The Expectations Hypothesis of the Term Structure: International Evidence of Non-Linear Adjustment*

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Abstract

This study tests whether changes in the short-term interest rate can best be modelled in a non-linear fashion. Using monthly data from several industrialized countries, namely Canada, UK, US, Germany, Switzerland and Sweden, we show that the short term interest rate movements are better explained, usually via the exponential smooth transition autoregression (ESTR). We consider a number of candidates for the transition variable. These include: an error correction term, estimated from an underlying cointegrating relationship predicted by the expectations hypothesis, the US spread, the domestic spread, inflation and output growth forecasts, and deviations from an inflation target in the case of Canada, the UK and Sweden.

The sample spans the period from 1960-1998. We cannot reject non-linearity in the behavior of interest rate changes most often when the (lagged) domestic spread serves as the transition variable. In the case of the inflation targeting countries in our sample, the most appropriate transition variable can be the deviation from the publicly announced inflation target. We supplement estimates with extensive diagnostic testing to ensure that we can reject the linear alternative with reasonable confidence. We believe that changes in central bank policies and in the reaction of market participants over time to such changes argue in favor of the non-linear estimation approach. We would also argue that any model of the term spread over a fairly long span of time necessitates resort to non-linear estimation methods.

JEL Codes: C22, C11, E30

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Introduction

One of the most widely examined series in finance is the term spread. More recently, policy makers and academics in industrial countries have been interested in the predictive role of the term structure. For example, several studies (e.g., Jorion and Mishkin 1991, Hu, 1993, Bernard and Gerlach 1996, Barr and Campbell 1997, to name just a few) have empirically demonstrated that future inflation and economic growth are each significantly explained by the slope of the yield curve or spread.

For the most part, however, existing empirical evidence tends to rely on linear models. Yet, as Campbell, Lo, and MacKinlay (1997, chapter 12) point out, the behavior of financial time series is inherently non-linear (also see Taylor 1986). Figure 1 plots a short-term and a long-term interest rate for the US at the monthly frequency since 1964. These time series have been used in many studies of the kind conducted here. The data reveal sharp changes in the spread between the two interest rates that might be better modeled via non-linear methods. Recent advances in estimation and inference in non-linear time series models (e.g., see Granger and Teräsvirta 1993, Teräsvirta 1998, van Dijk, Teräsvirta and Franses 2001) now make it possible to re-examine whether the relationship between long-term and short-term interest rates is non-linear and to try to identify the sources of non-linearities.

In this paper, we extend the linear error-correction model of the term structure of interest rates (see, e.g., Campbell and Shiller 1987) by allowing for non-linear adjustment to the equilibrium and for changes in regime, with smooth transition adjustment. In addition, we provide various theoretical reasons for non-linearities in the context of the term structure of interest rates. We allow for non-linearities in the adjustment process for the error-correction term itself and in addition for non-linearities in the short run dynamics. We apply recently developed econometric tools and test the commonly used linear error-correction model against the non-linear error-correction model. In addition, we carry out numerous specification tests for our non-linear models, including various tests for structural change.

The rest of the paper is organized as follows. First, we briefly review the essentials of the expectations hypothesis as summarized by the behavior of the term spread, as well as discuss sources of non-linearities in the behavior of the spread. Next, we outline the econometric specification and the strategy used to search for non-linearities in the data. Following a description of the data we present empirical evidence for a sample covering the 1960-98 period for a group of industrial countries, namely Canada, Germany, Sweden, Switzerland, the US, and the UK.[1] It is of some interest to note that three of the countries in our data set have targeted inflation since the early 1990s, though the period since inflation control targets were implemented may not be sufficiently lengthy to reach definitive conclusions about non-linearities in the term structure. The paper concludes with a summary and issues to be taken up in future research.

<u>The Term Spread, Expectations Hypothesis and Non-Linear Adjustment</u>

The Expectations Hypothesis (EH) of the term structure predicts that, in an unfettered market, differences in yields between government bonds that mature at different dates reflect expectations about the future course of interest rates. Put simply, the EH can be summarized by the following equation:

$$R_{k,t} = \frac{1}{k}\left[\sum_{j=1}^{k} E_t R_{1,t+j-1}\right] + \theta_{k,t} \tag{1}$$

[1] In an earlier draft of the paper we also used data from Australia and New Zealand. However, as CPI data, a key component in the determination of nominal interest rates, are available only at the quarterly frequency we opted to exclude these two countries from further analysis.

where $\theta_{k,t}$ is a term premium and E_t is the expectation based on information conditional on time t. If the term premium is non-linear then this can be one source of non-linearity in the spread.[2] This term is often ignored because it is unobservable or is not considered empirically relevant for the data set in question. Equation (1) says that investors are indifferent between holding a government bond that matures in k periods, and investing in a sequence of one-period bonds for k successive periods plus the term premium. It is straightforward to show that (1) can be expressed in terms of the spread, that is the slope of the yield curve, which highlights how it is dependent on investors' expectations of future changes in yields (e.g., see Campbell, Lo and MacKinlay 1997, Shiller 1990). The upshot is that one can think of long-term and short-term interest rates as being 'attracted' to each other, in the sense of cointegration, whereas short-term deviations represent error corrections (Campbell and Shiller 1987, Engle and Granger 1987). Cointegration tests, therefore, provide a natural way to determine whether interest rates across the term structure have a common stochastic trend. The error correction process, by contrast, is one vehicle for introducing non-linearities in the adjustment to equilibrium.

There are several reasons to expect non-linearities in the equilibrium adjustment process between long-term and short-term interest rates. Transactions costs may differ according to the maturity of the bond considered and may well change over time (Anderson 1997). Risk-premia may also be time-varying and exhibit non-linear behavior (Fama 1990). Policy regimes aimed at influencing the yield spread may also be sufficiently important as to create structural breaks in the underlying relationships of interest, and the adjustments from such regime changes may also

[2] Although most researchers would agree that, in principle, a term premium is important, there are disagreements about the best way to estimate it. Difficulties in estimating term premia are exacerbated in a cross-country comparison. Finally, the empirical success at estimating such premia has, so far, been mixed.

be non-linear.[3] Since (1) is expressed in terms of nominal interest rates, these can be decomposed into a real interest rate component and an inflation expectations component via the Fisher equation. However, inflation expectations are thought to have dominate movements in long-term rates and, together with sluggish adjustment of inflation expectations to shocks, may induce non-linearities in the short-long interest rate relationship. Two other considerations relate to the well-known phenomenon of interest rate smoothing practiced by central banks (Mankiw and Miron 1986, McCallum 1994, Woodford 1999), and differences in volatility between short-term versus long-term interest rates. Both may upset the likelihood of a linear adjustment in the spread between long-term and short-term interest rates (also see Figure 1). Bekaert, Hodrick and Marshall (1997), using a more restrictive framework than ours and data from the US, the UK and Germany, use a regime-switching approach to argue that the failure of the expectations hypothesis is due to fewer high interest rate regimes than expected. Tsavalis and Wickens (1997) argue instead that a time-varying risk premium (i.e., $\theta_{k,t} \neq \theta_k$) in (1)) renders the data consistent with the EH for US data. Clearly, failure to incorporate this effect into a model of the spread can also lead to non-linearity in the behavior of short-term interest rate movements.

