless markets

In a frictionless market, the CDS premium should equal the spread on a par fixed-rate bond (issued by the same entity as referenced by the CDS) over the riskfree interest rate (Duffie (1999)). Both the CDS premium and the risky bond's yield spread is compensation to investors for being exposed to default risk, and must therefore be priced equally in the two markets. However, for this no-arbitrage relationship to hold exactly, a number of specific conditions must be met, including that markets are perfect and frictionless, that bonds can be shorted without restrictions or cost, that there are no tax effects, etc. Any departures from this perfect environment will introduce potential wedges between the pricing of credit risk in CDS contracts and in bonds.

Moreover, given that floating rate notes are relatively uncommon, in particular for sovereigns, any comparison between CDS spreads and bond spreads based on fixed-rate bonds will introduce other distortions. Hence, the observed difference between the CDS premium and the bond spread, the basis, is typically not zero.

2.2 Markets with frictions

There are a number of recent papers that focus on the pricing of sovereign credit risk in the euro area, which all find that the theoretical no-arbitrage condition between CDS spreads and bond spreads does not hold (for example Fontana and Scheicher (2016), Gyntelberg et al. (2013), Arce et al. (2012), and Palladini and Portes (2011)). Gyntelberg et al. (2013) find that the basis across seven euro area sovereign entities[1] is almost always positive over the 2008-11 sample period for the 5 year and the 10 year tenor. Moreover, they find that the basis varies substantially across countries, with means ranging from 74 to 122 basis points for the 5-year tenor, and from 58 to 175 basis points for the 10-year tenor. Empirical research on corporate credit risk also points towards a non-zero basis as shown for example in Nashikkar et al. (2011), Blanco et al. (2005) and Zhu (2004), and for emerging markets sovereign credit risk according to Ammer and Cai (2007).

The CDS market is a search market as the contracts are traded over-the-counter (OTC) where parties have to search for each other in order to bargain and match a trade. Therefore, market trading is not continuous in the sense that it is not necessarily possible to buy or sell any amount immediately (Black; 1971). Moreover, other frictions and imperfections may make arbitrage trades difficult and costly. These imperfections include limited and time-varying liquidity in some or all market segments, unavailability of instruments with identical maturity and payout structures, and the fact that some arbitrage trades require tying up large amounts of capital for extended periods of time. As the costs associated with tying up space on banks' balance sheets have risen following the global financial crisis, this can represent a significant hurdle that traders face in the market. Furthermore, the no-arbitrage condition relies on the ability to short sell bonds, which is not always costless and sometimes even impossible due to illiquid markets. All of these imperfections contribute to explaining why the basis between CDS and bond spreads can deviate from zero, often substantially and persistently. However, we would expect to see arbitrage forces come into play if the basis becomes "too wide", thereby pushing it back towards zero. Clearly, we would also expect to see stronger adjustment forces in CDS and bond markets when the basis exceeds some critical threshold. The size of the threshold would reflect the various arbitrage costs traders face in markets, including costs for illiquidity as well as for tying up costly capital for possibly long periods of time.

3 Data

For our empirical analysis we use intraday price quotes for CDS contracts and government bonds for France, Germany, Greece, Ireland, Italy, Portugal and Spain. We choose this group of countries because they include those that were most affected by the euro sovereign debt crisis. Germany is included as a near-riskfree reference country, and France which we consider as a low-risk control country. We use 5- and 10-year USD-denominated CDS quotes for all countries in our sample. As documented in Gyntelberg et al. (2013), the

[1] France, Germany, Greece, Ireland, Italy, Portugal, Spain; 5- and 10-year tenor from October 2008 to end-May 2011

5-year segment is more liquid than the 10-year segment, particularly as the sovereign debt crisis intensified.

Our sovereign bond price data is provided by MTS (Mercato Telematico dei Titoli di Stato). The MTS data consists of both actual transaction prices and binding bid-offer quotes. The number of transactions of sovereign bonds on the MTS platform is however not sufficient to allow us to undertake any meaningful intraday analysis. Therefore, we use the trading book from the respective domestic MTS markets.[2]

The CDS data consists of price quotes provided by CMA (Credit Market Analysis Ltd.) Datavision. CMA continuously gathers information on executable and indicative CDS prices directly from the largest and most active credit investors. After cleaning and checking the individual quotes, CMA applies a time and liquidity weighted aggregation so that each reported bid and offer price is based on the most recent and liquid quotes.[3]

We construct our intraday data on a 30-minute sampling frequency for the available data sets that span from January 2008 to end-December 2011. The available number of indicative quotes for CDS does not allow higher data frequency than 30 minutes. The euro area sovereign CDS markets were very thin prior to 2008, which makes any type of intraday analysis before 2008 impossible (for a discussion please refer to Gyntelberg et al. (2013)).

When implementing our analysis we split the data into two sub-samples. The first sub-sample covers the period January 2008 to end-March 2010, and as such represents the period prior to the euro area sovereign debt crisis (van Rixtel and Gasperini; 2013). While this period includes the most severe phase of the financial crisis, including the default of Lehman Brothers, it is relatively unaffected by any major market concerns about the sustainability of public finances in euro area countries. The second sub-sample covers the euro area sovereign debt crisis period and runs from April 2010 to December 2011. We have tested other break downs in a pre-crisis and crisis period[4] and have found that our results remain robust.

In order to accurately match the maturities and the cash flow structures of the CDS and the cash components for the measurement of the CDS-bond basis, we calculate intra-

[2] We ignore quotes from the centralized European platform (market code: EBM), as quotes for government bonds on the centralised platform are duplicates of quotes on the domestic platforms. The MTS market is open from 8:15 to 17:30 local Milan time, preceded by a pre-market phase (7.30 to 8.00) and an offer-market phase (8:00 to 8:15). We use data from 8:30 to 17:30.

[3] The CDS market, which is an OTC market, is open 24 hours a day. However, most of the activity in the CMA database is concentrated between around 7:00 and 17:00 London time. As we want to match the CDS data with the bond market data, we restrict our attention to the period from 8:30 to 17:30 local Milan time.

[4] We have for example tested the 20 October 2009 as the beginning of the crisis period. At that date the new Greek government announced that official statistics on Greek debt had previously been fabricated. Instead of a public deficit estimated at 6% of GDP for 2009, the government now expected a figure at least twice as high.

day asset swap (ASW) spreads based on estimated zero-coupon government bond prices according to Nelson and Siegel (1987). Appendix A provides details. The use of ASW spreads is also in line with the practice applied in commercial banks when trading the CDS-bond basis. By calculating ASW spreads we ensure that we are comparing like with like in our empirical analysis, and we avoid introducing distortions by using imperfect cash spread measures, such as simple "constant maturity" yield differences.

An asset swap is a financial instrument that exchanges the cash flows from a given security - eg a particular government bond - for a floating market rate[5]. This floating rate is typically a reference rate such as Euribor for a given maturity plus a fixed spread, the ASW spread. This spread is determined such that the net value of the transaction is zero at inception. The ASW allows the investor to maintain the original credit exposure to the fixed rate bond without being exposed to interest rate risk. Hence, the ASW is similar to the floating-rate spread that theoretically should be equivalent to a corresponding CDS spread on the same reference entity.

Finally, we note that using intraday data in our empirical analysis should enable us to obtain much sharper estimates and clearer results with respect to market mechanisms and price discovery compared to any analysis carried out with a lower data frequency (see Gyntelberg et al. (2013)).

Using the above methodology, we derive the intraday asset swap spreads for each country for the 5- and 10-year maturities (displayed in Appendix B). The corresponding CDS series are also shown in Appendix B while the CDS-bond basis is displayed in Figures 2 and 3.

In Appendix C we present information on liquidity such as number of ticks, number of trades and bid-ask spreads for CDS and bonds. Interestingly, we find that for example the number of data ticks for our sovereign bonds remained quite stable over the whole sample period and that the 5-year tenor is typically more liquid than the 10-year tenor. The number of indicative CDS prices (see Figure C.1) remained stable for the 5-year tenor (Greece is an exception) and decreased for the 10-year tenor. The number of trades reported in the EuroMTS platform decreased slightly for most GIIPS countries since the onset of the euro area sovereign debt crisis (see Figure C.3). On the other hand, the sovereign CDS data shows that the number of ticks more than doubled in 2010, as the crisis spread. The bid-ask spreads for our sovereign CDS and bonds tighten over our sample period in France and Germany. While CDS bid-ask spreads in GIIPS countries are typically very tight, the spread size is quite volatile for bonds. While we can see that the bid-ask spreads for the Irish, Italian, Portuguese and Spanish 5-year bonds widen

[5] See Appendix A. Gyntelberg et al. (2013) and O'Kane (2000) further discuss the mechanics and pricing of asset swaps.

during the sovereign debt crisis period, we can not see the same behaviour in the 10-year bond segment (Figure C.6).

Thus, the dramatic increase of the CDS-bond basis during the euro area sovereign debt crisis can not be exclusively explained by market liquidity, but seems to be linked to overall transaction cost in these markets.

4 Threshold vector error correction model (TVECM)

We begin our empirical analysis by examining the statistical properties of our spread time series. This analysis shows that the series are I(1) and that the CDS and ASW series are cointegrated (see Appendix D and E). As a result, we can employ a vector error correction model (VECM) to study the joint price formation process in both markets. From the estimated error correction model we calculate measures that indicate which of the two markets is leading the price discovery process as well as examine the speed of adjustment towards the long-term equilibrium.

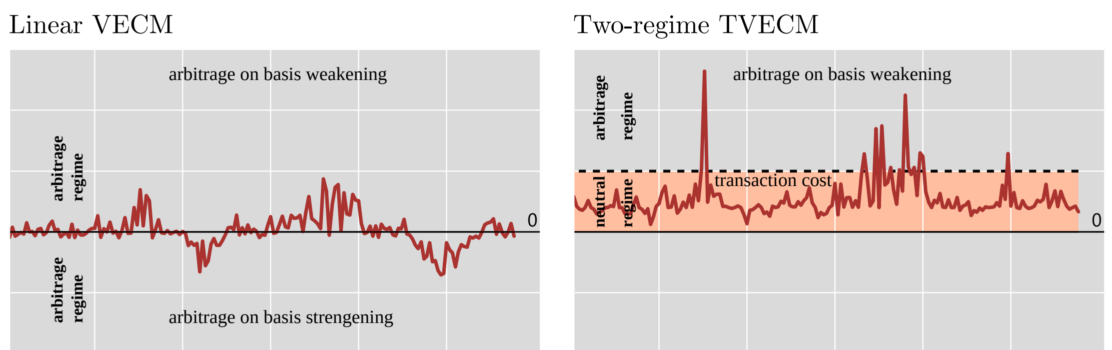
The linear VECM concept implies that any deviation from the long-run equilibrium of CDS and ASW spreads will give rise to dynamics that will bring the basis back to the equilibrium due to an error correction mechanism as illustrated in the left panel of Figure 1. Thus, in a market with no frictions (such as transaction costs) every deviation from the non-zero basis will initiate arbitrage trades on the pricing differential between the spot and the derivatives market (Figure 1). Hence, in a frictionless market, the basis will typically fluctuate around zero.

