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ABSTRACT

A major challenge for monetary policy is predicting how exchange rate movements will impact inflation. We propose a new focus: directly incorporating the underlying shocks that cause exchange rate fluctuations when evaluating how these fluctuations "pass through" to import and consumer prices. A standard open-economy model shows that the relationship between exchange rates and prices depends on the shocks which cause the exchange rate to move. We build on this to develop a structural Vector Autoregression (SVAR) framework for a small open economy and apply it to the UK. We show that prices respond differently to exchange rate movements based on what caused the movements. For example, exchange rate pass-through is low in response to domestic demand shocks and relatively high in response to domestic monetary policy shocks. This framework can improve our ability to estimate how pass-through can change over short periods of time. For example, it can explain why sterling's post-crisis depreciation caused a sharper increase in prices than expected, while the effect of sterling's 2013-15 appreciation was more muted. We also apply this framework to forecast the extent of pass-through from sterling's sharp depreciation corresponding to the UK's vote to leave the European Union.

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An online appendix is available at http://www.nber.org/data-appendix/w24773

I. Introduction

Exchange rates fluctuate over time, sometimes sharply. These fluctuations can have sizable effects on output and prices. Understanding the extent to which exchange rate fluctuations affect prices (i.e. the degree of exchange rate pass-through) is crucial to evaluate the impact of these fluctuations on the economy and set monetary policy appropriately. An extensive literature has improved our understanding of the link between exchange rates and prices. This includes earlier theoretical work (such as Krugman, 1987 and Dornbusch, 1987), a series of cross-country empirical studies (such as Campa and Goldberg, 2005 and 2010), and recent work using detailed goods-level pricing data (well summarized in Burstein and Gopinath, 2014). Despite the substantial advances in this literature and general understanding that exchange rate pass-through is state dependent, some key insights have not been incorporated into empirical macroeconomic models,[4] and a "rule of thumb" based on long-term historic relationships is often used to estimate how a given exchange rate movement will affect prices (see Forbes, 2015b, Fischer, 2015, and Savoie-Chabot and Khan, 2015). This paper takes the economic theory seriously and develops a framework that can bridge this gap. We explicitly incorporate the factors behind exchange rate movements when estimating their effects and show how these factors determine pass-through with an application to the UK—a country that has experienced sharp changes in pass-through over the past two decades. The results suggest that explicitly incorporating the shocks behind an exchange rate movement can improve our understanding of, and ability to predict, how exchange rate movements affect prices.

This paper begins by highlighting key results from a general open-economy framework which provides intuition on how exchange rates and prices are jointly determined. Firms' decisions to adjust their prices in response to exchange rate movements depend on why the exchange rate has moved and how corresponding conditions in the economy have changed. For example, if a given exchange rate appreciation was driven by a positive shock to domestic demand, a foreign exporting or domestic importing firm would be more likely to increase its mark-ups (and correspondingly less inclined to reduce its prices). This is due to the simultaneous increase in demand for the firm's output and reduced competition from domestic firms, as input costs increase and demand strengthens in the economy. In contrast, if the same exchange rate appreciation was driven by tighter monetary policy and a corresponding reduction in expected demand, the firm would be more likely to decrease its mark-ups and prices. The combination of these results suggests that pass-through is likely to be lower

[4] Several papers have pointed out what factors may affect the degree of exchange rate pass-through over time, including Gopinath *et al.* (2010), Amiti *et al.* (2016), Berger and Vavra (2013) and Devereux *et al.* (2015). Some of these attempt to control for these variables in their regressions, but none have explicitly modelled the factors we focus on in their empirical framework as done in this paper. The noteworthy exception is Shambaugh (2008), which is closely related to this paper, and discussed in more detail in Section II.

after a domestic demand shock than after a domestic monetary policy shock (for a given exchange rate movement). We also discuss how domestic supply and "risk" shocks, as well as persistent and temporary global shocks, affect the degree of pass-through. Each of these shocks can cause an exchange rate to move and simultaneously affect expected demand, input costs, mark-ups and the broader economic environment—therefore making the degree of pass-through from the exchange rate movement shock-dependent.

Next, we use the insights from this theoretical framework to develop an SVAR model in which we can estimate these relationships for the UK. The framework allows us to identify separate shocks to UK demand, UK supply, and UK monetary policy, as well as any exogenous exchange rate shocks and persistent and temporary global shocks. The SVAR model is identified using a series of short-run, long-run, and sign restrictions based on economic theory. We then evaluate the impact of exchange rate fluctuations caused by these different shocks. We follow the existing literature and focus on pass-through to import prices, but also report results about exchange rate pass-through to other variables, including final consumer prices.

Our empirical results confirm that standard measures of exchange rate pass-through (namely the correlation between changes in the exchange rate and changes in import prices or consumer prices) vary substantially depending on the source of the shock behind the exchange rate fluctuation. For example, domestic demand shocks that cause an appreciation (depreciation) tend to cause a smaller decrease (increase) in import prices than other shocks causing comparable currency movements. The boost to demand supports both domestic prices and import prices, so that the drag on inflation from cheaper imports is contained and firms have more ability to increase margins. As a result, there is substantially less pass-through to import prices from exchange rate movements primarily driven by demand shocks than other types of shocks. The estimates of shock dependent degrees of pass-through are consistent with the theoretical predictions and can be explained by the different general equilibrium effects causing firms to respond differently depending on the shocks causing the exchange rate fluctuation.

The results also show that this framework explicitly considering the shocks behind exchange rate fluctuations can help explain why the degree of exchange rate pass-through has varied significantly in the UK. For example, pass-through to both UK import and consumer prices was substantially greater than expected in the period after sterling's depreciation during the global financial crisis. This can be explained by the different distribution of shocks behind this depreciation (relative to the historic average). Negative global shocks and domestic supply shocks (which correspond to greater pass-through) were more important drivers of the 2007-2009 depreciation, while negative domestic demand shocks (which correspond to less pass-through) had a relatively smaller weight. Our model implies that this different composition of shocks caused pass-through to import prices to increase by almost one-third, and to consumer prices to roughly double, after the 2007-2009 crisis relative to pass-through after sterling's last sharp movement in 1996-97. The estimates also show how the distribution of shocks driving sterling changed again during sterling's appreciation from 2013-2015, and why this corresponded to substantially lower pass-through. The final section of the paper uses this framework to construct out-of-sample forecasts for how sterling's sharp depreciation around the June 2016 "Brexit" vote to leave the European Union would affect import prices and inflation, based on data available at that time. The distribution of shocks for this period suggested that pass-through would be substantially lower than after sterling's last sharp depreciation in 2007-09, and close to that after sterling's 2013-2015 appreciation. The most recent UK price data supports this forecast.

The findings of this paper have important implications for monetary policy. They suggest that policymakers should not assume exchange rate movements are primarily driven by exogenous risk shocks (a common modelling assumption) or use fixed "rules-of-thumb" to predict how an exchange rate movement will affect prices. Instead, they should explicitly account for the fact that pass-through is state dependent by modelling the shocks driving the exchange rate movement when estimating the effects on prices. Although this insight is not new (for example, see the discussions in Klein, 1990 and Shambaugh, 2008), it has not been widely incorporated or operationalized.[5] This paper, however, provides a straightforward methodology for bringing the insights from the theoretical literature to the data in a usable empirical framework. The proposed framework could improve policy makers' ability to forecast how exchange rate movements will affect prices in the face of different types of shocks, and thereby their ability to forecast inflation and set monetary policy appropriately.

The remainder of the paper is as follows. Section II briefly summarizes the literature on exchange rate pass-through and places our approach within that literature. Section III sets out the theoretical foundations for the link between exchange rates and prices and why this relationship changes based on the underlying shocks. Section IV discusses our empirical methodology for estimating shock-dependent pass-through, including the identification strategy, data, and estimation technique. Section V discusses the central results on how different shocks correspond to different degrees of pass-through to import prices and applies the framework to better understand observed changes in pass-through in the UK. Section VI then shows that this approach yields similar insights on

[5] For example, see Smets and Wouters (2002) for a discussion of how pass-through has routinely been modelled in DSGE frameworks used in policy institutions.

exchange rate pass-through to consumer prices. Section VII discusses a series of extensions and robustness checks, including out-of-sample forecasts for pass-through using this framework after the "Brexit" vote for the UK to leave the European Union. Section VIII concludes.

II. Previous literature on exchange rate pass-through

A large literature has contributed to our understanding of pass-through using a range of different approaches. Early work, including Krugman (1987), Dornbusch (1987), and Klein (1990), showed that pass-through was incomplete due to imperfect competition and pricing-to-market. In the past decade, the literature has used extensive micro data on firm pricing decisions to highlight factors such as the role of the currency of pricing (Gopinath *et al.*, 2010, Gopinath, 2015, and Devereux *et al.*, 2015), whether transactions take place within or between firms (Neiman, 2010), the frequency of price adjustment (Gopinath and Itskhoki, 2010), the role of local costs and mark-up adjustments (Nakamura and Zerom, 2010), the dispersion of price changes (Berger and Vavra, 2013) and the extent of competition in final product markets (Amiti *et al.*, 2016).

The standard approach for estimating exchange rate pass-through at the macroeconomic level has been to regress changes in some measure of domestic prices on past and present changes in the exchange rate and additional control variables. For example, in their *Handbook* article providing an overview of this literature, Burstein and Gopinath (2014) estimate distributed lag regressions for a number of countries using:

$$\boldsymbol{\Delta p_{n,t} = \alpha_n + \sum_{k=0}^{T} \beta_{n,k} \Delta e_{n,t-k} + \gamma_n X_{n,t} + \varepsilon_{n,t}}\,, \qquad (1)$$

where $\Delta p_{n,t}$ represents the quarterly log difference in the import price index or the consumer price index in country *n* at time *t*, expressed in country *n*'s currency; $\Delta e_{n,t-k}$represents the log change in the trade-weighted nominal exchange rate in country *n* at time *t – k; $X_{n,t}$* includes trade-weighted foreign export prices to control for changes in the trade-weighted cost of production in countries exporting to country *n* during the current and previous eight quarters. Long-run exchange rate pass-through is calculated as the sum of the estimated coefficients on the exchange rate changes for all periods included in the regression (i.e., for all $\beta_{n,k}$). Although most papers in this literature acknowledge that the exchange rate and prices are both endogenous variables and will be jointly determined by other shocks, this is usually not a focus of the analysis.

This basic framework for estimating average pass-through at the macroeconomic level is widely used not only in the academic literature, but also in policy institutions and by other professional forecasters. The resulting estimates are often treated as general "rules of thumb" for how an exchange rate movement would be expected to affect import prices and future inflation. For example, in the UK, the Bank of England (BoE) has estimated that on average the pass-through from exchange rate movements to UK import prices (the sum of the $\beta_{n,k}$ in equation (1)) is about 60%, and to consumer prices is about 20%.[6] In other words, a 10% appreciation would be expected to reduce import prices by 6% and consumer prices by about 2% in the long run. Similarly, Fischer (2015) indicates that in the US, a 10% appreciation is predicted to reduce non-oil import prices by about 3% and core PCE prices by 0.5%. Estimates for Canada are larger, with the same 10% appreciation predicted to decrease consumer prices by 6% (Savoie-Chabot and Khan, 2015).

The challenge is that these estimates of pass-through can change meaningfully over time. In the past, much of the focus on why pass-through could change over time focused on slow-moving structural factors , such as changes in the composition of imports, the monetary policy framework, or the role of China (e.g., Campa and Goldberg, 2005, Marazzi *et al*., 2005, Gagnon and Ihrig, 2004, and Gust *et al*., 2010 and Taylor, 2000). More recently, however, there is accumulating evidence that pass-through can change significantly over short periods of time—and more quickly than can be explained by slow-moving structural changes (e.g., Fleer *et al.* (2015) for Switzerland, Hara, *et al.* (2015) for Japan, Forbes (2015b) for the UK and Forbes *et al.* (2017) for a sample of small open economies). This is not surprising given the extensive theoretical and empirical literature showing how firms adjust their prices and mark-ups differently after different shocks, based on factors such as: how these shocks affect their current and future marginal costs, potential competitors' prices, and demand conditions (e.g., Bils, 1987, Rotemberg and Woodford, 1999, Gilchrist and Zakrajsek, 2015, Corsetti *et al.,* 2009, and Goldberg and Hellerstein, 2013).

The standard framework for estimating pass-through in equation (1), however, does not explicitly incorporate these many ways in which exchange rate movements are endogenously determined with prices. Empirical papers in this literature have attempted to address this by including variables in *X* to try to capture these omitted variables that affect mark-ups, such as controls for production costs, domestic demand (with proxies such as GDP), domestic competitive pressures (with proxies such as domestic producer prices) or changes in monetary policy.[7] These additional control variables will capture some of the changes in the economic environment that jointly affect exchange rates and prices, but since many of the omitted variables are difficult to measure, they will be unlikely to fully account for the underlying macroeconomic shocks.

[6] Calculated as this 60% multiplied by the 30% share of imported inputs in the consumer price index See Forbes (2015a, 2015b) and the Bank of England *Inflation Report*, November 2015.

[7] For example, Burstein and Gopinath (2014), Campa and Goldberg (2005) and Ihrig *et al.* (2006). Ito and Sato (2008) show the importance of simultaneously controlling for monetary policy changes when estimating pass-through.

Therefore, this paper develops an alternate approach to control for the widespread — and largely unmeasurable — factors that could influence pass-through: explicitly model and incorporate the shocks underlying exchange rate movements. This should help control for the multifaceted channels by which the initial shock affects a firm's desired margins and domestic costs. A limited number of papers have mentioned this strategy of controlling for the underlying source of the shock behind an exchange rate movement when measuring pass-through. Klein (1990) is the first paper we have found that makes this point, but does not operationalize it in the estimation. Corsetti *et al.* (2008) and Kirby and Meaning (2014) show that estimates of exchange rate pass-through are shock-dependent using a limited number of shocks.[8] An and Wang (2012) and Stulz (2007) focus on identifying exogenous exchange rate movements within a VAR framework—but do not use their frameworks to estimate shock-dependent pass-through.

The analysis that is closest to our approach, and makes the most progress in incorporating the factors behind an exchange rate movement when estimating pass-through, is Shambaugh (2008). It uses a simple and intuitive set of equations based on PPP and the quantity theory of money to show why different sources of an exchange rate movement can have different effects on prices. Then it estimates a VAR with five shocks (supply, relative demand, nominal, foreign price, and import price shocks) that affect the exchange rate and generate different degrees of pass-through. The shocks are identified using long run restrictions only (as proposed by Blanchard and Quah, 1989). In our view, this analysis did not receive the attention it deserved, and its insights were not incorporated in subsequent research and estimation of pass-through.

Our approach builds on this work in several ways, attempting to better link it to the current theoretical literature and make it more applicable for forecasting. First, our analysis is based on a different set of shocks that are more closely linked to the theoretical literature on pass-through and more straightforward to interpret for empirical analysis (such as monetary policy shocks, exogenous risk shocks, and differentiating "foreign" shocks into those which are temporary and permanent).[9] Second, our approach uses recent advances in SVAR methodology to better identify this richer set of shocks behind exchange rate fluctuations. We combine long run restrictions with short run zero and sign restrictions to extract shocks with a clearer interpretation. This also allows us to better mitigate well-documented concerns with weak identification in SVAR models with long-run restrictions.[10] Finally, our analysis considers the effects of these shocks on a broader set of variables—including on

[8] Corsetti *et al.* (2008) show that pass-through changes based on whether the shocks are real or nominal. Kirby and Meaning (2014) discuss how different shocks affect pass-through for the UK using the NIESR's global structural model.
[9] We also do not include import prices as one of our shocks, as done in Shambaugh (2008).
[10] See Pagan and Robertson (1998), Faust and Leeper (1997), Christiano *et al.* (2007).

interest rates and foreign export prices. These changes make our model closer to the theoretical and micro-empirical literature on pass-through, as well as making it more straightforward to forecast the degree of pass-through after an exchange rate movement.