Finally, several countries have recently adopted inflation targets (Bernanke et al. 1999, Siklos 1999). Theoretically, the spread between long-term and short-term interest rates, while subject to the formal constraint of the expectations hypothesis, could conceivably drift for a time. However, given a credible inflation target, inflation and inflation expectations are bounded by the target band and should be attracted toward the middle of the target band. As with the target zone literature on exchange rates, the spread is stationary, that is, mean reverting within the target zone and non-stationary when no target zone is specified (Amano, Black and Kasumovich

[3] A separate issue is whether linearity fails due to a structural break or is the result of an inherently non-linear process. Although our interest in

1997, and Siklos and Granger 1997). One potential problem in estimating the impact of inflation targets is that the span of the sample since their introduction is relatively short. Nevertheless, to the extent that most countries had an implicit inflation target, it is conceivable then that while the term spread is non-linear, there is a linear component that might be well captured via a linear error correction type mechanism.

There exist a variety of formulations that test the expectations hypothesis. For example, using continuously compounded yields (r), a version of the idea that long rates represent an average of short rates may be expressed (Campbell, Lo, and MacKinlay 1997, chapter 10), in regression format, as

$$r_{n-1,t} - r_{n,t} = \beta_0 + \beta_1 \frac{r_{n,t} - r_{1,t}}{n-1} + \varepsilon_t \qquad (2)$$

The left-hand side of (2) measures, at time t, the change in the yield from year n-1 to year n, i.e., $\Delta r_{1,t}$ or the short-run yield change. The right-hand side of the equation represents the average annual yield spread ($S_{n,t} = r_{n,t} - r_{1,t}$) , that is the spread between a long-term bond, maturing in *n* years, and one maturing in one year. Strictly speaking, the expectations hypothesis predicts that the slope of the yield curve, namely β_1, should be 1, since the average annual change in the long-term bond yield should be equivalent to a 1 year yield change. In addition, the constant, $\exists_0$, is expected to be zero in the absence of any risk premium. Our interest in this paper, in the context of (2), concerns the properties of ε_t, in particular, under the hypothesis of non-linear adjustment.

Obviously, (2) presupposes that long and short rates are attracted to each other in a statistical sense. This implies that the cointegration property applies to yields across the term structure. There is, of course, a large literature that documents this property for a wide variety of countries (e.g., Hall, Anderson and Granger 1992, Fuhrer 1996, and Siklos and Wohar 1997).

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this paper is more focused on linear versus non-linear alternatives we do consider structural stability questions. Also see Koop and Potter (1998) .

Cointegration, however, presupposes that the series individually possess a unit root. Alternatively, the expectations hypothesis, as expressed in (2), requires the presence of a large autoregressive root and, in that case, standard inference is not asymptotically valid (Elliott and Stock 1994). Lanne (1999) reports that this may be an important reason for the rejection of the expectations hypothesis over perods covering more than one policy regime. However, once the EH hypothesis is tested for separate sub-samples, it is no longer rejected. Also, Lanne's (1999) results pre-suppose that the location of the break is known with certainty. In contrast, our approach is to ask a somewhat different question, namely can a non-linear model explain the behavior of the term spread relatively better than a linear model across policy regimes, and which economic variables could possibly explain the transition from one regime to another. Clearly, while our approach avoids some of the problems with existing analyses of the term spread, it leaves others unresolved, such as the convenient assumption that unit roots in the short and long term interest rate are a reasonable approximation to the time-series behavior over the sample period considered.

Existing empirical evidence, naturally is more heavily weighted in the direction of using US data, and is not overwhelmingly favorable to the expectations hypothesis as stated above. Hardouvelis (1994) is one oft-cited study that finds evidence against the EH for US data while the evidence is more favorable for the remaining G7 countries considered in the sample. Dotsey and Otrok (1995), Wallace and Warner (1993), respectively, reject and accept the EH, although the latter study notes that the results are sample sensitive. Gerlach and Smets (1997) find that countries which participated in the European exchange rate mechanism (ERM) are more likely to produce spreads consistent with the EH. Hall et al. (1991), and Siklos and Wohar (1997), find evidence of cointegration across the term structure consistent with the EH for a sample consisting of data from the US and other industrialized countries.

Finally, more recent work on the EH and the role of the monetary authorities in influencing the spread finds that such considerations are important in the US and in other industrial countries. See, for example, Kugler (1996), Fuhrer and Moore (1995), Haubrich and Dombrosky (1996), Dillén (1997), Smets and Tsatsaronis (1997). With the exception of Siklos (2000), there have been no studies of the impact of inflation targeting in tests of the expectations hypothesis.

Econometric Specification

Equation (2) is the baseline specification. As is well-known, cointegration requires that long-term and short-term yields display unit root behavior. Hence, we follow the usual practice of generating the Augmented Dickey-Fuller (ADF) test statistic to examine the unit root hypothesis. The lag augmentation term in the test equation is estimated by applying Akaike's information criterion (AIC), following the suggestion of Agiakloglou and Newbold (1996). We imposed a maximum of 24 lags for the lagged differences in the interest rates for the full sample, which seemed reasonable based on an examination of the time series properties of the data. We also tested for two unit roots and rejected this hypothesis in all cases. Next, we proceed to test for cointegration using Johansen's method, perhaps the most widely used technique under the circumstances. The technique is based on maximum likelihood estimation of (2) in the form of a VECM (vector error-correction model). The VECM is specified with a constant term only in the cointegrating vector so that there are no deterministic time trends allowed for in the underlying data as an unrestricted constant term in the VECM would imply. The details of unit root and cointegration testing are well known and readers are referred to Johansen (1995) and Maddala and Kim (1998), among many excellent references on the subject, for additional details.

