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J.E.L. Codes: F31

Keywords: Exchange Rates, determination puzzle, non-linearities, cross-country asymmetries, automated model selection, indicator saturation

Non-linear Exchange Rate Relationships: An Automated Model Selection Approach with Indicator Saturation

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1 Introduction

The volume of trading in the foreign exchange market has increased dramatically in recent years from \$3.3 trillion daily in April 2007 to \$5.5 trillion in April 2013 (BIS 2013). Clearly understanding the driving forces behind exchange rate movements is more important now than ever given our increasingly globalized financial system and world economy. Despite this, connecting exchange rate movements to movements in fundamentals remains a daunting and contentious issue. Monetary models of the exchange rate have struggled to account for movements in the exchange rate even *ex post* (Rogoff 2001). This implies that the fundamentals which are supposed to drive the exchange rate in theory (namely relative money supplies, income, inflation, interest rates, trade etc.) have little explanatory power in reality. Certain sample periods have appeared well fitted (Mark 1995), but there has been little consistency as the samples have been extended (Cheung, Chinn and Pascual 2005). Some optimism has emerged regarding the longer-run ability of monetary models (MacDonald 1999, Engel, Mark, and West 2008), but the vast majority of short term and even longer term movements in exchange rates remain anomalous.

An important and promising strand of the literature has attempted to address this deficiency by allowing for non-linear effects of fundamentals on the exchange rate. Some of the empirical studies have allowed for recurrent shifts between two regimes in Markov switching models (Engel and Hamilton 1990, Frömmel, MacDonald and Menkhoff 2005, De Grauwe and Vansteenkiste 2007), or smooth transition threshold models (Sarantis 1999, Taylor and Peel 2000, Killian and Taylor 2003). While these approaches have offered an improvement over linear models in many cases, few would argue that there is not much left to uncover. Others have allowed for stark and unpredictable changes in the relationship based on tests for parameter instability, though with linear relationships within regimes, and have offered notable improvement via these piece-wise linear models (Goldberg and Frydman 1996a, 2001; Beckman, Belke, and Kühl 2010). Questionnaire evidence from actual traders supports the notion that the effects of fundamentals change over time but also indicates that they differ across countries (Chueng, Chinn, and Marsh 2004).

This study investigates how much improvement can be garnered by allowing for cross country asymmetries and non-linear dynamic effects of the fundamentals; for example allowing the effect of a change in the interest

rate to depend on the country and magnitude of the change. Two exchange rates are examined at the often perplexing monthly frequency, the US dollar per Japanese yen (USD/JY) and US dollar per British pound (USD/BP), from July 1982 to February 2012. These currencies constitute three of the most heavily traded in the world (BIS 2013). The information set also includes data on money supplies, production, consumer prices, three-month T-bill rates, 10-year bond rates, current accounts, and unemployment, as well as squared, cubic, and exponential terms for each regressor. This provides a very general functional form capable of approximating myriad elaborate non-linearities including smooth transition functions with asymmetries (Castle and Hendry 2009).

The model selection for both the linear and non-linear models is conducted using the Autometrics algorithm (Doornik 2009) with a model selection bias correction applied to the estimates which overcomes the usual detractors of step-wise regression (Hendry and Krolzig 2005). Autometrics allows for estimation even when the number of regressors exceeds the number of observations by conducting block searches with feasible subsets. This obviates the need to estimate models with fewer variables in order to conserve degrees of freedom, for example assuming linearity and symmetric effects across countries as is commonly done.

Of course, there are still many potential omitted variables in this (or any) analysis. In this context, such omissions may include microstructure effects, impacts from technical trading, autonomous expectations related to imperfect knowledge, currency interventions, non-economic news, and other policy or institutional changes. Structural change external to the model is captured through the use of impulse and step indicator saturation procedures (Santos, Hendry and Johansen 2008; Doornik, Hendry and Pretis 2013). This provides a form of robust estimation, and the indicators prove significant and necessary to achieve the well behaved residuals required for valid inference.

The linear models account for less than 20% of the variation in the monthly exchange rate changes, and about 10% if only including lagged regressors to avoid endogeneity problems. The non-linear models with asymmetries meanwhile can account for nearly three times the variation in either case. The non-linear model with asymmetries is preferred according to several model selection criteria, including an index test for non-linearity (Castle and Hendry 2010), and both the asymmetries and non-linear effects appear to be vital under a variety of model specifications. Several of the non-linear effects are significant at the 1% if not 0.1% level, and significant lagged effects

indicate Granger causation.

Many of the results are consistent with Taylor rule models of exchange rate determination (Engel and West 2006, Molodtsova and Papell 2009) and the emphasis by Engel, Mark, and West (2008) on the importance of the monetary policy rule. For example, increases in US inflation and the money supply lead to appreciation, interpreted as stemming from the expected central bank reaction of raising interest rates. This study adds the elaboration though that larger changes in fundamentals often lead to changes in the exchange rate at an increasing rate, which may reflect leverage effects, rational inattention, or signal extraction behavior.

There are also asymmetries present where the normally depreciative effects on the USD are partially offset by flights to quality. The Japanese current account exhibits diminishing returns possibly reflecting countervailing intervention by the Bank of Japan. Significant positive effects of the lagged change in the exchange rate are also observed; consistent with momentum and extrapolative chartist behavior (Frankel and Froot 1990, De Grauwe and Grimaldi 2006) and prior studies documenting trending behavior in the exchange rate (Engel and Hamilton 1990, Johansen et al. 2010), though it exhibits slight non-linearities in both samples.

One notable result is that the frequency of structural breaks is greatly reduced once allowing for the non-linearities. In the USD/BP sample, we have six indicators significant at the 0.1% level, whereas 13 would have been needed in the linear model. In the USD/JY sample, only one significant indicator is found, while four would have been needed in the linear model. This suggests that many of the outliers and structural breaks found in previous studies were an artifact of the mis-specified, linear functional form. Major structural breaks still appear highly relevant however, often proximate to major policy changes such as the Plaza Accord in 1985 and the UK's abrogation of the European Monetary System (EMS) fixed exchange rate in 1992. Interestingly, structural breaks would have been detected in the linear models around the 2008 financial crisis, but were not required in the non-linear models.