III. Exchange rate pass-through in a standard open-economy framework

To provide intuition on why pass-through may not be full (i.e., 100%) and may depend on the shocks corresponding to the exchange rate movement, this section discusses the factors that determine the degree of pass-through. We focus on understanding how pass-through depends on the underlying shocks, and although pass-through could also vary with the degree of price stickiness or the currency of invoicing, we do not consider how variations in these affect pass-through here as these factors are likely to be less important in explaining variations within the UK over the period we consider. A more detailed discussion, including a model developed using a specific variant of this general framework, is available in the Online Appendix to this paper.

Within any open-economy framework, the import price level in period t ($P_{F,t}$) is a function of: the exchange rate (s_t); marginal costs faced by foreign exporters (mc_t^*); and the mark-up over marginal costs ($mkup_t^*$). Any change in the import price level can then be decomposed into changes in: the nominal exchange rate, marginal costs, and the average mark-up over marginal costs:

$$\widehat{P_{F,t}} = \widehat{s_t} + \widehat{mkup_t^*} + \widehat{mc_t^*} \ , \qquad (2)$$

where hatted variables denote deviations from steady state. Equation (2) clarifies that the correlation between the nominal exchange rate and the import price depends on the extent to which foreign exporters' mark-ups and marginal costs change when the exchange rate moves. If these do not co-move with the exchange rate, then the import price level fully adjusts to any change in the exchange rate and pass-through is full.

Most shocks that move the exchange rate also cause foreign exporters' mark-ups to change, however, as exporting firms set their prices in a forward-looking manner to reflect their expected marginal costs, expected demand conditions and expected competitive pressures.[11] More specifically, if a shock is expected to change these marginal costs, demand conditions and competitive pressures, exporters might choose to reflect this in their prices and adjust their mark-ups. Because these determinants of exporters' pricing decisions will be affected differently by different shocks, the extent to which exchange rate changes are reflected into prices will depend on the shock. Other factors—

[11] Competitive pressures play a role when strategic complementarities are present. See Gopinath (2015) for an extensive discussion of models of strategic complementarities which imply variation in desired mark-ups.

such as the monetary policy response and the persistence of the exchange rate movement—can also be important.

For example, consider the case where a small open economy (such as the UK) experiences a domestic shock, e.g. to demand, supply or to monetary policy. Foreign exporters' marginal costs are not affected by this shock (given the assumption of a small open economy). Foreign exporters' mark-up, however, may be sensitive to the change in the exchange rate. In particular, foreign exporters who invoice in the domestic currency and face price rigidities will not be able to adjust their prices and will not pass-through the exchange rate movement. Instead, their mark-up will adjust in response to the exchange rate. At the same time, foreign exporters who get the opportunity to adjust their price may adjust mark-ups in response to simultaneous changes in demand conditions and competitors' prices—changes which could also be caused by the driver of the exchange rate movement.

More specifically, if the exchange rate appreciated due to a positive domestic demand shock, foreign exporters would face stronger demand from the domestic market, as well as increasing domestic prices and wages. In that environment, foreign exporters may find it optimal to respond to the appreciation by only marginally reducing their prices in the domestic market (or not reducing them at all), implying a low degree of exchange rate pass-through. In contrast, if the exchange rate appreciated due to tighter domestic monetary policy, demand conditions in the domestic economy would be less favourable and any price and wage increases would be more muted. As a result, foreign firms would reduce their prices by more, thereby passing through more of the exchange rate appreciation into lower prices for their goods in domestic currency. In a third scenario, if the exchange rate appreciated due to a domestic supply shock, the effect of demand conditions and competitive pressures on pass-through is less straightforward, as the effects on different variables affecting firm pricing decisions work in opposite directions. The positive supply shock would generate stronger domestic demand for foreign exporters (to the extent that the income effect dominates the substitution effect[12]), which would normally support less price reductions, but at the same time, the positive supply shock could reduce domestic price and wage pressures, supporting price reductions. In this case, the interplay between the two effects will determine the extent of pass-through.

Next, consider scenarios where the shock moving the exchange rate was global instead of domestic. The marginal costs of foreign exporters will now be affected. The extent to which they adjust their mark-up, or pass through the entire change in exchange rates and marginal costs to prices, will depend on the same factors discussed above: how the shock is expected to affect future demand

[12] For a detailed analysis of these effects in the face of supply shocks, see Corsetti *et al*. (2010).

conditions, competitive pressure, and marginal costs. Global shocks which are assessed to be transitory would be expected to have less impact on these variables in the future, and therefore firms would adjust prices by less and generate a lower degree of pass-through than global shocks which are believed to be more permanent.

To summarize, theory suggests a number of ways in which exchange rate-pass through is shock dependent. Are the predictions of these models—such as less pass-through when exchange rate movements are caused by a domestic demand shocks than those caused by monetary policy shocks—supported in the empirical evidence? And if pass-through does change based on the corresponding shocks—are any such changes in pass-through economically meaningful?

IV. Empirical methodology

1. Identification strategy

Our empirical framework for studying pass-through allows us to estimate how different shocks incorporated in many theoretical models impact the exchange rate, import prices and consumer prices. Specifically, we consider the impact of six shocks: domestic supply, domestic demand, domestic monetary policy, exogenous exchange rate, persistent global and transitory global shocks. This is a wider variety of shocks than previously considered in related literature and should encompass all shocks that could be important determinants of exchange rate movements.[13] For example, a persistent change in oil prices would be captured as a persistent global shock, an increase in domestic productivity would be captured as a domestic supply shock, and a sudden increase in domestic risk aversion would be captured as an exogenous exchange rate shock. To the extent that these shocks drive fluctuations in the exchange rate, they may also determine the characteristics of pass-through.

One challenge in this type of analysis—which applies to models of changes in monetary policy as well as exchange rates—is to use economic theory to identify the shocks of interest with appropriate restrictions on variables' impulse responses. The identification strategies used in the previous work estimating exchange rate pass-through conditional on underlying shocks have a number of limitations and can only identify a restricted set of shocks. More specifically, Shambaugh (2008) uses long-run restrictions to identify separately domestic supply, relative demand, nominal shocks and foreign price shocks. The interpretation of the latter three types of shocks, however, is not straightforward, does not easily translate into standard macroeconomic models and the identification strategy does not allow for disentangling shocks originating in different regions. Farrant and Peersman

[13] Our methodology allows us to identify unanticipated shocks, and we do not identify shocks such as news shocks to productivity.

(2006) instead use short-run sign restrictions to identify relative supply, relative demand and relative nominal shocks. Because their sign restrictions apply to relative output, relative prices and the real exchange rate, they are only able to investigate the impact of shocks on the real exchange rate and on relative prices. Therefore, it is not possible to examine pass-through from the nominal exchange rate to import prices or to consumer prices within their model, but only the correlation between the real exchange rate and relative prices. Moreover, as in Shambaugh (2008), the identification scheme is quite general, and does not allow for disentangling shocks with different origins.

To overcome these challenges in identifying separately the different types of shocks and then be able to analyse exchange rate pass-through to domestic prices, we use a combination of zero short- and long-run restrictions, as well as sign restrictions. These restrictions are summarized in Table 1 and consistent with standard open economy models (such as the one described in more detail in the Online Appendix for this paper). These restrictions for our example of the UK are based on three sets of assumptions.

Table 1: Identification restrictions

	UK supply shock	**UK demand shock**	**UK monetary policy shock**	**Exogenous exchange rate shock**	**Persistent global shock**	**Transitory global shock**
			Short-run restrictions			
UK GDP	+	+	–			
UK CPI	-	+	–	-		
UK interest rate		+	+	-/0		
UK nominal ERI		+	+	+		
UK import prices						
World (ex-UK) export prices	0	0	0	0		
			Long-run restrictions			
UK GDP		0	0	0		0
UK CPI						
UK interest rate						
UK nominal ERI						
UK import prices						
World (ex-UK) export prices	0	0	0	0		

Note: A '+' ('-') sign indicates that the impulse response of the variable in question is restricted to be positive (negative) in the quarter the shock considered hits and in the following quarter. A '0' indicates that the response of the variable in question is restricted to be zero (either on impact or in the long run).

First, we assume that only domestic supply shocks and the persistent global shock affect the growth rate or level of output in the long run. This is consistent with the idea that only changes in technology can affect the productive capacity of an economy in the long run, and that prices will adjust to ensure that markets clear. This identification restriction is based on work by Blanchard and Quah (1989) and Gali (1999),[14] and is widely used in the SVAR literature, including by Shambaugh (2008) and Erceg *et al.* (2005). Persistent global shocks can incorporate global technology shocks, as well as oil/commodity price shocks or any other shocks with a persistent effect on UK output.

Second, we assume that domestic shocks do not affect world (ex-UK) export prices, either on impact or in the long run. This restriction is necessary to identify domestic shocks and should hold for small open economies such as the UK (albeit not for larger economies such as the US). This assumption that small open economies cannot affect the rest of the world is commonly made in the literature, e.g. Liu *et al.* (2011) and Carrière-Swallow and Céspedes (2013). Instead, only global shocks (either persistent or transitory) may have an impact on world export prices, whether they also affect the UK directly or simply spill over to the UK. It is important to note that we do not separate relative shocks from global shocks. In addition, the global transitory shock is identified flexibly enough that it can incorporate a range of shocks, such as those caused by policy abroad (e.g., foreign monetary policy), an increase in global risk aversion or temporary mark-up shocks. Therefore, we do not impose any restrictions on how the exchange rate responds to these shocks.

Third, we impose several short-run sign restrictions on domestic shocks which are motivated by open-economy DSGE models such as the one discussed in the Online Appendix.[15] These sign restrictions have been widely used in the literature and shown to be consistent with theoretical models, for example in Fry and Pagan (2011). More specifically, we restrict supply shocks to be associated with a negative correlation between GDP and CPI in the first 2 periods. This is consistent with previous literature, such as Canova and de Nicolo (2003), who also point out that this combination of restrictions is shared by a large class of models with different micro-foundations.[16] We restrict positive demand shocks to be associated with a positive correlation between GDP and CPI, a counter-cyclical monetary policy response, and an exchange rate appreciation, as in Ellis *et al*. (2014). Monetary policy shocks are identified such that a lower interest rate is associated with a rise in GDP and the CPI and a depreciation of the nominal exchange rate. Hjortsoe, Weale and Wieladek (2016) show that these sign restrictions are consistent with a standard small open-economy model for a wide range of different parameterisations. They are also consistent with sign restrictions imposed in

[14] Gali (1999) discusses the conditions under which this restriction holds, as well as its consistency with a large class of RBC and New-Keynesian models. Our identification scheme allows demand shocks with a long-term impact (e.g., related to secular stagnation) to be classified as a persistent global shock as long as they are not only domestic in nature.

[15] The impulse responses from the theoretical framework discussed in Section III and derived from full model in the corresponding online Appendix support these key assumptions in our identification scheme.

[16] Note that by imposing sign restrictions on the domestic supply shock, we ensure that we do not pick up shocks which lead to highly persistent changes in output but are not technology-related. This avoids one of the critiques often mentioned with regards to the long-run restriction methodology, see Erceg *et al.* (2005).

the previous SVAR literature, such as Mountford (2005). Next, we assume that an exogenous exchange rate appreciation implies a fall in the CPI and no increase in the interest rate (with no assumption about whether the interest rate is unchanged or lowered). This is consistent with An and Wang (2012), but less restrictive in that we do not restrict the response of import prices.

Finally, our identification scheme does not impose any sign restrictions on the global shocks and only differentiates between the two based on the persistence of their impact on UK GDP. We also do not put any restrictions on how domestic import prices—a key variable for pass-through—respond to any of the shocks. This combination of sign restrictions—together with the zero restrictions described previously — constitutes the minimum number of economically sensible restrictions that allow us to identify the shocks of interest separately.[17]

2. Data

We estimate the SVAR model described above using quarterly data for the UK and the rest of the world over the period from 1993q1[18] through 2015q1 on the following six variables: UK real GDP growth, UK CPI inflation, the UK shadow Bank Rate (Shadow BR), changes in the Sterling exchange rate index (ERI), UK import price inflation[19], and changes in foreign export prices. More specifically, we use a version of the headline UK Consumer Price Index, excluding the contribution from VAT changes in the aftermath of the 2007/8 crisis. Shadow BR measures UK monetary policy as the UK policy rate (Bank Rate) until 2009 and then adjusts for the asset purchases/quantitative easing (QE) undertaken by the Bank of England (BoE) Monetary Policy Committee after that.[20] This avoids estimation difficulties stemming from the constant policy rate at the effective zero lower bound. We use the nominal sterling effective exchange rate index produced by the BoE, which weighs each bilateral sterling exchange rate by the respective country's relative importance in UK trade[21]. Finally, the series for foreign export prices is constructed by averaging the export price indices of all UK trade partners in foreign currency using the sterling ERI weights. All variables except the interest rate are transformed into quarterly log differences. We use the de-trended level of the interest rate to account for the downward trend observed in that series over the period considered.[22]

The SVAR model is estimated with two lags of the endogenous variables using Bayesian methods with Minnesota-style priors. The standard errors, percentiles and confidence intervals

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[17] Section VII discusses a range of robustness checks of the estimation methodology and finds little impact on the key results.
[18] The first and second quarter of 1993 are only used as explanatory variables in the estimation.
[19] We use the import price deflator for total imports, including all goods and services.
[20] This series is constructed by comparing the estimated effects of QE to the economic multipliers assigned to conventional changes in Bank Rate. For further detail on the economic impact of UK asset purchases, see Joyce *et al.* (2011).
[21] For further detail see http://www.bankofengland.co.uk/statistics/Pages/iadb/notesiadb/effective_exc.aspx
[22] Standard unit root tests suggested that the interest rate level is nonstationary but the de-trended level is stationary.

reported in this paper are based on a Gibbs sampling procedure, from which we save and use the final 1,000 repetitions. The sign restrictions shown in Table 3 are imposed for two periods (contemporaneously and in the quarter thereafter) for each shock. These are combined with short-run and long-run zero restrictions using the algorithm suggested by Rubio-Ramirez *et al.* (2010) and extended by Binning (2013) for under-identified models.[23]

V. Exchange rate pass-through to UK import prices

1. Shock-based metrics of exchange rate pass-through

Applying this identification strategy to the UK data allows us to estimate a series of impulse responses to the six shocks in our model. The resulting impulse responses are shown in Appendix B, Figures B.1 through B.6, and are consistent with economic theory (as discussed in the Online Appendix). We will not discuss each set in detail, and instead concentrate on what the results imply for exchange rate pass-through associated with each shock. The most straightforward way to capture this is through the corresponding ratios of the impulse responses of prices relative to the exchange rate. This section focuses on exchange rate pass-through to import prices, which has been the primary focus in the literature and is easier to measure, and Section VI extends the analysis to the pass-through to consumer prices.