In addition, since the relationship implicit in (2) is a bivariate one and, given the well-known sensitivity to the assumptions required to obtain the likelihood ratio test statistics of interest in Johansen tests for cointegration, we repeat all cointegration tests using the Engle-Granger (1987) formulation.[4] We next estimate a linear error correction model (ECM)

$$\Delta r_{1,t} = \mathrm{A}(L)\Delta r_{1,t-1} + B(L)\Delta r_{n,t-1} + \alpha(r_{1,t-1} - \beta_0 - \beta_1 r_{n,t-1}) + \varsigma_{0t}\,, \qquad (3)$$

where ς_{0t} is a mean-zero white noise error term, the last term in parentheses is the error correction term, A (L) and B(L) are distributed lag functions of order p, and the other terms were previously defined. Note that, to permit comparability, we follow past practice and model the relationships of interest in terms of changes in the short-run interest rate (e.g, Anderson 1997).[5] There is considerable cross-country evidence that long-term interest rates are weakly exogenous and we therefore specified (3) as a single equation ECM instead of a VECM. This allows us to specify meaningful and parsimoneous non-linear models below.

For the non-linear model we estimate a variety of smooth transition regressions (STR; see Granger and Teräsvirta 1993, Ter≅svirta 1998). Such models presume that there are regime shifts in the underlying data and that the transition from one regime to the next is a locally linear one. Among the many useful properties of STR models is that their structure permits specification, estimation and diagnostic testing to follow more or less the usual approach used to estimate linear ARIMA models of the Box-Jenkins variety (Teräsvirta 1994). Under the present circumstances this means estimating a non-linear error-correction model of the form

[4] See also Xiao and Phillips (1998).

[5] Corradi, Swanson and White (2000) consider the possibility of non-linear cointegration and find US evidence supportive of the hypothesis for US data covering the 1970-1988 period (Hall, Anderson and Granger (1992) used the same smaple). This excludes the most recent policy regime in the US. Anderson (1997) finds evidence of non-linear error correction in the same data set as do Enders and Siklos (2001), who used a different sample of US data. We do not consider such extensions in the present paper.

$$\Delta r_{1,t} = \beta' X_t + (\beta' X_t) F(\tau_t; \gamma, k) + \eta_t \,, \qquad (4)$$

where F(·) is generally bounded between 0 and 1, F(·) is the transition function, γ is a positive slope parameter to indicate how rapidly the transition from one regime to another takes place, k locates where the transition occurs in time, while τ_t is the transition variable. X_t is a vector of regressors that is defined as

$$X'_t = (\Delta r_{1,t-1},\ \Delta r_{1,t-2},\ ...,\ \Delta r_{1,t-p},\ \Delta r_{n,t-1},\ \Delta r_{n,t-2},\ ...,\ \Delta r_{n,t-p},\ (r_{1,t-1} - \hat{\beta}_0 - \hat{\beta}_1\, r_{n,t-1}))\,.$$

In what follows, denote the last term, which is the estimated linear error-correction term, by ec_{t-1}. The transition variable is key to the identification of a non-linear relationship since it is one of the economic variable that is believed to trigger the smooth transition from one regime to another. A variety of formulations for F(·) have been suggested in the literature (e.g., see Granger and Teräsvirta 1993, Teräsvirta 1998, Potter 1999). Granger and Teräsvirta (1993, Chapter 7), Teräsvirta (1998), and others, assume that the functional form for F(·) is either of the *logistic* (LSTR) or *exponential* (ESTR) variety. In the LSTR model, the transition function is monotonically increasing in τ_t and allows for asymmetric transition:

$F(\tau_t;\gamma,k) = \{1 + \exp[-\gamma(\tau_t - k)]\}^{-1}$

The ESTR model is a non-monotonic alternative that is symmetric around k:

$F(\tau_t;\gamma,k) = 1 - \exp[-\gamma(\tau_t - k)^2]$

The adjustment speed γ and location parameters k can be estimated via non-linear least squares. We follow Lütkepohl et al. (1999) and others (e.g., Hendry 1995, chapter 16, and Baba, Hendry and Starr (1992)) in focusing on non-linearities in the error correction mechanism. Note also that the linear ECM is a special case of (4). Hence, rejection of the null that γ=0 implies that the data support the non-linearity hypothesis. Unlike Lütkepohl et. al. (1999), however, we separately estimate the linear cointegrating vectors prior to estimating the linear ECM in equation (3), as opposed to performing the estimations of (3) in one step as they did. Equation (4) is not identified under the null hypothesis of linearity. Teräsvirta (1998) suggests estimating an auxiliary regression, consisting of the regressors multiplied by the transition variable, with the addition of non-linear terms, in order to test for nonlinearity. In the present case the auxiliary regression has the form

$$\Delta r_{1,t} = \beta' X_t + \delta_0' X_t \tau_t + \delta_1' X_t \tau_t^2 + \delta_2' X_t \tau_t^3 + \eta_t . \qquad (5)$$

where the null hypothesis of linearity is $\delta'_0=\delta'_1=\delta'_2=0$. Typically, the practice has been to let each regressor in X_t in turn be the transition variable. It is important that τ_t is moment stationary up to a certain order, except when it is dominated by a polynomial in time (see Lin and Teräsvirta 1994). In many applications, however, there is little theoretical or empirical guidance for the choice of a transition variable. However, in tests of the behavior of the spread, there is guidance from both sources. Hence, we examine in turn the error correction term, the lagged spreads, and forecasts for inflation and real GDP growth, as candidates for the transition variable. Therefore, τ_t is in turn represented by

$$\tau_t = (ec_{t-1}, S_{n\,t-1}{}^{US}, S_{n\,t-1}, \pi_t^e, y_t^e, (\pi_{t-1} - \pi^*)) \qquad (6)$$

where π^e_t and y^e_t are, respectively, private sector forecasts of inflation and real GDP growth for time t conditional on information at time *t-1*. All series are entered in their I(0) formulations in the regressions. Since one of the objectives of the study is to investigate differences in short term interest rate behavior as between inflation and non-inflation targeting countries we also consider deviations from the announced inflation target. Note that if the target is credible, $(B_{t-1} - B^*)$ is expected to be I(0). Analog to the linear error-correction process in equation (3), where the error-correction term enters in lagged form, we choose for τ_t a variable from the information set available at time t-1.[6]

We also believe, but cannot prove, that there are at least two other candidates for non-linearities in the term spread that have not been sufficiently emphasized so far in the literature. First, if, as has been pointed out (e.g., Bernanke at. al 1999), central bank policies have changed considerably over the past few decades, then this could possibly induce non-linearities in the term spread in the form of a structural break. The term spread is, after all, an important economic indicator monitored by these same monetary authorities. Alternatively, if the researcher's objective is to model the spread over a fairly long span of time, it is likely that non-linearities will be present in the time series, again because of changes in regimes that are difficult to identify via linear econometric methods (again, see Figure 1).