Section two discusses the data and model specifications in more detail. Section three discusses the automated model selection and compares the models with and without non-linearities and/or asymmetries in terms of the fit, model selection criteria, residual analyses, and an index test for non-linearity. Section four employs the indicator saturation procedures and discusses the estimated non-linearities. Lastly, section five concludes.

2 Data

The information set includes monthly data from 1982:07-2012:02. All of the data was collected from the FRED database. Variables include the USD versus BP and JY end of period spot exchange rates (represented by the symbol s), consumer price indices (p), three month T-bill rates (i), M2 money supplies (M), 10 year government bond rates (b), civilian unemployment rates (u), and industrial production (y). Quarterly current account data (ca) is also included as a % of GDP and interpolated to monthly values to match the frequency of the other variables.¹ All of the variables are measured as log differences, with the exception of the variables in percentage terms including the unemployment rate, the current accounts (which cannot be logged due to their occasional negative values) and the interest rates; though the latter has been divided by 1200 to correspond more closely to the units of the monthly changes in the log exchange rate (as is not uncommonly done, see for example Johansen et al. 2010).

Several of the variables undergo longer term trends, for example prices and industrial production. Consequently, all variables are measured in terms of their change minus their mean change, not dissimilar to detrending the data. This is designed to correspond to the notion that it is the "news" or unexpected change which drives the exchange rate. All variables are assumed to be $I(0)$ after differencing and correcting for breaks. These two adjustments are capable of creating a stationary series even from variables which otherwise appear as approximately $I(2)$. Graphs for each series are presented in the appendix.

All models include two lags for each variable including the dependent variable. Contemporaneous regressors are excluded to prevent endogeneity bias. The basic model is estimated in relative terms (domestic minus foreign variables), while the asymmetric models include each country's variables separately. The symbol $\Delta_m x_t$ is used to represent the difference between the change in the variable and its mean change ($\Delta x_t - \Delta \bar{x}_t$). The superscript r in $\Delta_m x_t^r$ denotes relative values of domestic (US) minus foreign e.g. $\Delta_m x_t^r = \Delta_m x_t - \Delta_m x_t^*$. Since all variables are demeaned, a constant

¹The Japanese current account data prior to 1985 is appended from the series excluding exceptional finance, which ends in 2008. The two series move very closely however until the mid-2000's. Industrial production is used as the denominator in this case, though again it mimics the movements in the shorter available sample of the current account as a % of GDP.

is redundant. The general unrestricted form of the linear relative model is estimated as follows:

$$\begin{aligned}\Delta_m s_t = & \beta_1 \Delta_m s_{t-1} + \beta_2 \Delta_m s_{t-2} + \beta_3 \Delta_m i_{t-1}^r + \beta_4 \Delta_m i_{t-2}^r + \beta_5 \Delta_m b_{t-1}^r \\ & + \beta_6 \Delta_m b_{t-2}^r + \beta_7 \Delta_m y_{t-1}^r + \beta_8 \Delta_m y_{t-2}^r + \beta_9 \Delta_m p_{t-1}^r \\ & + \beta_{10} \Delta_m p_{t-2}^r + \beta_{11} \Delta_m m_{t-1}^r + \beta_{12} \Delta_m m_{t-2}^r + \beta_{13} \Delta_m u_{t-1}^r \\ & + \beta_{14} \Delta_m u_{t-2}^r + \beta_{15} \Delta_m C A_{t-1}^r + \beta_{16} \Delta_m C A_{t-2}^r + \varepsilon_t\end{aligned}\quad (1)$$

In order to present the larger models in compact form, they are displayed in summation notation over the j lags and i regressors. Equation 1 translated into this summation notation is expressed as follows:

$$\Delta_m s_t = \sum_{i=1}^8 \sum_{j=1}^2 \beta_{ij} \Delta_m x_{i,t-j}^r + \varepsilon_t \quad (2)$$

where x_i^r is a vector of eight regressors $= [s_{t-j}, i_{t-j}^r, b_{t-j}^r, y_{t-j}^r, p_{t-j}^r, m_{t-j}^r, u_{t-j}^r, C A_{t-j}^r]$, and $j=1,2$. We can see that there are again, as in equation (1), $8 \times 2 = 16$ regressors.

The linear asymmetric model allows for differential effects of the foreign and domestic variables, so they enter with separate, unrestricted coefficients. Whereas the linear symmetric model has 16 regressors (as shown in equations 1 and 2), the asymmetric model has 30 (the two lagged dependent variables plus two times the other 14 independent variables).

$$\Delta_m s_t = \sum_{i=1}^{15} \sum_{j=1}^2 \beta_{ij} \Delta_m x_{i,t-j} + \varepsilon_t \quad (3)$$

x_i is now a vector of 15 regressors $= [s_{t-j}, i_{t-j}, i_{t-j}^*, b_{t-j}, b_{t-j}^*, y_{t-j}, y_{t-j}^*, p_{t-j}, p_{t-j}^*, m_{t-j}, m_{t-j}^*, u_{t-j}, u_{t-j}^*, C A_{t-j}, C A_{t-j}^*]$.

The non-linear models meanwhile allow for squared, cubic, and exponential effects for each regressor following Castle and Hendry (2009). So for example, the squared, cubic and exponential values of the variable $\Delta_m x_t$ are:

$$\text{sq} \Delta_m x_t = (\Delta x_t - \Delta \bar{x}_t)^2 \quad (4)$$

$$\text{cub} \Delta_m x_t = (\Delta x_t - \Delta \bar{x}_t)^3 \quad (5)$$

$$\exp \Delta_m x_t = \exp(-\text{abs}(\Delta x_t - \Delta \bar{x}_t)) * (\Delta x_t - \Delta \bar{x}_t) \quad (6)$$

where "exp" is the exponential function, and "abs" is the absolute value. This functional form is chosen solely for its very general form. These effects combined are capable of approximating smooth transition threshold models with asymmetries (Castle and Hendry 2005) and higher order polynomial effects, since for example a quadratic function can resemble a quartic function and a cubic function can look quite similar to a 5th order polynomial, given suitably compensatory coefficients and a sufficiently limited range of values undertaken by the variable.