Given that the CDS and bond markets are subject to market frictions and arbitrageurs face various trading costs, it is useful to extend the linear VECM approach[6] to a threshold vector error correction model (TVECM). Threshold cointegration was introduced by Balke and Fomby (1997) as a feasible mean to combine regime switches and cointegration. The TVECM model allows for nonlinear adjustments to the long-term equilibrium in CDS and bond markets. In our case, such nonlinear adjustment dynamics should be able to capture arbitrageurs' decisions to only step into the market when the basis exceeds some critical threshold, such that the expected profit exceeds the transaction costs. As a result, adjustments to the long-term equilibrium would then be regime-dependent, with a relatively weak adjustment mechanism below the threshold (a 'neutral' regime) and a stronger adjustment mechanism above it. This is illustrated in the right panel of Figure 1. The example in this figure displays a predominantly positive basis as this is also the case in our underlying data (see Figures 2 and 3).

[6] As in eg Fontana and Scheicher (2016), Gyntelberg et al. (2013) and Blanco et al. (2005).

Figure 1: Linear versus Threshold Vector Error Correction Model

The linear VECM model in the left panel represents markets where the theoretical no-arbitrage condition holds approximately as the basis does not deviate too much from zero. Otherwise arbitrageurs step in immediately to trade on pricing differentials between the spot and the derivatives market which reverts the basis back towards zero. The right-hand panel shows the case for markets that are subject to non-negligible transaction costs. Arbitrageurs will only step in once the expected gain from the trade is above the transaction costs, in the "arbitrage regime". A predominantly positive basis is shown in this example as this reflects the typical conditions in euro sovereign debt markets.



4.1 Model specification

Let $y_t = (CDS_t \quad ASW_t)^\intercal$ represent the vector of CDS and ASW spreads at time t for a specific sovereign entity. The TVECM approach allows the behaviour of y_t to depend on the state of the system. In our data, the basis for all reference entities is almost always positive. Hence, we expect to find at most two regimes with one threshold θ, above which arbitrageurs can be expected to step in to trade on the pricing difference in the two markets, but below which they will have little or no incentive to do so. One can formulate a two-regime TVECM as follows[7]:

$$\Delta CDS_t = \left[\lambda_1^L \mathrm{ec_{t-1}} + \Gamma_1^{\mathrm{L}}(\ell)\Delta \mathrm{y_t}\right] d_{Lt}(\beta,\theta) + \left[\lambda_1^U \mathrm{ec_{t-1}} + \Gamma_1^{\mathrm{U}}(\ell)\Delta \mathrm{y_t}\right] d_{Ut}(\beta,\theta) + \varepsilon_t^{CDS},$$
$$\Delta ASW_t = \left[\lambda_2^L \mathrm{ec_{t-1}} + \Gamma_2^{\mathrm{L}}(\ell)\Delta \mathrm{y_t}\right] d_{Lt}(\beta,\theta) + \left[\lambda_2^U \mathrm{ec_{t-1}} + \Gamma_2^{\mathrm{U}}(\ell)\Delta \mathrm{y_t}\right] d_{Ut}(\beta,\theta) + \varepsilon_t^{ASW}$$

or in vector form,

$$\Delta y_t = \left[\lambda^L \mathrm{ec_{t-1}} + \Gamma^{\mathrm{L}}(\ell)\Delta \mathrm{y_t}\right] d_{Lt}(\beta,\theta) + \left[\lambda^U \mathrm{ec_{t-1}} + \Gamma^{\mathrm{U}}(\ell)\Delta \mathrm{y_t}\right] d_{Ut}(\beta,\theta) + \varepsilon_t \qquad (1)$$

[7] for a derivation of the TVECM see for example Balke and Fomby (1997)

where $\mathrm{ec}_{t-1} = (CDS_{t-1} - \beta_0 - \beta_1 ASW_{t-1})$ is the error correction term, $\Gamma^j(\ell)\Delta y_t$, $j \in \{L, U\}$ represents the VAR term of some order, expressed in lag operator (ℓ) representation, and $\varepsilon_t = (\varepsilon_t^{CDS} \quad \varepsilon_t^{ASW})^\intercal$ is a vector of i.i.d. shocks. The lower regime (specified by the index L) is defined as $\mathrm{ec}_{t-1} \leq \theta$, and the upper regime (specified by the index U) as $\mathrm{ec}_{t-1} > \theta$. Hence d_{Lt} and d_{Ut} are defined using the indicator functions $I(\cdot)$ as follows:

$$d_{Lt}(\beta, \theta) = I(\mathrm{ec}_{t-1} \leq \theta),$$
$$d_{Ut}(\beta, \theta) = I(\mathrm{ec}_{t-1} > \theta).$$

The error correction term ec_{t-1} represents the long-term equilibrium of the two time series which has to be stationary by construction (Johansen; 1988). The number of lags in the VAR terms are determined using the Schwarz information criterion. We constrain β_1 to 1 which is motivated by our no-arbitrage discussion in Section 2. A non-zero estimated β_0 represents a persistent non-zero basis. The average transaction costs that arbitrageurs need to overcome, as implied by the model, can now be identified as $\theta + \beta_0$.

The speed of adjustment parameters λ^U and λ^L characterize to what extent the price changes in $\Delta y_t = (\Delta CDS_t \quad \Delta ASW_t)^\intercal$ react to deviations from the long-term equilibrium. In case price discovery takes place only in the bond market we would find a negative and statistically significant λ_1^j and a statistically insignificant λ_2^j, as the CDS market would adjust to correct the pricing differentials from the long-term relationship. In other words, in this case the bond market would move ahead of the CDS market as relevant information reaches investors. Conversely, if λ_1^j is not statistically significant but λ_2^j is positive and statistically significant, the price discovery process takes place in the CDS market only - that is, the CDS market moves ahead of the bond market. In cases where both λ's are significant, with λ_1^j negative and λ_2^j positive, price discovery takes place in both markets.

We expect to find the speed of adjustment parameters to indicate that arbitrageurs are engaging in CDS-ASW basis trades if the basis exceeds the average transaction costs of $(\theta + \beta_0)$. In a market with a positive basis (CDS > ASW), arbitrageurs will bet on a declining basis and will therefore short credit risk in the bond market and go long credit risk in the CDS market, ie sell the bond and sell the CDS (Gyntelberg et al.; 2013).[8] The predominantly positive basis throughout our sample suggests the presence of at most one threshold.

Moreover, we expect to find higher transaction costs $(\theta + \beta_0)$ in times of market stress. This can be explained by the fact that when the basis is subject to increased volatility, the risk increases that any arbitrage trade moves in the wrong direction in the short or medium

[8] In case of a negative basis (ASW > CDS), arbitrageurs bet on an increasing basis while carrying out the reverse trade. In markets where the basis regularly would fluctuate between being positive and negative, we would expect to find a 3-regime TVECM. With a lower regime $\mathrm{ec}_{t-1} \leq \theta^1$, a middle regime (neutral regime) $\theta^1 < \mathrm{ec}_{t-1} \leq \theta^2$, and a upper regime $\theta^2 < \mathrm{ec}_{t-1}$.

term. Therefore, arbitrageurs will demand higher compensation for taking such positions in times when the basis volatility is high, resulting in higher estimated thresholds.

4.2 Estimating the threshold

As discussed above, the positive basis in our sample suggests the presence of at most one threshold. In order to test for the presence of a threshold effect, we follow the method proposed by Hansen and Seo (2002) who extend the literature by examining the case of an unknown cointegrating vector.[9] They implement maximum likelihood estimation (MLE) of a bivariate TVECM with two regimes. Their algorithm involves a joint grid search over the threshold and the cointegrating vector while using the error-correction term as the threshold variable (see Equation (1)). All coefficients are allowed to switch between these two regimes. Only the cointegrating vector β remains fixed across all regimes, by construction. We follow this grid search estimation approach, subject to the constraint $\beta_1 = 1$, motivated by our no-arbitrage discussion in Section 2.

As in Hansen and Seo (2002) we estimate the model while imposing the following additional constraint:

$$\pi_0 \leq P(\mathrm{ec}_{t-1} \leq \theta) \leq 1 - \pi_0 \tag{2}$$

where $\pi_0 > 0$ is a trimming parameter and P is the share of observations in each regime. This constraint allows us to identify a threshold effect only if the share of observations in each regime is greater than π_0. If this condition is not met, the model reduces to a linear VECM. Andrews (1993) argues that setting π_0 between 0.05 and 0.15 are typically good choices. As we use intraday data of the order of 10,000 observations, we set the trimming parameter to $\pi_0 = 0.10$, which will still ensure an adequate number of observations in both regimes.

4.3 Statistical testing for a threshold

Once a threshold has been identified, the next step is to determine whether the estimated threshold θ is statistically significant. Under the null hypothesis $\mathscr{H}_0$ there is no threshold, so the model reduces to a conventional linear VECM where $\lambda^L = \lambda^U$. The two regime TVECM is the alternative hypothesis $\mathscr{H}_1$ with $\lambda^L \neq \lambda^U$ under the constraint in Equation (2). The linear VECM under $\mathscr{H}_0$ is nested in Equation (1), hence, a regular LM test with an asymptotic $\chi^2(N)$-distribution can be calculated based on Equation (1). However, the LM test can only be applied if the cointegrating vector β and the threshold variable θ are known a priori (Hansen and Seo; 2002). While the point estimate of β under $\mathscr{H}_0$ is

[9] Balke and Fomby (1997) and Tsay (1989) transform the TVECM specification into a univariate regression while the cointegrating vector is known a priori.

$\hat{\beta}$ from the linear model, there is no estimate of θ under $\mathscr{H}_0$. This implies that there is no distribution theory for the parameter estimates and no conventionally defined LM statistic.

As there is no formal distribution theory under the $\mathscr{H}_0$ we follow Hansen and Seo (2002) and perform two different bootstrap analyses in order to estimate the distribution for our model specification in Equation (1). First, we implement a non-parametric bootstrap on the residuals, called the "fixed regressor bootstrap", which resamples (Monte-Carlo) the residuals from the estimated linear VECM. The second bootstrap methodology is parametric, called "residual bootstrap". It is assumed that the residuals are i.i.d. Gaussian from an unknown distribution with fixed initial conditions. The parametric bootstrap then calculates the sampling distribution of the supremum LM test in Equation (3) below using the parameter estimates obtained under the $\mathscr{H}_0$. The distribution is bootstrapped using Monte-Carlo simulations from the residual vector under the $\mathscr{H}_0$ while the vector series y_t are created by recursion given the linear VECM model.

For the critical value, we employ a supremum LM statistic based on the union-intersection principle, proposed by Davies (1987):

$$\text{SupLM} = \sup_{\theta_L \leq \theta \leq \theta_U} LM(\hat{\beta}, \theta). \tag{3}$$

According to the constraint in Equation (2) we set the search region $[\theta_L, \theta_U]$ such that θ_L is the π_0 percentile of $\hat{\text{ec}}_{t-1}$, and θ_U is the $(1 - \pi_0)$ percentile. This grid evaluation over $[\theta_L, \theta_U]$ is necessary to implement the maximisation defined in Equation (3) because the function $\text{LM}(\hat{\beta}, \theta)$ is non-differentiable in θ.