Before discussing the key results on how exchange rate pass-through varies based on the source of the underlying shock, it is useful to begin by examining if the estimated exchange rate responses agree with economic theory and our model. To simplify the comparison, we calibrate each shock so that it initially causes a cumulative 1% appreciation of sterling within four quarters of the initial shock. The resulting exchange-rate paths for each respective shock (which will be used as the denominators in calculating the implied profiles of pass-through to domestic prices) are shown in the graphs in Appendix B. First, a positive domestic supply shock causes the exchange rate to appreciate in the median case, albeit with wide confidence bands (Figure B.1).[24] Second, a positive domestic demand shock leads to a sterling appreciation (consistent with the sign restrictions imposed on the first two quarters and with the prediction from the DSGE model outlined in the Online Appendix) and is more tightly estimated (Figure B.2). It is worth noting that, also in line with the theoretical model, this appreciation is associated with a less than one-for-one fall in import prices and a rise in consumer prices. Third, a shock from tighter monetary policy or an increase in the exchange rate due to

[23] For further details of the estimation procedure see Appendix A.

[24] The exchange rate response to a productivity shock has been shown to vary both in theoretical and empirical studies. Empirically, Shambaugh (2008) also finds a statistically insignificant real exchange rate appreciation in response to a positive supply shock. Theoretically, the result is consistent with a very low trade elasticity or high trade elasticity combined with very persistent shocks (Corsetti *et al.*, 2008).

exogenous factors both cause an appreciation – consistent with our identifying restrictions for the short-term responses (Figures B.3 and B.4, respectively).

Finally, the two global shocks generate exchange rate appreciations in the median case and both have very wide confidence bands (Figures B.5 and B.6). The persistent global shock could be interpreted as a positive global productivity shock or a long-term fall in oil or other commodity prices. The transitory global shock could be interpreted generally as a transitory shock that has a negative effect on global prices, such as a negative demand shock, monetary policy shock or temporary mark-up shock. The wide confidence bands may reflect the diverse sources and lack of strict identifying criteria for these global shocks. It is worth highlighting that for both global shocks, UK import prices appear to move substantially more than after the domestic shocks and more than directly warranted by just the exchange rate appreciation. This is consistent with the global shocks having effects not only on the exchange rate, but also on foreign export prices. As a result, the corresponding changes in import prices reflect both the direct effects of these global shocks on foreign export prices and their pass-through to import prices, as well as the pass-through effects from the exchange rate as occurs with the domestic shocks.

2. Exchange rate pass-through after different shocks

What do these results imply for exchange rate pass-through? Can these different shocks driving exchange rate fluctuations, and their corresponding effects on the six variables in our SVAR model, explain why pass-through to import prices can vary at different points in time? In order to answer these questions and more easily compare the pass-through implied by the different shocks in our framework, we focus on the ratios of the impulse responses of import prices to those of the exchange rate. We calculate these ratios for each of the 1,000 sets of impulse responses we have saved. Figure 1 graphs the median of these ratios, as well as the pass-through profile implied by the more standard reduced-form regressions estimated from equation (1) in Section II (as a black dashed line). We differentiate between the effects of the four domestic and two global shocks (Figures 1.a and 1.b, respectively) in order to highlight that the import price movements corresponding to global shocks also incorporate the direct effect of the global shocks on foreign export prices—as well as any exchange rate effects as occurs with the domestic shocks. The numerical estimates and different percentiles of the ratios at selected horizons are also reported in Appendix B, Table B.1.

Figure 1.a: Pass-through to import prices for domestic shocks

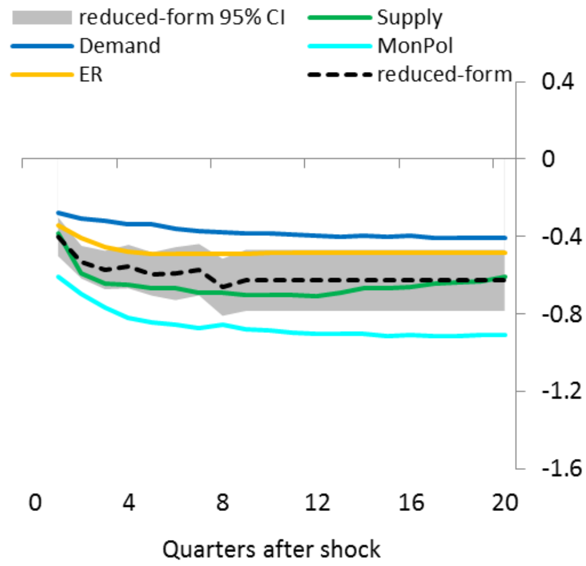
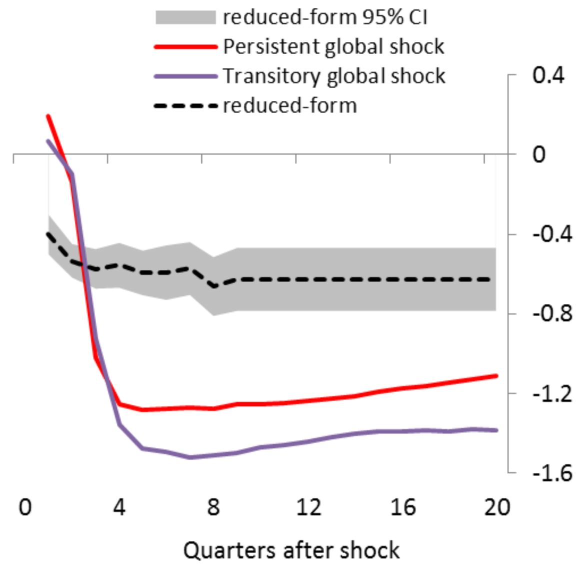


Figure 1.b: Pass-through to import prices for global shocks



Note: Pass-through is defined as the median ratio of cumulative impulse responses of import prices relative to the exchange rate.

These results clearly indicate that different shocks causing a 1% appreciation after 1 year have different effects on import prices. Of the domestic shocks, the domestic demand shock has the lowest degree of pass-through—with less than 40% of the exchange rate appreciation being passed through to import prices after 5 quarters. This weaker effect is intuitive; importers facing an appreciation linked to stronger domestic demand would have less incentive to reduce prices. The increase in domestic prices (corresponding to stronger demand) gives them some leeway to increase margins without losing market share, a result consistent with the discussion in Section III. At the other extreme, monetary policy shocks lead to the highest observed degree of pass-through. The magnitude of pass-through is large—with import prices falling by almost 70% of the appreciation in two quarters (and by 85% by quarter six). The theoretical framework suggests this may reflect the impact of the tighter monetary policy exerting some additional downward pressure on import prices by supressing domestic demand. Pass-through for the other domestic shocks is in between—at 67% for the domestic supply shock and 50% for the exchange rate shock after 5 quarters. It is worth noting that the reduced-form estimate of exchange rate pass-through to import prices shown in the dashed black line (i.e., the “rule-of-thumb”) appears close to an average of the responses for the four domestic shocks. But using this constant estimate and ignoring the source of the shock underlying the exchange rate move could lead to large errors; the shocks from the SVAR suggest substantially more variation in the degree of exchange rate pass-through by shock than would be implied by just adding two standard errors on each side of the reduced-form estimate. [25]

Finally, the two global shocks correspond to the sharpest falls in import prices—by magnitudes even greater than the appreciation in the exchange rate. As discussed above, this is not surprising as they incorporate the simultaneous large falls in foreign export prices from the underlying foreign shocks, as well as the direct exchange rate effects on import prices.

To summarise, the impulse responses from our SVAR support the theoretical predictions that a given appreciation or depreciation could have very different effects on import prices depending on what caused the initial currency movement. The estimates also suggest that the magnitude of these differences can be economically meaningful. This could explain why estimates of pass-through can change over time—even within a country—and why it is so hard to predict the effect of an exchange rate movement on inflation in real time, without fully understanding the reason behind the movement.

3. Applying the framework to evaluate pass-through in the UK

To assess the importance of shock-contingent exchange rate pass-through, this section investigates whether our framework can help understand the link between movements in sterling and UK import prices. It focuses on the period since the UK left the European Exchange Rate Mechanism (ERM), under which the value of sterling was pegged. (In the sensitivity analysis, we examine a longer period.) We analyse what types of shocks have driven UK exchange rate fluctuations and import prices over this period by examining the forecast error variance decompositions and historical shock decompositions from the SVAR. Then we evaluate if the shock decomposition of exchange rate movements can explain changes in the observed rates of pass-through over time.

To begin, Table 2 shows the variance decomposition of the six variables that are the focus of our model above for the UK (GDP, CPI, Shadow Bank Rate, Exchange Rate Index, Import Prices, and Foreign Export Prices). It reports the proportion of the variance for each of these variables explained by shocks to UK supply, UK demand, UK monetary policy, the exchange rate and the two global shocks. In order to better understand how this model helps explain changes in pass-through over time, it is useful to focus on the estimates explaining variations in the exchange rate, which are highlighted in

[25] Given the wide confidence bands around the impulse responses in Appendix B, Figures B.1 through B.6, there is significant uncertainty around these exchange rate pass-through estimates. However, the ranking of the shocks according to the associated exchange rate pass-through described in this section is more stable. For example, in over two-thirds of the models from which the median exchange rate pass-through profiles in Figure 1 are constructed, the domestic demand shock leads to lower exchange rate pass-through than either the monetary policy shock or the exogenous exchange rate shock, consistent with the theoretical predictions in Section III.

the middle of the table. These results suggest that demand shocks have accounted for around a quarter of unanticipated nominal exchange rate movements (or more precisely for 28% at the one-quarter horizon and 23% over the long run) over the period from 1993q1 to 2015q1. The exogenous exchange rate and monetary policy shocks are also each important—with each explaining around 20% of the variance after one quarter and 15% to 19% in the long run. The other three shocks play less of a role in the short term (with each accounting for about 10% of the variance after one quarter). There is, however, an increased role for both persistent and transitory global shocks over the longer term (accounting for 17% and 15% of the exchange rate variation, respectively, at five years).

Table 2: Forecast error variance decomposition

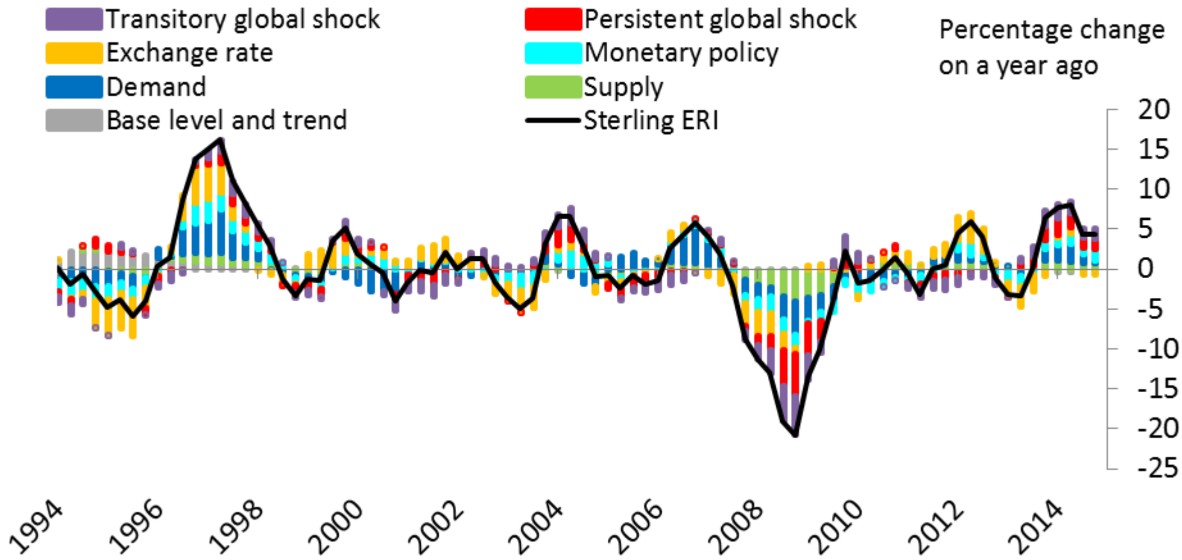
Variable	***Horizon (quarters)***	***Proportion of variance explained by shocks to:*** Supply	Demand	Monetary policy	Exchange rate	Persistent global shocks	Transitory global shocks
GDP	**1**	0.50	0.08	0.04	0.06	0.14	0.17
	20	0.47	0.05	0.03	0.04	0.28	0.13
CPI	**1**	0.14	0.15	0.17	0.07	0.33	0.13
	20	0.15	0.12	0.16	0.07	0.36	0.15
Shadow BR	**1**	0.22	0.10	0.07	0.12	0.25	0.25
	20	0.21	0.09	0.08	0.05	0.29	0.28
Exchange rate	**1**	0.09	0.28	0.18	0.22	0.12	0.11
	20	0.11	0.23	0.15	0.19	0.17	0.15
Import prices	**1**	0.08	0.11	0.22	0.12	0.23	0.24
	20	0.08	0.10	0.19	0.12	0.26	0.26
Foreign export prices	**1**	0.00	0.00	0.00	0.00	0.48	0.52
	20	0.01	0.01	0.01	0.00	0.46	0.51

Note: The forecast error variance decomposition is the average of the 1,000 variance decompositions obtained from the saved iterations of the estimation algorithm. See Appendix A for further detail on the estimation methodology.

This decomposition clearly indicates that structural shocks other than exogenous exchange rate shocks account for the majority of the variation in the exchange rate—for over ¾ of the variation over any time period to be precise. Therefore, treating all exchange rate fluctuations as exogenous exchange rate shocks (as is common in the macro literature discussed in Section II) might not adequately capture the underlying dynamics, especially if the mix of shocks driving the exchange rate varies over time.

Next, to better understand if the relative importance of these different shocks does vary over time in a meaningful way, we plot the corresponding historical decomposition of year-on-year exchange rate changes in Figure 2. A quick glance at the figure suggests that there are significant differences in the sources of exchange rate movements at different points in time. For example, the large depreciation during the 2007-2009 crisis was associated with larger global shocks (in red and purple) and domestic supply shocks (in green) than occurred in most other periods. Both of these types of shocks — and especially the global shocks — generate relatively higher exchange rate pass-through to import prices. In contrast, the sharp appreciation of sterling around 1996-7 was driven more by domestic demand shocks (in dark blue) and exchange rate shocks (in yellow) — which exhibit substantially lower pass-through. Providing yet another contrast, the appreciation from 2013-2015 is associated with a relatively greater role of global shocks (both persistent and transitory). These are correlated with large movements in import prices, but make it necessary to differentiate the direct impact on foreign export prices from global shocks separately from the effects of the exchange rate.

Figure 2: Historical decomposition of year-on-year changes in nominal sterling ERI



Note: The figure depicts the contribution of each of the six shocks to y/y changes in the ERI, in percent. These historical decompositions of the variables in the SVAR are the averages of the 1,000 historical decompositions obtained from the saved iterations of the estimation algorithm. See Appendix A for further detail on the estimation methodology.

To clarify the distinctions between these periods more formally, Table 3 decomposes the movements in sterling into the corresponding average contributions from the six shocks during three recent episodes when sterling has experienced its most extreme movements. In addition, the last column reports the corresponding shock decomposition of the sterling forecast error variance for the full estimation sample. A comparison between the different episodes highlights the importance of demand and exchange-rate shocks in driving the 1996-7 episode—not only relative to the historical average, but also relative to the 2007-9 depreciation. In contrast, global shocks play a substantially greater role in driving the 2007-9 episode, when compared to the historical averages and the earlier episode. Shocks to domestic supply are also very important in driving the 2007-9 episode, more than double the historical average and more than other periods of sharp exchange rate movements.

Turning to the most recent sterling appreciation, global shocks are identified as the two most important factors – even more than during the 2007-9 depreciation. The most important point from this analysis is that the contribution from different shocks varies across these episodes of sharp exchange rate movements, indicating that the resulting exchange rate pass-through might also differ across episodes.