The unrestricted nonlinear symmetric model then has four times the regressors of its linear counterpart in equation (2) or $4 \times 16 = 64$. An intercept is redundant in the linear models, since all variables are demeaned, but since the variables are demeaned before the non-linear transformations, some of the regressors in the non-linear models have non-zero means and therefore we would want to allow for a constant term c .

$$\begin{aligned} \Delta_m s_t = & c + \sum_{i=1}^8 \sum_{j=1}^2 \beta_{ij} \Delta_m x_{i,t-j}^r + \sum_{i=1}^8 \sum_{j=1}^2 \beta_{ij} (\Delta_m x_{i,t-j}^r)^2 + \\ & \sum_{i=1}^8 \sum_{j=1}^2 \beta_{ij} (\Delta_m x_{i,t-j}^r)^3 + \sum_{i=1}^8 \sum_{j=1}^2 \beta_{ij} \exp(-\text{abs}(\Delta_m x_{i,t-j}^r)) (\Delta_m x_{i,t-j}^r) + \varepsilon_t \end{aligned} \quad (7)$$

Meanwhile, the unrestricted nonlinear asymmetric model has four times the regressors of its linear counterpart in equation (3) or $4 \times 30 = 120$.

$$\begin{aligned} \Delta_m s_t = & c + \sum_{i=1}^{15} \sum_{j=1}^2 \beta_{ij} \Delta_m x_{i,t-j} + \sum_{i=1}^{15} \sum_{j=1}^2 \beta_{ij} (\Delta_m x_{i,t-j})^2 + \\ & \sum_{i=1}^{15} \sum_{j=1}^2 \beta_{ij} (\Delta_m x_{i,t-j})^3 + \sum_{i=1}^{15} \sum_{j=1}^2 \beta_{ij} \exp(-\text{abs}(\Delta_m x_{i,t-j})) (\Delta_m x_{i,t-j}) + \varepsilon_t \end{aligned} \quad (8)$$

3 Automated Model Selection and Index Tests for Non-Linearities

With 120 potential regressors, the non-linear models with asymmetries are quite heavily parameterized and could benefit tremendously from model reduction. The unrestricted, non-linear models contain a very large number of (seemingly) irrelevant variables. If however we conduct the model selection algorithm of Autometrics (Doornik 2009) to eliminate some of those highly insignificant variables, we can see that the preference for the remaining non-linear model with asymmetries is almost unambiguous.

Automated model selection has been dramatically improved over the last decade and a half, with much improved algorithms, beginning with for example the multi-path search of Hoover and Perez (1999). The excellent properties of the Autometrics procedure used here have been demonstrated in Doornik (2009), overcoming the previously documented biases of step-wise regression, namely upwardly biased R-squareds and t-values (Lovell 1983). These procedures rely on the general-to-specific methodology, where all potential variables are included from the outset. As Hendry and Krolzig (2004) note, the cost of not proceeding as such is omitted variable bias, uncontrolled significance levels if adding variables later, or a potential confirmation bias where issues are "fixed" successively should results not conform with priors.² The worry of confirmation bias is precisely why White (2000) argued in favor of automated model selection as a means to inhibit "data snooping".

It is useful to begin with a simple overview comparing the models' performances based on various criteria including the R-squared, adjusted R-squared, information criteria, and residual analyses. This helps to avoid becoming too deluged initially in an over-abundance of coefficient estimates. We examine a model with variables in linear and relative terms, linear and asymmetric terms, non-linear relative terms, and non-linear and asymmetric terms, in order to deduce the relative importance of the cross-country asymmetries and the non-linearities.

Below are presented the R-squared and adjusted R-squared for each model using the 5% significance level for automated model selection, though the ultimate deductions are not altered if using the 1% or 10% level instead. The models are also evaluated according to Akaike information criteria (AIC), Hannan-Quinn (HQ), and Schwarz or Bayesian criteria (SC) which more appropriately penalize for over-parameterization (Akaike 1973, Schwarz 1978, Hannan and Quinn 1979). The AIC is asymptotically efficient while the latter two are consistent. The preferred model according to the information criteria exhibits the lowest value. Due to spacing limitations, the linear relative model is labeled as Lin. Rel., the linear asymmetric model as Lin. Asym., the non-linear relative model as Nonlin. Rel., and the non-linear asymmetric model as Nonlin. Asym.

²See Campos, Ericsson and Hendry (2005) for a more comprehensive summary of the general-to-specific methodology.

TABLE 1: Model Selection Criteria with Automation at 5%

	Lin. Rel.	Lin. Asym.	Nonlin. Rel.	Nonlin. Asym.
USD/BP				
AIC	-4.639	-4.690	-4.696	-4.776
HQ	-4.617	-4.651	-4.648	-4.668
SC	-4.585	-4.592	-4.576	-4.503
Adj. R ²	0.118	0.171	0.180	0.271
R ²	0.128	0.189	0.203	0.321
USD/JY				
AIC	-4.475	-4.493	-4.493	-4.635
HQ	-4.462	-4.472	-4.454	-4.544
SC	-4.443	-4.439	-4.395	-4.405
Adj. R ²	0.104	0.125	0.135	0.273
R ²	0.109	0.135	0.154	0.314

It is generally clear that the non-linear model with asymmetries is preferred in both samples. It obtains the lowest value for the AIC and HQ, and highest value for the adjusted and overall R squared in both samples. According to the SC however, the linear asymmetric model is preferred in the USD/BP sample and the linear relative model in the USD/JY sample.

A crucial diagnostic though is the residual analysis, which finds the most support for the non-linear model with asymmetries, in terms of providing a potentially reliable model for inference. The diagnostics include the Lagrange multiplier test of serial correlation labeled as AR (Godfrey 1978), autoregressive heteroskedasticity or ARCH (Engle 1982), normality (Doornik and Hansen 1994), heteroskedasticity (White 1980) and the RESET test of model misspecification (Ramsey 1969).

One could argue that it would be reasonable to use the 1% significance level to reject the residual diagnostics (as Castle and Hendry 2009 do), since using a 5% level for each would lead to a type I error of rejecting an "adequate" model far more than 5% of the time based on one of the five tests. The residual analysis is not very favorable for the linear models, rejecting them outright at the 1% level. Only the non-linear models are not rejected even on the basis of this less stringent 1% threshold, and only the non-linear, asymmetric model is not rejected at 1% in the USD/BP sample.