Data

We use monthly data for a sample spanning the period 1960-1998. We use a Treasury bill rate to proxy the short-term interest rate while the yield on long-term government bonds, generally maturing in 10 years or more, represents our measure of long-term yields. Our data set consists of 6 industrialized countries. They are: Canada, Germany, Sweden, Switzerland, the UK and the US. Three of the countries, namely Canada, the UK and Sweden, adopted inflation targets in the 1990s (Siklos 1999 provides the precise dates and institutional details). The data were obtained from the International Financial Statistics CD-ROM (see the data appendix for more details). Data on inflation forecasts were obtained from various issues of the OECD *Economic Outlook* and from various issues of *The Economist's* Poll of Forecasters. The OECD forecasts are for the annual percent change in the current year GDP deflator published twice a year. Similarly, forecasts of the output gap were used to proxy expectations of future economic

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[6] See also Michael et al. (1997) on institutional factors in the case of purchasing power parity that may make longer delays in adjustment theoretically plausible.

activity. The raw data were converted into monthly data by fitting a cubic spline function to fill in the missing observations with the last observation matching the raw data. The main advantage of these series is their availability over a long span of time. *The Economist* Poll of Forecasters is an average of a dozen or more forecasts for current year annual CPI inflation and real GDP growth made by private banks (Siklos 1999 provides more details). The data usually appear in the second monthly issue of *The Economist*. Data from *The Economist* are, however, available only since August 1990. Therefore, wherever possible, we relied on the OECD data. We considered specifications in interest rate levels as well as in logs of the levels but the results reported in the next section are all based on the levels specifications. All calculations were carried out with the software package EViews 3.1, and some with Eviews 4.0.

Empirical Evidence

Tables 1 and 2 present unit root and cointegration tests. Using the AIC criterion, it is difficult to reject the null of a unit root for any of the nominal interest rate series in our data set. This is consistent with the existing evidence about interest rate behavior. The results are more mixed for the spread. Thus, although we can easily reject at the 5% level of significance the null of a unit root in the spread, the same null cannot be rejected for Germany and Switzerland. The selection criterion picks a zero lag in two of the three cases of non-rejection of the null of a unit root. In these cases, the rejections are somewhat sensitive to the chosen lag length in the augmentation term of the ADF test equation. In addition, as noted earlier, these results are also likely to be sensitive to the presence of breaks in the data which we model by estimating a non-linear approximation to the model of short term interest rate behavior. Turning to the forecast data, we find that one cannot reject the null of a unit root in inflation forecasts and in several output gap/GDP growth forecasts. For the countries considered, it is likely that breaks in the data such as the end of the Bretton Woods system of pegged exchange rates, or the introduction of a new monetary policy framework as in the adoption of inflation targets, may also explain apparent unit root behavior where one would not expect it to emerge.

Although estimation in this paper focuses on the full available sample, it is important to consider the possibility that, even if the linear model is rejected, diagnostic checking of non-linear models may reveal statistical inadequacies along one or more dimensions (see below). Indeed, extensive testing led us to re-estimate all of the non-linear models for US data for the post 1980 period due to a major change in the operating framework of monetary policy.

The cointegration tests shown in Table 2 reveal some evidence of a linear equilibrium type relationship between long and short rates. However, these tests are neither necessary nor sufficient for non-linear cointegration to exist or not to exist. Michael at al. (1997) point out that non-linearities could lead to the failure to reject the null hypothesis of no cointegration. Corradi, Swanson, and White (1998) explore the issue of testing for specific forms of non-linear cointegration. We instead analyze non-linearity within the error-correction model. Table 2 shows that the null of no linear cointegration can be rejected for some countries, but not for others. Also, results are sensitive to the test used.[7]

Table 3 presents tests of the null hypothesis of linearity against a smooth transition alternative (either of the ESTR or LSTR variety). The *p*-values are shown for each of the transition variables considered in (6). The preferred specification is shown in boldface, that is, the transition variable that yielded the *smallest* p-value across the various cases considered. In some cases, there is really little difference across *p*-values and it is, therefore, possible that there

[7] The Engle-Granger test is based on a regression of the short rate on the long rate. All tests were also run with the long rate as the dependent variable, as recommended by Engle and Granger (1987). As the chosen dependent variable did not affect the findings of cointergation only one set of results is shown in Table 2.

is more than one candidate for the transition variable. These are presented in shaded areas.[8] Note that not all transition variables are relevant in all cases, either because they are inapplicable (e.g., as in deviations from an inflation target for a non-inflation targeting country) or are unlikely to be directly relevant in explaining the spread (e.g., the US spread in the case of Sweden).

The null hypothesis is that all of the cross-products and higher order terms are jointly insignificant resulting in an F-test with (3p, T-4p) degrees of freedom (Teräsvirta 1998, p. 516, outlines step-by-step the calculation details), where p is the number of parameters and T the number of observations. Both the logistic STR (LSTR) and the exponential STR (ESTR) variants were estimated and the model that fits the data best was selected. All reported STR models lead to positive estimates of the adjustment speed γ and the estimates of the location parameter k were well within the bounds of the respective transition variable. Further, the chosen STR model was subjected to a variety of diagnostic tests as recommended by Teräsvirta (1998, p. 531 ff), namely no remaining non-linearity, no autocorrelation in the error term, the absence of ARCH, as well as parameter constancy. These are discussed later.

The null of linearity is strongly rejected in Table 3 when the lagged domestic interest rate spread is the transition variable in four cases. In one case, the rejection is not that strong (p=.033). However, in the case of Canada, Sweden and the UK, the error correction term and in the case of Canada and Sweden macroeconomic forecasts are also good transition variable candidates. Rejection of linearity using the inflation target variable occurs only for UK data. This result is interesting since it suggests that deviations from the UK inflation target, at least for the sample considered, are explaining the (smooth) transition from a policy of no stable nominal anchor to one where the inflation rate becomes the (credible) nominal anchor. In the case of the

8 Clearly, the search proceeds in a manner likely to yield some evidence of non-linearity in the term spread. Nevertheless, our interest is motivated to a greater extent by the search for economically sensible candidates to explain a preference of non-linear over linear models. Also, see Corradi, Swanson and White (2000).

other two inflation targeting countries in the sample, namely Sweden and Canada, one is unable to reject linearity when deviations from the target represent the transition variable. Note, however, that the design of the targets differs significantly in these three countries. In Canada, the mid-point of (π_{t-1} - π^*) has been falling gradually over time. In Sweden, the target was initially a point (2%) and then became a range (1-3%) after 1995. Finally, in the UK, the inflation control measures were first specified as a range (1-4%, until 1997) and then as an inflation rate below 2.5%. Of course, the fact that these targets were introduced in the early 1990s only undoubtedly represents another factor in the results obtained in Table 3. Finally, it is worthwhile noting that the ESTR model outperforms the LSTR model in all cases. This suggests that smooth transition tends to be symmetric around k.

