The Shocks Matter: Improving our Estimates of Exchange Rate Pass-Through

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Abstract

A major challenge for monetary policy has been 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. We show that in a standard open-economy model, the relationship between exchange rates and prices depends on the shocks which cause the exchange rate to move. Then we build on this model to develop an 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 understanding of why 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.

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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 (Fischer, 2015, Forbes, 2015b, Corsetti *et al.*, 2010). An extensive literature, summarized in Section II, 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, some key insights have not been incorporated into empirical macroeconomic models and it remains challenging for inflation-targeting central banks to predict how exchange rate movements will affect prices. This paper develops a new framework to bridge this gap. We explicitly incorporate the factors behind exchange rate movements when estimating their effects. We show that this can improve our understanding of, and ability to predict, how exchange rate movements affect prices.

The traditional approach to measuring exchange rate pass-through at the macroeconomic level has largely treated the link between exchange rates and aggregate prices as a time-invariant parameter, despite theoretical models and some discussion of why pass-through coefficients may fluctuate.[1] This parameter can be estimated and then is used as a general "rule of thumb" to predict how a given exchange rate movement will impact aggregate prices (see Forbes, 2015b, Fischer, 2015, and Savoid-Chabot and Khan, 2015). These estimates are useful in explaining the differences in average exchange rate pass-through across countries, or changes in pass-through over long periods of time resulting from structural shifts. This approach, however, has been less successful in accounting for changes in exchange rate pass-through within countries over shorter periods of time. Therefore, we propose a framework which allows us to explicitly incorporate and identify the macroeconomic shocks behind exchange rate movements. This allows us to control for many of the factors that could cause the relationship between exchange rate movements and prices to change over time and which are hard to measure directly. We apply this framework to the UK to show how it can work in practice; it can explain why exchange rate pass-through was surprisingly strong during the global financial crisis, but more muted following the 2013-15 appreciation.

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[1] A number of 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 (2015) and Devereux *et al.* (2015). Some of these papers attempt to control for these variables in their regressions, but none have explicitly modelled the relationships in their empirical framework as done in this paper.

This paper uses both theoretical and empirical models to show that it is critically important to evaluate the factors behind an exchange rate fluctuation, and the corresponding general equilibrium effects, when assessing how exchange rate movements pass through to inflation. To begin, we develop a standard open-economy model in which a certain proportion of exporters set their prices in the currency of the destination to which they export and face sticky prices. The model clearly illustrates that firms' decisions on how to adjust their prices in response to exchange rate movements depends on how economic conditions have changed. Many of the key relationships in this model are not new, but the theoretical framework is useful to provide structure for the assumptions in our empirical model, as well as to provide predictions for the relationships between exchange rates and prices.

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 the model and economic theory more generally. We then evaluate the impact of exchange rate fluctuations caused by these different shocks on import prices. We follow the existing literature and focus on pass-through to import prices, but the approach also provides insights about exchange rate pass-through to other variables, such as 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 different degrees of pass-through are consistent with the theoretical model's predictions and can be explained by the different general equilibrium effects and ways in which firms respond to the different shocks causing the exchange rate fluctuation. For example, if an exchange rate appreciation is driven by stronger domestic demand, 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. In contrast, if an exchange rate appreciation is driven by tighter monetary policy, the simultaneous contraction in demand reduces inflationary pressure. This amplifies the fall in import prices and thus the drag on inflation from cheaper imports, making it more difficult for firms to increase margins.

The results also show that this framework of considering the shocks behind exchange rate fluctuations can help explain why the degree of exchange rate pass-through can vary over time. For example, exchange rate pass-through to both UK import and consumer prices was substantially greater than expected in the period after sterling's depreciation from 2007-2009 (during the global financial crisis). This can be explained by explicitly considering the distribution of shocks behind this depreciation—which was substantially different than the typical distribution behind exchange rate fluctuations. 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 driving sterling's sharp post-crisis depreciation caused pass-through to import prices to increase by almost 30%, and to consumer prices to roughly double (relative to after sterling's previous sharp movement in 1996-97 which resulted from a very different composition of shocks). The distribution of shocks driving sterling's most recent appreciation in 2013-2015 is also different from the distribution of shocks driving the 2007-2009 depreciation and therefore suggests pass-through should be lower. This prediction has been supported by recent movements in import prices.

These findings have important implications for monetary policy. They suggest that policymakers should not assume that pass-through is constant or use "rules-of-thumb" to predict how an exchange rate movement will affect prices. Instead, they should regularly update their estimates based on the nature of the shocks driving the exchange rate movement. Although this insight follows from recent advances in the microeconomic and theoretical literature, and has been discussed to some degree in the macroeconomic literature (Klein, 1990 and Shambaugh, 2008), it has not been explicitly incorporated into analyses of pass-through. This framework could improve policy makers' ability to forecast how exchange rate movements will affect prices, and thereby their ability to forecast inflation and set monetary policy appropriately.

The remainder of the paper is as follows. Section II discusses 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 illustrates how pass-through depends on the shock affecting the exchange rate. 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 exchange rate pass-through to consumer prices. Section VII discusses some extensions and robustness checks. 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 (1986), Dornbusch (1987), and Klein (1990), showed that pass-through was incomplete due to imperfect competition and pricing-to-market. A series of papers then provided empirical evidence of this incomplete pass-through across countries and industries and suggested a number of explanations, such as the composition of imported goods and the extent of imported inputs used in consumption goods (Campa and Goldberg, 2005 and 2010), nominal rigidities (Devereux and Yetman (2003), Corsetti *et al*., 2008) and menu costs (Ghosh and Wolf, 2001). In the past decade, the literature has made additional advances through the use of new and extensive micro data on firm pricing decisions. This literature has highlighted 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, 2015) and the extent of competition in final product markets (Amiti *et al.*, 2016).

The traditional 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, Burstein and Gopinath (2014) estimate distributed lag regressions for a number of countries using:

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

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 (and in other specifications can also include controls intended to capture demand conditions or the competitive environment). An estimate of long-run exchange rate pass-through can be extracted from equation (1) as the sum of the estimated coefficients on the exchange rate changes for all periods included in the regression (i.e., for all $\beta_{n,k}$). The coefficient on the contemporaneous exchange rate change (i.e., $\beta_{n,0}$) gives an estimate of short-term exchange rate pass-through.

As an example of this approach, and for comparison with our main results in Sections V and VI, we estimate this standard regression for the UK using data from 1993q1 through 2015q1. Table 1 reports the resulting estimates of short-run and long-run exchange rate pass-through to both import and consumer prices.[2] Pass-through to import prices is quick but incomplete; a 1% sterling appreciation corresponds to a 0.4% fall in import prices within the same quarter and 0.6% after two years. As predicted and shown in the literature, the overall fall in import prices is less than the initial exchange rate movement, and consumer prices are even less sensitive to exchange rate movements. After the same 1% sterling appreciation, consumer prices fall by only 0.01% in the short run and 0.07% in the long run (with neither estimate statistically significant).

Table 1: Exchange rate pass-through in the UK estimated using a traditional approach

Exchange rate pass-through to:	**import prices**		**consumer prices**	
	Estimate	**SE**	**Estimate**	**SE**
Short-run	-0.40	0.05	-0.01	0.01
Long-run	-0.63	0.08	-0.07	0.03

Note: Data definitions and sources are discussed in Section IV. Standard errors are calculated using the Newey-West HAC estimator with a Newey-West fixed bandwidth.