TABLE 2: Residual Analysis with Automation at 5%

	Lin. Rel.	Lin. Asym.	Nonlin. Rel.	Nonlin. Asym.
USD/BP				
AR	0.091	0.153	0.676	0.172
ARCH	0.001	0.018	0.025	0.020
Normality	0.001	0.002	0.002	0.083
Hetero	0.000	0.000	0.046	0.013
Reset	0.112	0.095	0.001	0.089
USD/JY				
AR	0.174	0.259	0.111	0.455
ARCH	0.049	0.021	0.081	0.087
Normality	0.000	0.001	0.012	0.040
Hetero	0.533	0.271	0.219	0.967
Reset	0.844	0.545	0.093	0.649

Again, the one conflicting result above was that the SC preferred a linear model in both samples. We can discriminate between an asymmetric model with or without non-linearities by using the index test for non-linearity of Castle and Hendry (2010) which has been found to outperform the RESET test and other linearity tests under a number of scenarios where the alternative form is uncertain, particularly when the number of possible regressors is large and they are highly correlated.³ The test draws from White (1980) in that it includes squared and cubic terms for the regressors. However, the test uses the principal components of the regressors to overcome issues of high dimensionality and low power, and includes exponential effects as well. To better understand the nature of the resulting non-linearity, we also test for non-linearity in a simple AR(2) model (including only two lags of the dependent variable for regressors). The p-values for the tests are presented below.

TABLE 3: Core Index Test for Non-Linearity

	USD/BP	USD/JY
<i>Lin.Asym</i>	0.003	0.000
AR	0.620	0.524

³The RESET test performs poorly when confronted with outliers, when the non-linearities enter without the linear terms, or when many variables enter with only linear terms. Other alternatives include Teräsvirta (1994) and Brock, Dechert, Scheinkman, and LeBaron (1996). See Granger and Teräsvirta (1993) for a summary of other linearity tests.

As can be seen, the test is rejected at below the 1% level in both samples for the linear asymmetric model, indicating significant non-linearities. The AR(2) model fails to reject linearity however with a p-value of .524 for the USD/JY sample, and .620 in the USD/BP sample. Similar results are obtained for AR models with longer lag dynamics. This suggests that the observed non-linear impacts of fundamentals are not simply reflecting non-linear dynamics in the exchange rate itself.

4 Indicator Saturation and Coefficient Estimates

4.1 False Inclusion, False Exclusion and Bias-correction

The two potential pitfalls in model selection, or statistical inference more generally, are false inclusion and false exclusion (type I and type II errors in this context). Of course, the problem of false inclusion can be controlled by the chosen significance level α . Combined with the number of regressors k we would have an expected number of spuriously included variables, $k\alpha$. What is deemed an acceptable level of false inclusion depends on the researcher's preferences in terms of the trade-off between obtaining spurious variables and excluding relevant ones. In these samples, a 5% selection was necessary to eliminate serious issues of serial correlation and ARCH, even after indicator saturation. Again, the non-linear model with asymmetries begins the GUM with 120 regressors. Using the 5% level, we have an expected false inclusion of six variables. However, the coefficient bias arising from only maintaining the variable when it is sampled as significant can be adjusted, which helps to mitigate the influence of falsely included variables (Hendry and Krolzig 2004).

The intuition of the bias correction procedure is quite straight forward. All variables are more likely to be retained when there has been a "high draw" from the distribution in an absolute sense, so the coefficients are biased away from zero. The degree of this bias falls however with increases in the non-centrality of the distribution $\psi = \beta/\sigma_{\hat{\beta}}$. To understand why, consider a variable with $\psi = 2$. Using the approximation $t_{\hat{\beta}} \approx \hat{\beta}/\sigma_{\hat{\beta}} \sim N[\psi, 1]$ the variable will be sampled as significant at the 5% level ($\alpha = 0.05$) only about 50% of the time (the power is 0.5). Consequently, conditional on

being retained, the t-value will be upwardly bias since we are only sampling from the upper half of the distribution. This provides some intuition for the upward bias found in simulations of earlier stepwise regression procedures (Lovell 1983). In the case of $\psi = 4$ however, the variable will only be falsely excluded approximately 2% of the time at $\alpha = 0.05$ (the power is 0.98). Since we are now sampling from the upper 98% of the distribution, the bias is much smaller. As an aside, this example also highlights that the problem of false exclusion is contingent upon the non-centrality, as is well-known.

Therefore, the bias correction pushes the coefficients towards zero with the degree of this correction contingent upon the estimated non-centrality of the distribution ψ and the applied significance level. Greater correction is applied to lower non-centralities (the less significant variables) and lower significance levels. Conversely, variables with larger t-values retained at less stringent significance levels will be increasingly unaffected. While the intuition is quite clear, the statistical underpinnings and computational challenges of the procedure are quite complicated. An abridged exposition is provided below. See Hendry and Krolzig (2005) for further details and simulation results.

When a variable is maintained because its estimated t-value exceeds the critical value, i.e. $|t_{\hat{\beta}}| > c_{\alpha}$, using the approximation $t_{\hat{\beta}} \approx \hat{\beta}/\sigma_{\hat{\beta}} \sim N[\psi, 1]$, the expectation of the truncated t-value is:

$$E[t_{\hat{\beta}} | |t_{\hat{\beta}}| > c_{\alpha}; \psi] = \psi + \frac{\phi(c_{\alpha} - \psi) - \phi(-c_{\alpha} - \psi)}{1 - \Phi(c_{\alpha} - \psi) + \Phi(-c_{\alpha} - \psi)} = \psi + r(\psi, c_{\alpha}) \quad (9)$$

Where r is the inverse Mills ratio with ϕ representing the probability density function and Φ the cumulative distribution function. By subtracting this bias from the estimates, we can obtain an unbiased estimate of the non-centrality.

$$\psi = E[t_{\hat{\beta}} | |t_{\hat{\beta}}| > c_{\alpha}; \psi] - r(\psi, c_{\alpha}) \quad (10)$$

This function is non-linear in the unknown ψ but can be estimated through a two-step, iterative process using Newtonian methods. The bias corrected coefficient is:

$$\bar{\beta} = \hat{\beta} \left(\frac{\hat{\psi}}{\hat{\psi} + r(\hat{\psi}, c_{\alpha})} \right) \quad (11)$$

Where $\hat{\psi}$ is the estimated non-centrality. Given the fraction is necessarily less than or equal to one, we can see that the correction has the effect of pushing the estimates towards zero.