The fact that when the US spread is the transition variable results in a strong rejection of the null of linearity for Canada confirms the role of US disturbances in explaining movements in Canadian short-term interest rates. Nevertheless, the fact that forward looking variables are relevant in the case of Canada and Sweden (as well as the US), as is the error correction term, is important since these variables have not typically been used as transition variables in the estimation of non-linear models.

For the US, the full sample period leads to a rejection of the linear models with all possible transition variables considered. However, the results for Table 4 will show that the non-linear models over the full sample period are not stable. Due to structural change, only the sample form 1982 onwards leads to a stable non-linear model. In Table 3, this period corresponds to the second row for the US, where only the domestic spread leads to a rejection of linearity.

As noted earlier, it is not sufficient to simply reject linearity. The non-linear model must also pass a number of model adequacy tests. These are displayed in Table 4. Four sets of tests were considered. The application of these tests to STR models requires regressions involving the gradient vectors from the non-linear maximum likelihood function (see Teräsvirta, 1998, pp. 518-525; we implemented step 1' on p. 520). The test for ARCH-like behavior in the residuals and the degree of autocorrelation in these same residuals are commonly used diagnostic tests in both linear and non-linear models. Four of six countries display no ARCH(1) structure in the residuals (higher order ARCH – defined by the number in parentheses - were considered but are not reported). Moreover, with the exception of Canada, three is little evidence of significant autocorrelation in the residuals. Arguably, the two most important diagnostic tests are whether there is any remaining non-linearity as well as whether the estimated parameters are constant. The former is obtained by asking whether non-linear terms are statistically significant when added to the baseline STR model in (4) (see Teräsvirta 1998, pp. 520-22). The test denoted LM_1 is a test for smooth monotonic changes in the parameters of the STR model and as the speed of adjustment goes to infinity, the limiting case is a single structural break The LM_2 test is a test for a smooth non-monotonic change (in the STR parameters) symmetric about t-k, with the limiting case being two structural breaks. LM_3 modifies the transition function to permit non-monotonic, as well as monotonic, and non-symmetric changes in the STR model parameters (see Eitrheim and Teräsvirta 1996, and Teräsvirta 1998, pp. 522-24). As noted earlier, although it was found that while linearity could easily be rejected for the full sample using US data, the estimated model could not pass either the no remaining non-linearity or the parameter constancy tests for the full sample. However, upon re-estimation for the post 1982 sample, that is, following the "regime" change initiated by then Fed Chairman Paul Volcker, US data pass all the diagnostic tests. The same problem was not encountered in any of the other countries' data sets. While it is possible that the US experience represents a "shock" that was not replicated elsewhere, our results do appear to indirectly reinforce the existing literature's view that the US spread has behaved significantly differently than the spread of other countries. For the UK we provide diagnostic tests for two cases, owing to the relatively brief sample since inflation targets were introduced. Nevertheless, whether the deviations from the inflation target or the error correction term are the transition variables, both models pass almost all of the model adequacy tests.

Figure 2 plots values of the transition function against the chosen transition variable for each country in the data set. For four of the six countries, namely Canada, Germany, Sweden, and Switzerland, the function is U-shaped. The values of the adjustment speed γ, supported by the values of the transition function, are different from zero in these countries so that the finding of non-linearity in the behavior of the spread is further reinforced. For the UK the results are, not surprisingly, sensitive to the choice of transition variable and, indirectly, to the length of the sample in this particular case. The transition function takes on lower values when the deviations from the inflation target are considered indicating that the targets may indeed serve as a mechanism to constrain how large the spread can be. In contrast, when the error correction term is the transition variable, the transition function takes on quite large values. Overall, there is reasonably strong evidence pointing to the non-linear estimation approach to the spread in an international data set.

Conclusions

The premise of the paper is that there are good theoretical and empirical reasons to prefer non-linear estimation over a linear approximation. In particular, important changes in policy regimes and financial markets reactions to them argue for such an approach. Moreover, linear models are not as flexible as non-linear ones when the spread is modeled over a fairly long span of time. Finally, the non-linear approach allows the highlighting of economic variables likely to trigger the transition from one "regime" to another.

We considered in our study a linear versus a non-linear, smooth transition, error-correction model for the adjustment of short term interest rates. We used monthly data since 1960 to show that linearity is rejected in six countries. While the (lagged) domestic spread is the most likely candidate for the variable used in the transition function for the non-linear model, it is noteworthy that an error correction term and the US spread are possibly just as important transition variables. Deviations from the targeted inflation rate are important in the UK case. In addition, forward looking variables such as inflation, output gap or real GDP growth also figure as important candidates for the transition function. Given the relevant literature's emphasis on the role of the spread as a forward-looking indicator of inflation and economic activity, these findings are also significant. Finally, there are some differences in the speed with which the spread signals a change in regime with US and UK data, in particular, indicating that a threshold may exist such that it signals a rapid transition from one regime to another (also see Enders and Siklos 2001). Consistent with other recent evidence (e.g., Lanne 1999, Bekaert, Hodrick and Marshall 1997a) we also reject the EH for the full sample in all countries. It is, therefore, possible that finding non-linearities in the term spread is the price we pay for rejecting the EH hypothesis which is, however, fundamentally a linear relationship.

Nevertheless, a number of issues remain to be addressed. Although there are good theoretical reasons to expect non-linearities in the term structure none of the exisiting theoreies have, so far, proved decisive. Consequently, if the empirical results of this paper are taken seriously, they point to the need for more theoretical work with explicit non-linear models to better isolate the source(s) of departures from linearity. Perhaps most important is the fact that the linear and non-linear models have not been subjected to a comparison of forecasting performance. Unfortunately, the literature is rather sparse on the subject (see, however, Granger and Teräsvirta 1993, ch. 8) and the technical difficulties of forecasting non-linear models beyond one period are considerable. However, it is important to point out that while several variables led us to reject the linear model, clarity in the choice of variables for the transition function was readily obtained when the various non-linear models were put through various diagnostic tests. The latter prove to be more important and more weight should be placed on these than has heretofore been the case.