This basic framework for estimating 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. More specifically, the "rule of thumb" for the pass-through of exchange rate movements to import prices is generally taken directly from the above regression (with import prices for *p*) as the sum of the $\beta_{n,k}$ for the period of interest. The "rule of thumb" for the pass-through to consumer prices can be calculated in the same way (except with consumer prices for *p*), or calculated by multiplying the estimated pass-through coefficient for import prices by the share of imported inputs in the relevant price index.

In the UK, the Bank of England (BoE) has used a "rule of thumb" that pass-through from exchange rate movements to UK import prices is about 60% (agreeing with the estimates above) and to consumer prices is about 20% to 30% (calculated as this 60% multiplied by the 30% share of

[2] The estimates differ slightly from those reported in Burstein and Gopinath (2014) for the UK because of differences in the estimation sample and price indices. Our sample covers the period from 1993-2015q1, while they use the period 1983-2011 for the import price regressions and 1988-2011 for the consumer price regressions. We report results for overall import prices and headline CPI, while they report results for manufactured goods import prices and goods CPI. When we use their time period and identical price data, we are able to replicate their results. We focus on our more recent sample and price data to be consistent with the results reported in the remainder of this paper.

imported inputs in the consumer price index).[3] In other words, a 10% appreciation would be expected to reduce import prices by 6% and consumer prices by 2%-3% 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 inflation 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).

Although these "rule of thumb" estimates of pass-through resulting from models such as equation (1) have traditionally been treated as stable, they can change over time. Any changes over time, however, have largely been treated as resulting from structural changes and therefore generally expected to occur only slowly. For example, several papers document a fall in pass-through in the United States from the 1980s to the 1990s and attempt to explain this through slow-moving variables, 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).[4]

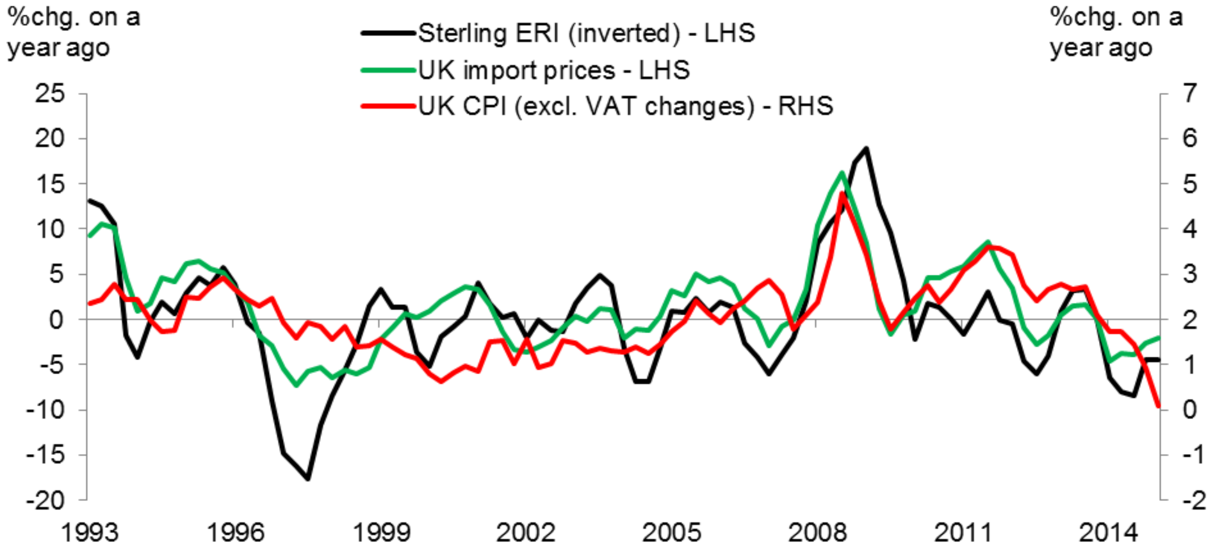
More recently, however, there is accumulating evidence that pass-through can change significantly over short periods of time—and more quickly than can be explained by slow-moving structural changes. Fleer *et al.* (2015) provide evidence for Switzerland, Hara, *et al.* (2015) for Japan, and Forbes (2015b) for the UK. The potential for pass-through to change over short periods of time is confirmed by returning to our above analysis for the UK. Figure 1 plots the historical changes in the sterling exchange rate index (inverted, so that an increase means a depreciation) alongside import and consumer price inflation since 1993. The comovement between exchange rates and these prices is a proxy for pass-through, and a cursory examination suggests this relationship is not stable. For example, the large sterling appreciation in 1996-7 had a low degree of comovement with import and consumer prices (suggesting low pass-through), while the large depreciation in 2007-8 corresponded to much tighter comovement (suggesting higher pass-through). It is difficult to explain these sharp changes in pass-through over such a short period with structural factors.[5] Using the fixed "rule of thumb" to estimate how exchange rate movements impact prices and inflation could lead to large forecasting and policy errors.

[3] See Forbes (2015a, 2015b) and the box "The effect of imported price pressures on UK consumer prices" in the Bank of England *Inflation Report*, November 2015.

[4] Also see Stulz (2007), which attempts to explain the decline in pass-through in Switzerland in the 1990s and Mumtaz *et al.* (2006) which examines the decline in pass-through to import prices in the UK between 1995 and 2004.

[5] Forbes (2015b) attempts to explain these changes in pass-through in the UK through structural factors, such as changes in the composition of imported goods and services, with little success.

Figure 1: Changes in sterling exchange rate index (ERI), UK import and consumer prices



The theoretical and empirical literature suggests a number of reasons why pass-through could vary over short periods of time. For example, an extensive literature shows that 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.[6] Exchange rates could move simultaneously with costs of production, changes in expectations of future demand conditions, and other variables that affect firm mark-ups and affect competitors. The standard framework for estimating pass-through in equation (1), however, assumes that any exchange rate movement is exogenous to changes in other macro variables that could affect prices. Papers 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) or domestic competitive pressures (with proxies such as domestic producer prices).[7] These additional control variables, however, are unlikely to fully capture these omitted variables as they don't directly account for the underlying macroeconomic shocks associated with the exchange rate movement (see Fitzgerald and Haller, 2014, Burstein and Jaimovich, 2012, and Burstein and Gopinath, 2014).[8]

[6] This literature includes Bils (1987), Rotemberg and Woodford (1999), and more recently Gilchrist and Zakrajsek (2015). Krugman (1987) and Dornbusch (1987) show that these same factors also determine how exporting firms change their mark-ups and prices after a change in the exchange rate. More recently, Corsetti *et al.* (2009) show that the degree of pass-through varies depending on whether shocks hit upstream or downstream producers. Also, Goldberg and Hellerstein (2013) show that over two-thirds of incomplete pass-through can be explained by domestic non-traded costs and variable firm mark-ups, implying that to understand exchange rate pass-through at the aggregate level, one needs to understand the relationship between aggregate marginal costs and mark-ups and the exchange rate.

[7] For example, Burstein and Gopinath (2014), Campa and Goldberg (2005) and Ihrig *et al.* (2006).

[8] For example, domestic producer prices are often included to capture competitive pressures, but they are unlikely to be an accurate measure in industries where competitors are mostly foreign.

