What drives exchange rate pass-throughs? Evidence from machine learning

Emanuel Kohlscheen and Aaron Mehrotra [1,2]

Abstract

We provide new evidence on the drivers of exchange rate pass-through across four decades and close to a hundred countries, combining econometrics and machine learning techniques. Machine learning is particularly useful for modelling highly non-linear relationships, as well as for precisely identifying the relative importance of the different factors for the degree of pass-through. The level of inflation emerges as the most important determinant of exchange rate pass-through, followed by product homogeneity and the size of the economy, all of which display highly non-linear relationships with the degree of pass-through. We also document important implications of macroeconomic policy regimes and outcomes, including those related to fiscal policy, for exchange rate pass-through.

JEL Classification: E30; E31; E58; F31; F41.
Keywords: inflation; exchange rate pass-through; exchange rate pass-through; Phillips curve.

1. Introduction

The extent to which exchange rates affect CPI inflation typically varies a great deal between countries and time periods. At the country level, identifying the impact of the exchange rate on inflation often involves substantial uncertainty, owing to the small number of time series observations and, at times, regime changes. At the same time, while there is a large empirical literature on measuring exchange rate pass-through, much less is known

[1] Bank for International Settlements. Centralbahnplatz 2, 4002 Basel, Switzerland. *E-Mail addresses*: emanuel.kohlscheen@bis.org and aaron.mehrotra@bis.org.
[2] The views expressed in this paper are those of the authors and do not necessarily reflect those of the Bank for International Settlements.

about precisely which factors drive its magnitude and the relative contribution of the different drivers.

A better understanding of the relationship between exchange rate pass-through and the macroeconomic and structural characteristics of different economies is of particular interest post-pandemic. This stems from the sudden and largely unexpected return of higher inflation globally; the associated changes in pricing behaviour and the dramatic shift in the fiscal and monetary landscape; as well as the shifting patterns of trade and globalisation due to geopolitical fragmentation. This raises questions about how the relationship between exchange rates and consumer prices might change if macroeconomic or structural characteristics of the economies were to undergo persistent changes.

The present study throws new light on these issues. It does so by analysing a broad panel of countries over the last 40 years in an empirical framework that, while taking advantage of the larger precision brought about by the large number of observations, also allows for heterogenous pass-through slopes across countries. Moreover, and in contrast to previous research on exchange rate pass-through, the study uses modern machine learning techniques to quantify precisely the relative contribution of the different economic factors to exchange rate pass-through. The non-parametric approach is particularly useful for modelling highly non-linear relationships. While non-linear effects have been noted in previous studies on exchange rate pass-through (see e.g. Jašová et al (2019)), our study is to our knowledge the first to employ machine learning techniques to model them.

We first show that while the exchange rate pass-through is typically fast, its extent has declined over time. The first-stage Pesaran and Smith (1995) mean group estimators show a pass-through decline from 6.6% over the full sample to a statistically insignificant 4.3% during the last decade in advanced economies. The corresponding pass-through for a broad group of EMDEs has changed less over time, hovering at around 17–20%.

We then show how machine learning can enrich the analysis further. More specifically, in the second step, we rely on the well-established technique of random forests (Breiman (2001)) to link the estimated pass-throughs to their potential determinants. This method has the key advantage that it is relatively transparent and does not require subtle tuning of the parameters (Athey and Imbens (2019)).[3]

The random forests approach pins down the level of inflation as the single most important factor affecting the extent of pass-through across countries and time. This is followed by the economy's size, the extent of product homogeneity and exchange rate volatility. Perhaps surprisingly, given its salience in the previous literature (e.g. Campa and Goldberg (2005, 2010) and Campa and Mínguez (2006)), the degree of trade openness

[3] Note that in this paper we follow the advice of Chakraborty and Murthy (2017), in that we limit the number of explanatory factors from the outset to ease economic interpretation. More specifically, we focus on factors that have been identified as being potentially important in the previous literature.

emerges as the least important factor, among the key variables considered in this paper, for determining pass-through.

We also highlight a number of additional findings.

Interestingly, without imposing any prior or functional form, partial effects from our non-parametric method reveal that pass-throughs become low when average inflation is below 2.5% – a level that is close to the central bank's inflation target in many countries. This suggests that a successful pursuit of low inflation is key to assure a modest degree of exchange rate pass-through.

Moreover, we find that the effect of exchange rate volatility on pass-through is highly non-linear. The strength of the pass-through initially declines as exchange rate volatility rises from low levels, and it reaches a minimum for intermediate levels of exchange rate volatility. The degree of pass-through then increases again as exchange rate volatility rises further. The shape of this U-curve during the last 40 years, and its minimum, are precisely mapped by our data-driven method. Policymakers that wish to stabilise domestic inflation and/or better insulate their economies from sharp global exchange rate movements could potentially assess FX market volatility against this benchmark.

Finally, we analyse the effects of policy regimes and outcomes on exchange rate pass-through. We document that the degree of pass-through is lowest for small deviations of inflation from its target, when the *de facto* exchange rate regime is either a managed or a free float, and when fiscal policy credibility – proxied here by sound fiscal accounts – is high. To our knowledge, our paper is the first to provide evidence that the degree of pass-through is related to the fiscal health of the sovereign.

Relation to the literature. As the extent of exchange rate pass-through is a crucial question in macroeconomics, both in open economy modelling and for policy making, the academic literature on the topic is very extensive. We do not aim to provide a full review of this literature here, but rather highlight a selection of papers which are more directly related to ours.[4]

Empirical studies generally concur that exchange rate pass-through has fallen significantly across the world. These include for instance Marazzi and Sheets (2007), Gust el al (2010), Frankel et al (2012) and Jašová et al (2019), among others. Furthermore, most papers conjecture that the fall is related to the drop in average inflation. Alternatively, Bergin and Feenstra (2009) attribute a large share of the decline in pass-through in the United States to increased trade with fixed exchange rate countries, most notably China.

Relatedly, Devereux and Yetman (2010) show how the degree of exchange rate pass-through in an open economy is essentially driven by the speed of adjustment of prices. When the authors allow the frequency of price adjustments in their theoretical model to be endogenous, they find that pass-through is increasing in the average level of inflation. Taylor

[4] For more complete surveys, see e.g. Menon (1995) and Aron et al (2014).

(2000), Choudhri et al. (2005) and Choudhri and Hakura (2006) reach similar conclusions using different methodologies. And, in the general equilibrium model of Devereux et al (2004), the degree of pass-through is tightly linked to monetary stability, such that countries with low money growth volatility feature low pass-through.

Another stand of the literature emphasises the relevance of exchange rate volatility. Among earlier studies, Krugman (1987) and Froot and Klemperer (1989) posit that the extent of pass-through is connected to the variability of the exchange rate. Following this rationale, Flodén and Wilander (2006) elaborate that if economic agents use (S,s) type price adjustment rules, higher exchange rate variability would mean more frequent touching of adjustment thresholds, implying a higher pass-through. Kohlscheen (2010) finds that emerging markets with higher exchange rate volatility indeed had higher pass-through coefficients in the years that followed the inception of a floating regime. That said, the sample was limited to only eight of the larger emerging markets.[5]

On the other hand, Corsetti et al (2008) show within a theoretical model that even modest nominal frictions can generate stable local currency pricing, and thus a small pass-through coefficient. And Jiménez-Rodríguez and Morales-Zumaquero (2016) empirically document that – with the exception of Japan – larger exchange rate volatility reduced pass-through. Given contrasting results, the effect of exchange rate volatility on pass-through remains a question of debate.

There have been fewer attempts to relate the degree of pass-through to the structural characteristics of economies. Dornbusch (1987) and Menon (1995) link it to country size, indicating that pass-throughs would be smaller in large countries. Similarly, Goldberg and Tille (2008) argue that the share of invoicing in the currency of the destination country would be higher for larger (destination) countries.[6] Campa and Goldberg (2005) however find no significant effect of country size in their analysis of the pass-through to import prices in 23 OECD countries.

Further, Campa and Goldberg (2005) and Auer and Chaney (2009) point out that the pass-through coefficient should theoretically be lower if a large share of traded goods is differentiated, as opposed to homogeneous. Antoniades and Zaniboni (2016), and Chen and Juvenal (2016) indeed find a lower pass-through for higher quality goods in the cases of, respectively, retail prices in the United Arab Emirates and Argentine wine exports. On the other hand, Auer and Chaney (2009) report only weak empirical evidence for their theoretical prediction when analysing granular U.S. import data.

The novelty of the current study is twofold. First, we provide novel estimates of pass-throughs relying on a large number of countries and observations, while at the same time

[5] Relatedly, Ben Cheik et al (2023) find pass-through to be higher when macroeconomic or geopolitical uncertainty is high.

[6] Benigno and Faia (2016) extend the Dornbusch model to show that an increase in the relative share of foreign products increases the pass-through.

allowing for heterogeneous effects across countries. Second, we link the estimated pass-throughs to their macroeconomic and structural drivers with precision, using a well-established machine learning technique.

While the machine learning methodology confirms some of the findings from the previous literature, in particular the importance of the average level of inflation and country size for pass-through, it also provides a number of new findings. This stems from the ability of the method to pin down non-linear dependencies and minimums, for instance with respect to exchange rate variability. More specifically, we find an inflection point at an intermediate level of exchange rate volatility. For significantly lower or higher levels of volatility, the pass-through is found to be much higher. This finding enables the reconciliation of apparent contradictions in the previous literature regarding the relationship between exchange rate volatility and pass-through.

Outline. The article proceeds as follows. Section 2 gives the background and presents the data that were used. Section 3 shows the first-stage econometric estimates. Section 4 explains the random forest method and shows the relative importance of the various factors as well as the partial effects of the key drivers of pass-throughs. Section 5 delves further into the importance of policy related variables for exchange rate pass-through. Section 6 concludes.

2. Background and Data

The analysis that follows is based on a comprehensive sample of countries for which the CPI index, the nominal effective exchange rate (NEER) and the output gap are available from the IMF's International Financial Statistics. We exclude countries whose current population is below 1 million and country-decades where there are less than 20 quarters of data within a given decade. The resulting sample of 98 economies is shown in Table A1 in the Appendix. The data used for estimating exchange rate pass-through are quarterly. The IMF's annual output gap is linearly interpolated to match this frequency.[7]

We classify economies whose GDP in 2023 exceeded $30,000 per capita as advanced economies. This group comprises 25 economies and includes countries whose income level is currently at or above those of Italy and Korea.[8] The remaining countries are classified as emerging market and developing economies (EMDEs).