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Table 1

***p*-Values for Unit Root Tests**

Country	**Series**					
	Short rate $r_{n,t}$	**Long rate** $r_{1,t}$	**Spread** $S_{n,t}$	**Inflation Forecast** π^e_t	**Output Gap, or Real GDP Growth Forecast** y^e_t	**Period**[2]
Canada	.23 (10)	.45 (11)	.01 (10)	.12 (23)	.04 (23)	1960:01-1998:12
Germany	.47 (2)	.56 (1)	.14 (0)	.49 (20)	.11 (20)	1975:07-1998:12
Sweden	.05 (0)	.45 (7)	.0001(0)	.89 (24)[1]	.61 (0)[1]	1962:12-1998:12
Switzerland	.38 (22)	.40 (23)	.15 (0)	.80 (0)[1]	.06 (12)[1]	1980:01-1998:12
UK	.06 (1)	.62 (3)	.04 (1)	.37 (20)	.03 (20)	1964:01-1998:12
US	.06 (16)	.43 (6)	.003 (16)	.49 (20)	.002 (23)	1964:01-1998:12
US	.42 (5)	.44 (12)	.13 (9)	.45 (12)	.23 (12)	1982:11-1998:12

Note: Data used are monthly from the source listed in the text for the periods shown in the last column, except for GDP forecasts for Canada (1971:06-1998:12), the UK (1968:06-1998:12), the US (1964:06-1998:12) and Sweden and Switzerland (1991:01-1998:12), and inflation forecasts for Canada (1960:12-1998:12), and Sweden and Switzerland (1991:01-1998:12). Interest rates and inflation rates are in percent. The test is the Augmented Dickey-Fuller t-ratio with the number of lags (in months) in parentheses. Generally, a time trend was not included in the test regressions. *p*-values have been calculated with the program from MacKinnon (1996).

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Inflation rates for Canada (.52 at 24 lags), the UK (.49 at 24 lags) and Sweden (.52 at 12 lags) exhibit unit root behavior. These rates will be used to calculate the deviations from the inflation target mid-range π^* in Table 3.

1. CPI inflation and real GDP growth forecasts from the Economist were used.
2. Before differencing or lags.

Table 2

***p*-Values for Cointegration Tests**

	Test Statistics	
Country	**Johansen**	**Engle-Granger**
Canada	.004 [1]	.14 [14]
Germany	.55 [1]	.09 [13]
Sweden	.007 [0]	.21 [23]
Switzerland	.25 [1]	.05 [24]
UK	.34 [1]	.46 [23]
US	.02 [2]	.02 [14]
US	.86 [1]	.19 [9]

Note: The Johansen test is the likelihood ratio statistic for the trace version of the test with lags in the VECM shown in brackets using Schwarz's information criterion. A constant is present only in the cointegrating vector of the VECM and there are no deterministic trends. The Engle-Granger test is the Augmented Dickey-Fuller test statistic for the residuals from the cointegrating equation of the short rate on a constant and the long rate with the lag augmentation given in brackets. A maximum of 14 lags was assumed in the test equation with the lag chosen according to the longest lag augmentation with a t-value greater than 1.6, in absolute value. *p*-values calculated with programs from MacKinnon, Haug, and Michelis (1999) and from MacKinnon (1996). See Table 1 for sample details and the appendix for variable definitions.

Table 3

***p*-Values for the Test of Linearity Against a STR**

	Transition Variable					
Country	**ec_{t-1}**	**$S_{n,t-1}^{US}$**	**$S_{n,t-1}$**	**B^e_t**	**y^e_t**	**B_{t-1} - B***
Canada	.004	**4.54 x 10^{-12}**	.033	5.97 x 10^{-6}	2.55 x 10^{-5}	.280
Germany	.408	**.014**	.53	.044	.797	n.a.
Sweden	7.86 x 10^{-9}	n.a.	**4.66 x 10^{-9}**	.196	1.14x10^{-6}	.427
Switzerland	.135	n.a.	**.008**	.352	.129	n.a.
UK	.024	n.a.	.342	.845	.758	**.022**
US	**0**	n.a.	**0**	5.48 x 10^{-7}	.001	n.a.
US	.147	n.a.	**.016**	.523	.273	n.a.

Note: The transition variables are in levels or first differences, depending on the unit root test results reported in Table 1. Also see Table 1 for definitions and sources for the time series, as well as sample length information. The smallest p-values in each row are shaded. Other transition variable candidates with *p*-values not much different from the lowest are in bold face. The first difference was used for the spread of Germany and Switzerland, for all inflation forecasts, and for the GDP forecast of Germany, Sweden and Switzerland. $S_{n,t-1}^{US}$ and $S_{n,t-1}$ are the yield spreads as defined in equation (2). The minimum and maximum values for the inflation target used to calculate the mid range of the inflation target π* are available as follows: for Canada 1991:02-1998:12, for Sweden 1993:03-1998:12, and for the UK 1992:10-1998:12. Otherwise samples are as shown in Table 1. n.a. means not applicable.

Table 3

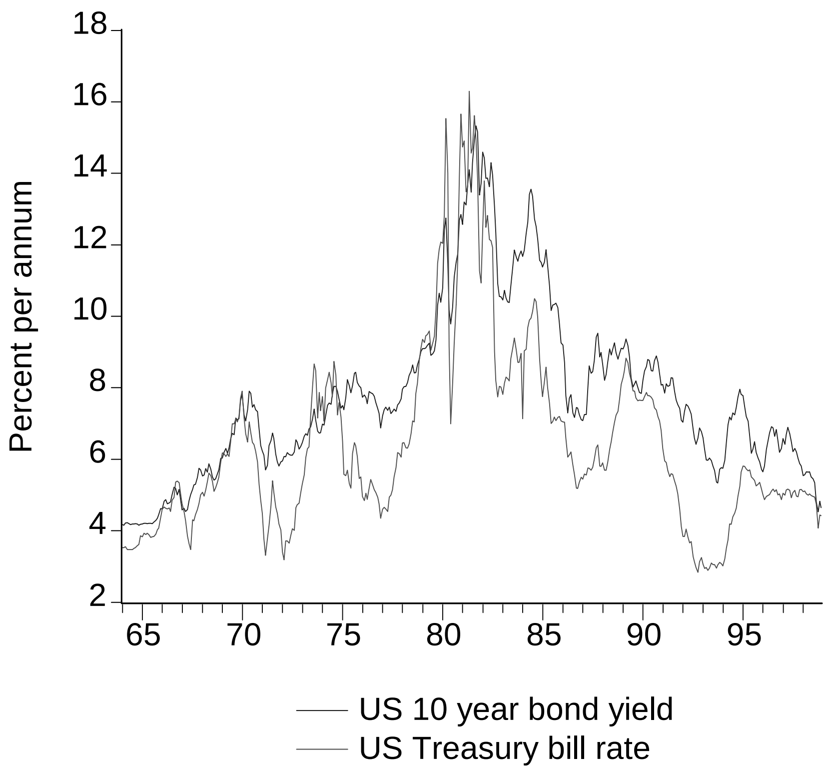
***p*-Values for Diagnostic Tests of STR Models**