Therefore, this paper proposes 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 and hard-to-measure channels by which the initial shock affects a firm's desired margins and domestic costs (including through expected demand conditions and competition), and which in turn determine the extent of pass-through. For example, if a given exchange rate movement was driven by a positive shock to domestic demand, the firm would adjust its mark-ups (and corresponding prices) after accounting for the simultaneous increase in the firm's expected demand and input costs. In contrast, if the same exchange rate movement was driven by a positive monetary policy shock, the firm would instead expect a simultaneous decrease in expected demand and input costs—yielding different adjustments in its mark-ups and prices. Instead of the traditional approach of controlling for the various ways in which these shocks causing the exchange rate movement simultaneously affect expected demand, input costs, and mark-ups, we instead explicitly model and incorporate the underlying source of the shock to the exchange rate (i.e., either domestic demand or monetary policy).

A limited number of papers have mentioned the potential importance of 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 been able to find that makes this point, and Astley, Pain and Smith (2009) have made it more recently, but neither operationalizes this insight in their estimates of pass-through. Corsetti *et al.* (2008) and Kirby and Meaning (2014) find evidence that estimates of exchange rate pass-through are shock-dependent.[9] An and Wang (2011) and Stulz (2007) make some progress by identifying exogenous exchange rate movements within a VAR framework, but their framework cannot take the next step of estimating shock-dependent pass-through. The analysis which makes the most progress, and is closest to our approach, is Shambaugh (2008). He conjectures that the decline in estimated exchange rate pass-through in the 1990s results from changes in the types of shocks driving exchange rate fluctuations. He tests this by identifying fundamental shocks in a VAR and estimating their effect on the exchange rate and prices. His results indicate that the degree of pass-through depends on whether the shocks are more related to supply, relative demand, nominal factors, or foreign price movements. Our analysis explores a richer set of causes behind exchange rate fluctuations, uses a different set of identifying assumptions (which include short-run and sign restrictions, as well as long-run restrictions) and considers the effects on a broader set of variables relevant to monetary policy.

[9] More specifically, Corsetti *et al.* (2008) show that pass-through changes based on whether the shocks affecting the economy are real or nominal. Kirby and Meaning (2014) discuss how different shocks affect the degree of exchange rate pass-through for the UK using the NIESR's global structural model.

All in all, given the number of papers that have highlighted different factors that could change the extent of pass-through over time, it is surprising that there has not yet been more formal consideration of why an exchange rate moves before evaluating its impact on prices at the macro level. There is an extensive academic literature on the different causes of exchange rate movements, and a general appreciation that exchange rates are endogenous variables.[10] Despite this, evaluations of the impact of currency price movements generally do not incorporate what caused those movements. This is in sharp contrast to evaluations of the impact of oil price movements, which usually start with an analysis of whether the movement was caused by changes in the global supply or demand for oil (e.g. Cashin *et al.*, 2014). One possible explanation for why pass-through has generally not been modelled and estimated as shock-contingent may be the challenges in explaining exchange rate movements with fundamentals.[11] The remainder of this paper, however, will show that this is possible using a fairly straightforward set of identifying assumptions, grounded in a theoretical model, and applying recent advances in the VAR literature.

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

We begin by developing a standard open-economy model in order to illustrate how and why pass-through depends on the underlying shocks moving the exchange rate. The model focuses exclusively on limited pass-through due to price rigidities and local-currency-pricing. While these are clearly not the only factors limiting pass-through, there is strong evidence that they play an important role, as shown in Devereux and Yetman (2003) for the role of price stickiness and Gopinath (2015) for the role of the currency of invoicing.[12] In Forbes *et al.* (2015), we show that our results are robust to a more complex model structure and that our main results are not sensitive to the specific parameter combination chosen for the illustration below.

1. A standard open-economy model

Our model consists of a world composed of two countries, denoted *H* (Home) and *F* (Foreign). There are respectively *n* and *1-n* households in these countries. Households supply a homogenous labour input and consume both domestically-produced and imported goods. Firms produce differentiated goods using labour inputs and set prices in a staggered fashion. Some firms set the price of their exported goods in their own currency, while others set prices in foreign currency and are

[10] See Clarida and Gali (1994) and Eichenbaum and Evans (1995) for early and influential examples, or Engel (2013) for a recent discussion.
[11] Thanks to Frank Smets for suggesting that the hesitation for constructing a shock-contingent framework may stem from the long literature on the UIP puzzle and challenges in explaining exchange rate movements.
[12] Other factors which might be important in determining the extent and the pace of pass-through include the monetary policy regime and the flexibility of the exchange rate (Corsetti and Pesenti, 2004), the production structure (Corsetti *et al.*, 2010), the market structure (Devereux *et al.*, 2015), or the degree of habits in consumption (Jacob and Uuskula, 2016).

allowed to price discriminate between the domestic and export markets. The monetary authorities follow a persistent interest rate rule with a flexible domestic CPI inflation target. The model set-up is standard and close to that analysed in Benigno (2009) and in Corsetti *et al.* (2010). Readers familiar with those models can go directly to Section III.2 which explains why exchange rate pass-through may be incomplete in this model. In the following, we describe the equilibrium by focusing on domestic agents' behaviour, but foreign agents behave similarly.

1.1. Households

The representative domestic household aims to maximize its welfare (W), which is a function of its expected future stream of discounted utility from private consumption (C) and disutility from working (L). The representative household's welfare is given by:

$$W_t = E_t \sum_{s=0}^{\infty} \beta^s \{U^c(C_{t+s}) - \kappa U^l(L_{t+s})\},$$

where E_t denotes the expectations at time t, β is the discount factor, and κ is a parameter determining the weight put on labour vs. consumption fluctuations in affecting utility. The functional forms are as follows:

$$U^c(C_t) = \gamma_t^C \frac{C_t^{1-\sigma_H}}{1-\sigma_H}$$

$$U^l(L_t) = \frac{L_t^{1+\eta_H}}{1+\eta_H},$$

where $\sigma_H > 0$ is the inverse of the inter-temporal elasticity of substitution and the relative risk aversion coefficient in the Home country, and $\eta_H > 0$ is the inverse of the Frisch labour supply elasticity. γ_t^C is a demand (or preference) shock.

The household's consumption is a CES index of the composite good produced at Home for the Home market, C_H, and the composite good produced in the Foreign country for the Home market, C_F:

$$C_t = \left[a_H^{\frac{1}{\varphi_H}} C_{H,t}^{\frac{\varphi_H - 1}{\varphi_H}} + (1-a_H)^{\frac{1}{\varphi_H}} C_{F,t}^{\frac{\varphi_H - 1}{\varphi_H}} \right]^{\frac{\varphi_H}{\varphi_H - 1}}, 0 < a_H < 1, \varphi_H > 0, \qquad (2)$$

where the constant elasticity of substitution between the Home and Foreign goods is denoted φ_H. a_H is the weight given to consumption of the composite Home good and is defined as $a_H \equiv 1 - (1-n)op$ where op is a measure of openness. Similarly, $1 - a_H \equiv (1-n)op$ is the weight attached to consumption of the composite Foreign good. If $op < 1$ so that $a_H > n$, then a home bias in consumption is present.