To focus on the second potential mistake in inference, the possibility of excluding a relevant variable, the power to retain correctly is not much altered from using a very large initial model compared to even the extreme case when one knows exactly which variables are relevant and includes only those from the outset (Hendry and Krolzig 2004), and as mentioned before the possibility of false exclusion is less worrisome for variables with larger impacts.

4.2 Indicator Saturation

As discussed in the introduction, an important strand of the literature has developed which relates the exchange rate determination and other puzzles in international finance to the presence of structural breaks. Goldberg and Frydman (2001) for example show that the practice of estimating time invariant models has obscured the influence of fundamentals. After allowing for structural breaks they obtain more significant results consistent with theory. An at least equally extensive econometric literature has developed on testing for structural breaks (see for example Bai and Perron 1998 and Hansen and Johansen 1999) and various alternatives abound.

In order to address structural breaks and ensure the reliability of the estimates, we use an impulse indicator saturation (IIS) and a step indicator saturation (SIS) procedure (see Santos, Hendry and Johansen 2008 for IIS, and Doornik, Hendry and Pretis 2013 for SIS). Shifts in the level of the exchange rate relationship would manifest as outliers in the differenced model, and shifts in the time varying trend would present as mean shifts. These indicators can control for omitted variables which impact the exchange rate aside from the included fundamentals and lagged changes in the exchange rate, for example policy changes, non-economic news, chartist and microstructure effects, or changes in forecasting due to learning or imperfect knowledge.⁴

⁴Lyons (2003) and Dominguez and Panthaki (2006) discuss microstructure/non-economic news. Frankel and Froot (1990), De Grauwe and Grimaldi (2006), and Schulmeister (2006) discuss technical trading. Goldberg and Frydman (1996b) and Frydman and Phelps (2012) discuss learning/imperfect knowledge.

These procedures include an impulse and step indicator for each observation, conducted in block searches, or sub-samples, to permit feasible estimation since the number of included variables automatically exceeds the number of observations. The indicators are included simultaneously with all potential fundamentals to prevent incorrect inclusion or exclusion of either. This is even more important when non-linearities are possible, given these can often mimic outliers when wrongly excluded (Castle and Hendry 2009). Castle and Hendry (2009) argue that if an economic variable truly has an effect, it should not be shrouded by the inclusion of indicators, and moreover the inclusion of indicators prevents correlations fabricated by chance coinciding of shifts in the variables. Following these previous papers, the indicators will be detected at the 0.1% level, meaning only one in 1,000 would be expected to be erroneously included. Thereafter, all of the fundamental regressors are re-included and model reduction is conducted at the 5% level. We can see that after inclusion of the indicators and model reduction, the model specification is much improved according to the residual diagnostics, now better according with the prerequisites for reliable inference.

TABLE 4: Residual Analysis with IIS and SIS

	USD/BP	USD/JY
AR	0.829	0.341
ARCH	0.522	0.466
Normality	0.429	0.034
Hetero	0.135	0.524
Reset	0.317	0.460

4.3 USD/BP Estimates

It is worth noting that Autometrics has been found to improve upon the common information criteria, so the results herein should be prioritized over those in section three in determining whether the non-linearities are relevant, when compared to the asymmetric model without them.⁵ We estimate equation 8 for the non-linear asymmetric model (which nests equation 3 for the linear asymmetric model), and conduct model selection first with IIS and SIS

⁵Of course, the relative and asymmetric models cannot be nested since it would create perfect multicollinearity. Given the majority of the information criteria results, we allow for asymmetries.

at 0.1%, then reincluding all of the regressors and conducting model selection at 5%.

Variables beginning with the capital letters SQ, CUB, and EXP represent the squared, cubic and exponentials of the variables as described in equations 4-6. The subscript m on the difference operator has been dropped, but it should be understood that the variables have been demeaned. The change in the exchange rate is denoted by Δs , the change in the interest rate by Δi , the change in bond rates by Δb , and inflation by Δp . The foreign (non-US) countries are denoted by a superscript asterisk thereafter, while the number at the end following the underscore indicates whether the variable is a first or second lag. The t-values are presented below the coefficient estimates in brackets. The far right column shows the results after bias correction.

It can be seen that the bias correction procedure has the effect of pushing the coefficients towards zero, with the size of the adjustment rising as the t-value falls. Originally, 13 variables were retained, far more than the six that would be expected based on pure chance. Four of those variables have been dropped since they are no longer significant after the bias-correction. Seven of the nine remaining variables are non-linear terms.

The lagged change in the exchange rate has a positive, slightly non-linear effect, consistent with chartist models of extrapolative or trend-following behavior (e.g. De Grauwe and Grimaldi 2006). This is true in the USD/JY sample as well. The coefficients on many of the terms, particularly the cubic effects, are quite large, but in fact are quite reasonable when put in context. The magnitudes of the estimates will be described in more detail following figure 1.

We see three impulse indicators and three step indicators significant at 0.1%. Of particular interest is that in the linear, asymmetric model there would be a much larger number of significant indicator variables, specifically 13 (see appendix table 9). This suggests that many of the structural breaks found in the previous literature were a by-product of the misspecified functional form, omitting non-linearities. Though sparser, structural breaks still appear quite relevant however, and the breaks here possess quite interpretable timing. Many are proximate to the period often invoked as a "bubble" in the US dollar (Frankel and Froot 1990) and the Plaza Accord. The other indicators are proximate to the UK's abrogation of the European Monetary System (EMS) exchange rate peg.