Inflation declined sharply in both income groups in the 1990s. Figure 1 shows the evolution of medians by country group and decade. Among EMDEs, the decline continued into the following decade, in part as more countries adopted inflation targeting regimes. During the 2010s, median inflation touched a low of 1.6% in advanced economies and 3.7% in EMDEs.

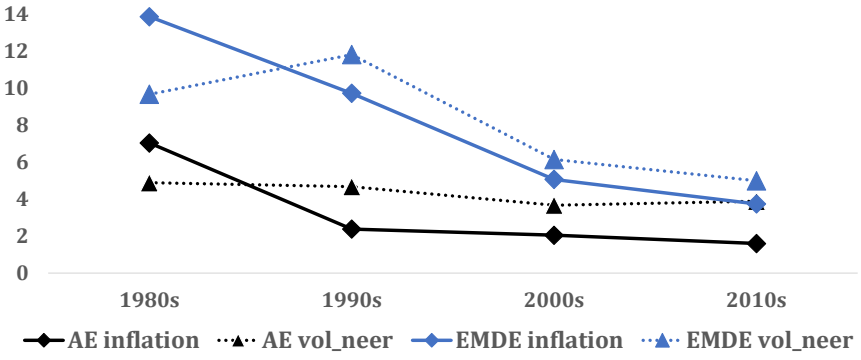
Figure 1 also shows corresponding evidence for nominal exchange rate volatility, measured by the average absolute log variation in the NEER. Exchange rate volatility has been low in advanced economies throughout the sample and declined further in the current millennium. By contrast, among EMDEs volatility increased during the crisis-prone 1990s. Since then, however, median exchange rate volatility has seen a sharp decline in this country group as well. While exchange rate volatility in EMEs was roughly double that of AEs in the 1980s and as much as 150% larger in the 1990s, the difference fell to 67% in the 2000s and then to only 29% during the last decade.

Note that the country coverage underlying these trends increases over time. Whereas 72 countries are included in the 1980s, the coverage increases to 98 countries by the 2010s – as data availability for EMDEs improves.

[7] Using the vintage of April 2023.

[8] The advanced economies according to this criterion are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Hong Kong SAR, Ireland, Israel, Italy, Japan, Korea, Luxembourg, the Netherlands, New Zealand, Norway, Qatar, Singapore, Sweden, Switzerland, United Arab Emirates, the United Kingdom and the United States.

Fig. 1 – Inflation and Exchange Rate Volatility
(balanced sample)



3. Econometric Estimation of Pass-Throughs

Pass-throughs are estimated using the Pesaran and Smith (1995) mean group estimator. This method has the key advantage that it allows for heterogeneity in the transmission of exchange rate changes to inflation across countries. More specifically, the estimated equation is given by

$$\pi_{i,t} = \alpha^i \cdot \pi_{i,t-1} + \beta^i \cdot ygap_{i,t} + \sum_{k=0}^{4} {\gamma_k}^i \cdot \Delta e_{i,t-k} + \theta_i + \varepsilon_{i,t} \,,$$

where $\pi_{i,t}$ is the log difference of the price level in country *i* at quarter *t*, $ygap_{i,t}$ is the output gap, $\Delta e_{i,t-k}$ is the log difference of the nominal effective exchange rate in country *i* at quarter *t-k*, θ_i is the country-specific intercept (i.e. country fixed effect)[9] and $\varepsilon_{i,t}$ the error term. The estimated coefficients are allowed to differ from country to country. That is, $\alpha^i = \alpha + \eta_{1i}$, $\beta^i = \beta + \eta_{2i}$ and so on.

The full sample results show that exchange rate pass-through is typically quite fast.[10] Table 1 shows the estimated mean effects for the full sample and by decade, as well as the resulting exchange rate pass-throughs within a 1-year horizon. The bulk of the impact on inflation occurs within the same quarter of the exchange rate change, or in the quarter immediately after. The average 1-year pass-through for this broad sample of 98 countries is 13.1%, with a *t*-statistic of 9.4.

Further, the control variables obtain the expected signs. The AR(1) term suggests significant persistence in inflation, while the output gap coefficient indicates that inflation is directly related to the degree of over- or underheating in the economy (with a *t*-statistic of 5.5) – an observation that is in line with a standard price Phillips curve.

[9] This factor will also capture differences in inflation targets.

[10] Note that the full sample has by far the largest number of observations. This has the effect of reducing uncertainty around the estimates, as reflected in the smaller standard errors.

Table 1
Estimation of Exchange Rate Pass Through (Pesaran-Smith mean group estimator)

Dependent variable: CPI (log change), quarterly. Unbalanced panel.

	full sample	1980s	1990s	2000s	2010s
lag CPI	0.324***	0.115***	0.138***	0.101***	0.026
	0.026	0.038	0.035	0.029	0.025
NEER $_{t}$	0.067***	0.041***	0.066***	0.038***	0.042***
	0.009	0.015	0.016	0.012	0.011
NEER $_{t-1}$	0.037***	0.042***	0.037***	0.018	0.054***
	0.006	0.016	0.011	0.014	0.009
NEER $_{t-2}$	0.007	0.019	0.001	0.016*	0.024***
	0.005	0.012	0.011	0.008	0.009
NEER $_{t-3}$	0.016***	0.031***	0.010	0.024***	0.005
	0.005	0.012	0.009	0.009	0.008
NEER $_{t-4}$	0.004	-0.003	0.012	0.027***	0.021**
	0.005	0.013	0.009	0.008	0.008
output gap	0.033***	0.006	0.019	0.047***	0.002
	0.006	0.024	0.017	0.013	0.008
1-year pass-through	0.131***	0.130***	0.126***	0.123***	0.147***
(sum of NEER coeffs.)	0.014	0.031	0.026	0.024	0.020
observations	13902	2163	3232	3636	3851
countries	98	72	88	95	98
Wald chi-2	280.25***	32.65***	48.58***	59.29***	68.63***
RMSE	0.030	0.043	0.035	0.016	0.011

Note: Estimated on quarterly data. Robust standard errors are shown below coefficients. ***/**/* denote statistical significance at 1/5/10% confidence level.

How do the results differ between advanced economies and EMDEs? Table 2 shows that the estimated 1-year pass-through in advanced economies, at 6.6%, is lower than the 17.2% estimated for EMDEs. What is more, the exchange rate pass-through in advanced economies reduced even further to a statistically insignificant 4.3% during the past decade. Among EMDEs, by contrast, the estimated 1-year pass-through during the 2010s falls within standard confidence intervals for the full sample – indicating no significant change in this very broad sample of countries.

Table 2
Advanced vs Developing Economies

Dependent variable: CPI (log change), quarterly.

	AEs		EMDEs	
	full sample	2010s	full sample	2010s
lag CPI	0.394***	0.004	0.300***	0.029
	0.041	0.040	0.032	0.033
NEER $_{t}$	0.035***	0.013	0.089***	0.056***
	0.011	0.014	0.013	0.014
NEER $_{t-1}$	0.018***	0.015	0.046***	0.068***
	0.006	0.014	0.009	0.011
NEER $_{t-2}$	0.000	0.002	0.012*	0.036***
	0.004	0.012	0.007	0.012
NEER $_{t-3}$	0.005	-0.011	0.020***	0.015
	0.006	0.011	0.007	0.011
NEER $_{t-4}$	0.008	0.023***	0.006	0.025**
	0.006	0.011	0.007	0.011
output gap	0.041***	0.009	0.024***	-0.001
	0.004	0.016	0.008	0.010
1-year pass-through	0.066***	0.043	0.172***	0.201***
(sum of NEER coeffs.)	0.016	0.027	0.020	0.026
observations	3771	976	10131	2875
countries	25	25	73	73
Wald chi-2	228.76***	8.30	185.52***	75.95***
RMSE	0.0084	0.0050	0.0347	0.0127

Note: Estimated on quarterly data. Robust standard errors are shown below coefficients. ***/**/* denote statistical significance at 1/5/10% confidence level.

While the mean coefficients in Tables 1 and 2 above are obtained for each decade subsample, the methodology also yields country-specific estimates for each regression. These allow us to compute pass-through estimates for each country-decade in the sample. We use the rich variation in the country-time specific estimates next, when examining which factors drive the degree of pass-through.

4. What Drives Pass-Throughs?

The econometric estimation above quantified pass-through for each country-decade. To identify its fundamental determinants, we examine how potential factors advanced in the literature affect the estimated pass-through coefficients.

To this end, we use a machine learning technique of random forests, developed by Breiman (2001). These are flexible but highly disciplined classification algorithms based on an ensemble of regression trees. Essentially, what a regression tree does is to repeatedly split the sample of (253 pass-through) observations based on the explanatory variable and the associated threshold level that minimise the sum of squared prediction errors after the split. This is done exhaustively on the resulting subsamples so that a regression tree takes shape, until a stopping criterion is reached. Outcome predictions are then just the average pass-through over all the observations contained in a terminal node of the tree.

To put it in mathematical terms, the splitting of observations at each node is based on a choice of predictor k and an associated threshold t_k at which the split happens, selected according to the expression

$$arg\ min\ (k, t_k) \qquad \frac{(S_A\ .\ MSE(S_A) + S_B\ .\ MSE(S_B))}{S},$$

where S corresponds to the number of observations in the training sample, i.e. the sample used to construct different candidate models. A and B represent the subsets of the training sample after a binary split.

To ensure robustness, random forests are based on an ensemble of trees – where each tree is grown after a fraction of observations and of explanatory factors are randomly thrown out of the sample. As Susan Athey and Guido Imbens (2019) put it, a key advantage of random forests is that this simple method typically has "great out-of-sample performance without requiring subtle tuning" (p. 696).[11] In this sense, the methodology is more transparent than most alternatives. The fact that this data driven method is non-parametric and does not rely on any a priori imposition of functional form (such as linearity), also makes it appropriate to detect critical threshold values, asymmetries, and/or inflection points.

We use five key covariates that have been put forth in the literature as potential explanatory factors for the degree of pass-through (in our case, for the 253 country-decade

[11] This is partly because the method relies on exhaustive resampling of the dataset and of the features that are used at each split. In this way, the outcomes rely as much as possible on the "law of large numbers".

estimates). These are the average level of CPI inflation in the respective country-decade, exchange rate volatility (the coefficient of variation of the nominal effective exchange rate), trade openness (the trade-to-GDP ratio), the size of the economy (the log of constant USD GDP) and the degree of homogeneity of goods (proxied by the share of food and fuel products in imports). A priori, one would expect countries with low levels of inflation, those that are smaller and more open, and those that rely on less homogeneous goods – where price differentiation and markups are likely larger – to have a weaker pass-through from the exchange rate to consumer prices.