The composite domestic and Foreign goods, destined for the Home market, are assumed to be composed of differentiated goods denoted $C_{H,t}(h)$ and $C_{F,t}(f)$, which are imperfectly substitutable with constant elasticity of substitution θ_H and θ_F:

$$C_{H,t} = \left[\left(\frac{1}{n}\right)^{\frac{1}{\theta_H}} \int_0^n C_{H,t}(h)^{(\theta_H-1)/\theta_H} dh\right]^{\theta_H/(\theta_H-1)},$$

$$C_{F,t} = \left[\left(\frac{1}{1-n}\right)^{1/\theta_F} \int_n^1 C_{F,t}(f)^{(\theta_F-1)/\theta_F} df\right]^{\theta_F/(\theta_F-1)}.$$

Households choose their relative traded consumption demand such as to maximize utility for given expenditures. The resulting domestic demand for, respectively, Home and Foreign traded goods are:

$$C_{H,t} = a_H \left(\frac{P_{H,t}}{P_t}\right)^{-\varphi_H} C_t, \tag{3}$$

$$C_{F,t} = (1-a_H) \left(\frac{P_{F,t}}{P_t}\right)^{-\varphi_H} C_t, \tag{4}$$

where P_H and P_F respectively denote the price of the domestically -produced generic good C_H and the foreign good C_F in domestic currency, whereas P denotes the price of the domestic consumption basket C.

The consumption-based price indices are defined analogously to the consumption bundles

$$P_t = \left[a_H P_{H,t}^{1-\varphi_H} + (1-a_H) P_{F,t}^{1-\varphi_H}\right]^{\frac{1}{1-\varphi_H}}, \tag{5}$$

where

$$P_{H,t} = \left[\frac{1}{n}\int_0^n p_t\,(h)^{1-\theta_H} dh\right]^{\frac{1}{1-\theta_H}}, P_{F,t} = \left[\frac{1}{1-n}\int_0^{1-n} p_t\,(f)^{1-\theta_F} df\right]^{\frac{1}{1-\theta_F}}.$$

Domestic households face complete financial markets at the domestic level; they own an equal share in every domestic firm and profits are therefore equally distributed among households. Households also have access to the international financial markets, but these are incomplete; only nominal one-period bonds denominated in Foreign currency are traded across countries. The interest on these internationally traded bonds depends on the Foreign interest rate and the level of external debt: the yields of the bonds are increasing in external debt, as in Schmitt-Grohe and Uribe (2003). Apart from implying stationarity of the steady state, modelling financial frictions through a debt-elastic yield on bonds allows for state-contingent yield differences across countries.

Every period, households use their labour income, wealth accumulated in domestic and foreign bonds (denominated in Foreign currency), and profits of firms in the domestic economy (PR)

to purchase consumption and both domestically-issued bonds (B_H) and Foreign bonds (B_F) and pay lump-sum taxes. The representative household budget constraint thus amounts to:

$$C_t + \frac{B_{H,t}}{P_t(1+i_t)} + \frac{s_t B_{F,t}}{P_t(1+i_t^*)\Phi\left(\frac{s_t B_{F,t}}{P_t}\right)} + T_t = \frac{W_t}{P_t} L_t + \frac{B_{H,t-1}}{P_t} + \frac{s_t B_{F,t-1}}{P_t} + PR_t, \tag{6}$$

where i_t is the nominal interest set by the Home central bank in period t and defines the return on domestically-issued bonds denominated in the Home currency (B_H), and i_t^* is the nominal interest set by the Foreign central bank in period t (starred variables denote Foreign variables), s_t is the nominal exchange rate, W_t is the nominal wage rate, L_t is hours worked, PR_t denotes profits made by domestic firms, T_t denotes lump-sum taxes paid by the household, and $B_{F,t}$ is the nominal holdings of Foreign bonds (denominated in Foreign currency). The function Φ is assumed to depend positively on deviations of external debt from its steady state level, $\Phi'(\cdot) < 0$, and satisfies $\Phi\left(\frac{sB_F}{P}\right) = 1$ in steady state.[13]

The first-order conditions of the representative domestic household's maximisation problem with respect to consumption, bond holdings and labour supply can be aggregated to yield:

$$\beta E_t \frac{\gamma_{t+1}^C C_{t+1}^{-\sigma}}{\gamma_t^C C_t^{-\sigma}} \frac{(1+i_t)}{\pi_{t+1}} = 1 \tag{7}$$

$$\beta E_t \frac{\gamma_{t+1}^C C_{t+1}^{-\sigma}}{\gamma_t^C C_t^{-\sigma}} \frac{(1+i_t^*)}{\pi_{t+1}^*} \frac{Q_{t+1}}{Q_t} = \frac{1}{\Phi\left(\frac{s_t B_{F,t}}{P_t}\right)} \gamma_t^S \tag{8}$$

$$\frac{L_t{}^{\eta}}{C_t^{-\sigma}} = \frac{W_t}{P_t}, \tag{9}$$

where $\pi_t \equiv \frac{P_t}{P_{t-1}}$ and $\pi_t^* \equiv \frac{P_t^*}{P_{t-1}^*}$, with P_t^* the Foreign consumer price index, denote CPI inflation respectively in the Home and in the Foreign country, and $Q_t \equiv \frac{s_t P_t^*}{P_t}$ is the real exchange rate.[14] γ_t^S represents an exogenous shock to the nominal exchange rate. The shock pushes the equilibrium away from uncovered interest parity.

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[13] We specify the yield premium associated with holding bonds to be linear in deviations of borrowing/lending from steady state: $\Phi(b_t) = 1 - \delta(b_t - \frac{B}{P})$, with $\delta > 0$ and $\frac{B}{P} = \frac{sB_F}{P}$. Note that because $\Phi'(\cdot) < 0$, whenever $\mathrm{B_F}$ is low, then the yield on debt is high ($\Phi(\cdot) > 1$). On the contrary, when bond holdings are high implying that Home households have claims on Foreign households, then $\Phi(\cdot) < 1$ and the price of bonds is high and purchasing even more bonds is expensive. For simplicity, we assume that individual households do not internalize the effect of changes in their own bond holdings on the yield, i.e. they take the function $\Phi(\cdot)$ as given.

[14] Note that the Foreign household only faces one Euler equation as it holds only its own internationally traded bonds. This assumption can be justified by the fact that most small open economies have the majority of their international debt denominated in the currency of a larger economy. Allowing for international trade in a second bond denominated in the Home currency would not change the results.

1.2. Firms

Firms produce differentiated goods using a technology which is linear in labour, so that output of domestic firm h is $y_t(h) = l_t(h)$. Firms are monopolistically competitive and set prices in a staggered fashion à la Calvo-Yun. That is, firms reset their price at a time-independent random frequency. More specifically, each firm faces the probability 1-α_H^k of being able to reset its price in each period.

A proportion γ_H^{PCP} of firms set the price of their exports in their own currency and do not discriminate across markets (i.e., engages in producer-currency pricing, PCP), while the remainder of firms set their export prices in the currency of the destination market and may set different prices in the two markets (i.e., engages in local-currency pricing, LCP). The price index of domestic goods is therefore $P_{H,t} \equiv \left[\gamma_H^{PCP} P_{H,t}^{PCP\,1-\theta_H} + (1-\gamma_H^{PCP}) P_{H,t}^{LCP\,1-\theta_H}\right]^{\frac{1}{1-\theta_H}}$, where $P_{H,t}^{PCP}$ ($P_{H,t}^{LCP}$) is the price of goods produced by PCP (LCP) firms, and the price index of imports is $P_{F,t} \equiv \left[\gamma_F^{PCP} s_t P_{F,t}^{PCP*\,1-\theta_F} + (1-\gamma_F^{PCP}) P_{F,t}^{LCP\,1-\theta_F}\right]^{\frac{1}{1-\theta_F}}$.