We consider our model as threshold cointegrated if we can reject the null hypothesis of a linear VECM by either the "residual bootstrap" or the "fixed regressor bootstrap" methodology. We verify that our results are robust with respect to the choice of the trimming parameter.

4.4 Measure of price discovery

We calculate the Hasbrouck (1995) measure to investigate in which market segment – the CDS market or the bond market – price discovery takes place. The Hasbrouck measure is calculated based on the estimated speed of adjustment parameters λ^U and λ^L as well as the estimated covariance matrix of the error terms, and is by construction confined to the closed interval [0,1]. This makes interpretation straightforward. We specify our Hasbrouck measures such that HAS > 0.5 can be interpreted as the CDS market contributing more to price discovery than the cash market. Similarly, HAS < 0.5 means that the bond (ASW) market contributes more to price discovery.[10]

Finally, we are interested in examining the speed of adjustment towards the long-term equilibrium in each regime. As the CDS and ASW spreads in the bivariate VECM share a common stochastic trend, the speed of adjustments of the cointegrating residual to the long-run equilibrium can be used to determine the impulse response function (Zivot and Wang; 2006). The vector error correction mechanism directly links the speed of adjustment of CDS and ASW spreads to the regime dependent cointegrating error u_t^j which follows an implied AR(1) process:

$$\begin{aligned} u_t^j &= (1 + \lambda_1^j - \beta_1 \lambda_2^j) u_{t-1}^j + \varepsilon_t^{CDS} - \beta_1 \varepsilon_t^{ASW} \\ &= (1 + \lambda_1^j - \lambda_2^j) u_{t-1}^j + \varepsilon_t^{CDS} - \varepsilon_t^{ASW} \equiv \phi^j u_{t-1}^j + \varepsilon_t^{CDS} - \varepsilon_t^{ASW} , \end{aligned} \tag{4}$$

where we have set β_1 to 1 in the second line of the equation.[11] The superscript j stands for L and U. The half-life of a shock for each regime, hl^j, can now be calculated from the AR(1) coefficient ϕ^j as:

$$hl^j = \frac{ln(0.5)}{ln(\phi^j)} . \tag{5}$$

5 Results

In this section we first present results for the period before the euro area sovereign debt crisis (January 2008 to end-March 2010). These are followed by our findings using data for the sovereign debt crisis period (April 2010 to December 2011).

As a general result, we find a functioning relationship between the CDS market and the bond market during both samples. In cases where we find threshold cointegration, the adjustment process towards the long-term equilibrium is faster in the upper regime compared to the lower regime, in line with our reasoning on the behaviour of arbitrageurs. The estimated transaction costs in the pre-debt-crisis period average around 80 basis points. For the second sub-period (sovereign debt crisis) we find much higher thresholds of around 190 basis points. These estimated transaction costs, which are not directly observable, represent the overall costs that arbitrageurs face, such as liquidity costs, repo costs, search costs, cost associated with committing balance sheet space, as well as risk compensation, etc. The two to three times higher transaction costs during the crisis period

[10] Specifically, we calculate the independent set of values HAS_1 and HAS_2 based on the CDS market for each regime, and we then define HAS as the average of HAS_1 and HAS_2.

[11] We include the intercept β_0 in our error correction term and set $\beta_1 = 1$, motivated by our no-arbitrage discussion in Section 2.

are in line with our expectations, as markets were subject to stress in peripheral sovereign credit markets. The significant increase of the basis level during the sovereign debt crisis period can not be uniquely explained by illiquidity as already discussed in Section 3. For example, we also find an increased basis for sovereigns such as France where liquidity increased during the crisis period (as number of ticks, bid-ask spread, number of trades see Appendix C).

Instead, much of the increase in the thresholds during the crisis is likely related to arbitrageurs demanding higher compensation for undertaking arbitrage trades, as the risk of the trade moving in the wrong direction is elevated. In the short run, this risk is directly proportional to the basis volatility. By calculating a daily basis trade gain we show below that arbitrageurs demanded a higher compensation for elevated basis volatility while on a risk-adjusted level the overall compensation remained comparable to the pre-debt crisis period.

The estimated transaction costs ($\theta + \beta_0$) are displayed as red horizontal lines in Figures 2 and 3 in comparison to the overall basis level that is shown as blue curves. We find that the estimated overall transaction costs increased during the crisis period. This finding holds for the 5-year and the 10-year tenor.[12] Empirically we find moderate or no adjustment dynamics below the estimated transaction costs. Thus, we can say that in the lower regime (below the transaction costs $\theta + \beta_0$), the price dynamics are consistent with the notion that arbitrageurs have no incentive to carry out arbitrage trades. However, once the transaction costs ($\theta + \beta_0$) are exceeded (upper regime) and arbitrage trades become profitable, we find rapid adjustment dynamics. Thus, the increase in the basis and in the thresholds during the crisis period is consistent with an increase in overall transaction costs that arbitrageurs face in the market for sovereign risk.

[12] Except for Germany where we either find no significant threshold (10-year tenor) or no threshold at all (5-year tenor) for the sovereign debt crisis period.

Figure 2: CDS-ASW basis, 5 year tenor

The basis is the difference between the CDS spread and the ASW spread expressed in basis points for the period from January 2008 until December 2011. The figure shows data with 30-minute sampling frequency. Due to the Greek debt restructuring the data for Greece ends in September 2011. The red horizontal line represents the overall transaction costs ($\theta + \beta_0$) for the average arbitrageur. During the crisis period the linear VECM model for Germany (superscript $^+$) is a better model fit than any threshold model based on maximum likelihood estimation. Therefore, we do not plot the red horizontal line representing the overall transaction costs for the crisis period in Germany.

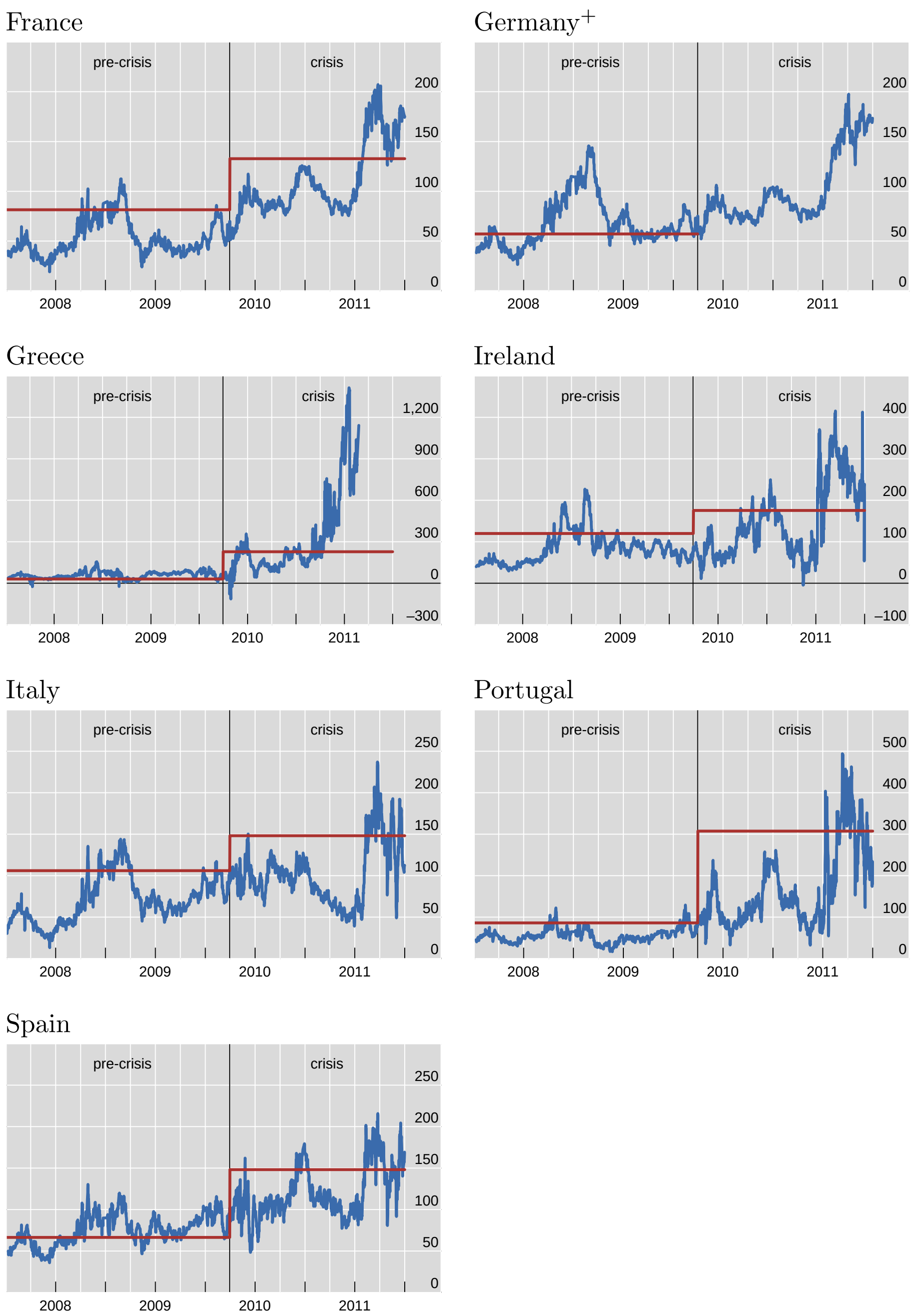
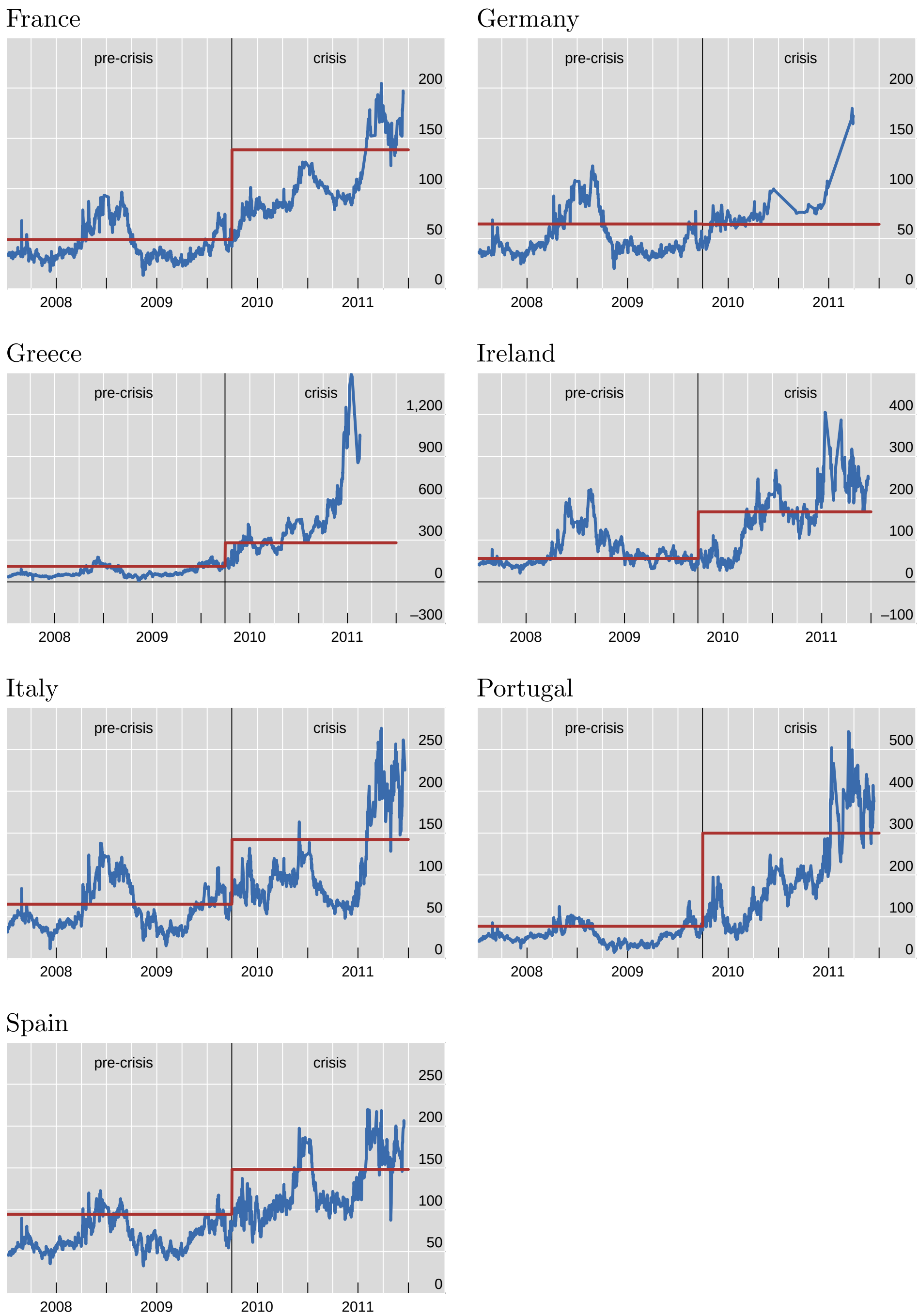