The analysis suggests that the mean squared errors already come close to a minimum when around ten regression trees are used. This is shown in Figure 2 which displays the mean squared prediction errors of the random forest model of pass-throughs, based on the five explanatory variables. However, there is little cost of adding more trees to obtain greater stability in model predictions. In what follows, we use an ensemble of 1,000 trees.

Fig. 2 - Model cross-validation (bagging)

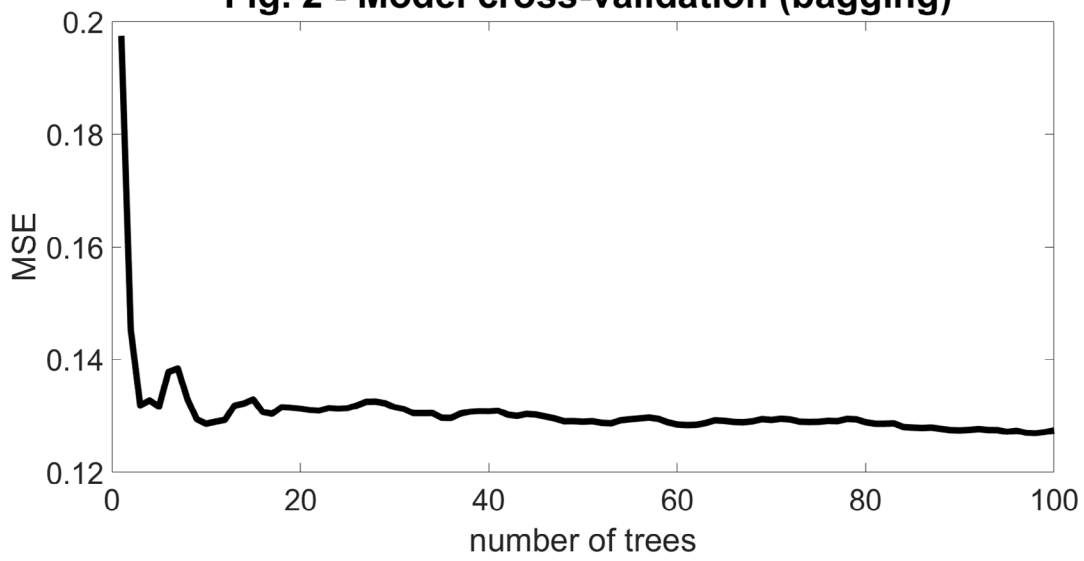
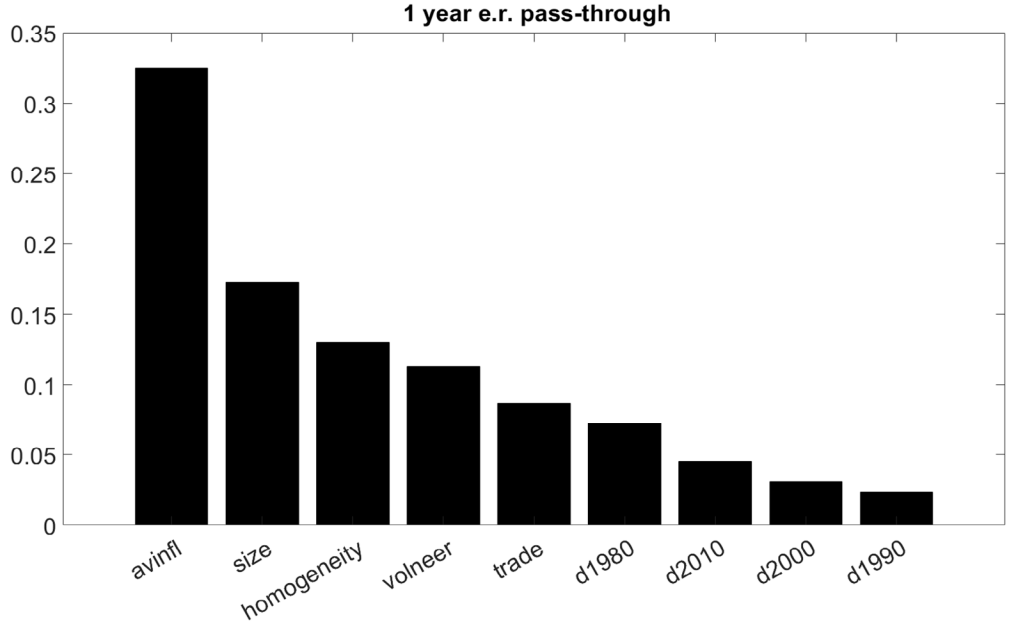


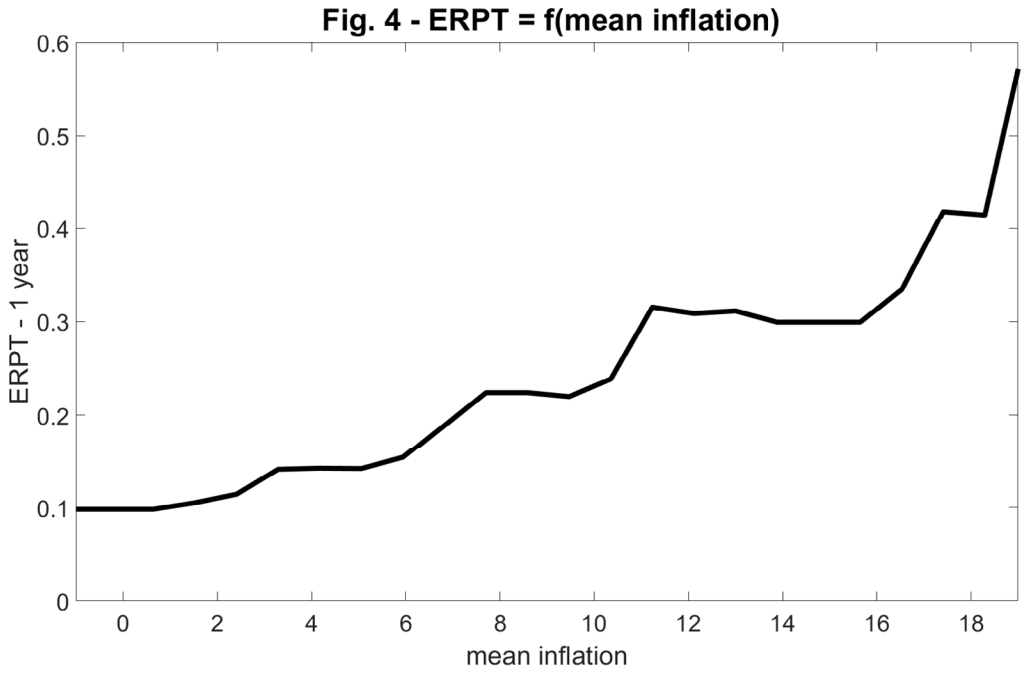
Figure 3 shows the resulting predictor importance of the random forest model of pass-throughs, that is, how much each covariate contributes to reducing the mean square errors of the model. This is based on the Shapley values for each observation – that is, indicators of how much each variable changes the predicted outcome when added to the remaining variables. In Figure 3, the mean of these absolute Shapley values is shown for each factor, without any directional interpretation. The figure shows that the level of CPI inflation is by far the most important determinant of ERPTs, followed by the size of the economy and the degree of homogeneity in imports.

Fig. 3 - Baseline Model - Mean Absolute Shapley Values by Factor (normalized)



Importantly, we can go further in the analysis by eliciting the equivalent of partial effects in econometrics. As in the latter, these are the fitted pass-through models where all variables but one are kept constant at their respective sample medians. Figure 4 shows the resulting partial effect for mean inflation levels.

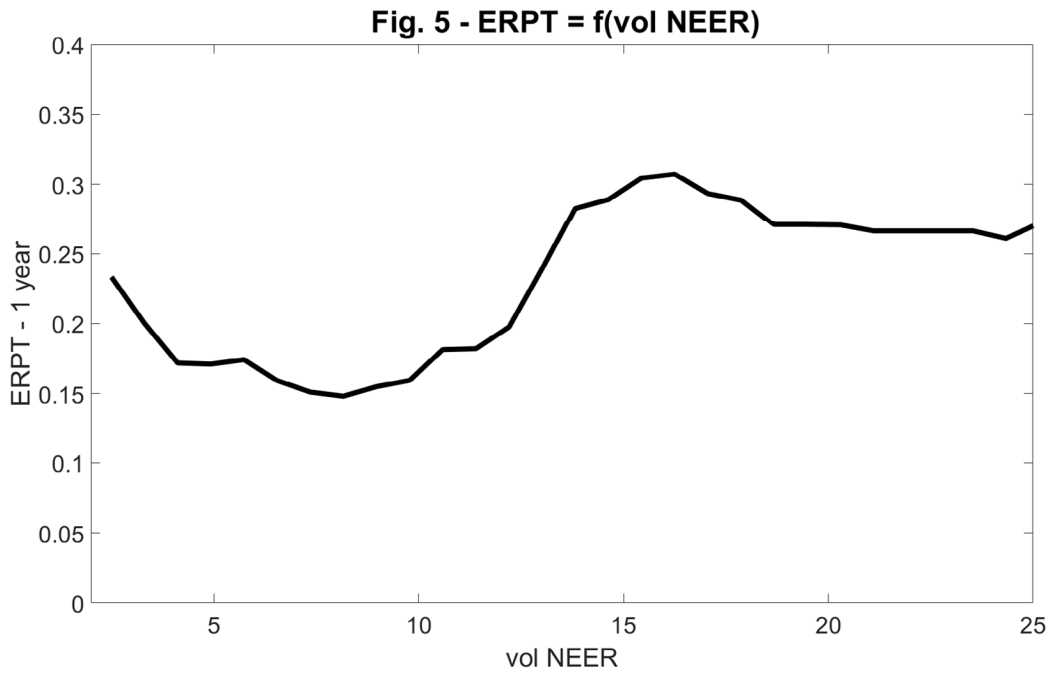
Figure 4 shows that, all else equal, pass-throughs are minimised for average inflation levels below 1.5%. Moreover, up to an average inflation of 2.5% there is little variation in the pass-through coefficient. Above this level, pass-throughs clearly rise with inflation. At 10% inflation, pass-through is twice as high as at an inflation rate of 2%. At an inflation rate of 19%, exchange rate pass-through is already five times as high, reaching 57% within a year. This result suggests that maintaining low average inflation is key to keeping exchange rate pass-through at moderate levels.