The optimisation problem of the PCP firm producing good h and getting the opportunity to reset its price at time t consists in choosing a price $p_t^{PCP}(h)$ such as to maximize expected discounted future profits:

$$\max_{p_t^{PCP}(h)} E_t \sum_{s=0}^{\infty} \alpha_H^s \mu_{t,t+s} \left[\left((1-\tau_H) p_t^{PCP}(h) - W_{t+s}\right) y_{t,t+s}^{PCP}(h)\right],$$

where E_t is the expectations operator, $\mu_{t,t+s}$ is the stochastic discount factor of the firm, and τ_H is a tax on sales. $y_{t,t+s}^{PCP}(h)$ is the domestic and foreign demand at time $t+s$ for good h at the price $p_t^{PCP}(h)$: $y_{t,t+s}^{PCP}(h) = \left(\frac{p_t^{PCP}(h)}{P_{H,t+s}}\right)^{-\theta_H} C_{H,t+s} + \frac{1-n}{n}\left(\frac{p_t^{PCP}(h)}{s_{t+s}P_{H,t+s}^{*}}\right)^{-\theta_H} C_{H,t+s}^{*}$ where $P_{H,t}^{*} \equiv \gamma_H^{PCP}\frac{P_{H,t}^{PCP}}{s_t} + (1-\gamma_H^{PCP}) P_{H,t}^{LCP*}$ is the import price index in the Foreign economy. Given that firms are owned by the households, their stochastic discount factor is identical to the stochastic discount factor of the representative household: $\mu_{t,t+s} = \beta^s \left(\frac{U_{C,t+s}}{P_{t+s}}\right) / \left(\frac{U_{C,t}}{P_t}\right)$, where β is the households' discount factor and $U_{C,t}$ is the households' marginal utility from consumption in period t.

The resulting first order conditions imply that prices are set according to expectations of future marginal costs and demand in the following way:

$$p_t^{PCP}(h) = \frac{\theta_H}{(\theta_H-1)(1-\tau_H)} \frac{E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s P_{t+s}^{-1} U_{C,t+s} W_{t+s} y_{t,t+s}^{PCP}(h)}{E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s P_{t+s}^{-1} U_{C,t+s} y_{t,t+s}^{PCP}(h)}. \quad (10)$$

Because all PCP firms that get to reset their price in a given period face the same expectations of marginal costs and demand, they all set the same price. Hence, the price index of PCP firms, P_H^{PCP}, is given by:

$$P_{H,t}^{PCP} = \left[\alpha_H^k P_{H,t-1}^{PCP1-\theta_H} + (1-\alpha_H^k) p_t^{PCP}(h)^{1-\theta_H}\right]^{\frac{1}{1-\theta_H}}. \quad (11)$$

LCP firms can set different prices across the domestic and foreign markets and thus face two optimisation problems. The choice of the domestic price is chosen by solving the following maximisation problem:

$$\max_{p_t^{LCP}(h)} E_t \sum_{s=0}^{\infty} \alpha_H^s \mu_{t,t+s} \left[\left((1-\tau_H) p_t^{LCP}(h) - W_{t+s}\right) y_{t,t+s}^{LCP}(h)\right],$$

where $y_{t,t+s}^{LCP}(h)$ is the domestic demand at time $t+s$ for good h at the price $p_t^{LCP}(h)$: $y_{t,t+s}^{LCP}(h) = \left(\frac{p_t^{LCP}(h)}{P_{H,t+s}}\right)^{-\theta_H} C_{H,t+s}$. The first-order condition can be written as:

$$\frac{p_t^{LCP}(h)}{P_{H,t}^{LCP}} = \frac{\theta_H}{(\theta_H-1)(1-\tau_H)} \frac{E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s P_{t+s}^{-1} U_{C,t+s} W_{t+s} y_{t,t+s}^{LCP}(h)}{E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s P_{H,t}^{LCP} P_{t+s}^{-1} U_{C,t+s} y_{t,t+s}^{LCP}(h)}. \quad (12)$$

Finally, the choice of the export price is chosen by solving the following maximisation problem:

$$\max_{p_t^{LCP*}(h)} E_t \sum_{s=0}^{\infty} \alpha_H^s \mu_{t,t+s} \left[\left((1-\tau_H) s_{t+s} p_t^{LCP*}(h) - W_{t+s}\right) y_{t,t+s}^{LCP*}(h)\right],$$

where $y_{t,t+s}^{LCP*}(h)$ is the foreign demand at time $t+s$ for good h at the foreign currency price $p_t^{LCP*}(h)$: $y_{t,t+s}^{LCP*}(h) = \left(\frac{p_t^{LCP*}(h)}{P_{H,t+s}^*}\right)^{-\theta_H} C_{H,t+s}^*$. The resulting first-order condition is:

$$\frac{p_t^{LCP*}(h)}{P_{H,t}^{LCP*}} = \frac{\theta_H}{(\theta_H-1)(1-\tau_H)} \frac{E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s P_{t+s}^{-1} U_{C,t+s} W_{t+s} y_{t,t+s}^{LCP*}(h)}{E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s s_{t+s} P_{H,t}^{LCP*} P_{t+s}^{-1} U_{C,t+s} y_{t,t+s}^{LCP*}(h)}. \quad (13)$$

Aggregating output across firms yields $Disp_t Y_t = L_t$ where $Disp_{k,t} \equiv \int_0^n \left(\frac{p_t(h)}{P_{H,t}}\right)^{-\theta_H^k} dh \geq 1$ is a measure of the degree of price dispersion.

1.3. Fiscal and monetary authorities

The government levies taxes and re-distributes them to households as lump sum transfers so that it balances its budget every period.

$$-T_t = \tau_H P_{H,t} Y_{H,t}. \quad (14)$$

Sales taxes are fixed to ensure that the steady state is efficient:

$$\tau_H = \frac{1}{1-\theta_H}. \quad (15)$$

We abstract from monetary frictions and can thus consider a "cashless economy", as in Woodford (2003). The domestic monetary policy instrument is the nominal interest rate paid on one-period bonds, denoted i. The monetary policy authority sets the interest rate on domestic bonds with an aim to stabilize domestic CPI inflation and smooth interest rate changes. In particular, the Home monetary authority follows a rule of the following form:

$$\log\left(\frac{1+i_t}{\bar{\imath}}\right) = (1-\alpha_H^{\pi})\log\left(\frac{1+i_{t-1}}{\bar{\imath}}\right) + \alpha_H^{\pi}\log\left(\frac{\pi_t}{\bar{\pi}}\right) + \psi_t^I, \quad (16)$$

where α_H^{π} indicates the relative weight put on inflation targeting. ψ_t^I is a monetary policy shock. The Foreign monetary authority follows an analogous monetary policy rule. Monetary policy affects the real economy in the presence of nominal rigidities, and through its effect on the debt burden of countries.

1.4. Goods and asset market equilibrium

Aggregate demand facing domestic producers of traded goods amounts to:

$$Y_{H,t} = a_H\left(\frac{P_{H,t}}{P_t}\right)^{-\varphi} C_t + \frac{1-n}{n}(1-a_F)\left(\frac{P_{H,t}}{P_t}\right)^{-\varphi} Q_t^{\varphi} C_t^*, \quad (17)$$

and aggregate demand for foreign traded goods amounts to:

$$Y_{F,t} = \frac{n}{1-n}(1-a_H)\left(\frac{P_{F,t}^*}{P_t^*}\right)^{-\varphi} Q_t^{-\varphi} C_t + a_F\left(\frac{P_{F,t}^*}{P_t^*}\right)^{-\varphi} C_t^*. \quad (18)$$

Output is demand-determined in equilibrium, and, hence, the above equations can also be viewed as goods market clearing conditions.