Figure 3: CDS-ASW basis, 10 year tenor

The basis is the difference between the CDS spread and the ASW spread expressed in basis points for the period from January 2008 until December 2011. The figure shows data with 30-minute sampling frequency. Due to the Greek debt restructuring the data for Greece ends in September 2011. The red horizontal line represents the overall transaction costs $(\theta + \beta_0)$ for the average arbitrageur.



5.1 Results for the pre-debt-crisis period

The results for the first sub-sample from January 2008 to end-March 2010, ie prior to the euro area sovereign debt crisis, show that arbitrage trading intensifies in CDS and bond markets once some basis threshold is exceeded. In the lower (neutral) regime we find as expected either no adjustment dynamics, or speed of adjustments that are much smaller in magnitude than in the upper regime. The price discovery results for the 5-year and 10-year tenor are presented in Table 1. Countries in bold have a statistically significant threshold according to either the "fixed regressor bootstrap" or the "residual bootstrap" methodology, as well as speed of adjustments as expected by arbitrage theory. The sum $\theta + \beta_0$ represents the estimated transaction costs while the significance levels of the threshold significance test are represented by the superscript *, **, *** (90%, 95% and 99% CL). The column observations (obs.) denotes the share of observations in the lower regime as a percentage of the total number of observations.

For the 5-year tenor, we fail to find threshold effects for most countries. As expected we find more thresholds for the less liquid 10-year tenor in the pre-crisis period, because less liquid market segments have more frictions and higher arbitrage costs and are thus more likely to exhibit multi-regime behaviour.

The results are supportive of our hypothesis regarding arbitrageurs behaviour in markets with frictions. We find either faster adjustment dynamics towards the long-term equilibrium in the upper regime compared to the lower regime, or no adjustments in the lower regime (ie simple VAR dynamics). Table 2 shows that the half-lives of any basis widening are also either significantly shorter in the upper regime compared to the lower regime or undefined in the lower regime (the only exception is France). This suggests that arbitrage trading activity is much higher in the upper regime and therefore pricing differences due to credit risk shocks are reabsorbed much faster once the threshold is exceeded. Typically, the upper regime can be viewed as an extreme regime as the bulk of observations is in most cases concentrated in the lower (neutral) regime. This is due to the fact that if the basis moves into the upper regime, the actions of arbitrageurs will quickly move the basis back into the lower regime.

We also show the Hasbrouck (HAS) price discovery measure, which gives information on the relative price leadership of the respective markets (CDS versus bond). Here, the superscripts U and L denote the upper and lower regime, respectively. Overall, the price discovery results are mixed. Focusing on the countries in bold, in the upper regime, there appears to be a tendency for the CDS market to lead the bond market in the 10-year segment. In the 5-year segment, on the other hand, there is a (weak) tendency for the bond market to lead in the upper regime. The results for the lower regime are inconclusive across both maturities.

Table 1: Price discovery TVECM - pre-crisis period

This table reports the price discovery analysis for the period from January 2008 to end-March 2010. The values of the VECM coefficients λ are expressed in units of 10^{-4}. HAS is defined as the average of HAS_1 and HAS_2 (Hasbrouck; 1995). The transaction costs $\theta + \beta_0$ are presented in basis points. The superscripts U and L denote the upper and lower regime, respectively. The upper regime is above the overall transaction costs $\theta + \beta_0$ for the arbitrage trade and the lower regime is equal and below the transaction costs. The average of the transaction costs in the last line of each table takes only the significant thresholds into account. Boldfaced country names represent entities for which we have found a significant threshold and where at least one speed of adjustment in the upper regime is significant and has the correct sign to move the basis back to the long-run equilibrium.

Panel A - 5-year tenor

Sovereign	$\theta + \beta_0$	HAS^U	λ_1^U	λ_2^U	HAS^L	λ_1^L	λ_2^L	obs.
France	81.4	0.63	-14.93*	-21.60**	0.17	-1.81*	1.40	87.2%
Germany	57.0**	0.81	0.19	0.60	0.93	2.22	-7.46*	16.9%
Greece	30.1	0.94	-10.69	105.04***	0.67	-67.32*	254.66	12.6%
Ireland	120.1*	0.71	5.23	6.24	0.82	2.28	-5.66	87.6%
Italy	106.1**	0.06	-7.13	-1.48	0.01	6.29	1.01	83.17%
Portugal	86.0*	0.07	-54.32*	-1.36	0.73	13.25	30.95**	89.9 %
Spain	66.4*	0.24	-25.96*	13.77	0.19	-14.90	7.46	18.3%
average	87.1							

Panel B - 10-year tenor

Sovereign	$\theta + \beta_0$	HAS^U	λ_1^U	λ_2^U	HAS^L	λ_1^L	λ_2^L	obs.
France	49.1	0.90	13.45	79.29**	0.00	-7.22**	0.00	66.2%
Germany	64.7	0.92	0.54	3.87	0.55	1.92*	-2.01**	78.5%
Greece	113.0	0.72	-16.40	23.58**	0.05	20.97***	5.70	81.7%
Ireland	56.0*	0.93	-2.23	4.93**	0.66	4.18	-6.70	39.1%
Italy	65.1**	0.84	-2.92	6.79*	0.21	6.07*	-4.55	55.5%
Portugal	77.2**	0.75	-15.33	24.14**	0.06	14.39**	-4.15	81.1%
Spain	94.7**	0.01	-23.98**	-2.05	0.51	14.66**	7.74	90.0%
average	73.3							

Table 2: Half-life of shocks in days - pre-crisis period

This table reports the half-life of shocks of 5-year and 10-year CDS and ASW for the period from January 2008 to end-March 2010. The half-lives of shocks are expressed in days, and are calculated using the impulse response function to a one unit shock on the cointegrating error, using Equations (4) and (5). In case the speed of adjustment is of the wrong sign we do not report any half-life. "Lower" denotes results for the region below the threshold, and "upper" above it.

	5-year tenor		10-year tenor	
Sovereign	lower	upper	lower	upper
France	119.9	-	53.3	5.8
Germany	-	939.2	-	115.6
Greece	1.2	3.3	-	9.6
Ireland	-	381.2	-	53.8
Italy	-	68.1	-	39.6
Portugal	21.7	7.3	-	9.7
Spain	17.2	9.7	-	17.5

5.2 Results for the euro area sovereign debt crisis period

The results for the euro area sovereign debt crisis period that spans from April 2010 to end-December 2011 show that arbitrage forces continue to function despite the turbulent market conditions. Arbitrageurs step into the market once the basis exceeds the overall transaction costs ($\theta + \beta_0$), at which point the adjustment process towards equilibrium speeds up. During the crisis period we find either no, or much slower adjustment speeds in the lower regime, where significant thresholds are identified (Table 3). These results are in line with our findings for the pre-crisis period. However, we find that the estimated transaction costs are around two to three times higher than in the pre-crisis period with an average of 190 basis points.

The sharply higher estimated transaction costs can be explained by decreased liquidity in peripheral sovereign credit markets, in combination with a markedly higher volatility of the basis (see Appendix C and F). As arbitrageurs face the risk that the arbitrage trade will go against them in the short- to medium-run, they will demand a higher compensation for undertaking the trade in volatile markets. The crisis period is characterised by much higher basis volatility across the countries in our sample compared to the pre-crisis period.

For the crisis period we cannot draw any general conclusion with respect to which market typically leads in the price discovery for credit risk as we find mixed results (based on the HAS measure). For the 5-year tenor, we find CDS leadership for Portugal and

Greece (upper regime, above the transaction costs). Results for the French and Irish cases suggest bond leadership. For the 10-year tenor we find CDS leadership in the upper regime for France and Greece, whereas bonds dominate for Germany. In the lower regime we find either bond leadership or no error correction at all.

Table 3: Price discovery TVECM - crisis period

This table reports the price discovery analysis for intraday data on a 30-minute sampling frequency from the TVECM for the period from April 2010 to end-December 2011 for the 5- and 10-year tenor. In the case of Germany, 5 year tenor (superscript $^+$), the VECM is a better fit compared to any threshold model based on maximum likelihood estimation. For further details see Table 1.