How does pass-through vary with exchange rate volatility? The partial effects plotted in Figure 5 suggest the shape of a parable, with a minimum over the 40-year sample obtained at a NEER standard deviation of 8%. Compared to exchange rate volatility in the 2010s, the minimum corresponds to the 80th percentile of the distribution over that decade (and close to the level experienced in Australia or Colombia).[12] [13] The degree of pass-through clearly increases as exchange rate volatility reduces to very low or rises to high levels. Thus, at least part of the reduction in pass-through across time stems from lower exchange rate volatility in recent decades (see Figure 1).

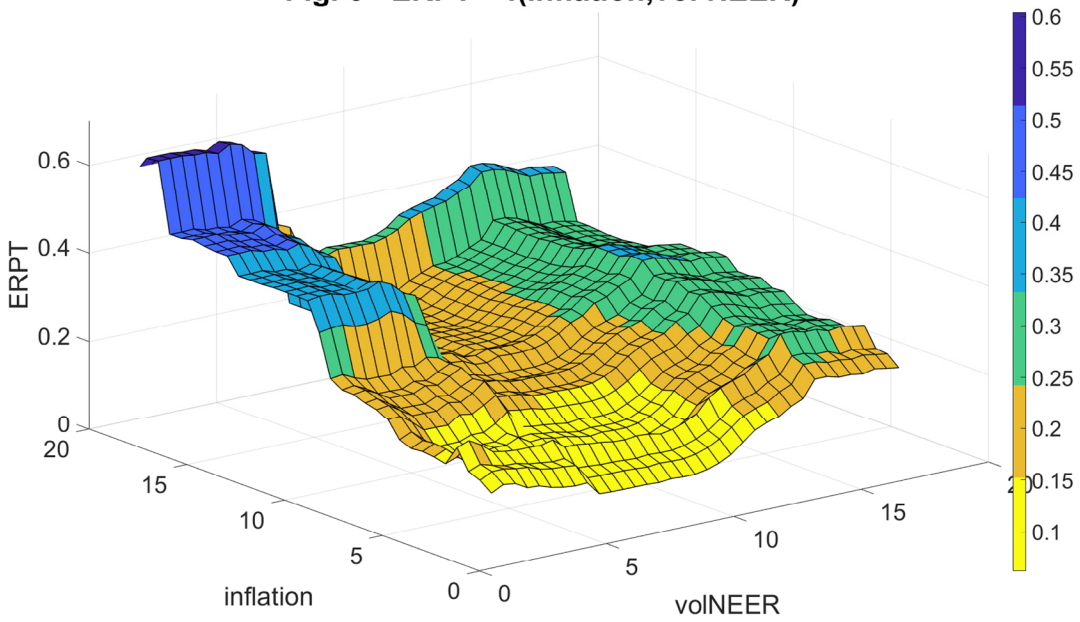
[12] For the last decade, the range of variation is between 1.8% for Singapore (which uses NEER as the intermediate target for monetary policy) and 15.0% for Malawi. For the full sample, the maximum volatility was of 65.9% for Paraguay in the 1990s.

[13] The global map of nominal effective exchange rate volatilities is shown in Appendix Graph A3.



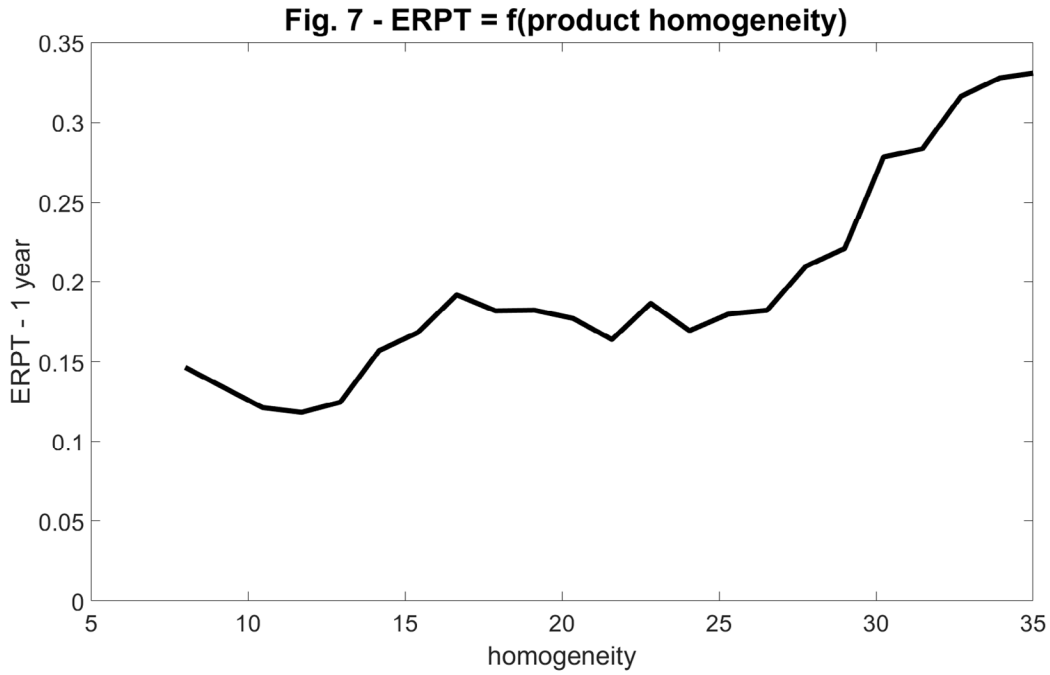
The joint importance of the former two factors is illustrated in Figure 6 in the form of a partial dependence plot. The figure confirms that the lowest pass throughs are attained when average inflation is low and exchange rate volatility is neither too low nor too high (yellow area in the graph). Further, exchange rate pass-through spikes to very high levels when inflation is high and the (nominal) exchange rate volatility is very low (dark blue area in the graph).

Fig. 6 - ERPT = f(inflation,vol NEER)



Conforming to the theoretical prior, pass-through tends to increase as the degree of product homogeneity increases (Figure 7). When food and fuel account for around 15% of total imports – so that product homogeneity is low – the one-year pass through amounts to around 15%. A doubling in the degree of product homogeneity – to around 30% – also roughly doubles the degree of pass-through. This could reflect the fact that price differentiation or an increase in profit margins tends to be more difficult for less differentiated and less sophisticated goods. The number of suppliers for such goods may be large, compressing room for mark-ups.

Further, the degree of pass-through declines with country size (as shown in Appendix Graph A5) – a result in line with the original conjecture of Dornbusch (1987) and of Menon (1995). The decline of the one-year pass-through accelerates when the economy size surpasses around 72 billion USD – close to the level of the Dominican Republic in the last decade. A one-year pass-through of 10% is reached when the size of the economy is around 530 billion USD, not far from that of Belgium in the last decade.



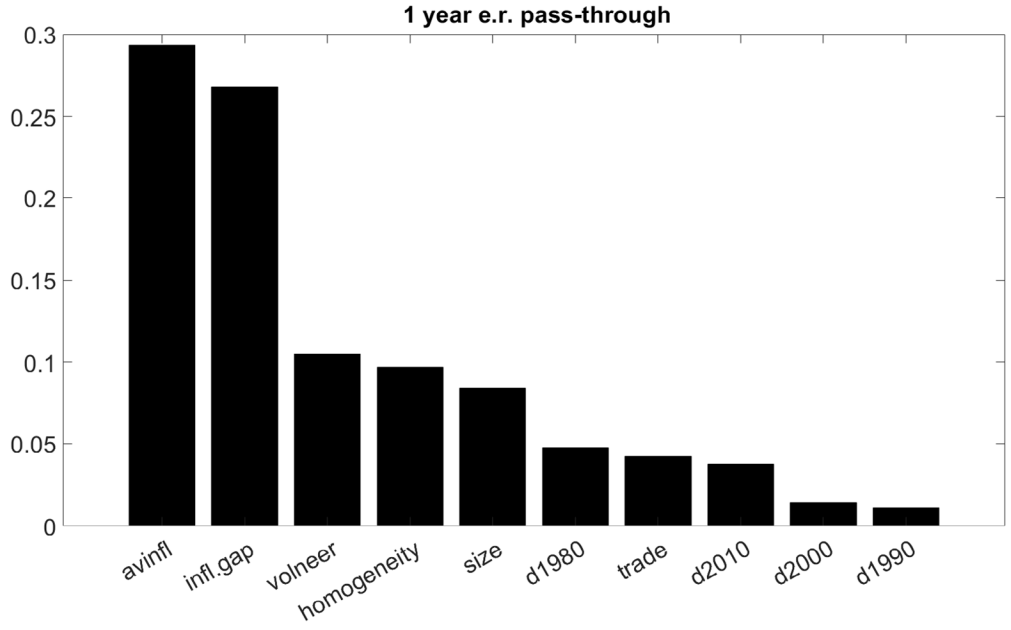
5. The role of policy choices

The previous results already partly reflect the influence of macroeconomic policy, in particular the association of exchange rate pass-through with the average level of inflation and with exchange rate volatility. In fact, the agnostic random forest model tells that, for practical considerations, the pass-through is close to its minimum when inflation is 2%. This of course coincides with the inflation target of many countries in the sample.

It is also of interest to consider the influence of policy-related variables more explicitly. In what follows, we do this for four variables: the deviation of inflation from the central bank's target (the "inflation gap"), the *de facto* exchange rate regime, and the health of the government's fiscal accounts, as reflected in the level of public debt and deficits. Formally, we include additional variables one by one to the benchmark specification of the previous section.