Equilibrium in the financial markets requires that bonds and assets issued in the Home economy are in zero net supply within the domestic economy,

$$B_{H,t} = 0, \quad (19)$$

and that internationally traded bonds issued in Foreign currency by the Foreign country are in zero net supply:

$$nB_{F,t} + (1-n)s_t B_{F,t}^* = 0, \quad (20)$$

where $B_{F,t}^*$ denotes Foreign holdings of the Foreign bond.

Appendix A presents the equilibrium equations for this standard open-economy model.

2. Exchange rate pass-through in the model

In this model, pass-through to import prices will not be full (i.e., 100%) for several reasons. First, some foreign exporters set their price in the Home currency (i.e., they are local-currency pricing or LCP exporters), but face sticky prices and are therefore not able to change their price immediately after a change in the exchange rate. The import price of goods produced by these foreign LCP firms will therefore only adjust sluggishly to changes in the exchange rate. This is true whatever shock hits, and pass-through to import prices is therefore always going to be less than 100 percent in the short run in the presence of LCP exporters.

But there are other reasons why pass-through to import prices may not be full – even when exporters eventually adjust their prices. Exporters set their prices in a forward-looking manner to reflect their expected marginal costs and expected demand conditions. If these marginal costs and demand conditions are expected to change as a result of the shock, exporters might choose to reflect that in their prices and adjust their mark-ups instead. Moreover, these determinants of exporters' pricing decisions will be affected differently by different shocks – even if these shocks all lead to similar exchange rate movements. They will also depend on the monetary policy response and the persistence of different shocks. Therefore, within this relatively standard framework, the degree to which exporters pass through any move in the exchange rate to the import price – or instead adjust their mark-ups – depends on the shock which caused its move.

Within our model, 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, which depend on foreign wages (W_t^*); and the mark-up over marginal costs ($mkup_t^*$). In other words,

$$P_{F,t} = s_t mkup_t^* W_t^* \ .$$

We can then decompose any change in the import price level (relative to the level of prices) into changes in the real exchange rate, changes in marginal costs, and changes in the average mark-up over marginal costs:

$$\frac{\widehat{P_{F,t}}}{P_t} = \widehat{Q_t} + \widehat{mkup}_t^* + \frac{\widehat{W_t^*}}{P_t^*} \ , \tag{21}$$

where hatted variables denote deviations from steady state. If exchange rate pass-through was full, then the mark-up charged by exporters would not change when the exchange rate changed. Instead, the import price level would adjust to the change in the exchange rate and the potential change in foreign marginal costs.

3. <u>A quantitative illustration of shock-dependent exchange rate pass-through</u>

Next, we illustrate how pass-through might differ according to the drivers of the fluctuations in the exchange rate by considering the impact of three domestic shocks in this model: a shock to demand (a preference shock), a monetary policy shock, and a shock to the UIP condition (an exogenous exchange rate shock). In our model simulations of these shocks, we restrict the Home country to be a small open economy producing 5% of world GDP in steady state. The other parameter values of the model are listed in Table 2 and are fairly standard in the literature, see Corsetti *et al.* (2010). The degree of openness is chosen to be 30%, in line with the UK's import share of CPI. We assume that 60% of foreign exporters set prices in the local currency and may discriminate between markets, while the rest set prices in their own currency. The Calvo price stickiness parameter is chosen to be 0.6, which implies that 40% of firms get the opportunity to reset their price every quarter.

There is obviously uncertainty about the precise estimates of the structural parameters in our model. Forbes *et al.* (2015) takes this into account and shows that our results do not hinge on a particular parameter combination. We have also checked that the persistence of shocks, while potentially important in affecting exchange rate pass-through, does not affect our main results.

Table 2: Parameter values

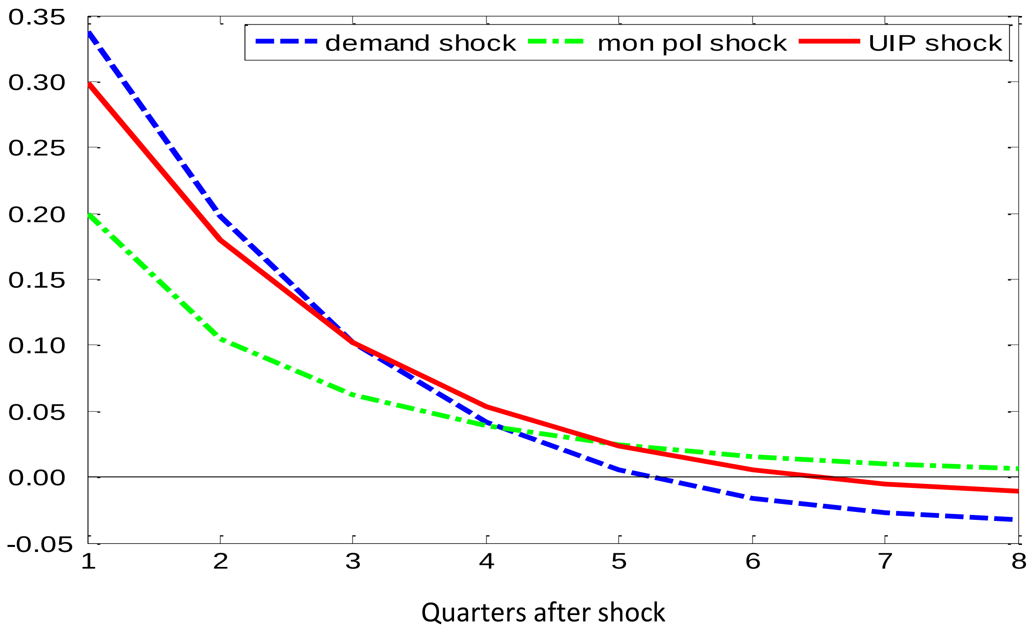
Description	**Parameter**	**Value**
Population in Home country	n	0.05
Discount factor	β	0.99
Yield sensitivity to external debt	δ	0.01
Degree of openness	op_H, op_F	0.3
Inverse of the Frish elasticity of labour supply	η_H, η_F	2
Risk aversion coefficient	σ_H, σ_F	1.1
Price stickiness parameter	α_H, α_F	0.6
Intra-temporal elasticity of substitution	θ_H, θ_F	7
Elasticity of substitution between H and F goods	ϕ_H, ϕ_F	0.75
Proportion of firms setting export prices in their own currency (PCP)	γ_H, γ_F	0.4
Home/Foreign monetary policy rule parameters:		
Interest rate persistence	α_H^R, α_F^R	0.7
Interest rate sensitivity to CPI inflation	$\alpha_H^\pi, \alpha_F^\pi$	1.5
Shock processes		
Persistence parameter for demand shocks	ρ_H^d, ρ_F^d	0.9
Persistence parameter for UIP shocks	$\rho_H^{uip}, \rho_F^{uip}$	0.9

Using the decomposition in equation (21), we investigate how import prices respond to changes in the exchange rate caused by different shocks. First, consider how import prices change following a shock which only changes the exchange rate but not any other fundamentals – an *exogenous exchange rate shock* (or UIP shock). This shock affects neither exporters' marginal costs nor the demand conditions they face directly and can therefore serve as a benchmark.[15] As already noted, those exporters which are able to change prices will do so. Only a certain proportion of exporters get the opportunity to change their price in a given quarter, however, and therefore the adjustment of

[15] The exchange rate change does not affect foreign marginal costs, as the foreign economy is assumed to be very large compared to the domestic economy.

average import prices to the exchange rate will be sluggish. This implies that the average exporting firm does not fully pass-through the exchange rate movement into import prices, but instead adjusts its mark-up. The solid red line in Figure 2 shows the estimated changes to mark-ups over eight quarters after such an exogenous exchange rate shock that causes a 1% appreciation.