To better understand what these shock decompositions imply for changes in pass-through over time, we can use our model estimates of the pass-through ratios shown in Figures 1.a and 1.b. This exercise gives us an estimate of the unadjusted (but shock-contingent) exchange rate pass-through, which does not control for movements in any other variables during each episode. More specifically, although our framework will control for the effects of each of our shocks on each of the variables in the SVAR, it is not able to control for other events causing simultaneous movements in commodity prices and foreign export prices more broadly. This can be a particularly important issue when there are changes in global prices (such as when oil prices fell sharply in 2013-2014 when Saudi Arabia changed its policy on oil production and the US shale industry experienced rapid changes). Reduced-form regressions estimating pass-through (such as discussed in Section II) usually address this by controlling for these changes in foreign export prices (whatever their causes), in order to attempt to isolate the effects of exchange rate movements on import prices.

To relate our results to the standard approach we also report "adjusted pass-through" coefficients at the bottom of Table 3. These coefficients are meant to illustrate that movements in foreign export prices can affect the "unadjusted" pass-through to import prices, based on assumptions. More specifically, and in order to capture the imprecision around these additional assumptions, we use a range and assume that 50% to 100% of changes in foreign export prices are passed-through to UK import prices.[26]

Focusing on the adjusted pass-through estimates at the bottom of Table 3, the shock decomposition from the 1996-7 episode suggests that a 10% exchange rate appreciation would have caused import prices to fall by around 7%. In contrast, using the decomposition from the 2007-9 episode, the same 10% exchange rate movement would cause import prices to adjust by 9%. In other words, using the pass-through coefficients from the 1996-7 episode as a rule of thumb would have underestimated the impact of the 2007-9 depreciation on the level of UK import prices by almost 30%.

[26] This range corresponds to approximately two standard errors below and above the long-run impact of foreign export prices on UK import prices, estimated using the reduced form regressions described in Section II, and should therefore capture any likely outcomes.

Table 3: Shock decomposition of sterling exchange rate changes[(a)] and implied pass-through coefficients for import prices after large exchange rate movements

Shocks	***1996-7 appreciation***	***2007-9 depreciation***	***2013-2015q1 appreciation***	***Full sample FEVD[(b)]***
Supply	10%	21%	14%	10%
Demand	33%	20%	22%	25%
Monetary policy	19%	11%	17%	17%
Exchange rate	24%	13%	0%	21%
Persistent global shock	6%	18%	25%	14%
Transitory global shock	8%	17%	23%	13%
Unadjusted pass-through to import prices (not controlling for foreign export prices)	*-0.67*	*-0.86*	*-0.99*	*-0.79*
Adjusted pass-through to import prices[(c)]	***-0.69 to -0.71***	***-0.89 to -0.92***	***-0.40 to -0.69***	

Note: Estimated using SVAR model described in Section IV. Implied-pass-through is for 8 quarters after the shock.
(a) We look at the average 4-quarter change during each episode and the respective average contribution from each shock. This avoids issues arising when offsetting shock contributions lead to an overall change in the exchange rate close to zero in any given period.
(b) Average contribution of each shock to the forecast error variance decomposition (FEVD) of the exchange rate over the first eight quarters of the forecast horizon.
(c) The "adjusted pass-through" measure assumes 50% to 100% pass-through from world export prices. The calculations are based on the actual peak-to-trough or trough-to-peak changes in the sterling ERI and corresponding changes in world export prices (including oil) during each episode.

The estimates from the most recent appreciation episode starting in 2013 show another sharp shift in the extent of pass-through. The shock decomposition to the right of Table 3 suggests that a 10% exchange rate appreciation would have caused import prices to fall by 4% - 7%. These estimates are less precise due to the large movements in commodity prices that occurred during this period and the corresponding uncertainty about how much of the changes in sterling import prices reflected movements in commodity prices or effects of sterling's appreciation. Even using this broad range of estimates, however, pass-through has fallen substantively compared to that following the 2007-9 depreciation. Using the pass-through coefficients from the 2007-9 episode to predict the impact of the 2013-15 appreciation on import prices would have substantially overestimated the reduction in import price inflation.

As a check on these results, Appendix Figure B.7 shows the same decomposition for import price inflation. It highlights that after sterling's depreciation in 2007-9, import price inflation was boosted by global shocks (in red and purple) and domestic supply shocks (in green)—both of which played a large role on an absolute basis and relative to previous historical episodes. After the 2013-15 appreciation, both global shocks played a key role in the decline in import prices (even explaining all of the decline in some quarters). These estimates agree with the above estimates for pass-through to import prices.

This series of results highlights the importance of regularly adjusting estimates of pass-through over time to incorporate the nature of the underlying shocks. After the 2007-9 depreciation, the surprisingly high levels of pass-through caused institutions such as the BoE to adjust their estimates of pass-through upward as a new "rule of thumb". This upward adjustment was justified by the increased pass-through observed at the time. The results in this section, however, suggest that using this higher estimate after the 2013-15 appreciation would lead to inaccurate estimates of the extent of pass-through, due to the different shocks driving these two large exchange rate movements. More specifically, this "rule-of-thumb" would have generated forecasts predicting a greater drag on import price inflation than was likely to occur in the aftermath of the recent sterling appreciation.[27] Similarly, lower pass-through from the 2013-15 appreciation might also not be an accurate indicator of the extent of any pass-through that will occur subsequently—such as after the "Brexit" vote for the UK to leave the European Union. Instead, it is critically important to evaluate the nature of the shocks driving the currency movements when predicting how they will affect inflation.

VI. Exchange rate pass-through to consumer prices

Even more important for monetary policy is the pass-through to consumer prices (or corresponding variable for any inflation target). This section shows that exchange rate pass-through to consumer prices is also shock-contingent, that the rankings of the effects of different types of shocks is similar to that for pass-through to import prices, and that in some cases the differences resulting from different shocks are even starker.

To begin, Figure 3 plots the same measures of exchange rate pass-through as shown in Figure 1 for import prices, but this time for consumer prices. As before, we compare these to the reduced-form estimates obtained in Section II. Different percentiles of the ratios of consumer price to exchange rate impulse responses at selected horizons are also reported in Appendix B, Table B.2. Before discussing these results, however, it is useful to compare them to the results for pass-through to import prices and the standard findings in the literature. A quick comparison between the estimates for the first-stage of pass-through (Appendix Table B.1, Figures 1.a and 1.b) and those for overall pass-through to consumer prices (Appendix Table B.2, Figures 3.a and 3.b) indicates that pass-through is significantly lower to final consumer prices than to import prices. This is a well-documented finding in

[27] The Bank of England recently adjusted its assumptions about the extent of exchange rate pass-through to import prices from about 90% (as observed after sterling's depreciation in 2007-9) to a base case of 60%. For further detail, see the box "The effect of imported price pressures on UK consumer prices" in the BoE *Inflation Report*, November 2015.

the literature (see Gopinath, 2015). These tables and figures also support evidence that pass-through to import prices is quicker than to final consumer prices. Figures 3.a and 3.b suggest that a given movement in the exchange rate has its full impact on consumer prices around six to eight quarters after the initial shock (compared to around four quarters for import prices).

Figure 3.a: Pass-through to consumer prices for domestic shocks

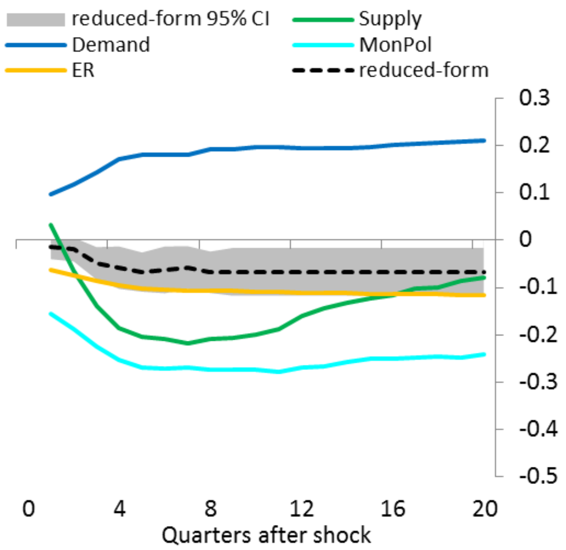
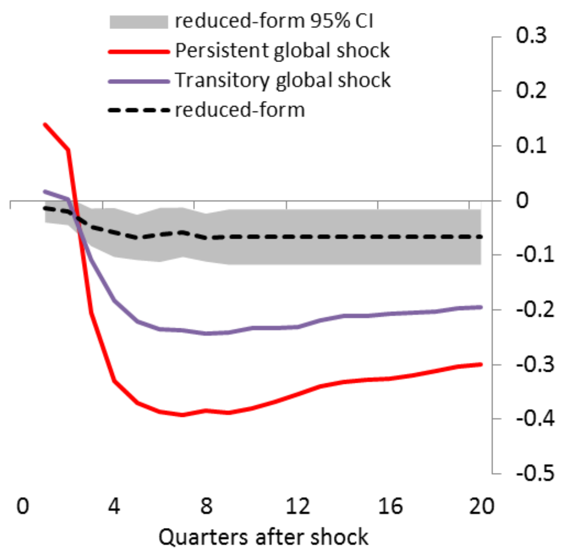


Figure 3.b: Pass-through to consumer prices for global shocks



Next, the profiles for overall exchange rate pass-through in Figure 3 reveal that appreciations driven by five of the six shocks (all except domestic demand) generate the traditional result of lower consumer prices, with consumer prices falling by about 20% of the initial exchange rate appreciation after 8 quarters. The exogenous exchange rate shock has a somewhat lower estimated pass-through, and the monetary policy shock has the greatest pass-through. In contrast to the drag on domestic prices from five of the six shocks, an appreciation corresponding to a domestic demand shock generates an increase in consumer prices—resulting in a positive pass-through 'coefficient'. This is consistent with the theoretical results discussed in the Online Appendix, as well as the results for pass-through to import prices shown in the previous section. Not only do appreciations corresponding to positive demand shocks lead to less drag on import prices, but the support to the economy from the positive demand shock drives up prices overall—more than counteracting the drag from import prices. In other words, appreciations resulting primarily from positive domestic demand shocks would be expected to exhibit much less pass-through, and possibly no decline in overall inflation. This is a sharp distinction relative to the effects of appreciations driven by other types of shocks.

As shown in the previous section, the different composition of shocks behind the recent large moves in the sterling exchange rate generated differing degrees of pass-through to import prices.[28] We can apply the same calculations as before to consumer prices and weigh the exchange rate pass-through profiles shown in Figure 3 by the exchange rate decompositions in Table 3 to get an "unadjusted" exchange rate pass-through coefficient for each episode. The resulting multipliers are reported in the first row of Table 4. To adjust these for the simultaneous changes in foreign export prices, we use the impact of foreign prices on UK import prices calculated in Table 5 and scale it by the import intensity of the UK CPI basket of around 30%.[29]

The resulting "adjusted" pass-through coefficients lead to very similar conclusions as the equivalent measure for import price pass-through. The mix of shocks associated with sterling's depreciation in 2007-9 led to pass-through to consumer prices twice as high as that observed following the preceding appreciation. Using that higher pass-through estimate to quantify the effects of the 2013-15 appreciation on consumer prices, however, would have substantially overestimated the effects of the exchange rate move; consumer prices would have been predicted to fall by 1.7-1.8% after a 10% appreciation using the 2007-08 shock decomposition, rather than by between 0.1 and 1% using the actual 2013-15 shock decomposition. In other words, the impact on inflation would have been more than double what occurred.

Table 4: Implied pass-through coefficients for consumer prices after large exchange rate movements

	1996-7 appreciation	*2007-9 depreciation*	*2013-2015q1 appreciation*	*Full sample FEVD[(a)]*
Unadjusted pass-through to consumer prices (not controlling for foreign export prices)	*-0.08*	*-0.16*	*-0.18*	*-0.13*
Adjusted pass-through to consumer prices[(b)]	***-0.09 to -0.09***	***-0.17 to -0.18***	***-0.01 to -0.10***	

Note: Estimated using SVAR model described in Section III. Implied-pass-through is for 8 quarters after the shock.
(a) Average contribution of each shock to the forecast error variance decomposition (FEVD) of the exchange rate over the first eight quarters of the forecast horizon.
(b) The "adjusted pass-through" measure assumes 50% to 100% pass-through from world export prices to import prices and a 30% CPI import intensity. The calculations are based on the actual peak-to-trough or trough-to-peak changes in the sterling ERI and corresponding changes in world export prices (including oil) during each episode.

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[28] The decomposition of the shocks driving changes in UK consumer price inflation yields estimates very similar to the decomposition of UK import prices. See Forbes *et al.* (2015) for the corresponding graphs.

[29] This 30% imported share of the CPI is calculated by the UK's Office of National Statistics and should include both imported goods as well as the share of imported content in non-traded goods (to the best that it can be calculated). Clearly, the pass-through from foreign prices in foreign currency can also change over time, but using constant import-intensity estimates and assuming 100% pass-through from import prices to consumer prices is a common assumption (see Gopinath, 2015). An alternative is to directly use the coefficients from the reduced-form regression of CPI inflation on the exchange rate and foreign export prices, as estimated in Section II. That approach gives the same ranking of exchange rate pass-through coefficients associated with the three episodes as the two-stage approach.

VII. Extensions, Robustness, and Out-of-Sample Predictions for the "Brexit" Vote

In order to test if the results reported above are robust to various specifications, this section begins by summarizing a series of extensions and sensitivity tests: for different types of exchange rate movements and regimes, and then for modifications to the baseline specification and estimation framework. The section ends by applying the framework using estimates from before the UK vote to leave the European Union (in June 2015) to calculate out-of-sample forecasts of pass-through resulting from sterling's sharp depreciation after the "Brexit" vote. It then compares these estimates to the most recent data on UK import prices and inflation.

1. Extensions: Asymmetries, nonlinearities and regime changes

There is some empirical and theoretical evidence that firms could respond differently to larger exchange rate movements than smaller ones, to appreciations than to depreciations, and based on the monetary and exchange rate regime.[30] For example, if there are "menu costs" or wages are downwardly rigid, companies may be more reluctant to adjust prices in response to small changes in the exchange rate or after appreciations, implying less pass-through in these circumstances. The model used to estimate pass-through in this paper is linear and symmetric, however, so it is difficult to explicitly test for all of these effects. It is possible, however, to focus on specific episodes with different types of exchange rate movements or regimes to see if the nature of the shocks tends to differ—and which could in turn drive different degrees of pass-through. For example, if domestic demand shocks have historically played a greater role in driving appreciations than depreciations, when combined with the evidence in Figures 1 and 3 that demand shocks correspond to lower pass-through, then appreciations might be expected to correspond to periods of lower pass-through.

To test for these types of effects, we perform two sets of analyses. First, we divide the sample into periods of "large" exchange rate moves, defined as periods when the exchange rate moves by at least 3% relative to a year earlier. Periods of small exchange rate moves are the rest of the sample. We also divide the sample into periods during which the exchange rate appreciated by at least 3% on an annual basis, and those when the exchange rate depreciated by at least 3%. Then we examine whether certain shocks tend to be associated more with a particular type of exchange rate movement, and whether that implies a different degree of pass-through. The results are described in detail in Forbes *et al.* (2015). The shocks driving large (relative to small) exchange rate movements, and appreciations (relative to depreciations) are broadly similar. The minor differences that exist are

[30] Berger and Vavra (2013) find no evidence of asymmetries in the extent of pass-through in the US, while Rincón-Castro and Ridríguez-Nino (2016) and Caselli and Roitman (2016) find evidence of asymmetries in pass-through in emerging markets. Lewis (2016) finds a higher degree of pass-through to UK import prices for large exchange rate moves than for small ones.

intuitive (such as the exogenous exchange rate shock explaining a slightly larger share of small fluctuations in sterling compared to large ones), but given the limited observations, it is impossible to draw any firm conclusions from these small differences.