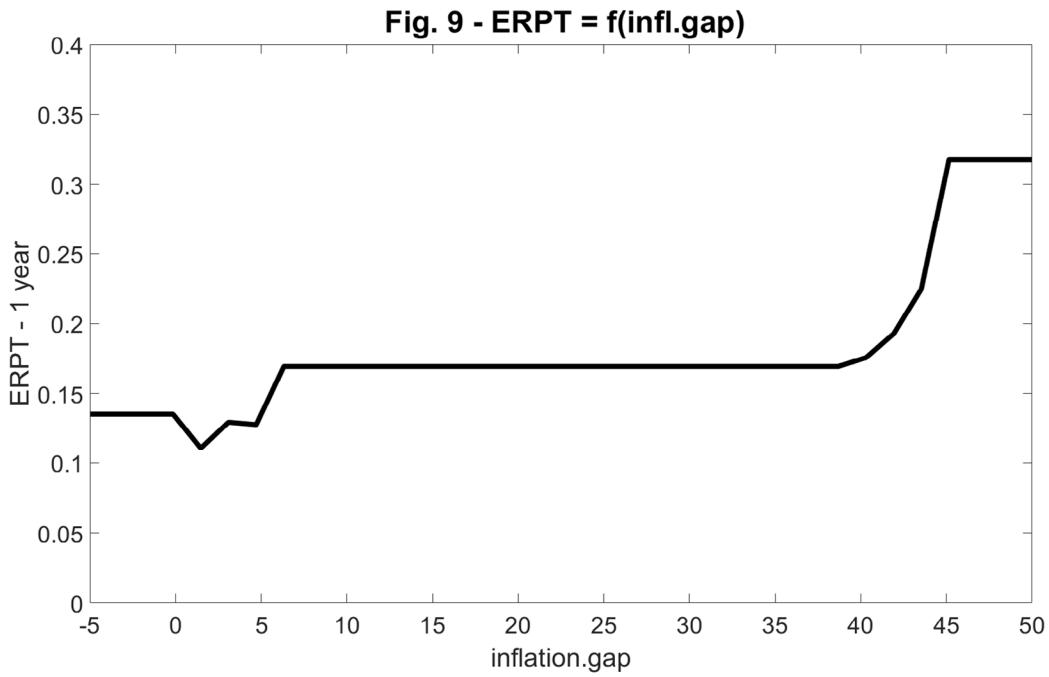
First, we consider the importance of inflation gaps – i.e. the deviation of actual inflation from the central bank's target – computed as country-decade averages. Not surprisingly, the median inflation gap in the sample is low, at 0.7 percentage points, indicating that central banks that have formally pursued inflation targeting have by and large been successful in meeting their targets. That said, given some outliers among EMDEs, the average inflation gap in the sample is notably higher than the median.

Fig. 8 - Model with Inflation Gap - Mean Absolute Shapley Values by Factor (normalized)



Inflation gaps emerge as highly relevant predictors, when evaluating their importance based on Shapley values (Figure 8). Their importance is roughly comparable to that of average inflation. We take this as *prima facie* evidence that the strength of the monetary policy framework is highly relevant for the degree of pass-through.

Further, partial effects show that the inflation gaps have a non-linear relationship with the degree of exchange rate pass-through (Figure 9). When inflation is below the central bank's target or in the presence of a positive but small inflation gap, the one-year pass-through is just below 15%. There is a further small decline in the one-year pass-through, to around 10%, for inflation gaps very close to the central bank's targets. As inflation targeting regimes have generally been successful in stabilising inflation (e.g. Duncan et al (2022)), most observations for inflation gaps in the data are small in magnitude.



Overall, the results for inflation gaps are consistent with those obtained for the level of average inflation and underscore the importance of maintaining low inflation from the perspective of achieving a low exchange rate pass-through. From a more technical viewpoint, an important caveat is that the results with inflation gaps are based on a much smaller sample. This is because only 22% of the country-decade observations pertain to inflation targeters – thus allowing for the computation of inflation gaps.

Besides including realised exchange rate volatility as in the baseline model, exchange rate regimes can also be considered within this framework. Here we use the "coarse" *de facto* exchange rate classification of Ilzetzki *et al* (2019) and (2021). The index in question takes values from 1 to 6, with higher values indicating more flexible exchange rate arrangements.[14]

The results with the exchange rate regime indicator are broadly consistent with the prior ones based on exchange rate volatility. The pass-through is higher with more fixed exchange rate regimes, declining as one moves towards flexible arrangements. That said, the variation of pass-through is generally much smaller than the one obtained with exchange rate volatility itself (which is also included in the current model). The absolute Shapley value associated with the exchange rate regime is the third-highest, behind the size of the economy but before exchange rate volatility (see Graph A7 in the Appendix).

[14] 1 refers to a *de facto* peg, 2 to crawling or narrow pegs, 3 to managed floats, 4 to free floats, 5 to freely falling exchange rates and 6 to dual markets with missing parallel market data.

Fig. 10 - ERPT = f(regime.llzetzki)

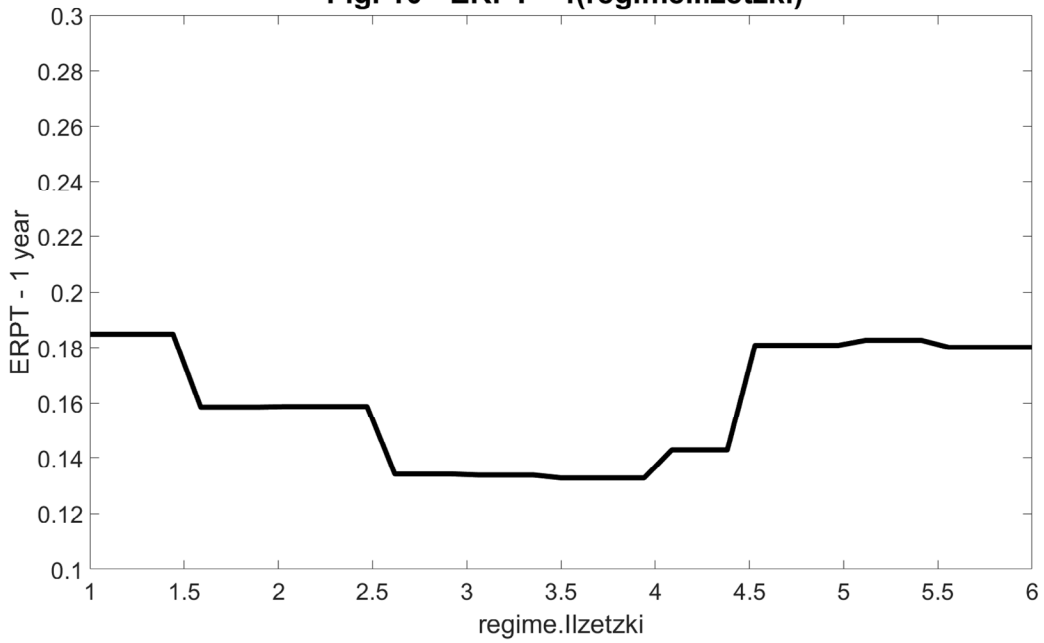
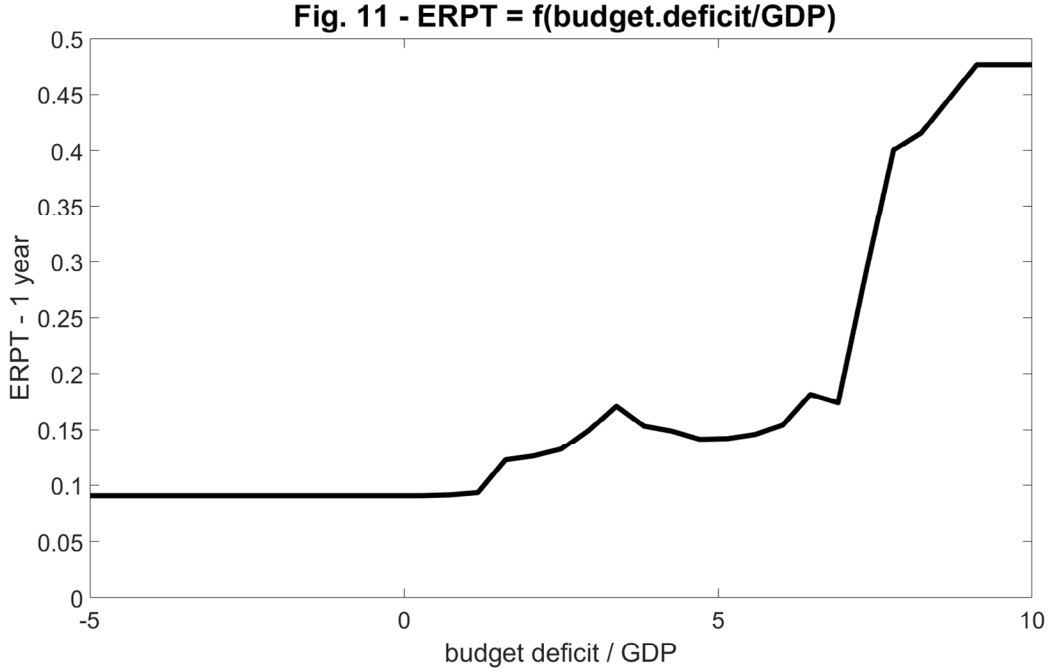


Fig. 11 - ERPT = f(budget.deficit/GDP)



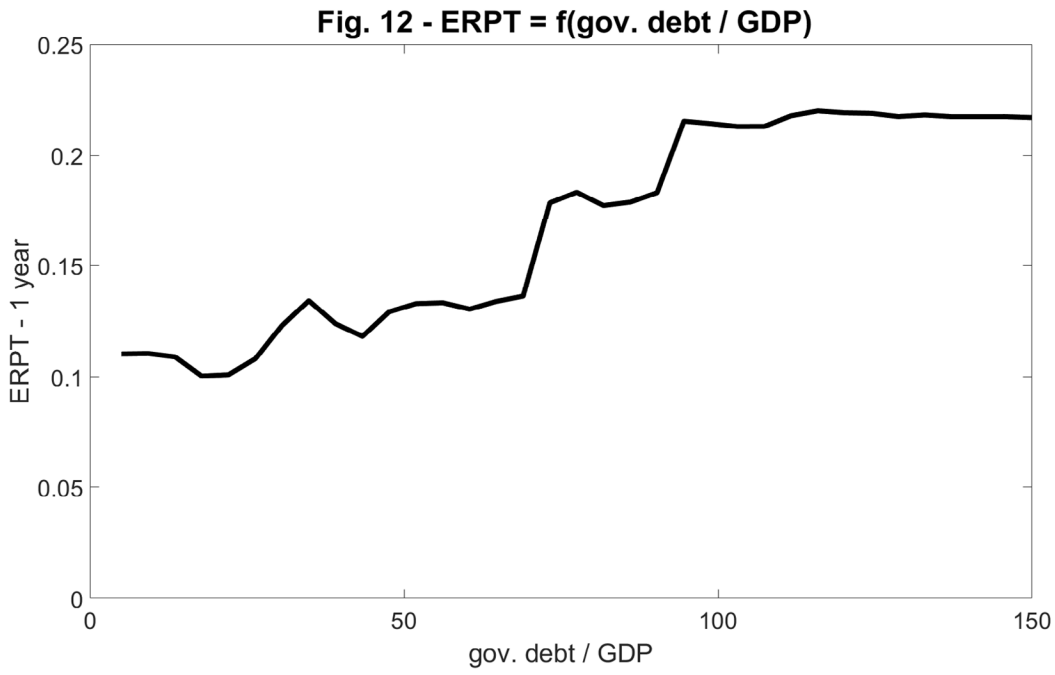
Finally, we contribute to the literature by examining the role of fiscal variables in affecting the degree of exchange rate pass-through. Fiscal variables could matter for pass-

through through their effects on inflation. Such effects are highlighted in the fiscal theory of price level (see eg Leeper (1991); Sims (1994); Cochrane (2003)). A higher price level is required to stabilise the real value of public debt when the fiscal authority does not raise future primary surpluses in response to higher fiscal deficits (i.e., when fiscal policy is not Ricardian). Leeper et al (2024) show that, in the absence of a commitment to time-inconsistent fiscal and monetary policies, the temptation to use inflation surprises to stabilise debt rises with the level of public debt. Banerjee et al (2022) document empirically that in "fiscally-led regimes", where governments do not stabilise debt over time and monetary policy independence is in question, higher fiscal deficits lead to large increases in inflation. More generally, the level of public deficit and debt can proxy for the health of the fiscal accounts and thus for the broader credibility of macroeconomic policy.