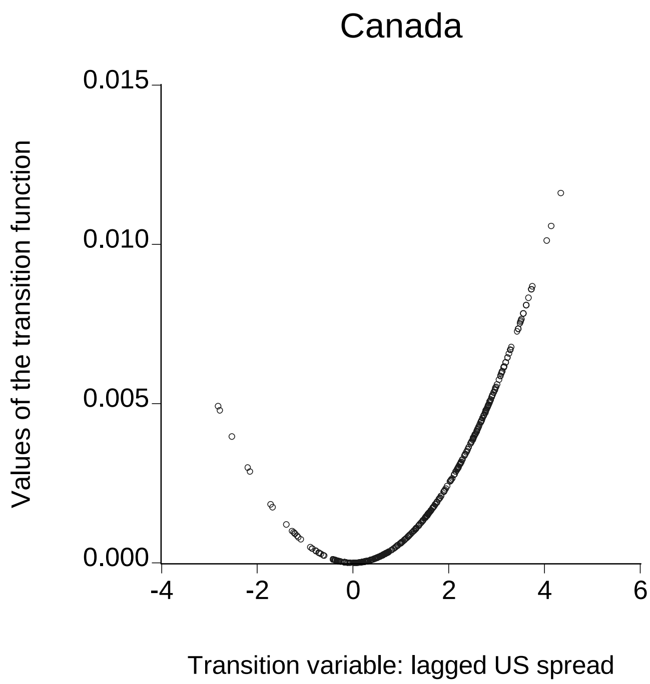
	Country						
	Canada	**Germany**	**Sweden**	**Switzerland**	**UK**		**USA**
	Transition Variable						
Type of Non-linear model	ESTR	ESTR	ESTR	ESTR	ESTR		ESTR
Transition variable	*US Spread*	*US Spread*	*Domestic Spread*	*Domestic Spread*	*IT band*	*ec*	*Domestic Spread*
Type of Test							
No remaining ARCH	.00	.98	.33	.003	.85	.00	.29
No error Auto-correlation	(3) .01 (6) .01 (12) .06	(3) .89 (6) .07 (12) .02	(3) .02 (6) .14 (12) .48	(3) .21 (6) .22 (12) .20	(3) .44 (6) .24 (12) .37	(3) .31 (6) .17 (12) .16	(3) .12 (6) .17 (12) .31
No *Remaining Non-linearity*	.42	.05	.99	.32	.93	.27	.85
Parameter constancy	LM_1 =.58 LM_2 =.89 LM_3 = .75	LM_1= .26 LM_2 =.18 LM_3 =.33	LM_1 =.35 LM_2 =.50 LM_3 =.45	LM_1=.05 LM_2=.05 LM_3=.003	LM_1 =.05 LM_2 =.31 LM_3 =.02	LM_1 =.70 LM_2 =.73 LM_3 =.57	LM_1=.55 LM_2=.13 LM_3=.33

Note: Samples are given in Table 1. For the US, results are for the 1982-98 sample. No remaining ARCH is an LM test for ARCH order q, where q=1. Higher order ARCH tests were also considered but did not affect the conclusions. No remaining autocorrelation gives the p-value for autocorrelations at lags shown in parenthesis. No remaining non-linearity gives the p-value of the test proposed by Eitrheim and Teräsvirta (1996). The parameter constancy tests are a generalization of Lin and Teräsvirta (1994), as described in Teräsvirta (1998, pp. 522-24) that test for the constancy of all parameters in the estimated equation. *ec* is the lagged error correction term derived from the underlying cointegrating relationship between long and short rates.

Figure 1 US Long and Short-Term Interest Rates, 1964-98

Figure 2 Transition Functions




Canada
0.015
0.010
0.005
0.000
Values of the transition function
-4
-2
0
2
4
6
Transition variable: lagged US spread

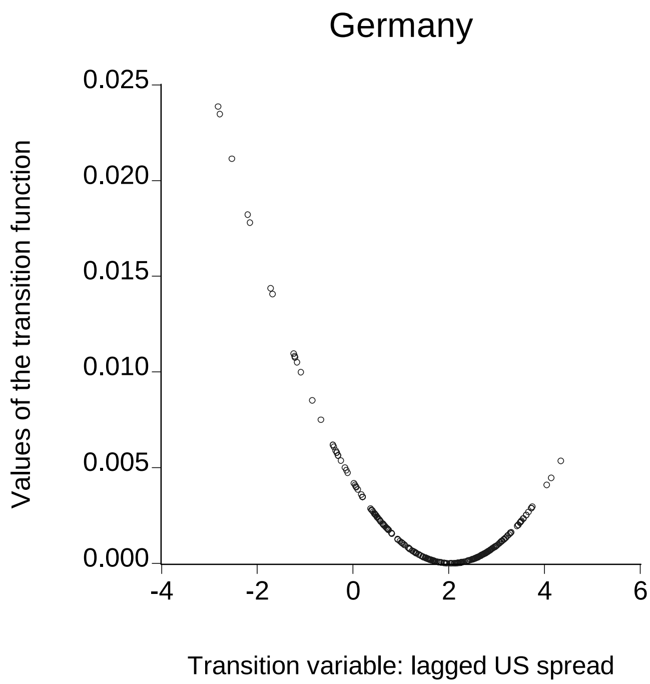
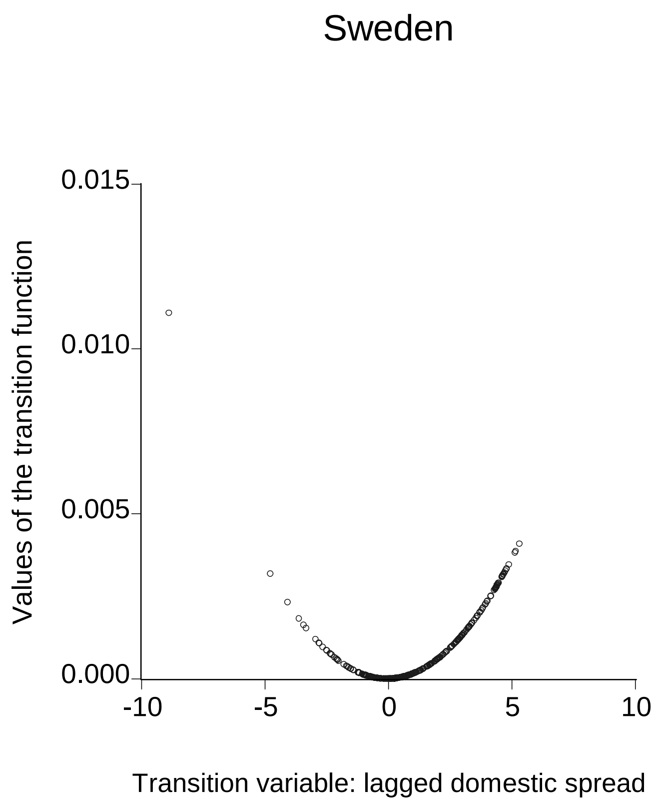