Next, in order to test for different relationships under different monetary and exchange rate regimes, we extend our analysis to start in 1980 (instead of from 1993 as in our central analysis). This extended period incorporates a range of monetary and exchange rate regimes: UK monetary policy targeted various monetary aggregates between 1976 and 1987 and switched to exchange rate targeting between 1987 and 1992, with sterling entering the European Exchange Rate Mechanism (ERM) from 1989 to 1992. The resulting estimates of pass-through in this extended period are described in detail in Forbes *et al.* (2015). They indicate substantial changes in the distribution of shocks driving exchange rate movements, as well as the extent of pass-through corresponding to these shocks, under these different regimes. For example, monetary policy shocks explain a larger proportion of the exchange rate variance in the longer period, while global shocks explain much less—a result consistent with the fact that the UK economy has become more open and therefore more sensitive to global shocks since the early 1980s. These substantial changes in the parameter estimates under different monetary and exchange rate regimes support the decision to start the baseline analysis in this paper in 1993—after sterling had left the ERM, began to float, and the UK adopted an inflation target—the same framework that largely remains in place today.[31]

2. Robustness tests

In addition to the extensions reported above, we have also estimated a number of different variants of our model to test if the main results are sensitive to: the 2008 crisis, different measures for prices, different measures for interest rates, changes to the model lag order, and different sign restrictions.

First, we examine if there was a structural change in our sample associated with the global financial crisis and sharp recession between 2007 and 2009.[32] We begin by estimating the model over the baseline 1993-2015q1 period with a dummy for the period from 2007. Our key results are reported in column 2 of Table 5 and are little changed from the baseline analysis (in column 1). Then,

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[31] We also tested if our findings were robust to starting the sample in 1998 (rather than 1993), which was when the Bank of England became independent. The resulting variance decompositions and implied pass-through ratios are reported in Forbes *et al.* (2015) and the key results are quite close to those using 1993 as the start date. The most noteworthy change is that the average implied pass-through for the period starting in 1998 is higher than that that starting in 1993, largely reflecting the greater role of persistent global shocks (that correspond to higher pass-through) in the more recent period. Other key results discussed throughout this paper are unchanged.

[32] We do not have enough data after the crisis to split our baseline estimation sample into two different periods: pre- and post-crisis.

in order to test for any structural change after 2007, we re-estimate our model with data from 1993 until the end of 2007. We use this to test whether the mean out-of-sample forecasts for the following 20 quarters either individually or jointly violate the model's assumptions of independent, normally-distributed shocks with a zero mean and constant variance.[33] The results suggest no evidence of a structural change in the data or estimated relationships during and after the financial crisis.

Table 5: Robustness tests: Forecast error variance decompositions of the exchange rate and implied pass-through for different price and interest rate measures

	SVAR estimated with:					
	Baseline: CPI, BoE shadow rate (1)	**Post-crisis dummy (2)**	**PPI (3)**	**Core CPI (4)**	**1-year forward gilt yield (5)**	**Wu-Xia shadow rate (6)**
Supply	10%	10%	8%	11%	10%	10%
Demand	25%	21%	23%	22%	25%	25%
Monetary policy	17%	15%	19%	15%	24%	23%
Exchange rate	21%	25%	23%	22%	21%	21%
Persistent global shock	14%	17%	15%	18%	12%	11%
Transitory global shock	13%	12%	12%	12%	9%	9%
Implied ERPT to:						
Import prices	***-0.79***	***-0.85***	***-0.79***	***-0.86***	***-0.66***	***-0.76***
Consumer prices	***-0.13***	***-0.11***	***-0.25***	***-0.03***	***-0.10***	***-0.11***

Note: Estimated using SVAR model described in Section III. Implied-pass-through is for 8 quarters after the shock.

Second, we examine the impact of using the PPI and core CPI (instead of CPI) to measure domestic prices. Column 3 of Table 5 shows that using producer rather than consumer prices leads to very similar conclusions in terms of the effects of the five different shocks and the overall pass-through to import prices. The one notable difference is the higher implied exchange rate pass-through to producer prices than consumer prices (despite nearly identical pass-through to import prices for both, as would be expected). This higher pass-through to the PPI basket is not surprising, however, as this basket is largely comprised of manufactured goods, which are more likely to be traded and sensitive to exchange rate movements. In contrast, the CPI basket holds a large share of consumer services, which are less likely to be traded and tend to be less sensitive to the exchange rate. Column 4 shows the corresponding estimates for core CPI (excluding energy, food and non-alcoholic beverages, also adjusted for VAT changes). Once again the results are similar to the baseline, except the degree of pass-through to final prices—which is now substantially lower than found for the CPI. This is because

[33] We implement the tests for structural change based on one and on several forecast periods described in Lutkepohl (2005), Chapter 4, pp. 184-188.

the core-CPI excludes some highly import-intensive goods (such as oil and food) which exhibit a very high degree of pass through.

Third, we test for any impact of using different measures for UK domestic interest rates than the shadow Bank Rate calculated by the Bank of England. We use two alternatives: the one-year instantaneous forward UK government bond yield[34] and the UK shadow rate calculated by Wu and Xia (2016) from financial instruments. The main results are reported in columns 5 and 6 of Table 5, with minimal changes. A higher proportion of the variance is attributed to the monetary policy shock, and a slightly higher proportion attributed to the two global shocks. The monetary policy shocks estimated with the one-year yield and the Wu-Xia shadow rate have lower pass-through than in our baseline, however, possibly due to being noisier monetary policy indicators compared to the BoE shadow rate in the baseline specification.[35]

As a fourth set of robustness tests, we examine any impact of changes to the lag order and timing of the sign restrictions and report results in Table 6. We begin by changing the lag structure by estimating the model using one, three and four lags of the endogenous variables (instead of two lags as in our baseline results). There are no notable differences in these results (shown in columns 2-4 of Table 6) compared to our baseline results (replicated in column 1). We also test whether our results are sensitive to imposing the sign restrictions for a shorter period of one quarter, and a longer period of four quarters. The results are shown in columns 5 and 6 and are also similar to the baseline.

For a final set of robustness tests, we assess the sensitivity of our results to the sign restrictions imposed on the CPI – a key price index for an assessment of pass-through. Column 2 of Table 7 shows the exchange rate forecast error variance decomposition and implied pass-through to import and consumer prices from dropping all sign restrictions on consumer prices. In our identification scheme, this implies relying solely on our long-run zero restrictions to distinguish between UK supply shocks and other domestic shocks. Columns 3-5 add an additional UK price variable to the SVAR from column 2– the GDP deflator, core CPI (excluding energy and food) or PPI, respectively – and impose on these additional price variables the sign restrictions that we impose on CPI in our baseline model, while leaving the CPI itself unrestricted. Our results remain robust to each of these model variants.

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[34] Using interest rates of longer maturity was not appropriate in our set-up as these are often driven by term premia and the long-term bond term premia have been found to co-move considerably across countries, presumably reflecting international shifts in risk sentiment. Such a measure would not be consistent with our identification of a UK-specific monetary policy shock which does not affect foreign prices.

[35] These financial market proxies of the shadow policy rate probably capture factors other than just monetary policy surprises. One-year interest rates might, for example, also reflect changes in term premia and not just expected policy rates – albeit to a lesser degree than longer-term policy rates.

Table 6: Robustness tests: Forecast error variance decompositions of the exchange rate and implied pass-through for different lag order and sign restriction periods

	SVAR estimated with:					
	Baseline: 2 lags, 2-period sign restrictions (1)	1 lag (2)	3 lags (3)	4 lags (4)	Sign restrictions for 1 period (5)	Sign restriction for 4 periods (6)
Supply	10%	10%	11%	13%	11%	13%
Demand	25%	24%	26%	27%	21%	30%
Monetary policy	17%	16%	18%	18%	14%	12%
Exchange rate	21%	29%	21%	20%	25%	20%
Persistent global shock	14%	11%	12%	12%	17%	16%
Transitory global shock	13%	10%	11%	11%	12%	10%
Implied ERPT to:						
Import prices	***-0.79***	***-0.77***	***-0.80***	***-0.77***	***-0.86***	***-0.75***
Consumer prices	***-0.13***	***-0.11***	***-0.12***	***-0.12***	***-0.14***	***-0.09***

Note: Estimated using SVAR model described in Section III. Implied-pass-through is for 8 quarters after the shock.

Table 7: Robustness tests: Forecast error variance decompositions of the exchange rate and implied pass-through for different sign restriction on CPI

	SVAR estimated with:				
	Baseline: with sign restrictions on CPI (1)	No sign restrictions on CPI (2)	No sign restrictions on CPI, restrict GDP defl. (3)	No sign restrictions on CPI, restrict core CPI (4)	No sign restrictions on CPI, restrict PPI (5)
Supply	10%	11%	12%	13%	11%
Demand	25%	21%	19%	28%	23%
Monetary policy	17%	22%	14%	14%	18%
Exchange rate	21%	21%	19%	17%	20%
Persistent global shock	14%	15%	21%	14%	16%
Transitory global shock	13%	10%	14%	12%	13%
Implied ERPT to:					
Import prices	***-0.79***	***-0.76***	***-0.79***	***-0.74***	***-0.77***
Consumer prices	***-0.13***	***-0.12***	***-0.12***	***-0.08***	***-0.12***

Note: Estimated using SVAR model described in Section III. Implied-pass-through is for 8 quarters after the shock.

3. Out-of-Sample Forecasts: Pass-through after the "Brexit" vote

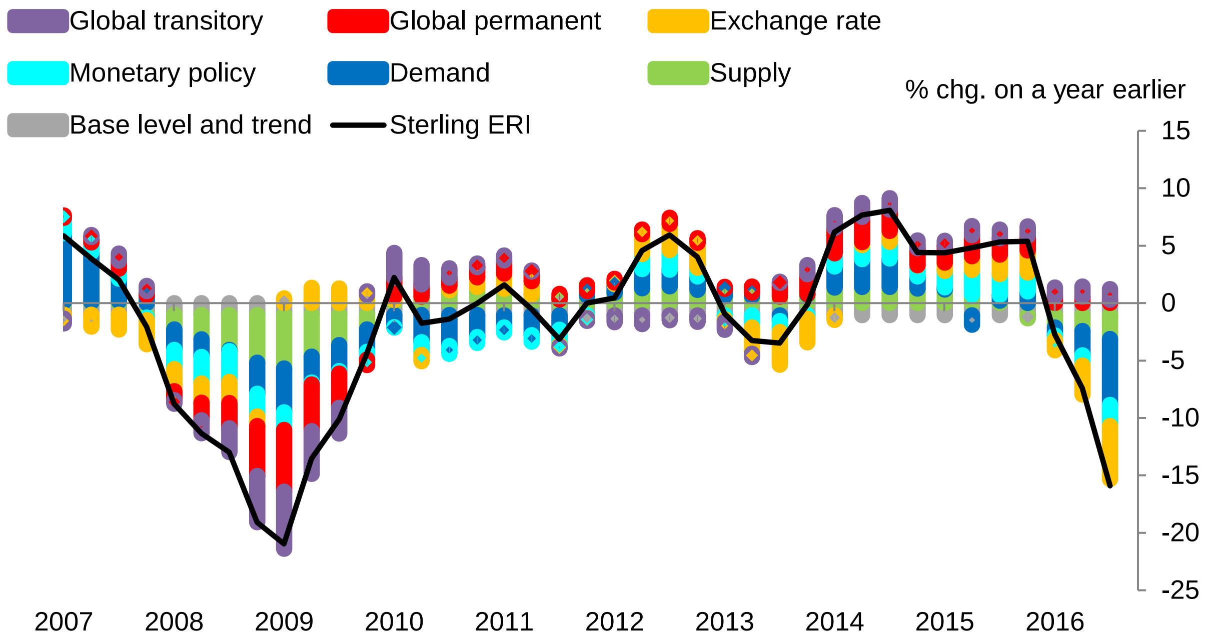
While the framework developed in this paper appears to be robust to various extensions, variable definitions, and estimation strategies, can it be used in real-time to better forecast the extent of pass-through from a given exchange rate movement? To demonstrate how the methodology can be used for out-of-sample forecasts, this section uses the framework developed above to forecast pass-through following sterling's sharp depreciation in 2016, around the time of the United Kingdom referendum on membership of the European Union (which took place on 23 June 2016). We show real-time model forecasts using data available at two dates: immediately after the referendum (mid-way through sterling's subsequent depreciation) and about 4 months later (after the Bank of England had announced a substantial easing in monetary policy and sterling was more stable). At the end of the section, we compare the real-time model predictions from these two dates with the subsequent change in import prices.

The UK referendum on EU membership—what we will refer to as the "Brexit" vote for simplicity—was a key factor contributing to the sharp depreciation of sterling over 2016. Two weeks after the UK referendum, sterling had fallen by almost 13% (compared to the last quarter of 2015). To assess how the methodology developed in this paper could predict the pass-through from this depreciation in real time, we begin by updating the estimates reported above with data available on 6 July 2016, two weeks after the "Brexit" vote. We use market data available at the close of business, as well as the real-time Bank of England forecasts for Q2 and Q3 that existed at that time.[36] We also assume that the sterling exchange rate index would not move further in Q3 (consistent with a random walk forecast).

The resulting shock-dependent pass-through estimates of this model updated in July are very similar to those depicted in Figures 1.a-b and 3.a-b, and the forecast error variance decomposition over the entire period is almost identical to that for the baseline estimates shown in Table 3 (which end in 2015Q1). Figure 4 shows the resulting historical shock decomposition of sterling's movements, extending that from Figure 2 with the six additional quarters of data. The figure shows that the model attributes basically all of sterling's depreciation during the first three quarters of 2016 to domestic shocks. More specifically, 46% of sterling's depreciation is attributed to domestic demand shocks, 36% to exchange rate shocks, and 14% to domestic supply shocks—all well above the corresponding averages for the full sample. Albeit not surprising given the domestic nature of the "Brexit" vote, this is in sharp contrast to other periods when sterling moved sharply and global shocks usually played a meaningful role. The model also suggests that monetary policy shocks only played a minor role at this stage (and less than the average over the full sample period), which is also not surprising as the Bank of England had not yet changed its monetary policy stance.

[36] These forecasts are confidential but were close to those published in the August 2016 Inflation Report.

Figure 4: Historical decomposition of year-on-year changes in sterling ERI – July 2016 update



Note: The figure depicts the contribution of each of the six shocks to y/y changes in the ERI, in percent. These historical decompositions of the variables in the SVAR are the averages of the 1,000 historical decompositions obtained from the saved iterations of the estimation algorithm. See Appendix A for further detail on the estimation methodology.

This different composition of shocks causing sterling's sharp depreciation around the time of the "Brexit" vote could also cause the resulting pass-through to prices to differ from historical averages, as well as other episodes when sterling depreciated sharply. To asses this, Table 8 reports the weight of the five different shocks corresponding to sterling's movements for the full sample period, from 2007-2009 (sterling's previous sharp depreciation), and immediately after the "Brexit" vote (July 2016)—based on the model's estimates as of July 2016. This confirms that global shocks were a less important driver of sterling's 2016 depreciation, and domestic demand shocks more important, relative to the 2007-2009 depreciation (as well as compared to the sample average). Since pass-through after domestic demand shocks tends to be lower than that after global shocks, this suggests that pass-through would be lower after the 2016 depreciation than that after the 2007-2009 depreciation. Substituting the estimated pass-through from each type of shocks confirms this assessment. As shown at the bottom of Table 8, the July 2016 estimates predicts that sterling's "Brexit" depreciation would have a relatively low degree of pass-through to import prices of 40% after 4 quarters (and around 45% in the long run). This is about half of the model's prediction of more than 90% pass-through in the long run after the financial crisis, and around 80% for the full sample.