TABLE 5: USD/BP Estimates of Equation 8 with selection at 5% and IIS and SIS at 0.1%

	Coeff.	Bias-adjusted
Δs_1	0.209 [4.47]	0.208 [4.45]
$\text{EXP}\Delta s_2$	-0.138 [-2.85]	-0.115 [-2.36]
$\text{CUB}\Delta y_2$	833.91 [4.00]	821.95 [3.95]
Δp_2	-1.435 [-3.17]	-1.302 [-2.88]
$\text{SQ}\Delta i_2$	-52,797 [-2.83]	-43,512 [-2.33]
$\text{CUB}\Delta i_2$	-2.410e+7 [-2.80]	-1.963e+7 [-2.28]
$\text{CUB}\Delta p^*_2$	-1,817.7 [-2.72]	-1,429.6 [-2.14]
$\text{CUB}\Delta m_1$	-3,735.6 [-2.78]	-3,017.5 [-2.25]
$\text{SQ}\Delta ca^*_1$	0.023 [3.60]	0.022 [3.47]
I:1985(4)	0.088 [4.36]	0.081 [3.98]
I:1985(7)	0.068 [3.43]	0.044 [2.20]
I:1991(3)	-0.081 [-4.05]	-0.069 [-3.45]
SI:1985(2)	-0.023 [-4.81]	-0.022 [-4.63]
SI:1992(8)	0.080 [6.75]	0.080 [6.75]
SI:1992(11)	-0.071 [-6.13]	-0.071 [-6.12]

The significant step indicator in 1985:2 is capturing an appreciative trend in the dollar outside of the effects of lagged fundamentals and even outside of the normal trend following behavior for the exchange rate. This is compatible with characterizations of the the mid-1980's as a bubble in the dollar. We see depreciative mean shifts represented by the two impulse indicators, which could be capturing effects of the Plaza accord, though the timing precedes this agreement and therefore would need to be capturing expectations of intervention. Alternatively, these depreciative effects may be capturing a rising risk premium in the USD as it became further overvalued relative to purchasing power parity, as predicted by the Imperfect Knowledge Economics gap model of the risk premium (Frydman and Goldberg 2004 and

Frydman, Goldberg and Stillwagon 2013). We observe a significant impulse indicator in 1991:03 which signifies downward pressure on the mean of the pound, consistent with speculative pressure on the pound. Just prior to the Black Wednesday UK currency crisis on September 16, 1992 we see an appreciative step indicator capturing the Bank of England's attempt to prop up the currency. This effect is essentially undone by the step indicator three months after, following the collapse as the Bank of England abandoned its efforts at intervention.

We see a positive cubic effect of US industrial production, consistent with trade effects, where rising income leads to increased imports and demand for foreign currency. US inflation and M2 have signs contrary to monetary models but consistent with Taylor rule models of the exchange rate and previous empirical findings (Engel and Frankel 1984; Clarida and Waldman 2008). The interpretation is that surprise increases in inflation or the money supply lead to expected central bank tightening and therefore appreciations of the currency. The effect of the money supply again takes on a cubic functional form, indicating that larger changes have increasing effects.

This particular non-linearity, that larger changes in the variables have larger effects, is observed for several variables; therefore it is worth taking an aside to contemplate the possible reasons for this behavior. The explanation for this non-linearity would of course require further research, but a few hypotheses seem immediately apparent. The first is that the market generally predicts the right direction of change, but larger changes tend to correspond with greater than proportional forecast errors and "news". Such behavior is potentially consistent with Gourinchas and Tornell (2004) who find, using interest rate survey forecasts, that individuals underestimate the persistence to interest rate shocks and that this distorted belief can account for the forward discount anomaly and delayed overshooting puzzle. A second possible explanation ventured here is that this may reflect market participants extracting a larger than proportional signal from larger shocks. In other words, they may view smaller shocks as more likely to be transitory and larger shocks as more likely to be permanent or consisting of a larger permanent proportion. This hypothesis could be similarly tested using interest rate forecast data. Third, this may result from the use of leverage, where larger changes require more individuals to unwind their positions or cause individuals to unwind them to a greater extent. This is potentially consistent with the work of Brunnermeier, Nagel, and Pedersen (2009). A fourth explanation is that the limited impact of small changes may be a by-product of rational inattention

which Bacchetta and van Wincoop (2005) proposed as an explanation for the forward discount puzzle.

UK inflation also exhibits a cubic functional form with a sign compatible with the monetary models where UK inflation leads to pound depreciation. We also see a squared and cubic effect of the US interest rate. Much of the interest rate effects have already been anticipated in the US inflation and money supply variables, given their signs are consistent with Taylor rule models of the exchange rate. The interest rate non-linear functional form is largely capturing an asymmetry where decreases in the US interest rate are less likely to yield dollar depreciation. This was less true however for the largest observed decline in the US interest rate, corresponding to 1982:07. This asymmetry may be capturing flight to liquidity effects or an influence of the zero lower bound, where downward trends to the interest rate cannot be extrapolated to the same extent.

The result for the UK current account is the most difficult to interpret. One possibility is that this variable has simply been falsely included. We would expect six falsely included variables, and only four were initially maintained but then dropped after the bias correction. The variable is highly significant however so it would be a bit hasty to simply dismiss this result as an aberration. Another possibility is that an asymmetry exists for the effect of the current account, toward pound appreciation, but the other linear, exponential, or cubic terms of the functional form have been falsely excluded or are already sufficiently captured in the trade effects represented by US production. The effect of the current account does enter with a more interpretable function for Japan in the next sample.

The estimated functional forms after bias-correction are displayed in figure 1 below as a scatterplot against the observed values for the individual variables; to provide a better grasp of the nature of the estimated nonlinearities. The y-axis represents the effect on the demeaned log difference of the exchange rate. A y-axis value then of, for example, .01 would be a 1% appreciation of the pound, relative to its longer-run average trend of -.0002 over the sample (see table 8). The longer run trend may capture productivity differentials as in the Balassa-Samuelson effect (Balassa 1964, Samuelson 1964). According to the estimates, an increase in the exchange rate of say 10% would tend to be followed by an increase of about 1% in the next month, all else equal, suggesting some momentum or extrapolation. This may also be capturing persistence to changes in some omitted or unobservable fundamentals.

Figure 1: Estimated Non-linearities for the USD/BP in Table 5

The effects of the variables plotted against the observations for the variable. Clockwise from upper right: UK inflation, changes in the UK current account, US industrial production growth, US M2 growth, changes in the US T-bill rates, and the lagged change in the exchange rate.

Based on the estimated relationships, a 2% fall in US output below its trend growth would be associated with an appreciation of the dollar of about 1% (holding interest rates for example constant), while a 4% decline of output below trend would be associated with about a 7% dollar appreciation given the cubic functional form. For the US money supply, a 1% increase above the normal growth rate has little impact, while 2% above would lead to approximately a 3% dollar appreciation (again interpreted as due to expected central bank tightening as discussed in previous empirical studies). For UK inflation, 1% above the average would have little effect, while 3% above would lead to about a 4% pound depreciation.