There is stark variation in exchange rate pass-through across different sizes of headline deficits. While the one-year exchange rate pass-through remains broadly stable (at around 10%-20%) at moderate headline fiscal deficits, pass-through increases sharply when deficits become large, more than doubling in magnitude (Figure 11). The sharp increase occurs at deficit levels of around 7% of GDP (i.e. around four percentage points above the sample mean).

Similar evidence obtains for government debt – i.e. the exchange rate pass-through tends to rise with the level of government debt. And there appears to be an upward shift when debt rises above 70% of GDP (Figure 12). In terms of predictor importance, however, sovereign indebtedness on its own does not feature among the most relevant drivers of pass-throughs (Appendix Figure A.8).

Overall, the results with public debt and deficits are consistent with the premise that fiscal fragilities affect inflation risks and could therefore also be reflected as stronger exchange rate pass-through. Notably, the results obtain even as we include the average level of inflation separately in the model.



6. Concluding Remarks

We have documented how econometric estimates can be combined with modern machine learning techniques to disentangle economic and structural drivers of exchange rate pass-through across countries and time. Using the random forest method, we have shown that the degree of pass-through is minimised when average inflation is close to the central bank's target. Importantly, we have also shown that previous, apparently contradictory results in the empirical literature, can be reconciled by the observation that the pass-through is a U-shaped function of exchange rate volatility.

We have also documented that pass-throughs are lower when overall macroeconomic policy credibility – including fiscal – is high, when product homogeneity is low, and when the economy in question is not too small. For all of these factors, we find an important degree of non-linearity, suggesting that non-parametric methods as the one used here are better suited for uncovering the empirical relationships.

Our methodology that combines first-stage econometric estimates with a second-stage machine learning based dissection of coefficients can easily be used to address other important questions in economics. These are left for future research.

References

Antoniades, A. and N. Zaniboni (2016) Exchange-rate pass-through into retail prices. *International Economic Review*, vol. 57, 4, 1425-1447.

Aron, J., R. MacDonald and J. Muellbauer (2014) Exchange rate pass-through in developing and emerging markets: a survey of conceptual, methodological and policy issues, and selected empirical findings. *Journal of Development Studies*, vol. 50, 1, 101-143.

Athey, S. and G. W. Imbens (2019) Machine learning methods that economists should know about. *Annual Review of Economics*, vol. 11, pp. 685-725.

Auer, R. and T. Chaney (2009) Exchange rate pass-through in a competitive model of pricing-to-market. *Journal of Money, Credit and Banking*, vol. 41, 1, 151-175.

Banerjee, R., V. Boctor, A. Mehrotra and F. Zampolli (2022) Fiscal deficits and inflation risks: the role of fiscal and monetary policy regimes. BIS Working Paper no. 1028.

Benigno, P. and E. Faia (2016) Globalization, pass-through, and inflation dynamics. *International Journal of Central Banking*, vol. 16, 263-306.

Bergin, P.R. and R.C. Feenstra (2009) Pass-through of exchange rates and competition between floaters and fixers. *Journal of Money, Credit and Banking*, vol. 41, 11, 35-70.

Breiman, L. (2001) Random forests. *Machine Learning*, vol. 45, pp. 5- 32.

Burstein, A. and G. Gopinath (2014) *Handbook of International Economics*, vol. 4, chapter 7.

Campa, J.M. and Goldberg, L.S. (2005) Exchange rate pass-through into import prices. *The Review of Economics and Statistics*, vol. 87 (4), 679-690.

Campa, J.M., Goldberg, L.S. (2010) The sensitivity of the CPI to exchange rates: distribution margins, imported inputs, and trade exposure. *The Review of Economics and Statistics*, vol. 92 (2), 392-407.

Campa, J.M. and J.M.G. Mínguez (2006) Differences in exchange rate pass-through in the euro area. *European Economic Review*, vol. 50, 121-145.

Chakraborty, C. and A. Joseph (2017) Machine learning at central banks. Bank of England Working Paper no. 674.

Cheik, N.B., Y.B. Zaied and H.B. Ameur (2023) Recent developments in exchange rate pass-through: what have we learned from uncertain times? *Journal of International Money and Finance*, vol. 131, 102805.

Chen, N. and L. Juvenal (2016) Quality, trade, and exchange rate pass-through. *Journal of International Economics*, vol. 100, 61–80.

Choudhri, E. U., H. Faruqee and D.S. Hakura (2005) Explaining the exchange rate pass-through in different prices. *Journal of International Economics*, vol. 65, 2, 349-374.

Choudhri, E.U., Hakura, D.S. (2006) Exchange rate pass-through to domestic prices: does the inflationary environment matter? *Journal of International Money and Finance*, vol. 25, 614-639.

Cochrane, J. H. (2023) *The fiscal theory of the price level*. Princeton University Press.

Corsetti, G., Dedola, L. and Leduc, S. (2008) High exchange-rate volatility and low pass-through. *Journal of Monetary Economics*, *55,* 6, 1113-1128.

Devereux, M.B., C. Engel and P.E. Storgaard (2004) Endogenous exchange rate pass-through when nominal prices are set in advance. *Journal of International Economics*, vol. 63, 2, 263-291.

Devereux, M.B. and J. Yetman (2010) Price adjustment and exchange rate pass-through. *Journal of International Money and Finance*, vol. 29, 1, 181-200.

Dornbusch, R., (1987) Exchange rates and prices. *American Economic Revie*w, vol. 77, 93-106.

Duncan, R., E. Martinez-Garcia, and P. Toledo (2022) Just do IT? An assessment of inflation targeting in a global comparative case study," Globalization Institute Working Paper no. 418, Federal Reserve Bank of Dallas.

Fernandez-Delgado, M., E. Cernadas, S. Barro, and D. Amorim (2014) Do we need hundreds of classifiers to solve real world classification problems? *Journal of Machine Learning Research*, vol. 15, 1, pp. 3133-3181.

Flodén, M., Wilander, F., (2006) State-dependent pricing, invoicing currency, and exchange rate pass-through. *Journal of International Economics* 70, 178–196.

Froot, K., Klemperer, P. (1989) Exchange rate pass-through when market share matters. *American Economic Review*, 637–654.

Frankel, J., D. Parsley and S. Wei (2012) Slow pass-through around the world: a new import for developing countries? *Open Economies Review*, vol. 23, 213–251.

Goldberg, L. and C. Tille (2008) Vehicle currency use in international trade. *Journal of International Economics*, vol. 76, 2, 177–192.

Gust, C., S. Leduc and R. Vigfusson (2010) Trade integration, competition, and the decline in exchange rate pass-through. *Journal of Monetary Economics*, vol. 57, 3, 309–324.

Ilzetzki, E., C. Reinhart and K. Rogoff (2019) Exchange arrangements entering the 21st century: which anchor will hold? *Quarterly Journal of Economics*, vol. 134, 2, 599–646.

Ilzetzki, E., C. Reinhart and K. Rogoff (2021) Rethinking exchange rate regimes (with Reinhart, C. and K. Rogoff). *Handbook of International Economics*, vol. 5, Gopinath, G., E. Helpman and K. Rogoff, eds.

Jašová, M., R. Moessner and E. Takats (2019) Exchange rate pass-through: what has changed since the crisis? *International Journal of Central Banking*, 15, 3, 27–58.

Jiménez-Rodríguez, R. and A. Morales-Zumaquero (2016) A new look at exchange rate pass-through in the G-7 countries. *Journal of Policy Modelling*, vol. 38, 985–1000.

Kohlscheen, E. (2010) Emerging floaters: pass-throughs and (some) new commodity currencies*. Journal of International Money and Finance*, vol. 29, 1580-1595.

Krugman, P. (1987) Pricing to market when the exchange rate changes. In: Arndt, Richardson (Eds.), Real Financial Linkages among Open Economies. MIT Press, Cambridge/MA, pp. 49–70.

Krugman, P. (1989) Exchange Rate Instability. MIT Press, Cambridge, MA.

Leeper, E.M. (1991) Equilibria under 'active' and 'passive' monetary and fiscal policies. *Journal of Monetary Economics*, vol. 27, 1, 129–147.

Leeper, E.M., L. Campbell and D. Liu (2021) Optimal time-consistent monetary, fiscal and debt maturity policy. *Journal of Monetary Economics*, vol. 117, 600-617.

Marazzi, M. and N. Sheets (2007) Declining exchange rate pass-through to U.S. import prices: the potential role of global factors. *Journal of International Money and Finance*, vol. 26, 924–947.

Menon, J. (1995) Exchange rate pass-through. *Journal of Economic Surveys*, vol. 9, 2, 197–231.

Sims, C.A. (1994) A simple model for study of the determination of the price level and the interaction of monetary and fiscal policy. *Economic Theory*, vol. 4, 3, 381–399.

Taylor, J. (2000) Low inflation, pass-through, and the pricing power of firms. *European Economic Review,* vol. 44, (7), 1389–1408.