Panel A - 5-year tenor

Sovereign	$\theta + \beta_0$	HAS^U	λ_1^U	λ_2^U	HAS^L	λ_1^L	λ_2^L	obs.
France	132.8**	0.01	-65.84***	-8.51	0.16	-1.58	1.30	77.1%
Germany$^+$	-	-	-	-	-	-	-	-
Greece	227.7**	0.55	123.78	498.80*	0.27	-10.45*	11.56	89.5%
Ireland	175.5*	0.14	-53.32***	33.74	0.01	-10.84***	-0.31	70.6%
Italy	148.2***	0.02	-15.16	-0.85	0.76	-6.95	16.78	87.5%
Portugal	307.3***	0.78	-10.45	75.54**	0.03	-16.52*	3.94	87.9%
Spain	148.27	0.12	-17.14	2.48	0.75	-31.68	70.51***	80.7%
average	198.3							

Panel B - 10-year tenor

Sovereign	$\theta + \beta_0$	HAS^U	λ_1^U	λ_2^U	HAS^L	λ_1^L	λ_2^L	obs.
France	138.6*	0.99	4.44	25.98***	0.02	-18.46**	-3.43	86.0%
Germany	64.5*	0.13	-13.12**	5.16	0.06	37.13*	-9.58	36.9%
Greece	280.0***	0.57	10.00	15.16*	0.93	-1.64	4.42	44.6%
Ireland	167.7	0.26	-12.66	4.26	0.00	19.02	0.31	62.2%
Italy	142.3*	0.13	-22.94	-4.92	0.91	9.50	17.30	89.0 %
Portugal	300.1*	0.88	-8.43	-19.72	0.83	4.24	7.99	89.9%
Spain	95.4	0.17	-13.95	-5.29	0.18	-293.89	76.58	16.1%
average	185.1							

All half-lives are displayed in Table 4. The few cases where the speed of adjustments have a wrong sign (either CDS or ASW move away from the long-term equilibrium) the half-lives are not reported as the implied dynamics are unstable. As in the case of the pre-crisis period, the half-lives of any basis widening tend to be shorter in the upper regime compared to the lower regime. Again, this is in line with the notion that arbitrage trading activity is higher in the upper regime, leading to quicker readjustment of the basis. There are, however, a few cases where the estimated speed of adjustment is somewhat lower in the upper regime, possibly due to market disruptions among some of the worst affected sovereigns during the sovereign debt crisis.

Table 4: Half-life of shocks in days - crisis period

This table reports the half-life of shocks of 5-year and 10-year CDS and ASW for the period from April 2010 to end-December 2011. The half-lives of shocks are expressed in days, and are calculated using the impulse response function to a one unit shock on the cointegrating error, using Equations (4) and (5). In case the speed of adjustment is of the wrong sign we do not report any half-life. "Lower" denotes results for the region below the threshold, and "upper" above it.

	5-year tenor		10-year tenor	
Sovereign	lower	upper	lower	upper
France	133.7	6.7	25.6	17.9
Germany	-	-	-	21.0
Greece	17.5	1.0	63.5	74.6
Ireland	36.6	4.4	-	22.7
Italy	16.2	26.9	49.4	21.4
Portugal	18.8	4.5	102.7	-
Spain	3.7	19.6	1.0	44.4

5.3 Adjusted basis trade gain

To get a sense of the risk-return trade-offs arbitrageurs face in the market once the basis exceeds the estimated trading cost $(\theta + \beta_0)$, we calculate the so-called adjusted basis trade gain (BTG_{adj}). This measure represents the daily risk and cost adjusted potential basis trade gain, expressed in basis points, that an arbitrageur can typically expect in the upper regime, as implied by the model estimates. In the upper regime, the arbitrageur will bet on a declining basis while going short credit risk in the bond market and going long credit risk in the CDS market, ie by selling the bond and selling the CDS (Gyntelberg et al.; 2013). We assume that the typical basis, arbitrageurs encounter in the upper regime, is the mean value of the basis in the upper regime. After deducting the overall estimated transaction cost $(\theta + \beta_0)$ from this typical basis, we get the expected basis trade gain denoted as E(BTG) in Equation (6).

In order to get a time dimension associated with the trade gain (along the lines of an expected return per period of time), we scale E(BTG) by the half-life in the upper regime, hl_{d}^{U} (when defined). Here, the subscript d denotes that the half-lives are measured in days. In the short run, the arbitrageur faces the risk of the trade moving in the wrong direction which is directly proportional to the basis volatility. To generate a risk-adjusted measure, we adjust the daily potential trading gain by the daily basis volatility ($\mathrm{vola}_{\mathrm{d}}$).[13] Given this, the daily adjusted basis trade gain ratio $\mathrm{BTG}_{\mathrm{adj}}$ is then given by

$$\mathrm{BTG}_{\mathrm{adj}} = \frac{\mathrm{E(BTG)}}{hl_{\mathrm{d}}^{U}} \cdot \frac{1}{\mathrm{vola}_{\mathrm{d}}} \tag{6}$$

Table 5 shows that the expected basis trade gain is typically larger, and sometimes substantially so, in the crisis period compared to the pre-crisis period (Germany is an exception). Hence, despite higher trading costs facing arbitrageurs in the crisis period, the typical gains they may expect net of costs also tend to be higher. Once we adjust for the expected speed of adjustment and the risk (as measured by the basis volatility) associated with implementing arbitrage trades, the differences between the two periods are less stark. This suggests that part of the rise in the expected trading gains in the crisis period reflects higher compensation for risk. However, the fact that our $\mathrm{BTG}_{\mathrm{adj}}$ estimates do not fully equalize is likely due to a combination of imprecise parameter estimates and the imperfect nature of the basis volatility as a measure of arbitrage trade risk.

[13] Daily volatilities of the basis are displayed in Appendix F.

Table 5: Daily risk and cost adjusted basis trade gain

This table reports the daily risk and cost adjusted basis trade gain (BTG_{adj}) from Equation (6) on a typical basis widening trade (arithmetic mean of the basis in the upper regime), in basis points. The few cases where the speed of adjustments have wrong signs are left empty.

Panel A - 5-year tenor

	pre-crisis		crisis	
Sovereign	E(BTG)	BTG_{adj}	E(BTG)	BTG_{adj}
France	12.53		34.63	4.02
Germany	24.70	0.02		
Greece	35.58	2.24	190.88	19.55
Ireland	42.22	0.05	82.59	5.27
Italy	15.39	0.13	26.27	0.49
Portugal	12.53	0.71	60.97	2.73
Spain	18.56	1.15	21.30	0.66

Panel B - 10-year tenor

	pre-crisis		crisis	
Sovereign	E(BTG)	BTG_{adj}	E(BTG)	BTG_{adj}
France	19.12	1.58	24.30	1.02
Germany	24.70	0.16	11.84	0.62
Greece	23.76	0.77	143.94	0.73
Ireland	41.89	0.30	55.95	1.11
Italy	24.44	0.29	60.13	1.27
Portugal	13.64	0.59	94.09	
Spain	8.40	0.32	33.87	0.37

6 Conclusions

The persistence of a positive basis between sovereign CDS and sovereign bond spreads in the euro area points to the presence of arbitrage costs that prevent a complete adjustment of market prices to the theoretical no-arbitrage condition of a zero basis. These include transaction costs and costs associated with committing balance sheet space for implementing arbitrage trades. Using a TVECM modelling approach, we are able to quantify these unobservable costs and study their properties.

We find that the adjustment process towards the long-run equilibrium intensifies once the CDS-bond basis exceeds a certain level/threshold. Above this estimated threshold, arbitrage trades become profitable for arbitrageurs while below the threshold, arbitrageurs have no incentive for trading as the costs they face are higher than the expected gain from the trade. As a result, we typically find faster adjustment dynamics towards the long-term equilibrium once the estimated threshold is exceeded (upper regime) compared to the lower regime, and the half-life of any basis widening therefore tends to be shorter in the upper regime compared to the lower regime. This supports our assumption that arbitrageurs step in and carry out basis trades only when the expected gain from the arbitrage trade is greater than the trading costs.

During the euro sovereign credit crisis in 2010-11, we find very high estimated transaction costs of around 190 basis points on average, compared to around 80 basis points before the crisis. This increase was likely due to higher costs facing arbitrageurs in the market, as well as higher risk that the trade would go against them due to substantially more volatile market conditions. In response, arbitrageurs demanded higher compensation for undertaking such trades during the crisis, resulting in higher thresholds. In line with this, we find that the expected trading gains facing arbitrageurs when the basis exceeds the threshold are higher in the crisis period than pre-crisis. Risk-adjusted trading gain ratios, which adjust for the expected speed of adjustment of the basis and for the volatility of the basis, displayed less stark differences, suggesting that part of the rise in expected trading gains during the crisis reflects compensation for higher trading risk.

Finally, we note that the divergence of CDS and ASW spreads during the crisis period can not be fully explained by decreased liquidity in peripheral sovereign credit markets. In fact, we find a significant increase of the CDS-bond basis in countries where measures of market liquidity increased during crisis period, as for example in France and Spain.

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A Asset Swap Spreads

The asset swap spread, ASW, is the fixed value A required for the following equation to hold[14] (O'Kane (2000))

$$\underbrace{100 - P}_{\substack{\text{Upfront payment for bond}\\ \text{asset in return for par}}} \quad + \overbrace{\underbrace{C \sum_{i=1}^{N_{\text{fixed}}} d(t_i)}_{\text{Fixed payments}} = \underbrace{\sum_{i=1}^{N_{\text{float}}} \big(L_i + A\big) d(t_i)}_{\text{Floating payments}}}^{\text{Interest rate swap}}, \tag{7}$$

where P is the full (dirty) price of the bond, C is the bond coupon, L_i is the floating reference rate (eg Euribor) at time t_i, and $d(t_i)$ is the discount factor applicable to the corresponding cash flow at time t_i.

In order to compute the spread A several observations and simplifications have to be made. First, in practice it is almost impossible to find bonds outstanding with maturities that exactly match those of the CDS contracts and second, the cash-flows of the bonds and the CDS will not coincide. To overcome these issues, in what follows we use synthetic asset swap spreads based on estimated intraday zero-coupon sovereign bond prices. Specifically, for each interval and each country, we estimate a zero-coupon curve based on all available bond price quotes during that time interval using the Nelson and Siegel (1987) method. With this procedure we are able to price synthetic bonds with maturities that exactly match those of the CDS contracts, and we can use these bond prices to back out the corresponding ASW. As this results in zero coupon bond prices, we can set C in Equation (7) to zero.

A CDS contract with a maturity of m years for country j at time interval k of day t, denoted as $S_j(t_k, m)$, has a corresponding ASW $A_j(t_k, m)$:

$$100 - P_j(t_k, m) = \sum_{i=1}^{N_m} \big(L_i(t_k) + A_j(t_k, m)\big) \cdot d(t_k, t_i), \tag{8}$$

where $P_j(t_k, m)$ is our synthetic zero coupon bond price.

For the reference rate L_i in Equation (8), we use the 3-month Euribor forward curve to match as accurately as possible the quarterly cash flows of sovereign CDS contracts. We construct the forward curve using forward rate agreements (FRAs) and Euro interest rate swaps. We collect the FRA and swap data from Bloomberg, which provides daily (end-of-day) data. 3-month FRAs are available with quarterly settlement dates up to 21 months ahead, ie up to 21×24. From two years onwards, we bootstrap zero-coupon swap

[14] This assumes that there is no accrued coupon payment due at the time of the trade; otherwise, an adjustment factor would need to be added to the floating payment component.

rates from swap interest rates available on Bloomberg and back out the corresponding implied forward rates. Because the swaps have annual maturities, we use a cubic spline to generate the full implied forward curve, thereby enabling us to obtain the quarterly forward rates needed in Equation (8).