Table 8. Comparison of shock decompositions and estimated pass-through of exchange rate changes

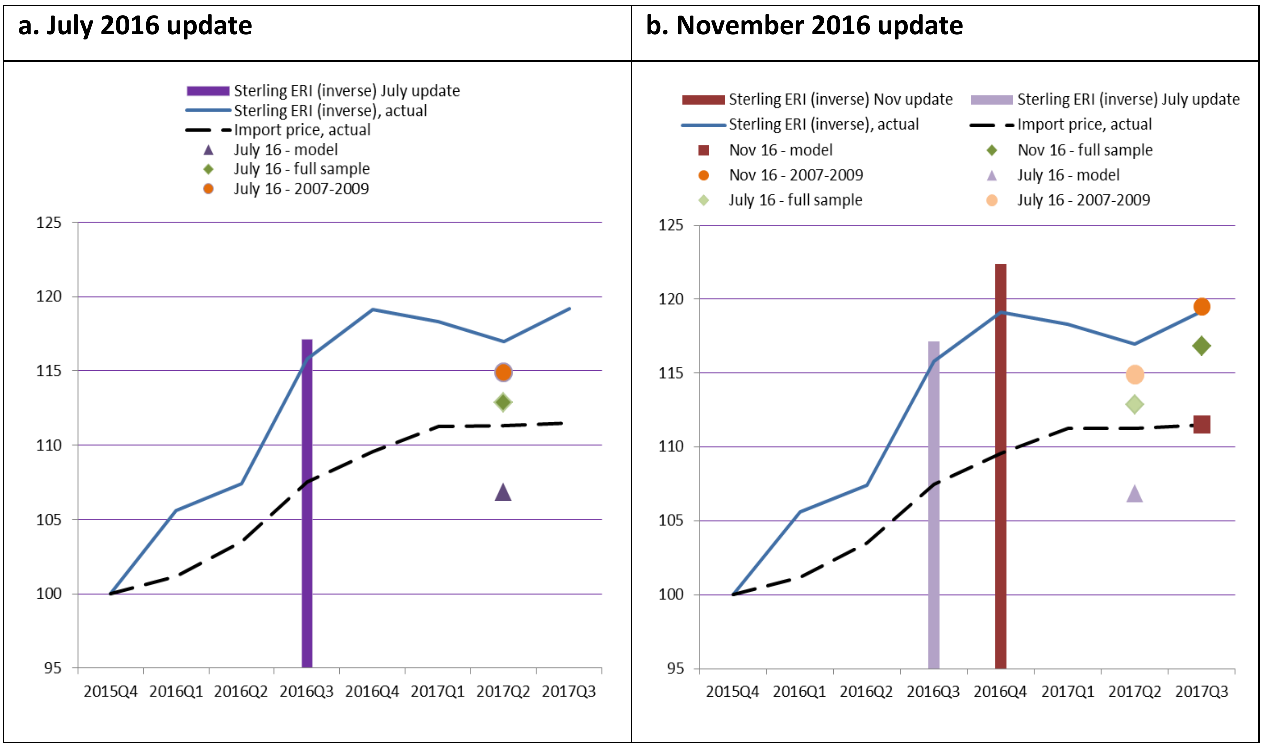
Shocks	*Full sample FEVD[(a)]*	*2007-9 depreciation*	*2016q1-q3 – July update*	*2016q1-q4 – Nov update*
Supply	10%	21%	14%	15%
Demand	25%	20%	46%	31%
Monetary policy	16%	12%	13%	23%
Exchange rate	20%	5%	36%	34%
Persistent global shock	15%	22%	-2%	1%
Transitory global shock	14%	19%	-7%	-4%
Unadjusted pass-through to import prices after 4 quarters (not controlling for foreign export prices)	*-0.75*	*-0.87*	*-0.40*	*-0.52*

Note: Estimated using SVAR model described in Section IV. Implied-pass-through is for 8 quarters after the shock. See notes to Table 4 for more details.
(a) Average contribution of each shock to the forecast error variance decomposition (FEVD) of the exchange rate over the first eight quarters of the forecast horizon.

Next, to assess the performance of these forecasts, Figure 5a graphs several key statistics. The small shapes on the right of the graph show the predicted level of import prices in 2017Q2 based on July 2016 data, using the shock decomposition from Table 8 for the "Brexit" depreciation (the purple triangle), the 2007-9 depreciation (the orange circle) and the historic average decompositions (the green diamond). Using the shocks behind the "Brexit" depreciation, import prices are forecast to rise by only 7% (from 2015q4)—substantially less than they would have been forecast to rise if the shocks behind the 2007-9 depreciation or historic averages were used to forecast pass-through. The solid blue line at the top of the graph shows the evolution of sterling at this time, and the dashed black line shows the evolution of import prices. A quick glance at the graph might suggest that the July 2016 model forecasts were not very accurate; import prices subsequently rose by more than predicted—and pass-through appears to be closer to that predicted by historic shock decompositions than the more domestic-based shocks estimated to drive the "Brexit" depreciation.

This initial assessment, however, misses two important developments. First, sterling did not remain at its July 2016 level (shown by the wide, vertical purple line). Instead, sterling subsequently depreciated by about 5% (before later appreciating). Second, the Bank of England's Monetary Policy Committee introduced a larger-than-expected stimulus package in August – generating a "monetary policy shock" (and likely contributing to sterling's further depreciation after our July 2016 update). Both of these developments would impact the predicted path of import prices. The further depreciation would provide an additional boost to import prices even if there was no change in the composition of shocks behind the exchange rate movement, and the degree of pass-through would likely increase due to the greater role of monetary policy shocks (which generate higher pass-through).

Figure 5. Sterling and import prices around the EU referendum



In order to incorporate these two developments, we update the model using data available on November 2, 2016. This incorporates market pricing at that time (including the additional depreciation), the monetary policy actions, and updated GDP forecasts.[37] The subsequent shock decomposition is shown in the column on the right of Table 8, with the estimated role of monetary policy shocks almost doubling, while that of domestic demand shocks falls (and the role of other shocks is roughly unchanged). Given that monetary policy shocks generate greater pass-through than domestic demand shocks, this would be expected to increase the expected degree of pass-through—as confirmed in the estimates at the bottom of the table.

Next, Figure 5b updates Figure 5a, incorporating the accumulated sterling depreciation as of 2 November 2016 (with the date shown in the thick red vertical line), plus the different estimates of pass-through from the different shocks decompositions (from Table 8). This includes updates of the previous decompositions, plus a new forecast using the November 2016 decompositions and shown in a red square. The updated model now predicts that pass-through would be about 52%, so that import prices will increase by 11.5% by the end of 2017q3 (after four quarters). This is greater than predicted in July 2016, but substantially less than the 19% increase in import prices predicted using the shock decompositions from the 2007-2009 depreciation (in the orange circle), or the 17% predicted based on

[37] These forecasts were produced by the Bank of England for the November *Inflation Report*.

historic averages (in the green diamond). In fact, the dashed black line, which shows the subsequent path of import prices, shows that import prices as of 2017Q3 were exactly in line with the forecast made in November 2016.

This out-of-sample forecast exercise shows the potential benefits of adjusting pass-through estimates in real time, rather than relying on specific episodes (such as the previous exchange rate change) or historic averages.

VIII. Conclusions

Many countries have experienced sharp currency movements over the past few years. These movements have highlighted the importance of better understanding how exchange rate fluctuations pass-through into import prices and overall price levels. Although the academic literature has made noteworthy strides in improving our understanding of pass-through across countries and industries, it has had less success estimating why currency movements can have such different effects over short periods of time within a given country. This limited understanding is particularly challenging for central banks, which must forecast how currency fluctuations will affect inflation in the future in order to set monetary policy appropriately.

This paper has proposed an approach that should improve our ability to evaluate these effects of exchange rate fluctuations on prices—especially over time within a country. It suggests that we should not take an exchange rate movement as exogenous—a concern acknowledged in some papers, but generally not addressed sufficiently within a clear framework. Instead, we should explicitly model and understand what drives the exchange rate movement and incorporate other changes in the economic environment. Different types of shocks causing an appreciation (or depreciation) could have different effects on the economy and broader set of prices and economic variables that determine firm behaviour—even if the shocks generate an equivalent currency movement. We show that different types of exchange-rate shocks can affect prices in different ways in terms of both magnitude, duration, and even sign. We also discuss and model the intuition behind these different effects, drawing on how the economy and firms respond to exchange rate fluctuations resulting from changes in domestic demand, domestic supply, monetary policy, an exogenous exchange rate shock, or global variables.

Although this approach can improve our understanding of how exchange rate movements affect inflation—and especially help explain how that relationship can change so quickly over time in a country such as the UK—it is not meant to be exhaustive and does not capture all the complexities of how exchange rate movements affect inflation. For example, there are many structural differences across countries that are important in explaining different effects of exchange rate fluctuations, such as the currency composition of invoicing, the share of debt in foreign currency, the dispersion of price changes, and the monetary policy framework.[38] The fact that the exchange rate can move in different directions with respect to different currencies might also play a role.[39] Currency appreciations may have different effects than depreciations, and the effects of currency movements may be non-linear. The framework in this paper is not meant or able to capture all of these complexities—but still adds an important new dimension to the standard approach for analysing exchange rate pass-through.

The results indicate that explicitly modelling pass-through as shock-dependent can improve our understanding on several dimensions. It can help explain why pass-through can change over time. It can help explain episodes when currency movements had surprisingly large or small effects on import prices and inflation. For example, it shows how the different nature of the shocks causing sterling's depreciation during the 2007-8 crisis generated substantially higher inflation than would have been expected based on previous estimates of pass-through, and why pass-through from sterling's 2013-15 appreciation and post-Brexit vote depreciation has been more muted. New work has recently extended this framework to estimate shock-dependent pass-through to four countries in the euro area (Comunale and Kunovac, 2017)[40], and to a large set of small open emerging markets and advanced economies (Forbes, Hjortsoe and Nenova, 2017). Utilizing this shock-dependent framework to estimate pass-through should improve our ability to predict the impact of currency movements and, as a result, hopefully improve the ability of central banks to set monetary policy appropriately in the future in countries around the world.

[38] See Gopinath (2015) for the role of currency invoicing and Stulz (2007) for the role of monetary policy expectations. Also see Berger and Vavra (2013) and Fleer *et al.* (2015), which show that sectors with high price-change dispersion tend to have larger pass-through than sectors with low price dispersion.
[39] See Casas *et al.* (2017) for evidence on the special role of US dollar bilateral exchange rates.
[40] See Coeuré (2017) for an example of how this shock-based approach to estimating pass-through is affecting the monetary policy debate.

Appendix A: Bayesian estimation of SVAR model

This appendix outlines the key steps in the Bayesian procedure used to estimate the SVAR model described in Section IV.

We start with the reduced-form Vector Autoregression (VAR) model in matrix form below:

$$Y = X * beta + \varepsilon,$$

where Y is a matrix of the endogenous variables with *n* rows (equivalent to the number of quarters in the estimation sample) and *k* columns (equivalent to the number of endogenous variables in the model). X is a matrix containing all explanatory variables (exogenous as well as endogenous), which also has *n* rows and *p*k+1* columns, implying that each equation in the VAR has *p* lags of each endogenous variables and a constant term on the right hand side.[41] ε is a matrix of reduced-form VAR residuals of size *n*-by-*k*. We define $\Sigma = \varepsilon'\varepsilon$ as the residual covariance matrix. The six reduced-form shocks in ε are correlated, so we need to extract a set of structural uncorrelated shocks from them by imposing sign and zero restrictions on the residual covariance matrix Σ as well as the resulting impulse responses – we will call the new matrix of structural shocks *u.*

We use a Bayesian simulation method known as Gibbs sampling to approximate the distributions of estimated parameters in our model. This algorithm uses a user-specified prior for the first and second moments of the VAR coefficients (*beta*) and the residual covariance matrix (Σ) and draws different values of these parameters from the associated conditional or posterior distributions. Specifically, we apply a widely-used Minnesota-style prior, which is based on the assumption that the endogenous variables in the VAR model follow an AR(1) process (Litterman, 1986). However, we relax the strict Minnesota prior's assumption that the VAR residual covariance matrix is diagonal[42] by incorporating the prior specification into our Gibbs sampling algorithm and using random draws of the covariance matrix. We proceed in the following three steps:[43]

i. We specify our prior for the coefficient matrix *beta* by setting all coefficients' prior means apart from the ones on each variable's own first lag to zero. The first autoregressive coefficient for each endogenous variable is set to 1 in our baseline specification but using 0.5 or 0.9 produced very similar results. We then specify a diagonal matrix that defines the variance of our prior about the coefficient matrix (see Lutkepohl (2005) pp. 225-8). We opt

[41] We chose to use two lags of endogenous variables in our baseline model in line with the lag length favoured by the Akaike information criterion. However, as the Schwarz criterion preferred one lag, we re-estimated the model with one lag as well as three and four lags and found these changes did not affect the results significantly.

[42] This assumption is problematic in the type of structural analysis undertaken here (Kadiyala and Karlsson, 1997).

[43] For a more thorough explanation of the simulation technique refer to Canova (2007) pp. 361-367.

for a relatively loose prior on the VAR coefficients.[44] Then, we draw a new coefficient matrix from the corresponding Normal posterior distribution.

ii. We draw a residual covariance matrix estimate from the Inverse Wishart distribution, using a *k*-by-*k* identity matrix as the scale matrix in only the first iteration and the previous draw in the following iterations.

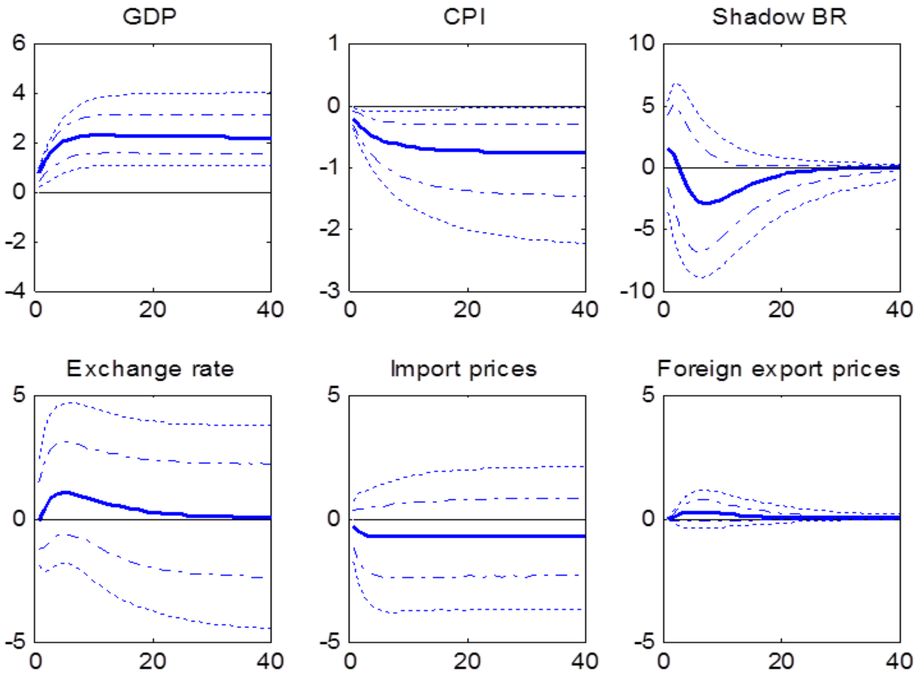
iii. We obtain an orthogonal decomposition of the resulting covariance matrix that satisfies the sign and zero restrictions and produces uncorrelated structural shocks by applying the algorithm suggested by Rubio-Ramirez *et al.* (2010) and extended by Binning (2013) for under-identified models.