Figure 2: Foreign exporters' mark-up after selected shocks

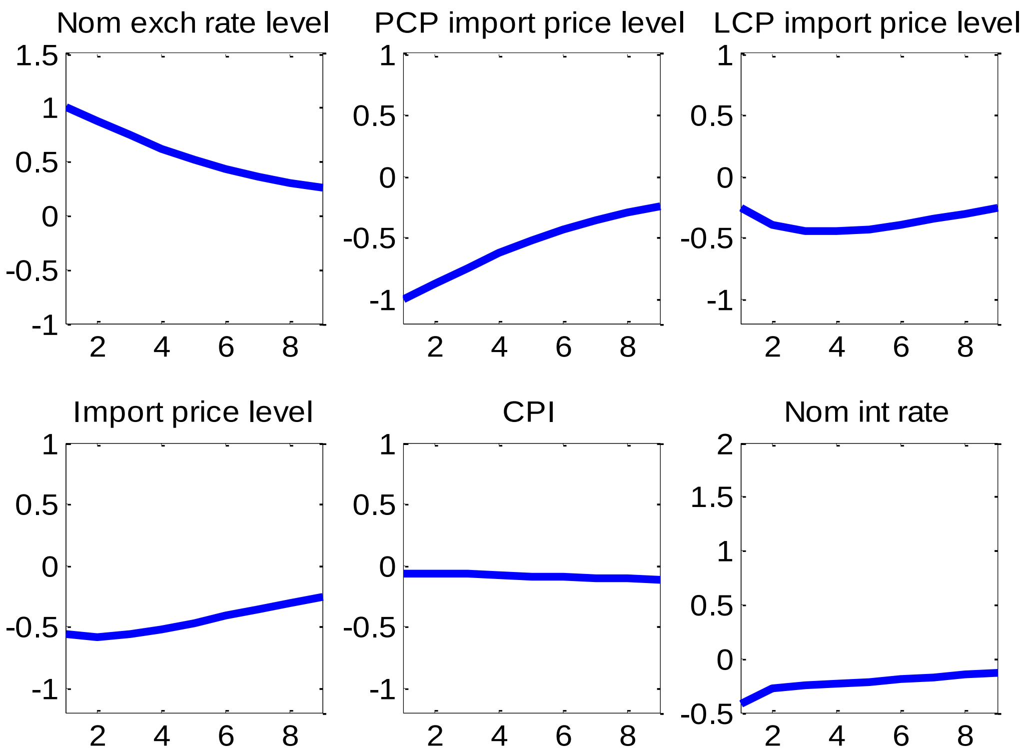


Note: The figure depicts the percentage change in foreign exporters' average mark-up following a shock which appreciates the exchange rate by 1%.

Figure 3 provides more details on the adjustments that occur in response to this 1% appreciation caused by the exogenous UIP shock. Import prices of PCP firms follow exchange rate movements and thus instantaneously fall following the 1% appreciation. LCP firms do not fully pass-through the exchange rate change, however, and instead only reduce their price slowly and by less than 0.5%. This is because they are forward-looking and do not expect the exchange rate change to be permanent. Therefore, they increase their mark-up following the domestic appreciation (as shown in Figure 2). After a year, pass-through to import prices – as measured by the change in the level of import prices relative to the change in the level of the exchange rate – is approximately 90%, increasing to 100% within two years. The change in import prices slowly feeds through to the CPI according to the share of imports in the consumption basket.[16]

[16] The monetary policymakers in the model are assumed to follow a flexible inflation targeting rule, so that they loosen monetary policy in response to the fall in the CPI. This is a simplification as it assumes that policymakers react in the same way to changes in the CPI whatever the origin or persistence of the change, ignoring other factors that are part of the monetary policy decision process.

Figure 3: The impact of an exogenous exchange rate change on selected variables



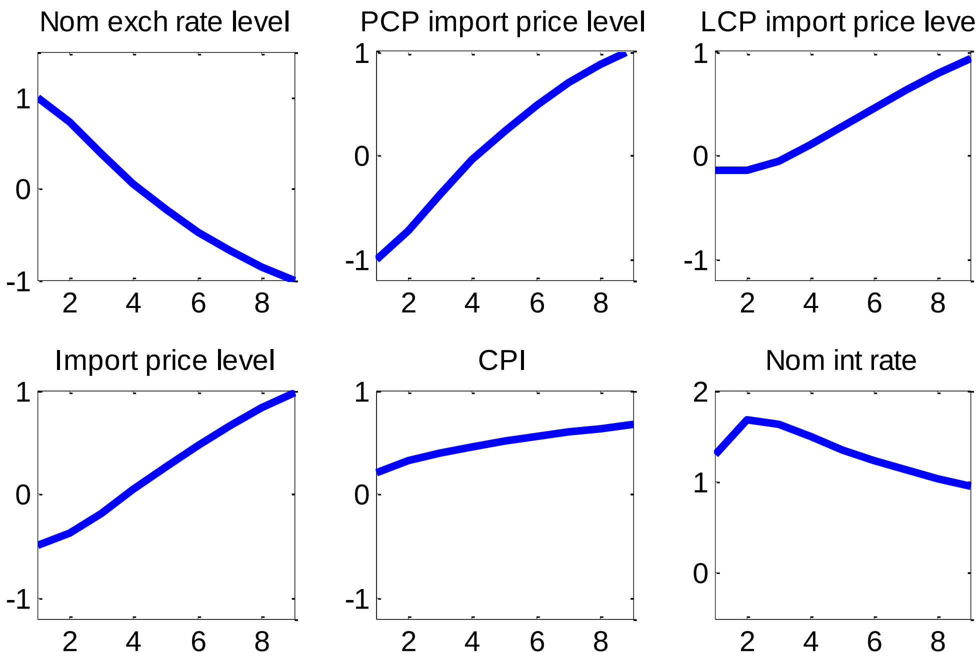
Note: This figure depicts the effects of an exogenous exchange rate shock causing the nominal exchange rate to appreciate by 1% in the first quarter on: the percent change in the level of the nominal exchange rate, in the import price level of PCP firms, in the import price level of LCP firms, in the overall import price level, in the CPI, and the percentage point change in the annualised nominal interest rate. The x-axis shows the quarters following the shock, which happens in quarter 1.

The behaviour of import prices following an exogenous exchange rate shock shows that mark-ups of exporters will move in the opposite direction of import prices, simply because of LCP and sticky prices. The extent to which the average mark-up increases (decreases) in the face of an appreciation (depreciation), however, will depend not only on the change in the exchange rate, but also on how the shock causing that change affects the economy through other channels (especially expected demand and marginal costs). Therefore, the final impact on prices will vary based on not just the magnitude of an exchange rate movement, but also the shock which caused this movement.