4.4 USD/JY Estimates

The notation for this sample follows the same conventions as that for the previous samples and again the t-values are presented in brackets below the coefficient estimates. In this sample however, the t-values have been estimated using heteroskedasticity and auto-correlation consistent standard errors (Newey and West 1987), as there are some minor issues of auto-correlation and ARCH effects at various lag lengths for the USD/JY sample (see appendix). We estimate equation 8 (which again nests equation 3), and conduct model selection first with IIS and SIS at 0.1%, then reincluding all of the regressors and conducting model selection at 5%.

TABLE 6: USD/JY Estimates of Equation 8 with Selection at 5% and IIS and SIS at 0.1%

	Coeff.	Bias-adjusted
EXP Δ s_1	0.271 [6.41]	0.271 [6.41]
CUB Δ y_1	-4,290.6 [-3.16]	-3,885.7 [-2.87]
EXP Δ y_1	-191.60 [-2.57]	-138.87 [-1.87]
Δ y_1	190.34 [2.58]	138.82 [1.88]
EXP Δ m*_2	1.249 [2.79]	1.013 [2.26]
SQ Δ m*_2	-275.71 [-5.69]	-275.69 [-5.69]
CUB Δ m_1	-14,789 [-4.23]	-14,672 [-4.20]
SQ Δ m_1	256.98 [3.40]	242.18 [3.20]
CUB Δ i*_1	-1.042e+8 [-3.63]	-1.006e+8 [-3.50]
SQ Δ i*_1	64,575 [3.23]	59,280 [2.96]
CUB Δ p_1	-8181.6 [-10.56]	-8181.6 [-10.56]
EXP Δ ca*_2	0.022 [3.21]	0.020 [3.16]
EXP Δ ca_1	0.052 [3.04]	0.046 [2.71]
EXP Δ ca_2	-0.050 [-3.05]	-0.044 [-2.66]
I:1982(12)	0.073 [18.34]	0.073 [18.34]

In the USD/JY sample, we have an even larger number of significant variables, with 16 originally and two others dropped as no longer significant after bias correction. 13 of those 14 remaining are non-linear in nature. In this sample, we have only one significant indicator variable, again proximate to the beginning of the USD "bubble" in the 1980's following the Volcker disinflation. Meanwhile, we would have four significant indicator variables in the asymmetric model without non-linearities (see appendix table 10). Similarly to the USD/BP sample, it suggests that many of the breaks found in linear models are in fact compensating for the mis-specified linear functional form.

For the regressors, again we see a significant, extrapolative effect of the lagged change in the exchange rate with a slight non-linearity. The point estimates suggest that small changes in US output appear to reflect expected interest rate effects, while large changes are consistent with trade effects (as in the USD/BP sample) with the exception of the largest decline during the Great Recession.

The sign on US inflation is again consistent with Taylor rule models, though in this case it takes on a cubic form. The US money supply has a similar effect to the previous sample, where decreases in the money supply lead to depreciation. This is contrary to the monetary models but consistent with Engel and Frankel (1984), interpreted as due to the central bank's expansionary reaction. In this case though, the functional form is slightly more complicated, with increases (relative to the mean change) leading to depreciation (as they are not undone by monetary policy, reflecting an asymmetry or bias towards easing) but the large increases in the money supply are also associated with future tightening and appreciation of the dollar.

We have a larger number of current account effects in this sample, which is sensible given the greater difference between the US and Japan's, compared to the US and UK's. Notably, the current account is one of the few variables to exhibit diminishing returns. This seems sensible as well, particularly in this sample where the Bank of Japan has frequently intervened in currency markets with the objective of stabilizing trade.

The effects of Japan's interest rate and money supply are quite unconventional. This likely reflects Japan's very unique experience over the last 25 years of a liquidity trap and balance sheet recession (Krugman 1998, Koo 2009). For example, increases in the interest rates have had largely ambiguous effects on the exchange rate, with the exception of the largest increase in 1982:07. This may reflect the fact that rising interest rates for Japan

could have at times been reflecting rising debt concerns, or that monetary tightening at times could have been viewed by markets as premature and counter-productive. Supporting this latter interpretation, decreases in the interest rates have led to future appreciation of the yen, likely viewed by markets as ultimately being good for the struggling Japanese economy. Decreases in the Japanese money supply have led to yen depreciation, similar to the US effects likely reflecting expected reactions by the BoJ to offset this, and small increases have led to yen appreciation, likely viewed as a sign of recovery for the moribund Japanese economy. The largest increases in the money supply meanwhile have been depreciative, reflecting rising inflation expectations. These large increases have coincided with more aggressive expansionary policies since the most recent financial crisis, where investors would not expect the money supply increases to be offset with future monetary tightening.

In the USD/JY sample, we again see some exchange rate momentum, even outside of the effects of fundamentals. A 10% increase in the exchange rate above its trend of .0026 (see appendix table 8) has been associated with about another 2.5% increase above its trend in the next period. This is about twice as large as the trending effect in the USD/BP sample, though again the non-linearities are very minor. For US inflation, 1% below its mean leads to a 1% USD depreciation, while 2% below leads to about a 5% USD depreciation (again interpreted as a Taylor rule effect where falling inflation leads to falling interest rates). This cubic effect could reflect expectations of a more drastic reaction by the Federal Reserve when inflation is further below its target. The current account is not logged (due to its occasional negative values) and is presented as a percent of industrial production. A surplus of about 0.7%, leads to about a 1% increase in the USD/JY, but further increases have very quickly diminishing effects.

Figure 2: Estimated Non-Linearities for the USD/JY from Table 6

The effects of the variables plotted against the observations for the variable. Clockwise from upper right: US industrial production growth, US M2 growth, US inflation, changes in the US current account, changes in Japan's current account, changes in the Japanese T-bill rate, Japanese M2 growth, and the lagged change in the exchange rate.

5 Conclusion

This work finds compelling evidence of cross country asymmetries and non-linear effects of fundamentals on the exchange rate. Allowing for such effects greatly improves the explanatory power of monetary models of the exchange rate. The non-linear effects are often significant at the 1% if not 0.1% level and in many cases the economic interpretation of the non-linearities are quite

intuitive. The overriding theme seems to be that larger changes in fundamentals lead to changes in the exchange rate at an increasing rate, with the exception of the Japanese current account, likely reflecting the Bank of Japan's tendency towards currency intervention to stabilize trade. There are also at times evidence of asymmetries between increases and decreases in the money supply and interest rates, which are consistent with flight to quality effects for the USD (where it tends to depreciate less during periods of economic turmoil). The signs for US inflation and money growth are consistent with countervailing central bank responses (as in the Taylor rule models of exchange rates), and the positive effects of the lagged change in the exchange rate indicate trending behavior in the exchange rate, possibly as a result of extrapolative chartist expectations.