Appendix

Figure A1 –
Estimated Pass-Throughs by Horizon and Country Development
(balanced sample average)

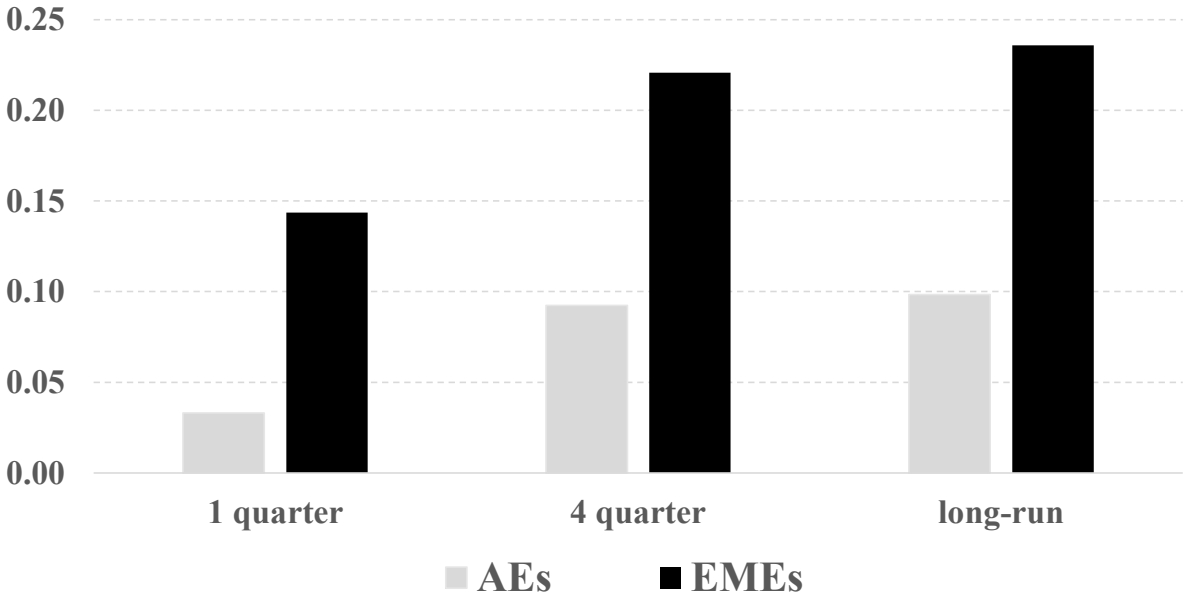


Fig. A2 – Example of Grown Regression Tree (only top)

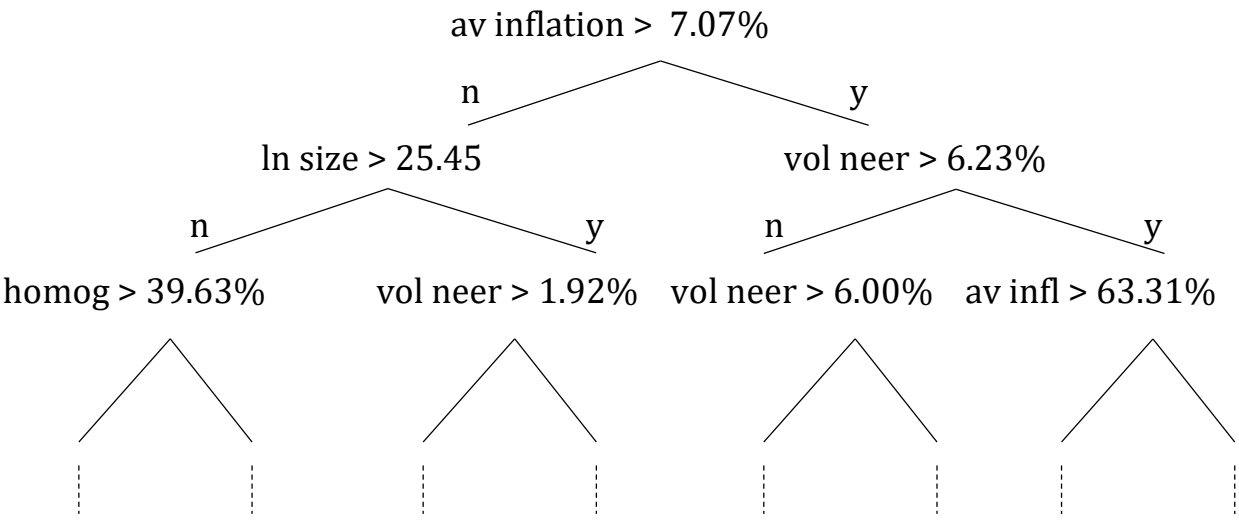


Fig. A3 – Volatility of NEERs (2010–2019)

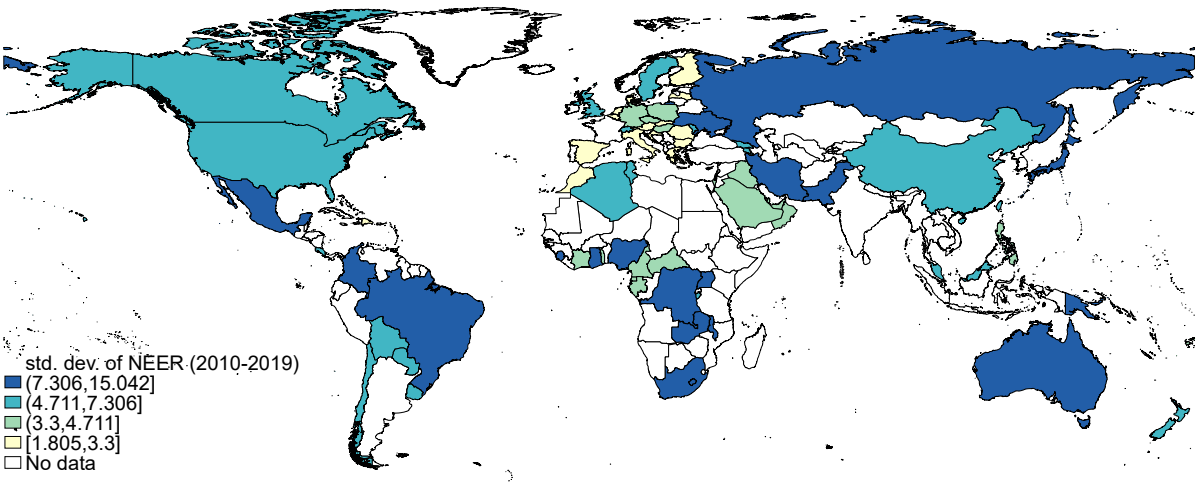


Fig. A4 - ERPT = f(vol NEER): varying inflation levels

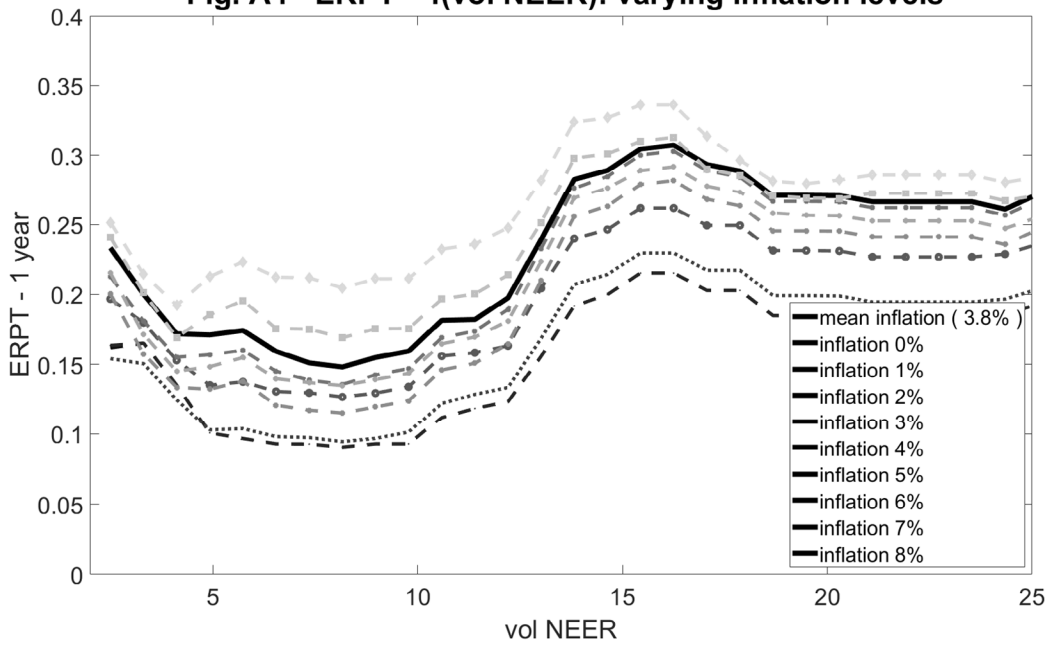


Fig. A5 - ERPT = f(ln size)

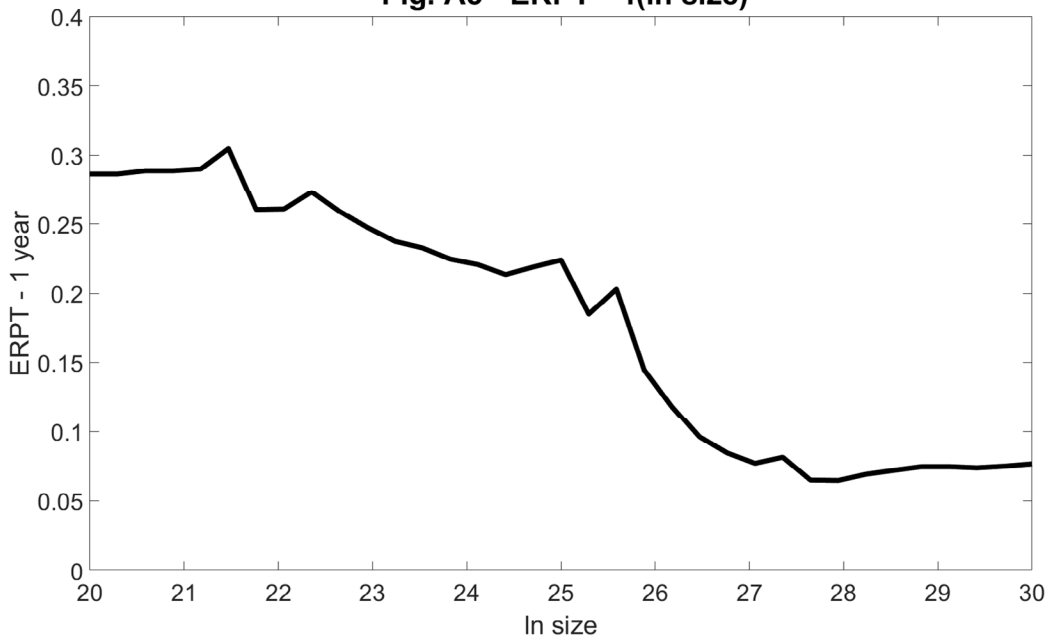


Fig. A6 - ERPT = f(trade openness)