Given our interest in intraday dynamics, we follow Gyntelberg et al. (2013) and generate estimated intraday Euribor forward rates by assuming that the intraday movements of the Euribor forward curve are proportional to the intraday movements of the German government forward curve.[15] To be precise, for each day, we calculate the difference between our Euribor forward curve and the forward curve implied by the end-of-day Nelson-Siegel curve for Germany.[16] We then keep this difference across the entire curve fixed throughout that same day and add it to the estimated intraday forward curves for Germany earlier on that day to generate the approximate intraday Euribor forward curves. This approach makes the, in our view, reasonable assumption that the intraday variability in Euribor forward rates will largely mirror movements in corresponding German forward rates.

Finally, we need to specify the discount rates $d(t_k, t_i)$ in Equation (8). The market has increasingly moved to essentially risk-free discounting using the overnight index swap (OIS) curve. We therefore take $d(t_k, t_i)$ to be the euro OIS discount curve, which is constructed in a way similar to the Euribor forward curve. For OIS contracts with maturities longer than one year, we bootstrap out zero-coupon OIS rates from interest rates on long-term OIS contracts. Thereafter, we construct the entire OIS curve using a cubic spline. We use the same technique as described above to generate approximate intraday OIS discount curves based on the intraday movements of the German government curve.

[15] Euribor rates are daily fixing rates, so we are actually approximating the intraday movements of the interbank interest rates for which Euribor serves as a daily benchmark.

[16] Here we use the second to last 30-minute interval, because the last trading interval is occasionally overly volatile.

B CDS and ASW spreads

Figure B.1: CDS and ASW spreads in basis points

The figures are based on data with a 30-minute sampling frequency. Source: CMA Datavision, MTS

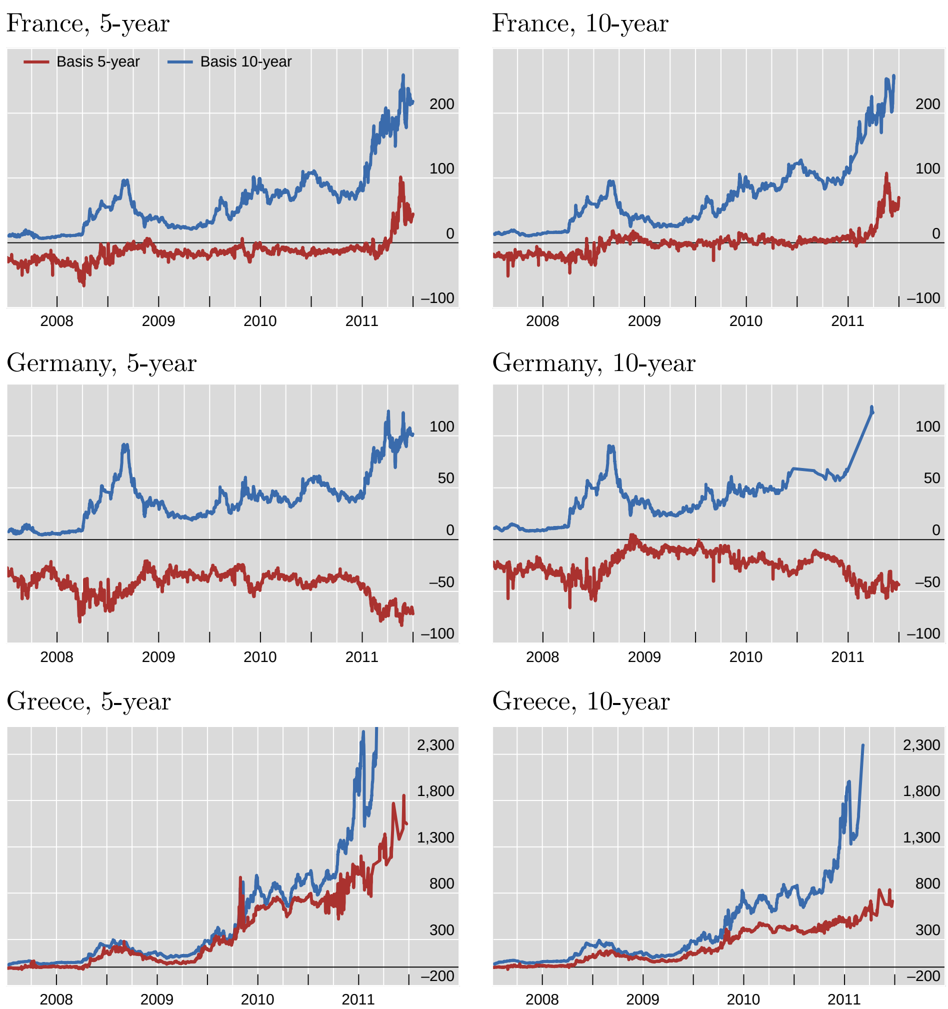
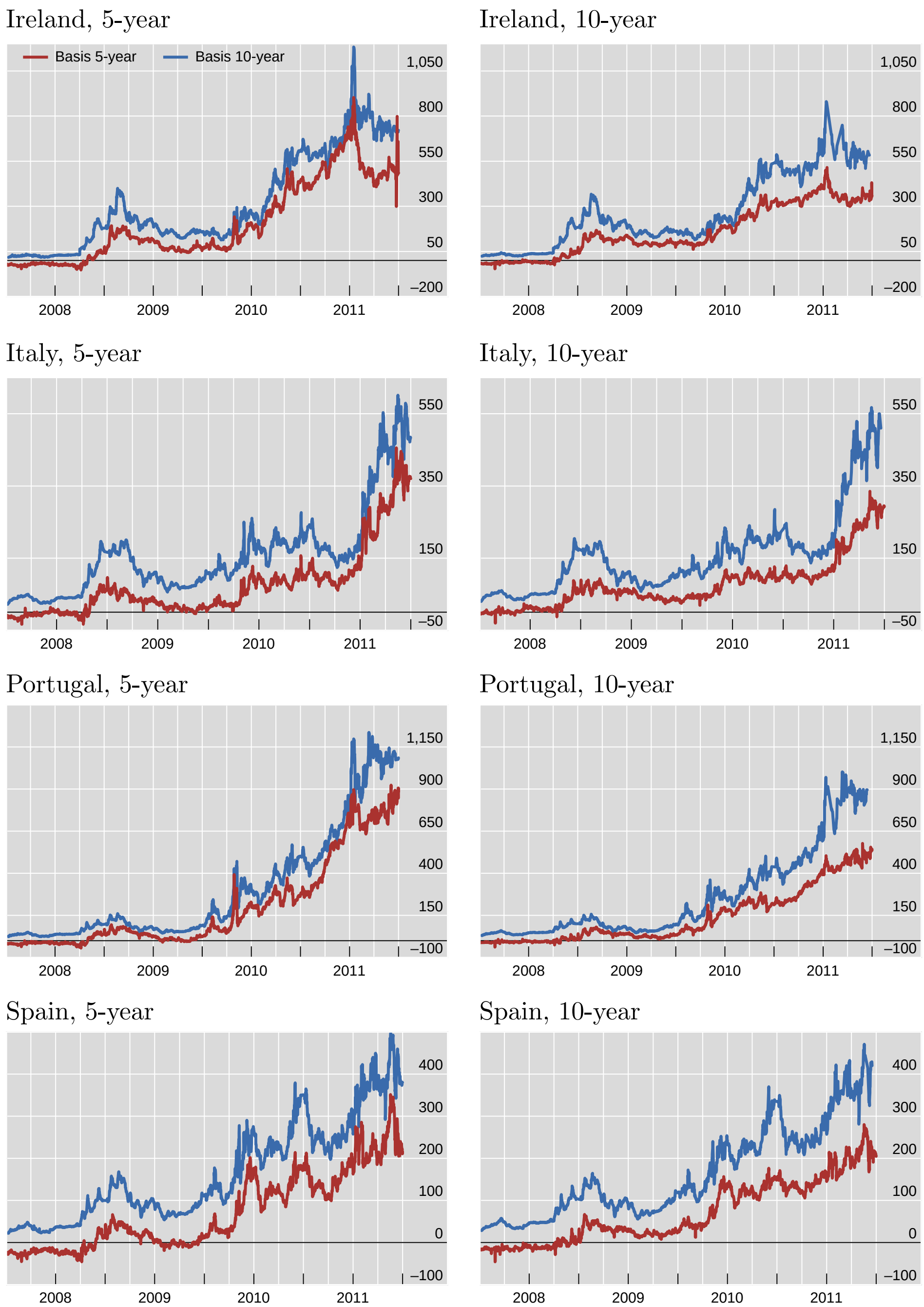


Figure B.1: (Cont.) CDS and asset swap spreads



C CDS and Bond data and liquidity

Figure C.1: CDS data from CMA Datavision – tick-by-tick data

The right-hand scale shows the number (in thousands) of data ticks per year.

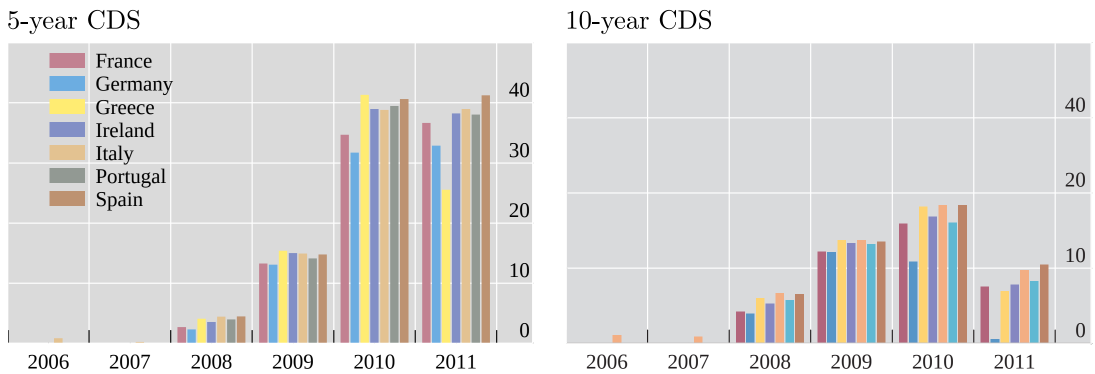


Figure C.2: CDS data from CMA Datavision – 30 min aggregates

The right-hand scale shows the number (in thousands) of non-empty half hour intervals per year. We consider 18 half hour slots per trading day, from 8:30 to 17:30 CET/CEST. The left-hand side scale shows the percentage of 30 min. intervals which contain at least one data tick during the 18 daily half-hour intervals we consider.

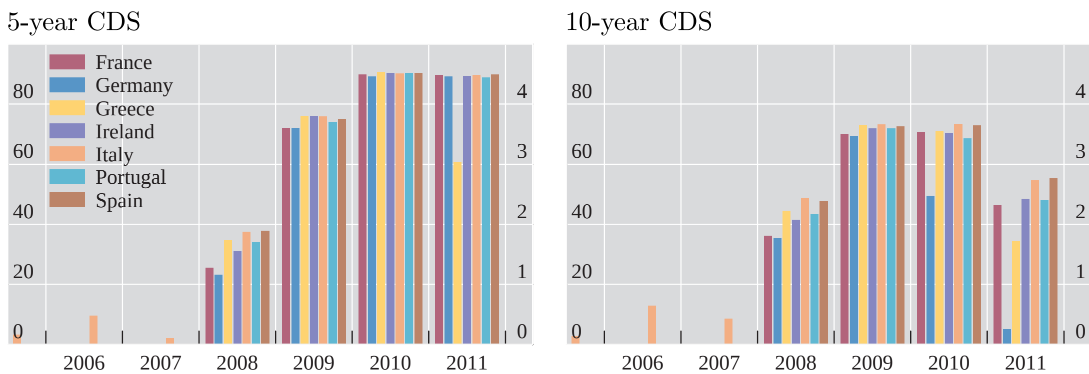


Figure C.3: EuroMTS number of trades

The right-hand side scale shows the number (in thousands) of trades per year. Italy is shown separately because the number of trades are more than an order of magnitude higher than for the other countries.