We repeat this algorithm 11,000 times but discard the initial 10,000 and only save the final 1,000 draws. Rather than using a median of these 1,000 models or applying the median target method suggested by Fry and Pagan (2011) to conduct further analysis presented in the main text (such as forecast error variance decompositions and historical decompositions), we save the respective result from each iteration and show averages of these. For example, we save 1,000 different forecast error variance decompositions and show the average of the contribution of each shock to each variable's variance in Table 2. This provides more robust results than using one single model.

[44] We set the hyperparameter determining the tightness of our prior about coefficients on exogenous variables to 10,000 (implying an uninformed prior); the one defining our uncertainty about the prior on own lags to 0.2; the hyperparameter on priors regarding the coefficients on other variables to 0.5 (implying that coefficients on lags of other variables are clustered more tightly around their prior value, which is 0); the priors are tighter for the second lags of all variables.

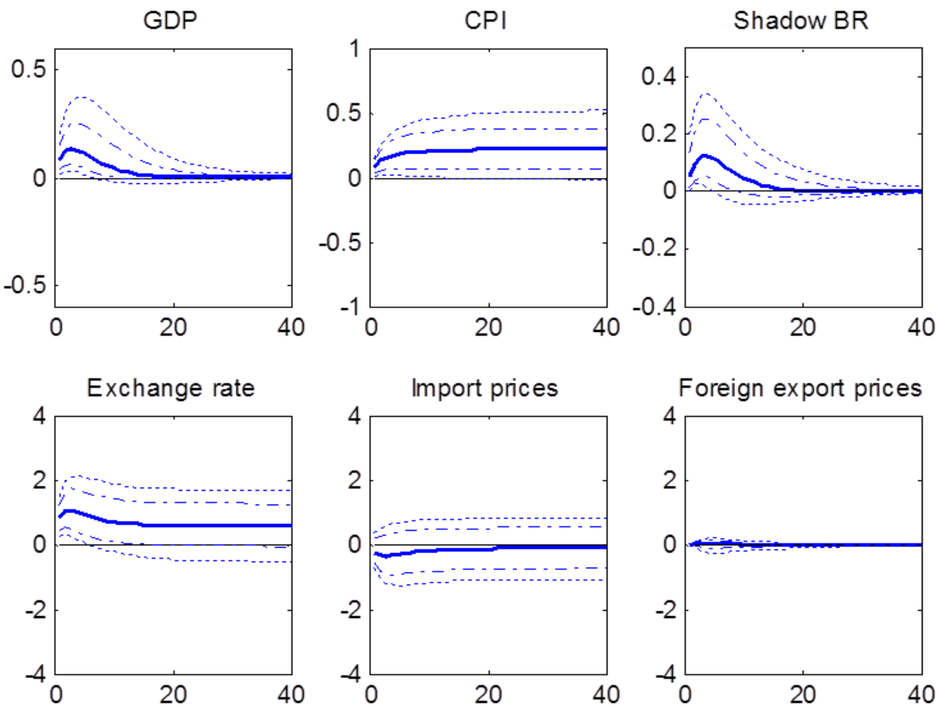
Appendix B: Impulse responses and additional output from SVAR

Figure B.1: Impulse responses to a UK supply shock



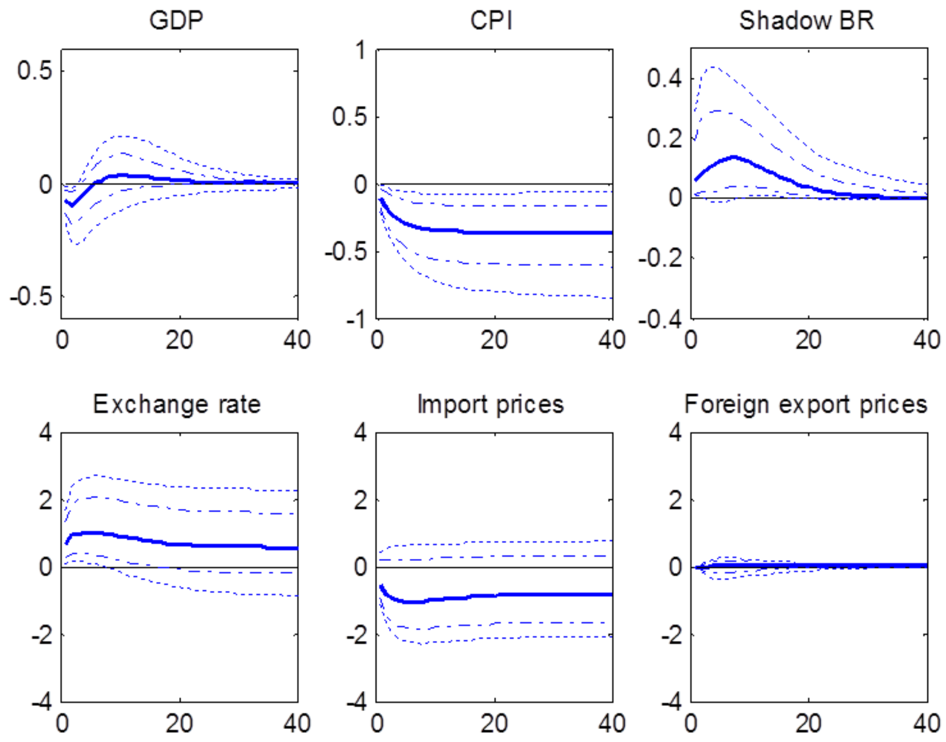
Note: These graphs report the median impulse responses (in solid lines) along with confidence bands at the 68% threshold (dashed lines) and 90% threshold (dotted lines) for all six variables to the respective shock. The responses for all variables except the interest rate – which is already expressed in de-trended levels – are accumulated, so that the figure shows the impact on the level of each variable over time. In addition, **all responses are rescaled so that each shock causes the sterling exchange rate to appreciate by 1% within the first year** in the median case.

Figure B.2: Impulse responses to a UK demand shock



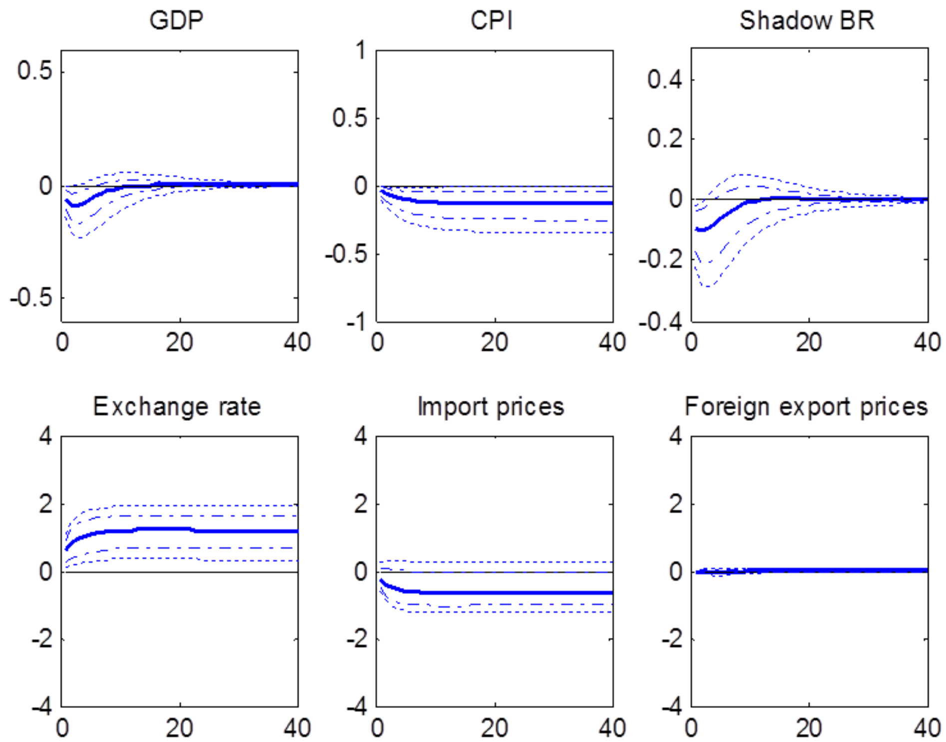
Note: See note to Figure B.1.

Figure B.3: Impulse responses to a UK monetary policy shock



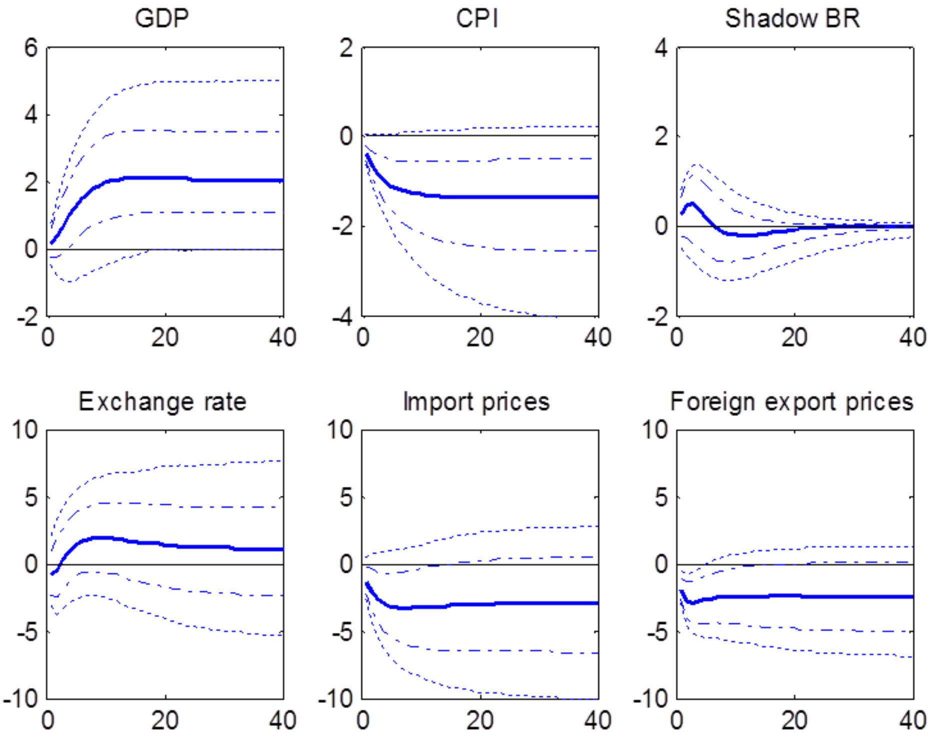
Note: See note to Figure B.1.

Figure B.4: Impulse responses to a UK exchange rate shock



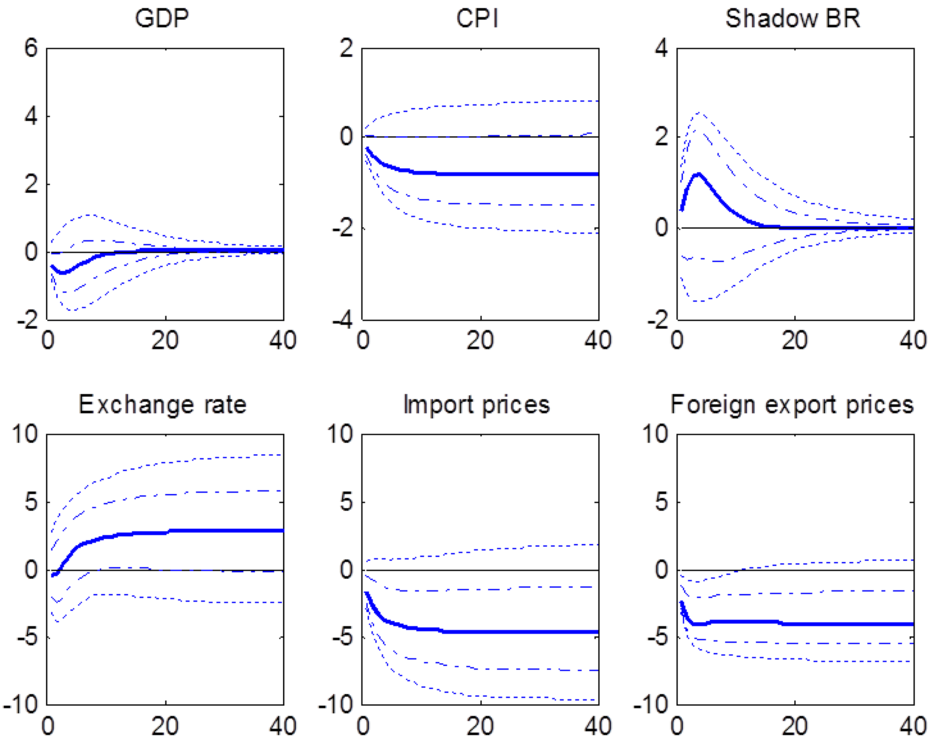
Note: See note to Figure B.1.

Figure B.5: Impulse responses to a persistent global shock



Note: See note to Figure B.1.

Figure B.6: Impulse responses to a transitory global shock



Note: See note to Figure B.1.

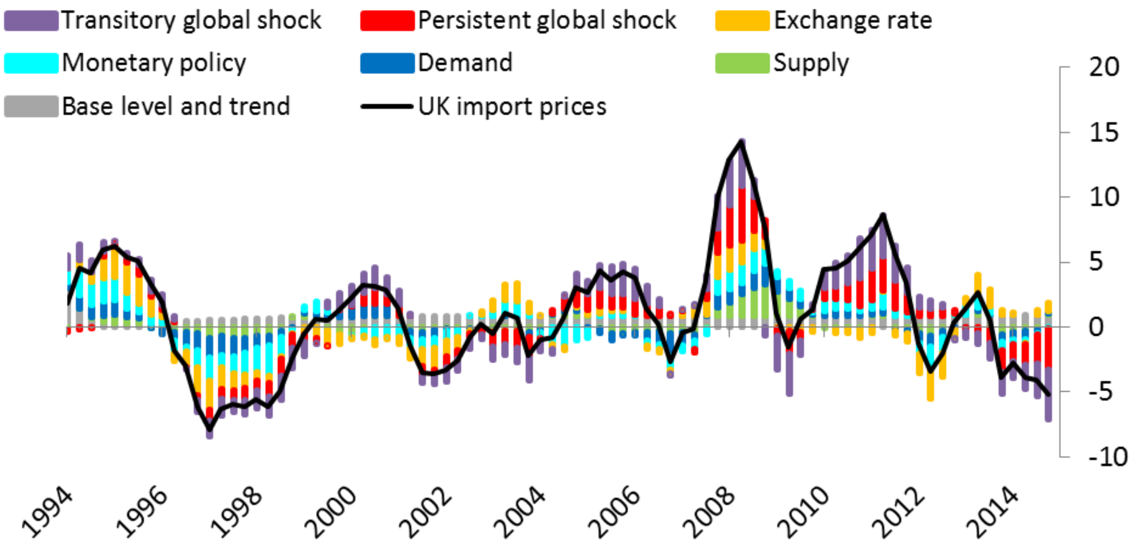
Table B.1: Pass-through to import prices by shock (ratio of import prices response to exchange rate response)

Period	Percentile	Supply	Demand	Monetary policy	Exchange rate	Persistent global shock	Transitory global shock
1	**50**	**-0.4**	**-0.2**	**-0.6**	**-0.4**	**0.1**	**0.0**
	16	*-1.2*	*-0.5*	*-1.4*	*-0.7*	*-2.1*	*-2.6*
	84	*0.3*	*0.5*	*0.3*	*0.2*	*1.8*	*2.1*
5	**50**	**-0.7**	**-0.3**	**-0.9**	**-0.5**	**-1.2**	**-1.5**
	16	*-1.3*	*-0.7*	*-1.6*	*-0.7*	*-2.8*	*-3.2*
	84	*0.0*	*1.0*	*0.1*	*-0.1*	*0.3*	*0.7*
20	**50**	**-0.6**	**-0.4**	**-1.0**	**-0.5**	**-1.1**	**-1.4**
	16	*-1.7*	*-1.3*	*-2.3*	*-0.7*	*-2.8*	*-2.3*
	84	*0.4*	*1.0*	*0.4*	*-0.1*	*0.4*	*-0.6*

Table B.2: Pass-through to consumer prices by shock (ratio of consumer prices response to exchange rate response)

Period	Percentile	Supply	Demand	Monetary policy	Exchange rate	Persistent global shock	Transitory global shock
1	**50**	**0.0**	**0.1**	**-0.2**	**-0.1**	**0.1**	**0.0**
	16	*-0.4*	*0.0*	*-0.7*	*-0.2*	*-0.4*	*-0.3*
	84	*0.4*	*0.2*	*0.0*	*0.0*	*0.6*	*0.4*
5	**50**	**-0.2**	**0.2**	**-0.3**	**-0.1**	**-0.3**	**-0.2**
	16	*-0.7*	*0.0*	*-0.9*	*-0.2*	*-1.1*	*-0.7*
	84	*0.3*	*0.6*	*-0.1*	*0.0*	*0.5*	*0.2*
20	**50**	**0.0**	**0.2**	**-0.2**	**-0.1**	**-0.2**	**-0.2**
	16	*-0.9*	*-0.2*	*-1.1*	*-0.3*	*-1.2*	*-0.5*
	84	*0.7*	*0.9*	*0.7*	*0.0*	*0.8*	*0.2*

Figure B.7: Historical decomposition of year-on-year changes in UK import prices



Note: See note to Figure 2.