One intriguing result is that many of the significant breaks are eliminated once allowing for non-linear effects, including those around the 2008 financial crisis, suggesting that much of the structural change found in linear models is compensating for the misspecification from omitted non-linearities. Even in the non-linear models however, we have several location shifts significant at the 0.1% level and proximate to major policy changes, for example following the Volcker disinflation in 1982, the Plaza Accord in 1985, and the UK's abandonment of the exchange rate peg in 1992.

Of course, it would be a bit hasty to presume we have fully identified the (or all) relevant functional forms even for the given samples. Additionally, the underlying reasons for the observed non-linearities have only been hypothesized; aside from some suggestive similarities to empirical results using survey forecast data. Survey data on expected future fundamentals or interaction terms *between fundamentals* may prove useful in investigating the conjectured mechanisms behind the non-linearities. Interactions between fundamentals and volatility is another possible avenue for future research. Future research may be beneficial to allow for structural change in (and not only external to) the non-linear effects; as the distinctions between the yen and pound samples suggest a degree of context dependence to the non-linearities, for example being dependent upon central bank proclivities towards intervention and experiences with prolonged deflation. Further, while this approach has offered some progress for the exchange rate determination puzzle or in-sample problems of exchange rate models, it would be worthwhile to investigate whether the automated approaches with indicator saturation and non-linearities could also help to improve upon the forecasting puzzle of Meese and Rogoff (1983), or the out of sample difficulties of exchange rate models. This is left for

future research.

What can be more confidently deduced from this work however is that future research should (i) allow for non-linear effects of fundamentals and cross country asymmetries, and (ii) use indicator saturation to address the significant and prevalent shifts external to monetary models, which are liable to muddle inference otherwise. These insights can be used to supplement other proposed resolutions to the exchange rate determination puzzle including learning/imperfect knowledge or microstructure effects, which the indicators may be capturing.

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Appendix

Table 7: Supplemental Residual Diagnostics for Various Lag Lengths

	BP AR	BP ARCH	JY AR	JY ARCH
1 lag	0.333	0.863	0.668	0.060
3 lags	0.628	0.452	0.313	0.235
6 lags	0.820	0.841	0.244	0.360
12 lags	0.969	0.476	0.055	0.539

Table 8: Descriptive Statistics Prior to Demeaning

	Mean	Std. Dev.
$\Delta s^{USD/BP}$	-.00020	.02473
$\Delta s^{USD/JY}$	.00256	.02725
Δi^{US}	-2.51e-5	.00022
Δi^{UK}	-2.31e-5	.00036
Δi^J	-1.61e-5	.00014
Δb^{US}	-2.52e-5	.00023
Δb^{UK}	-2.37e-5	.00023
Δb^J	-1.72e-5	.00019
Δp^{US}	.00233	.00257
Δp^{UK}	.00253	.00425
Δp^J	.00053	.00403
Δy^{US}	.00196	.00642
Δy^{UK}	.00049	.01037
Δy^J	.00092	.01860
Δm^{US}	.00476	.00377
Δm^{UK}	.00667	.00588
Δm^J	.00343	.00326
Δun^{US}	-.00693	.16353
Δun^{UK}	-.01360	.10497
Δun^J	.00427	.10789
Δca^{US}	-.00378	.12078
Δca^{UK}	-.01533	.34498
Δca^J	-.01862	.30204

Figure 4: Demeaned differenced variables with US in blue and UK in red

Caption: Clockwise from upper right - three-month T-bill rate, consumer prices, 10-year bond rate, and exchange rate

Figure 5: Demeaned differenced variables with US in blue and UK in red

Caption: Clockwise from upper right - industrial production, current account, money supply, unemployment

Figure 6: Demeaned differenced variables with US in blue and Japan in red

Caption: Clockwise from upper right - three-month T-bill rate, consumer prices, 10-year bond rate, and exchange rate

Figure 7: Demeaned differenced variables with US in blue and Japan in red

Caption: Clockwise from upper right - industrial production, current account, money supply, unemployment

TABLE 9: USD/BP Estimates of Equation 3 with Selection at 5% and IIS and SIS at 0.1%

	Coeff.	Bias-adjusted
Δs_2	−0.136 [−3.03]	−0.119 [−2.65]
Δp_2	−1.614 [−3.40]	−1.521 [−3.20]
Δm_1	−0.845 [−2.79]	−0.685 [2.26]
I:1985(4)	0.077 [3.88]	−0.076 [3.84]
SI:1985(2)	−0.028 [−5.70]	−0.028 [−5.70]
SI:1988(5)	0.042 [4.02]	0.041 [3.94]
SI:1988(9)	−0.055 [−3.69]	−0.053 [−3.56]
SI:1988(12)	0.057 [4.15]	0.056 [4.09]
SI:1989(6)	−0.043 [−4.71]	−0.043 [−4.71]
SI:1991(2)	0.065 [5.95]	0.065 [5.95]
SI:1991(6)	−0.062 [−5.47]	−0.062 [−5.47]
SI:1992(8)	0.092 [7.43]	0.092 [7.43]
SI:1992(11)	−0.084 [−7.43]	−0.084 [−7.43]
SI:2008(7)	0.046 [6.09]	0.046 [6.09]
SI:2009(3)	−0.093 [−6.99]	−0.093 [−6.99]
SI:2009(6)	0.049 [4.35]	0.049 [4.35]

TABLE 10: USD/JY Estimates of Equation 3 with Selection at 5% and IIS and SIS at 0.1%

	Coeff.	Bias-adjusted
Δs_1	0.256 [7.21]	0.256 [7.21]
Δca_1	0.039 [2.92]	0.033 [2.46]
Δca_2	-0.041 [-3.06]	-0.036 [-2.69]
I:1985(10)	0.089 [41.37]	0.089 [41.37]
SI:1995(4)	0.018 [4.38]	0.018 [4.38]
SI:1998(8)	-0.089 [-26.00]	-0.089 [-26.00]
SI:1998(10)	0.075 [52.03]	0.075 [52.03]