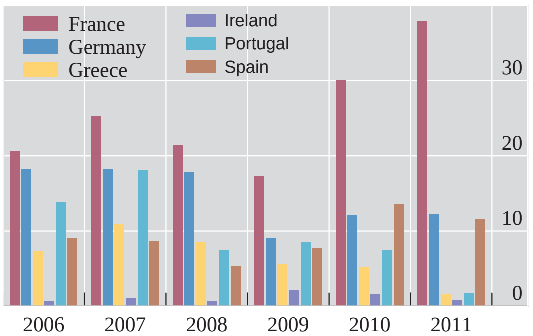
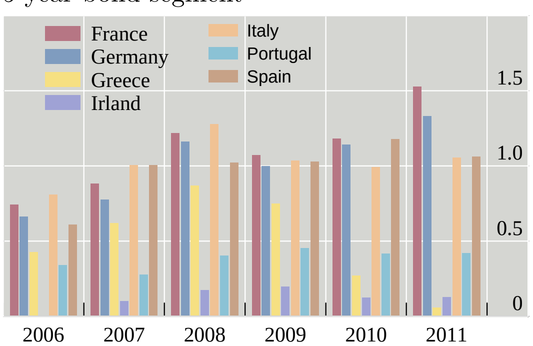


Figure C.4: EuroMTS bond price data from the trading book – tick-by-tick data

The right-hand side scale shows the number (in millions) of data ticks in the trading book. This includes all bonds with a maturity between 4 and 6 years and 9 and 11 years in the 5-year and 10-year segment, respectively.

5-year bond segment



10-year bond segment

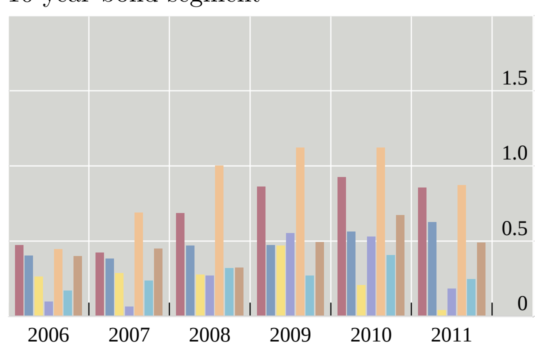


Figure C.5: EuroMTS bond price data from the trading book – 30 min aggregates

The left-hand side scale shows the percentage of 30 min. intervals during the trading period, which contain at least one data tick in the trading book. The right-hand scale shows the number (in thousands) of non-empty half hour intervals per year. We consider 18 half hour slots per trading day, from 8:30 to 17:30 CET/CEST.

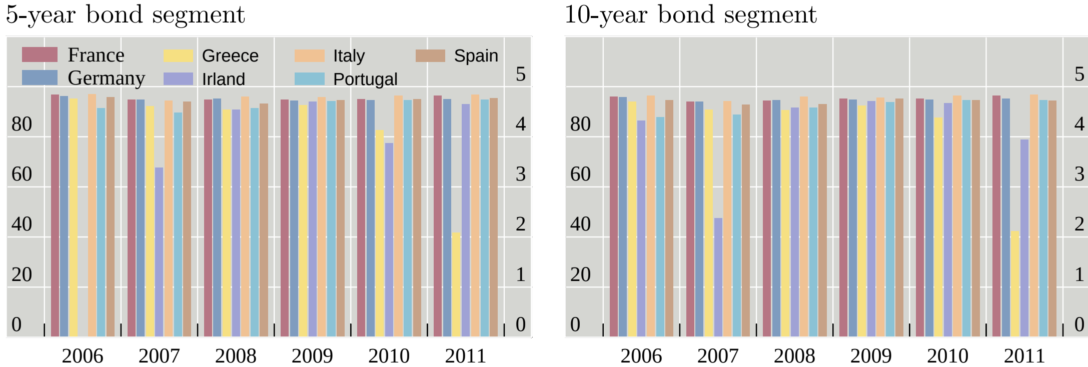


Figure C.6: Bid-Ask spreads for CDS and ASW in basis points

The figures are based on data with 30 minute sampling frequency. Source: CMA Datavision, EuroMTS

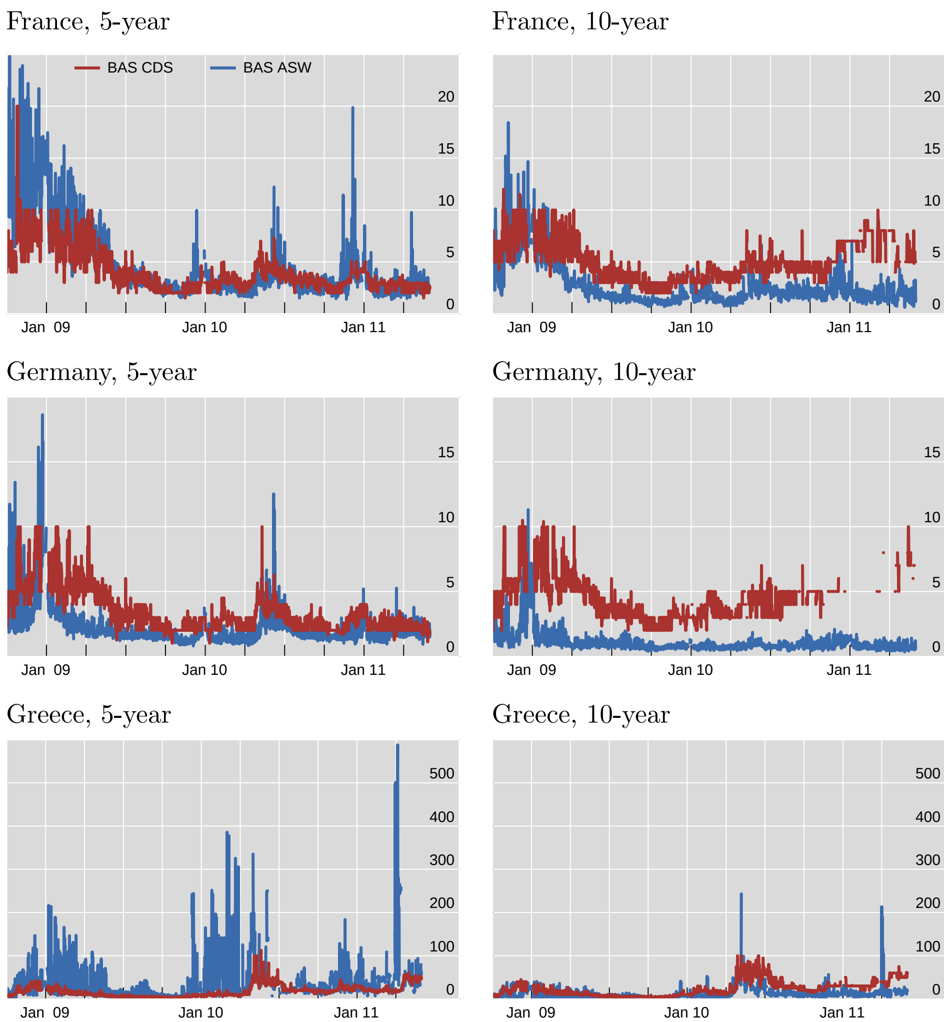
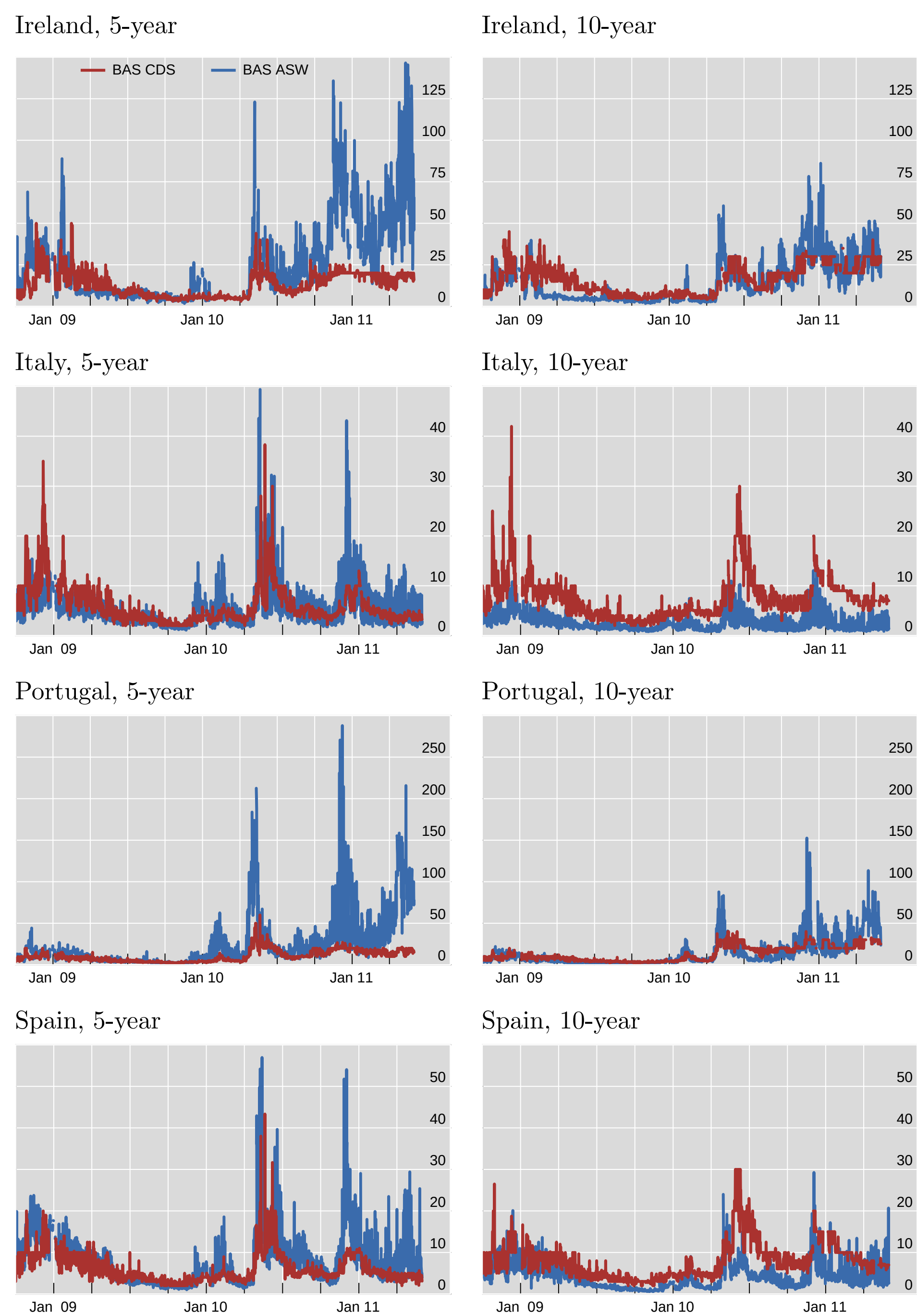


Figure C.6: (Cont.) Bid-Ask spreads for CDS and ASW in basis points



D Unit root and stationarity tests

We test for unit roots and stationarity in the CDS and ASW time-series using the following three methods:

1. the Augmented Dickey-Fuller (ADF) test,
2. the Phillips-Perron (PP) test and
3. the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test.