References

Amiti, Mary, Itskhoki, Oleg and Konings, Josef (2016). "International Shocks and Domestic Prices: How Large Are Strategic Complementarities?," *NBER Working Paper,* No. 22119, March.

An, Lian and Wang, Jiang (2012). "Exchange Rate Pass-through: Evidence Based on Vector Autoregression with Sign Restrictions", *Open Economies Review*, 23(2), 359-380.

Berger, David and Vavra, Joseph (2013). "Volatility and Pass-through", *NBER Working Paper,* No. 19651, May.

Bils, Mark (1987). "The Cyclical Behavior of Marginal Cost and Price", *American Economic Review*, 77(5), 838–55.

Binning, Andrew (2013). "Underidentified SVAR models: A framework for combining short and long-run restrictions with sign-restrictions", *Norges Bank Monetary Policy Working Paper*, No. 14.

Blanchard, Olivier and Quah, Danny (1989). "The Dynamic Effects of Aggregate Demand and Supply Disturbances", *The American Economic Review*, Vol. 79, No. 4, 655-673.

Burstein, Ariel, and Gopinath, Gita (2014). "International Prices and Exchange Rates", in *Handbook of International Economics*, 4th Ed., 4:391-451.

Burstein, Ariel and Jaimovich, Nir (2012). "Understanding movements in aggregate and product-level real exchange rates", *UCLA Working Paper*.

Campa, José and Goldberg, Linda (2005). "Exchange rate pass-through into import prices", *The Review of Economics and Statistics*, 87(4), 679–690.

Campa, José and Goldberg, Linda (2010). The sensitivity of the CPI to exchange rates: Distribution margins, imported inputs, and trade exposure. *Review of Economics and Statistics*, 92(2):392-407.

Canova, Fabio (2007). "Methods for Applied Macroeconomic Research", *Princeton University Press*, ISBN: 9781400841028, pp. 361-367.

Canova, Fabio and de Nicolo, Gianni (2003). "On the sources of business cycles in the G-7", *Journal of International Economics*, vol. 59(1), 77-100.

Carrière-Swallow, Yan and Céspedes, Luis Felipe (2013). "The impact of uncertainty shocks in emerging economies", *Journal of International Economics*, vol. 90(2), 316-325.

Casas, Camila, Diez, Federico, Gopinath, Gita and Gourinchas, Pierre-Olivier (2017). "Dominant Currency Paradigm: A New Model for Small Open Economies", *IMF Working Papers 17/264*, International Monetary Fund.

Caselli, Francesca and Roitman, Agustin (2016), "Non-Linear Exchange Rate Pass-Through in Emerging Markets", *IMF Working Paper,* No. 16/1.

Christiano, Lawrence, Eichenbaum, Martin and Vigfusson, Robert (2007). "Assessing Structural VARs", NBER Chapters, in: *NBER Macroeconomics Annual 2006*, Volume 21, pages 1-106, National Bureau of Economic Research, Inc.

Corsetti, Giancarlo, Dedola, Luca and Leduc, Sylvain (2009). "Optimal Monetary Policy and the Sources of Local-Currency Price Stability", in *International Dimension of Monetary Polic*y edited by Jordi Gali and Mark Gertler, Chicago University Press, 2009, 319-367.

Corsetti, Giancarlo, Dedola, Luca and Leduc, Sylvain (2008). "High Exchange-Rate Volatility and Low Pass-Through", *Journal of Monetary Economics,* 55 (6), 1113-1128.

Corsetti, Giancarlo, Dedola, Luca and Leduc, Sylvain (2010), "Optimal Monetary Policy in Open Economies" in *Handbook of Monetary Economics*, Vol. 3B, pp. 861-933.

Corsetti, Giancarlo and Pesenti, Paolo (2004). "Endogenous Pass-Through and Optimal Monetary Policy: a Model of Self-validating Exchange Rate Regimes", *CEPR Working Paper,* No. 8737

Coeuré, Benoit (2017). "The transmission of the ECB's monetary policy in standard and non-standard times", Speech given in Frankfurt am Main on 11 September 2017.

Comunale, Mariarosaria and Kunovac, Davor (2017). "Exchange Rate Pass-Through in the Euro Area", *ECB Working Paper*, No. 2003 / January.

Devereux, Michael, Tomlin, Ben and Dong, Wei (2015). "Exchange Rate Pass-Through, Currency of Invoicing and Market Share", *NBER Working Paper,* No. 21413, July.

Dornbusch, Rudiger, (1987). "Exchange rates and prices", *American Economic Review*, 77, 93-106.

Ellis, Colin, Mumtaz, Haroon and Zabczyk, Pawel (2014). "What Lies Beneath? A Time-Varying Favar Model for the UK Transmission Mechanism", *The Economic Journal*, 124 (May), 668–699.

Erceg, Christopher, Gust, Christopher and Guerrieri, Luca (2005). "Can long-run restrictions identify technology shocks?", *Journal of the European Economic Association,* 3(6), 1237–1278.

Farrant, Katie and Peersman, Gert (2006). "Is the Exchange Rate a Shock Absorber or a Source of Shocks? New Empirical Evidence", *Journal of Money, Credit, and Banking*, Vol. 38, No. 4

Faust, Jon, and Leeper, Eric (1997). "When Do Long-Run Identifying Restrictions Give Reliable Results?", *Journal of Business & Economic Statistics*, vol. 15(3), pp. 345–353.

Fischer, Stanley (2015). "The Transmission of Exchange Rate Changes to Output and Inflation", Speech given at the Federal Reserve Board on November 12, 2015, http://www.federalreserve.gov/newsevents/speech/fischer20151112a.htm.

Fleer, Rita, Rudolf, Barbara and Zurlinden, Mathias (2015). "Price change dispersion and time-varying pass-through into consumer prices", mimeo.

Forbes, Kristin (2015a). "Risks around the Forecast", Speech given in London on January 22, 2015.

Forbes, Kristin (2015b). "Much ado about something important: How do exchange rate movements affect inflation", Speech given at the Money, Macro and Finance Research Group Annual Conference in Cardiff on September 11, 2015.

Forbes, Kristin, Hjortsoe, Ida and Nenova, Tsvetelina (2017). “Shocks versus Structure: Explaining Differences in Exchange Rate Pass-Through across Countries and Time”, *Bank of England External MPC Unit Discussion Paper,* No. 50.

Forbes, Kristin, Hjortsoe, Ida and Nenova, Tsvetelina (2015). “The Shocks Matter: Improving our Estimates of Exchange Rate Pass-Through”, *Bank of England External MPC Unit Discussion Paper,* No. 43.

Fry, Renée, and Pagan, Adrian (2011). "Sign Restrictions in Structural Vector Autoregressions: A Critical Review", *Journal of Economic Literature*, 49(4), 938-60.

Gagnon, Joseph and Ihrig, Jane (2004). “Monetary Policy and Exchange Rate Pass-Through”, *International Journal of Finance & Economics*, Vol. 9, Issue 4, 315–338.

Gali, Jordi (1999). “Technology, Employment, and the Business Cycle: Do Technology Shocks Explain Aggregate Fluctuations?”, *The American Economic Review*, Vol. 88, No.1.

Gilchrist, Simon and Zakrajsek, Egon (2015). “Customer Markets and Financial Frictions: Implications for Inflation Dynamics”, Federal Reserve Bank of Kansas City Economic Symposium, Jackson Hole.

Goldberg, Pinelopi and Hellerstein, Rebecca (2013). “A Structural Approach to Identifying the Sources of Local Currency Price Stability”, *Review of Economic Studies*, Oxford University Press, vol. 80(1), pp. 175-210.

Gopinath, Gita (2015). “The International Price System”, Federal Reserve Bank of Kansas City Economic Symposium, Jackson Hole.

Gopinath, Gita and Itskhoki, Oleg (2010). “Frequency of Price Adjustment and Pass-Through”, *The Quarterly Journal of Economics*, 125 (2): 675-727.

Gopinath, Gita, Itskhoki, Oleg and Rigobon, Roberto (2010). “Currency Choice and Exchange Rate Pass-Through,” *American Economic Review*, American Economic Association, vol. 100(1), pp. 304-36, March.

Gust, Christopher, Leduc, Sylvain and Vigfusson, Robert (2010). "Trade integration, competition, and the decline in exchange-rate pass-through", *Journal of Monetary Economics*, vol. 57(3), 309-324.

Hara, Naoko, Hiraki, Kazuhiro and Ichise, Yoshitaka (2015). “Changing Exchange Rate Pass-Through in Japan: Does It Indicate Changing Pricing Behavior?”, *Bank of Japan Working Paper Series, No. 15-E-*4, June.

Hjortsoe, Ida, Weale, Martin and Wieladek, Tomasz (2016). “Monetary Policy and the Current Account: Theory and Evidence”, *Bank of England External MPC Unit Discussion Paper*, No. 45.

Ihrig, Jane, Marazzi, Mario and Rothenberg, Alexander D. (2006). "Exchange-rate pass-through in the G-7 countries," *International Finance Discussion Papers 851*, Board of Governors of the Federal Reserve System (U.S.)

Ito, Takatoshi and Kiyotaka Sato (2008), “Exchange Rate Changes and Inflation in Post-Crisis Asian Economies: VAR Analysis of the Exchange Rate Pass-Through,” *Journal of Money, Credit and Banking,* vol. 40 (7), 1407-1438.

Joyce, Michael, Tong, Matthew and Woods, Robert (2011). "The United Kingdom's quantitative easing policy: design, operation and impact*", Bank of England Quarterly Bulletin*, Q3, 200-212.

Kirby, Simon and Meaning, Jack (2014). "Exchange rate pass-through: a view from a global structural model", *National Institute Economic Review,* No. 230, November.

Klein, Michael (1990). "Macroeconomic Effects of Exchange Rate Pass-Through", *Journal of International Money and Finance*, vol. 9 (4), 376-387.

Krugman, Paul (1987). "Pricing to Market When the Exchange Rate Changes", in *Real-Financial Linkages among Open Economies*, edited by Sven W. Arndt and J. David Richardson. Cambridge, Mass.: MIT Press.

Lewis, John (2016). "What can Big Data tell us about the pass-through of big exchange rate changes?" *Bank of England Staff Working Paper,* No. 579.

Litterman, Robert (1986). "Forecasting with Bayesian Vector Autoregressions-Five Years of Experience," *Journal of Business & Economic Statistics*, American Statistical Association, vol. 4(1), pp. 25-38, January.

Liu, Mumtaz and Theophilopoulou (2011). "International transmission of shocks: a time-varying factor-augmented VAR approach to the open economy", *Bank of England Working Paper,* No. 425.

Lutkepohl, Helmut (2005). "New Introduction to Multiple Time Series Analysis", Springer.

Marazzi, Mario, Sheets, Nathan, Vigfusson, Robert J., Faust, Jon, Gagnon, Joseph , Marquez, Jaime, Martin, Robert F., Reeve, Trevor and Rogers, John (2005). "Exchange rate pass-through to U.S. import prices: some new evidence", I*nternational Finance Discussion Papers*, 833, Board of Governors of the Federal Reserve System (U.S.).

Mountford, Andrew (2005). "Leaning into the Wind: A Structural VAR Investigation of UK Monetary Policy", *Oxford Bulletin of Economics and Statistics*, Department of Economics, University of Oxford, vol. 67(5), 597-621.

Nakamura, Emi and Zerom, Dawit (2010). "Accounting for Incomplete Pass-Through", *Review of Economic Studies*, 77(3), 1192-1230.

Neiman, B. (2010). "Stickiness, synchronization, and pass-through in intrafirm trade prices", *Journal of Monetary Economics*, 57(3):295-308.

Pagan, A. R. and Robertson, J. C. (1998). "Structural Models of the Liquidity Effect", *The Review of Economics and Statistics*, MIT Press, vol. 80(2), pp. 202-217.

Rincón-Castro, Hernán and Rodríguez-Niño, Norberto (2016). "Nonlinear Pass-Through of Exchange Rate Shocks on Inflation: A Bayesian Smooth Transition VAR Approach", *Borradores de Economia*, Banco de la Republica de Colombia.

Rotemberg, Julio, and Woodford, Michael (1999). "The Cyclical Behavior of Prices and Costs", In *Handbook of Macroeconomics*. , ed. John B. Taylor and Michael Woodford, 1051–135.

Rubio-Ramirez, Juan, Waggoner, Daniel and Zha, Tao (2010). “Structural Vector Autoregressions: Theory of Identification and Algorithms for Inference”, *The Review of Economic Studies*, Vol. 77, No. 2, 665-696.

Savoie-Chabot, Laurence and Mikael Khan (2015). “Exchange Rate Pass-Through to Consumer Prices: Theory and Recent Evidence.” *Bank of Canada Discussion Paper* 2015-9.

Shambaugh, Jay (2008). “A new look at pass-through”, *Journal of International Money and Finance*, No. 27, 560-591.

Smets, Frank and Wouters, Raf (2002). “Openness, imperfect exchange rate pass-through and monetary policy,” *Journal of Monetary Economics*, vol. 49(5), 947-981.

Stulz, Jonas (2007). “Exchange rate pass-through in Switzerland: Evidence from vector autoregressions”, *Swiss National Bank Economic Studies*, No. 4.

Taylor, John (2000). “Low inflation, pass-through and the pricing power of firms”, *European Economic Review* 44(7): 1389-1408.

Wu, Jing Cynthia and Xia, Fan Dora (2016). "Measuring the Macroeconomic Impact of Monetary Policy at the Zero Lower Bound", *Journal of Money, Credit and Banking*, Blackwell Publishing, vol. 48(2-3), pp. 253-291, March.