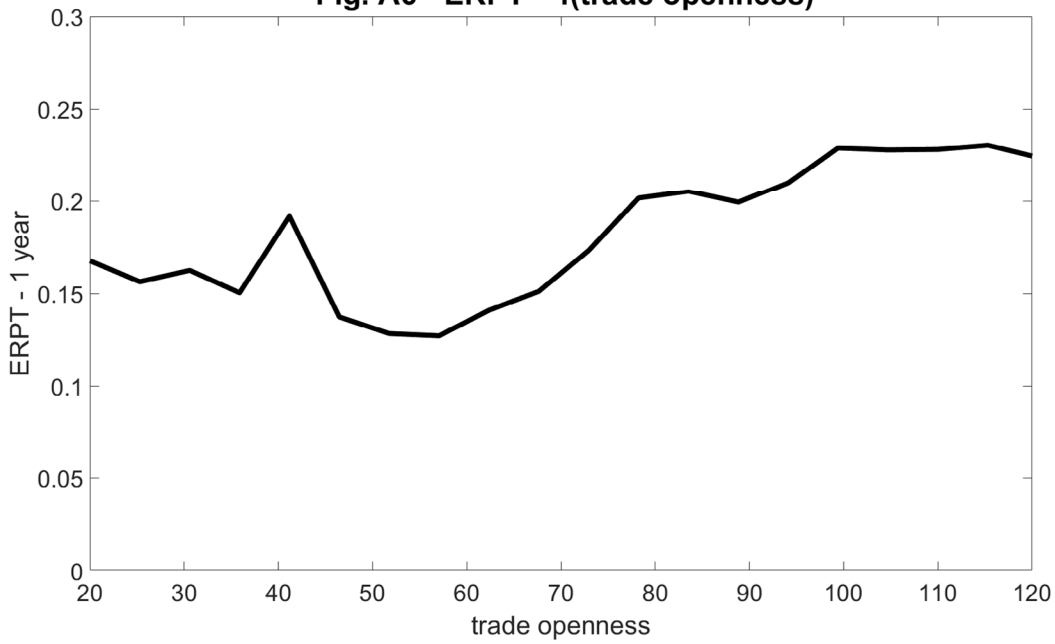


Fig. A7 - Model with ER Regime - Mean Absolute Shapley Values by Factor (normalized)

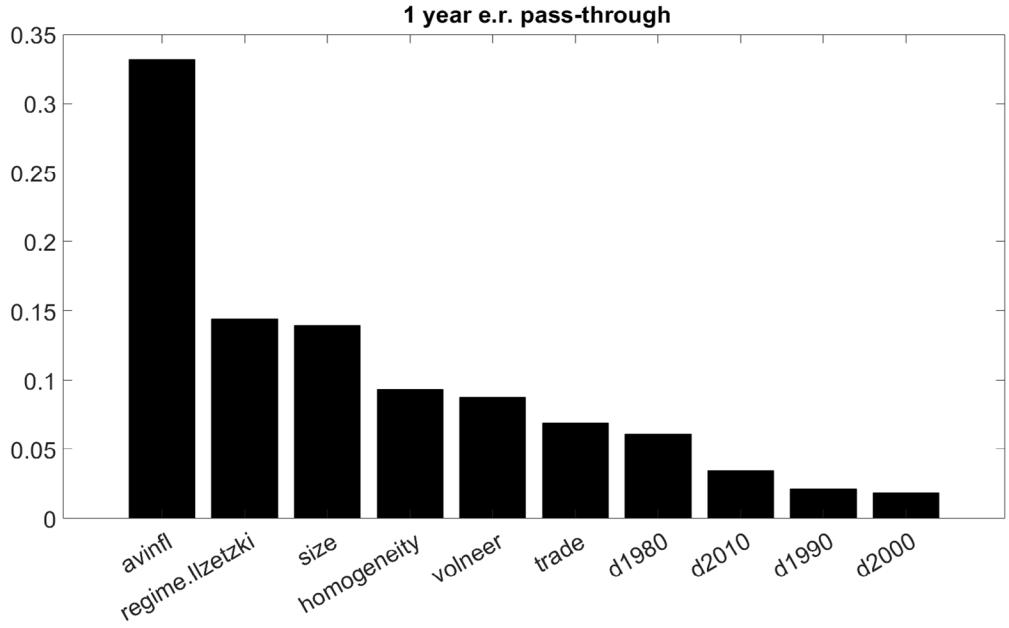


Fig. A8 - Model with Debt - Mean Absolute Shapley Values by Factor (normalized)

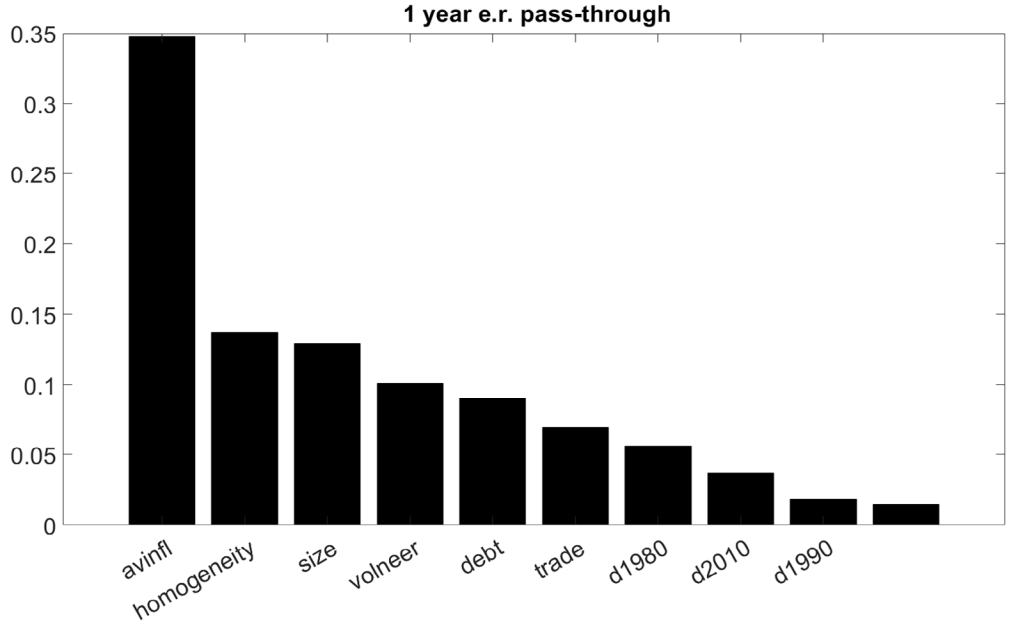


Table A1 - List of economies

	decades		decades
Algeria	1980, 1990, 2000, 2010	Lebanon	2010
Armenia	2000, 2010	Lesotho	2000, 2010
Australia	1980, 1990, 2000, 2010	Luxembourg	1990, 2000, 2010
Austria	1980, 1990, 2000, 2010	Malaysia	1980, 1990, 2000, 2010
Belgium	1980, 1990, 2000, 2010	Mexico	1980, 1990, 2000, 2010
Bolivia	1980, 1990, 2000, 2010	Moldova	2000, 2010
Brazil	1980, 1990, 2000, 2010	Morocco	1980, 1990, 2000, 2010
Bulgaria	2000, 2010	Netherlands	1980, 1990, 2000, 2010
Burundi	1990, 2000, 2010	New Zealand	1980, 1990, 2000, 2010
Cameroon	1980, 1990, 2000, 2010	Nigeria	1990, 2000, 2010
Canada	1980, 1990, 2000, 2010	Norway	1980, 1990, 2000, 2010
Central African R.	1980, 1990, 2000, 2010	Oman	2000, 2010
Chile	1990, 2000, 2010	Pakistan	1980, 1990, 2000, 2010
China	1990, 2000, 2010	Papua New Guinea	1980, 1990, 2000
Colombia	1980, 1990, 2000, 2010	Paraguay	1980, 1990, 2000, 2010
Costa Rica	1990, 2000, 2010	Philippines	1980, 1990, 2000, 2010
Cote d'Ivoire	1980, 1990, 2000, 2010	Poland	1990, 2000, 2010
Croatia	2000, 2010	Portugal	1980, 1990, 2000, 2010
Czechia	2000, 2010	Qatar	2000, 2010
Denmark	1980, 1990, 2000, 2010	Romenia	1990, 2000, 2010
Dominican R.	1980, 2000, 2010	Russia	2000, 2010
DR Congo	2010	Saudi Arabia	1980, 1990, 2000, 2010
Fiji	1980, 1990, 2000, 2010	Sierra Leone	2010
Finland	1980, 1990, 2000, 2010	Singapore	1980, 1990, 2000, 2010
France	1980, 1990, 2000, 2010	Slovakia	2000, 2010
Gabon	1980, 1990, 2000	South Africa	1980, 1990, 2000, 2010
Gambia	1980, 1990, 2000, 2010	Spain	1980, 1990, 2000, 2010
Georgia	2000, 2010	Sweden	1980, 1990, 2000, 2010
Germany	1980, 1990, 2000, 2010	Switzerland	1980, 1990, 2000, 2010
Ghana	1980, 1990, 2000, 2010	Togo	1980, 1990, 2000, 2010
Greece	1980, 1990, 2000, 2010	Tunisia	1990, 2000, 2010
Hong Kong	1980, 1990, 2000, 2010	Uganda	1990, 2000, 2010
Hungary	1990, 2000, 2010	Ukraine	2000, 2010
Iran	1990, 2000, 2010	United Arab Emirates	2010
Ireland	1980, 1990, 2000, 2010	United Kingdom	1980, 1990, 2000, 2010
Israel	1990, 2000, 2010	United States	1980, 1990, 2000, 2010
Italy	1980, 1990, 2000, 2010	Uruguay	1980, 1990, 2000, 2010
Japan	1980, 1990, 2000, 2010	Zambia	1990, 2000, 2010
Latvia	2000, 2010		