Germany
0.025
0.020
0.015
0.010
0.005
0.000
Values of the transition function
-4
-2
0
2
4
6
Transition variable: lagged US spread

Figure 2 cont'd



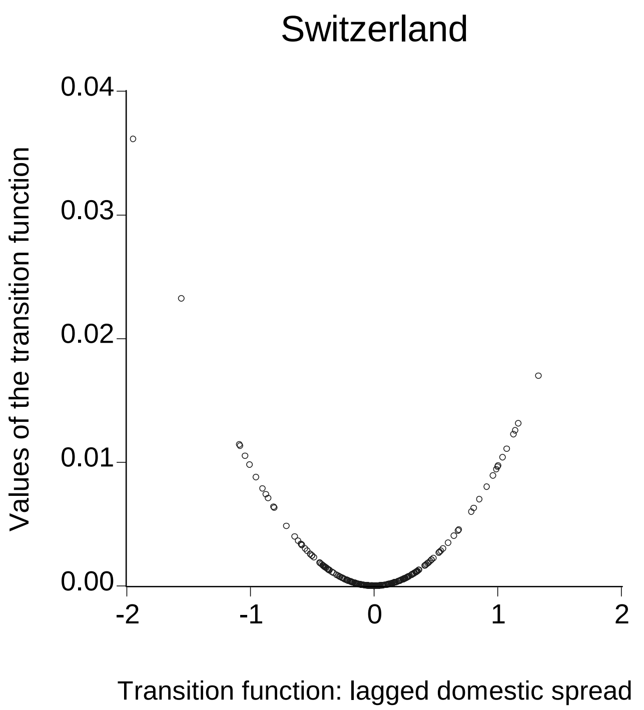
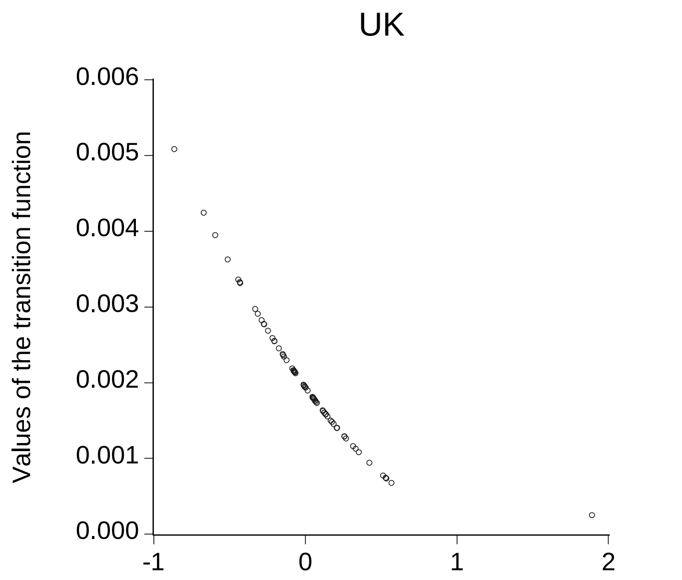
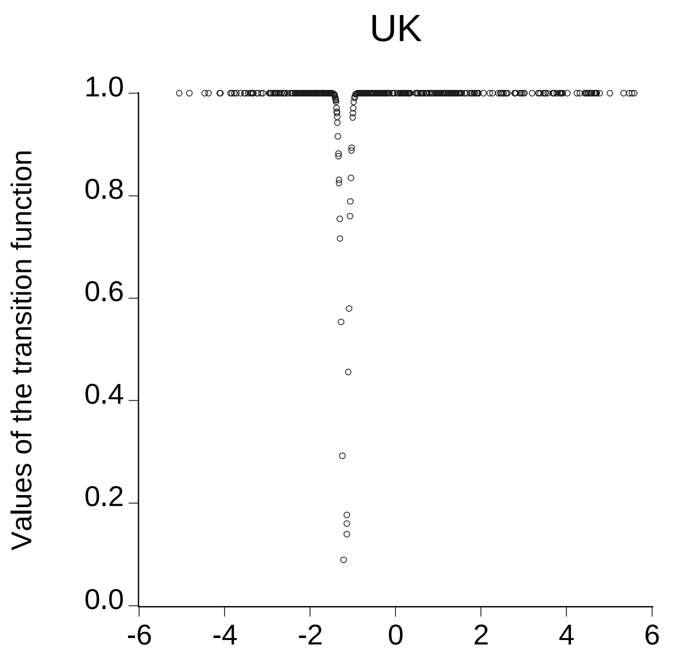


Figure 2 cont'd

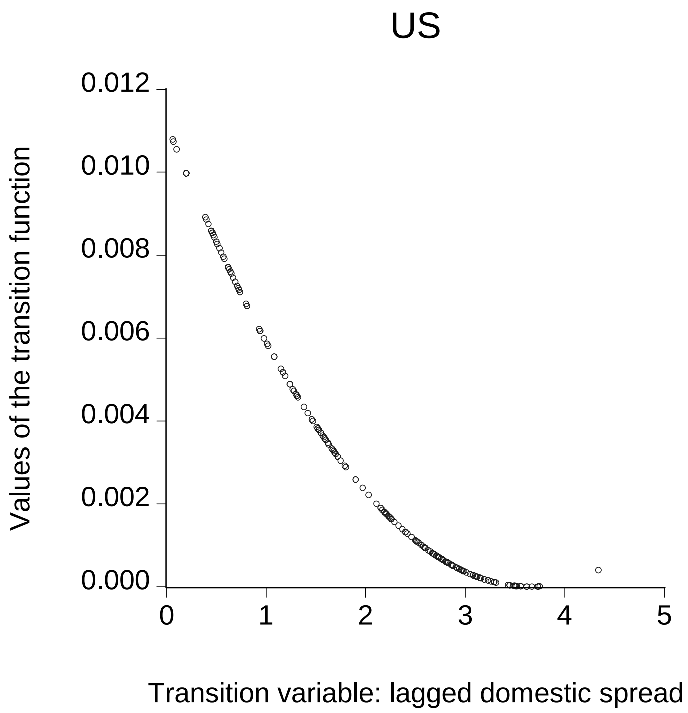


Transition variable: deviations from the inflation target



Transition variable: lagged error correction term

Figure 2 cont'd



Data Appendix: IFS series definitions

Country	Short-term rate	Long-term rate
Canada	90 day Treasury bills	10 years and over government bonds
Germany	Treasury bill rate	Long-term government bonds
Sweden	3 month treasury discount notes	Long-term government bonds
Switzerland	Treasury bill rate	Long-term government bonds
UK	Treasury bill rate	Long-term government bonds
US	Treasury bill rate	10 years government bonds