The null hypothesis of the ADF and PP test states: *the series has a unit root.* The null hypothesis of the KPSS test is: *the series is stationary.* Therefore, if our CDS and ASW data are $I(1)$ time series, we should be unable to reject the null hypothesis in levels for the ADF and PP test and reject H0 under the KPSS test, and vice versa for first differences.

Based on these three different tests we conclude that both the CDS and the asset swap spreads have a unit root for both tenors and periods (pre-crisis and crisis).

Our findings in Tables D.1 and D.2 show that for none of the CDS series in levels we are able to reject the null hypothesis of a unit root using either the ADF or the PP test. For the asset swap spread series the null is rejected for a few countries and tenors in levels using both the ADF and PP test. The KPSS rejects stationarity for all countries and both maturities. Test results for the first differenced spread data show that for all test methods we reject the unit root hypothesis across the board, indicating that all series are integrated of order one. To conserve space, we do not show these test results, but they are available from the authors on request.

Table D.1: Unit root and stationarity tests in levels - pre-crisis

The table reports the statistics of unit root and stationarity tests for the period from January 2008 to end-March 2010. The ADF and PP test for a unit root under the null hypothesis. For the KPSS test, the null is stationarity, and the 0.01, 0.05 and 0.10 critical values for the test statistics are 0.739, 0.463 and 0.347, respectively.

Panel A: 5-year spreads

	Credit default swap			Asset swap		
Sovereign	p_{ADF}	p_{PP}	KPSS stat.	p_{ADF}	p_{PP}	KPSS stat.
France	0.88	0.91	1.35	0.01	0.00	5.57
Germany	0.27	0.28	1.52	0.02	0.00	2.94
Greece	0.91	0.87	6.21	0.98	0.76	6.67
Ireland	0.48	0.48	2.87	0.13	0.12	7.04
Italy	0.45	0.62	2.24	0.01	0.00	3.73
Portugal	0.80	0.78	3.46	0.07	0.02	5.22
Spain	0.50	0.42	4.45	0.22	0.00	5.60

Panel B: 10-year spreads

	Credit default swap			Asset swap		
Sovereign	p_{ADF}	p_{PP}	KPSS stat.	p_{ADF}	p_{PP}	KPSS stat.
France	0.66	0.76	2.31	0.00	0.00	8.00
Germany	0.92	0.75	2.18	0.14	0.00	7.54
Greece	0.92	0.93	7.23	0.74	0.83	8.49
Ireland	0.47	0.28	4.68	0.20	0.62	9.58
Italy	0.31	0.30	3.36	0.06	0.23	6.77
Portugal	0.72	0.66	4.26	0.05	0.07	7.92
Spain	0.68	0.37	5.83	0.01	0.02	9.21

Table D.2: Unit root and stationarity tests in levels - crisis

The table reports the statistics of unit root and stationarity tests for the period from April 2010 to end 2011. Further details are presented in Table D.1.

Panel A: 5-year spreads

	Credit default swap			Asset swap		
Sovereign	p_{ADF}	p_{PP}	KPSS stat.	p_{ADF}	p_{PP}	KPSS stat.
France	0.80	0.74	7.57	0.15	0.18	4.43
Germany	0.80	0.62	7.35	0.60	0.31	7.16
Greece	1.00	1.00	7.79	0.00	0.00	9.67
Ireland	0.30	0.29	10.12	0.06	0.19	9.01
Italy	0.77	0.71	7.17	0.67	0.35	8.45
Portugal	0.79	0.69	10.80	0.26	0.14	11.29
Spain	0.11	0.08	7.83	0.03	0.03	7.51

Panel B: 10-year spreads

	Credit default swap			Asset swap		
Sovereign	p_{ADF}	p_{PP}	KPSS stat.	p_{ADF}	p_{PP}	KPSS stat.
France	0.99	0.98	7.94	0.49	0.81	5.21
Germany	0.48	0.49	4.10	0.59	0.09	6.58
Greece	0.94	0.97	8.68	0.17	0.00	5.36
Ireland	0.10	0.26	10.44	0.01	0.02	9.30
Italy	0.92	0.90	6.65	0.82	0.46	8.46
Portugal	0.77	0.79	11.26	0.01	0.09	11.26
Spain	0.86	0.73	8.02	0.19	0.15	8.51

E Cointegration analysis

We test for a long-run relationship in the form of cointegration between the bond and CDS market using the tests of Phillips and Ouliaris (1990) and Johansen (1988).

We view two series as cointegrated if either the null hypothesis of no cointegration is rejected using the Johansen or the Phillips-Ouliaris methodology. We use the Johansen test with intercept but no deterministic trend in the co-integrating equation. We use the Schwarz information criterion to estimate the optimal lag length for the Johansen test.

The test results indicate that in all cases, the CDS and the ASW spread series are cointegrated.

Table E.1: Cointegration - p-values, pre-crisis

This table reports the probabilities in decimals obtained from the Johansen cointegration and the Phillips-Ouliaris cointegration tests for the period from January 2008 to end-March 2010. For the Johansen test a constant is included in the co-integrating equation and the number of lags in the vector autoregression is optimized using the Schwarz information criterion. The Phillips-Ouliaris tests for no cointegration under the null hypothesis by estimating the long-term equilibrium relationship from a regression of CDS_t on ASW_t or from a regression of ASW_t on CDS_t among the levels of the time series. The column header ASW and CDS indicates which variable is used as dependent variable in the test.

Panel A: Johansen test

	Trace test				Maximum eigenvalue test			
	5-year		10-year		5-year		10-year	
Sovereign	None	at most 1	None	at most 1	None	at most 1	None	at most 1
France	0.000	0.435	0.003	0.612	0.000	0.435	0.001	0.612
Germany	0.143	1.000	0.159	0.664	0.039	1.000	0.104	0.664
Greece	0.001	0.786	0.000	0.441	0.000	0.786	0.000	0.441
Ireland	0.022	0.949	0.015	0.557	0.005	0.949	0.008	0.557
Italy	0.004	0.517	0.001	0.944	0.002	0.517	0.000	0.944
Portugal	0.001	0.354	0.000	0.728	0.001	0.354	0.000	0.728
Spain	0.024	0.783	0.000	0.618	0.009	0.783	0.000	0.618

Panel B: Phillip-Ouliaris test

	τ-statistics				z-statistics			
	5-year		10-year		5-year		10-year	
Sovereign	CDS	ASW	CDS	ASW	CDS	ASW	CDS	ASW
France	0.182	0.002	0.935	0.000	0.379	0.026	0.935	0.000
Germany	0.023	0.001	0.393	0.053	0.147	0.043	0.511	0.138
Greece	0.006	0.024	0.001	0.001	0.002	0.004	0.002	0.002
Ireland	0.002	0.001	0.017	0.016	0.028	0.022	0.080	0.076
Italy	0.000	0.000	0.000	0.000	0.005	0.000	0.001	0.000
Portugal	0.001	0.000	0.039	0.004	0.022	0.008	0.035	0.008
Spain	0.523	0.000	0.010	0.000	0.585	0.021	0.028	0.002

Table E.2: Cointegration - p-values, crisis

This table reports the probabilities in decimals obtained from the Johansen cointegration and the Phillips-Ouliaris cointegration tests for the period from April 2010 to end 2011. Further details are presented in Table E.1.

Panel A: Johansen test

	Trace test				Maximum eigenvalue test			
	5-year		10-year		5-year		10-year	
Sovereign	None	at most 1	None	at most 1	None	at most 1	None	at most 1
France	0.149	0.732	0.022	0.057	0.086	0.732	0.097	0.057
Germany	0.001	0.682	0.975	0.955	0.000	0.682	0.940	0.955
Greece	0.984	0.978	0.016	0.990	0.951	0.978	0.003	0.990
Ireland	0.011	0.104	0.050	0.224	0.030	0.104	0.077	0.224
Italy	0.209	0.721	0.168	0.516	0.134	0.721	0.145	0.516
Portugal	0.000	0.312	0.360	0.374	0.000	0.312	0.458	0.374
Spain	0.023	0.130	0.326	0.441	0.054	0.130	0.364	0.441

Panel B: Phillip-Ouliaris test

	τ-statistics				z-statistics			
	5-year		10-year		5-year		10-year	
Sovereign	CDS	ASW	CDS	ASW	CDS	ASW	CDS	ASW
France	0.951	0.106	0.008	0.401	0.945	0.103	0.163	0.319
Germany	0.000	0.000	0.028	0.015	0.001	0.001	0.102	0.074
Greece	0.000	0.000	0.019	0.034	0.000	0.000	0.012	0.019
Ireland	0.034	0.024	0.000	0.000	0.008	0.006	0.002	0.003
Italy	0.002	0.001	0.000	0.000	0.014	0.011	0.000	0.000
Portugal	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Spain	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000

F Basis volatility

Table F.1: Basis volatility - 5-year tenor

The table shows the volatility based on log changes and in bps. The pre-crisis period starts in January 2008 and ends in March 2010. The crisis period begins in April 2010 and our data ends in December 2011. The upper regime is above the estimated overall transaction cost $\theta + \beta_0$ and the lower regime is equal or below this level.

	pre-crisis		crisis	
Sovereign	lower regime	upper regime	lower regime	upper regime
France	2.14	1.25	1.08	1.29
Germany	1.01	1.08		
Greece	26.71	4.81	11.69	9.29
Ireland	2.40	2.31	7.27	3.56
Italy	2.18	1.72	2.26	1.99
Portugal	2.86	2.43	5.12	5.01
Spain	1.73	1.67	2.44	1.65

Table F.2: Basis volatility - 10-year tenor

The table shows the volatility based on log changes and in bps. The pre-crisis period starts in January 2008 and ends in March 2010. The crisis period begins in April 2010 and our data ends in December 2011. The upper regime is above the estimated overall transaction cost $\theta + \beta_0$ and the lower regime is equal or below this level.

	pre-crisis		crisis	
Sovereign	lower regime	upper regime	lower regime	upper regime
France	3.03	2.07	1.21	1.33
Germany	1.43	1.30	1.23	0.91
Greece	3.85	3.22	4.05	2.62
Ireland	2.84	2.62	4.24	2.21
Italy	3.05	2.15	2.31	2.23
Portugal	3.05	2.36	3.69	3.84
Spain	2.21	1.49	2.48	2.05

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