To clarify what mechanisms determine how pass-through might differ across shocks, we consider two additional examples of factors that could cause a similar 1% appreciation: stronger domestic demand and tighter monetary policy.

An appreciation caused by a positive *domestic demand shock* will increase the mark-up charged and the profits earned by foreign exporters who do not change their price, as explained above. The positive demand shock also increases domestic demand for imports, however, as well as domestic inflationary pressures. These effects will cause domestic competitors to increase prices. In response to higher domestic demand and less competition from domestic producers of similar goods, foreign LCP exporters will face less pressure to reduce their prices. Therefore, import prices would be expected to fall less than in the benchmark case of an exogenous exchange rate shock. These dynamics are shown in the simulations of the effects of a positive domestic demand shock in Figure 4.

Figure 4: The impact of a demand shock on selected variables

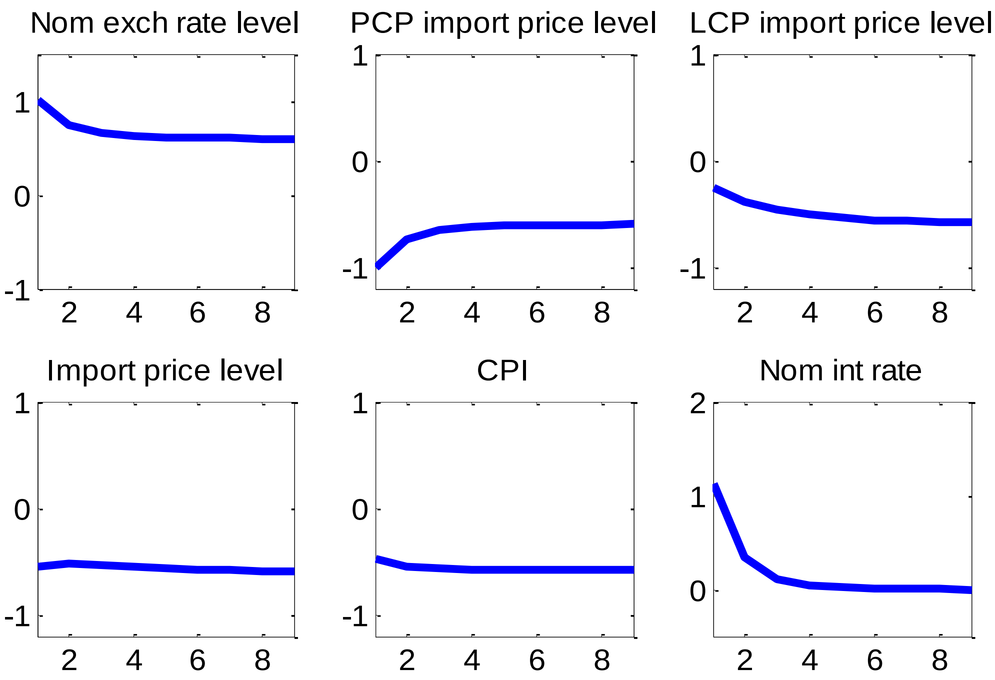


Note: This figure depicts the effects of a positive demand shock causing the nominal exchange rate to appreciate by 1% in the first quarter on: the percent change in the level of the nominal exchange rate, in the import price level of PCP firms, in the import price level of LCP firms, in the overall import price level, in the CPI, and the percentage point change in the annualised nominal interest rate. The x-axis shows the quarters following the shock, which happens in quarter 1.

Figure 2 compares the resulting mark-up from this scenario with the former example of an exogenous exchange rate shock. It shows that importers increase their mark-up more after the demand shock. As a result, pass-through is lower than after the UIP shock, with pass-through to import prices only around 85% after 4 quarters following the demand shock (relative to 90% in the previous scenario). Also, even though import prices fall as a consequence of the appreciation, the inflationary impact of the positive demand shock on the CPI more than outweighs the impact of lower import prices; the CPI rises despite the fall in import prices.

Finally, consider a *monetary policy shock* associated with an increase in the nominal interest rate which also leads to an appreciation of the nominal exchange rate of 1%. This appreciation reduces import prices, but the tighter monetary policy also reduces domestic demand and domestic inflationary pressures, as shown in Figure 5. Exporters will therefore more fully incorporate the exchange rate move by reducing import prices, rather than increasing their margins. Indeed, Figure 2 shows that in this scenario, margins only increase by 0.2% after the appreciation—much less than in the previous two scenarios—and quickly fall back to zero. Exchange rate pass-through to the CPI will also be high, as the CPI falls more than it does in the face of the exogenous exchange rate shock and domestic demand shock.

Figure 5: The impact of a monetary policy shock on selected variables



Note: This figure depicts the effects of a monetary policy tightening causing the nominal exchange rate to appreciate by 1% in the first quarter on: the percent change in the level of the nominal exchange rate, in the import price level of PCP firms, in the import price level of LCP firms, in the overall import price level, in the CPI, and the percentage point change in the annualised nominal interest rate. The x-axis shows the quarters following the shock, which happens in quarter 1.

These illustrations show that even a standard model predicts that exporters vary their margins in response to different causes of an exchange rate movement and that pass-through is shock dependent. In the examples chosen here, these margins depend not only on the exchange rate movement, but also on other factors, such as simultaneous and expected future changes in demand conditions related to the shock moving the exchange rate. For example, although the demand and monetary policy shocks moved the exchange rate in the same direction, they moved demand in opposite directions, thereby generating different implications for foreign exporters' mark-ups and pass-through. Exchange rate pass-through could also vary across shocks because the shocks have different persistence or different effects on exporters' marginal costs (especially if the shocks are global in nature). In addition, varying the persistence of shocks, while potentially important in affecting exchange rate pass-through, does not affect our conclusions that demand shocks tend to be associated with low degrees of exchange rate pass-through while monetary policy shocks tend to be associated with higher degrees of exchange rate pass-through. In any of these cases, theory clearly predicts that pass-through differs across shocks. Next, we use these insights to develop an empirical framework for estimating pass-through which is able to explicitly incorporate pass-through as shock-dependent.

IV. Empirical methodology

1. Identification strategy

Our empirical framework for studying pass-through allows us to estimate how different shocks incorporated in the theoretical model 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. 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. 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 also determine the characteristics of pass-through that we observe and measure.

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 either short-run sign restrictions or zero restrictions (in the short or long-run). 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 and the identification strategy does not allow for disentangling shocks originating in different regions. Farrant and Peersman (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 3 and consistent with the theoretical framework developed in Section III. These restrictions for our example of the UK are based on three sets of assumptions.

Table 3: 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 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),[17] and is widely used in the SVAR literature, including by Shambaugh (2008) and Erceg *et al.* (2005). We incorporate this identifying assumption for both the UK supply shock and a more generic global persistent shock separately—either of which can impact UK GDP in the long run. 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.

[17] 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.

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 the open-economy DSGE model presented in Section III. These sign restrictions are also widely used in the literature and have been shown to be consistent with other theoretical models, such as 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.[18] 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 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 (2011), 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

[18] 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 long-run restriction methodology, see Erceg *et al.* (2005).

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.[19]

The impulse responses from our theoretical model presented in Section III support these key assumptions in our identification scheme. For example, in the model a domestic demand shock implies a positive correlation between output and CPI, an appreciation of the exchange rate, an increase in inflation, and an increase in the nominal interest rate (as the monetary policymaker follows a flexible inflation-targeting interest rate rule). Also consistent with our identification assumptions, a monetary policy shock that leads to an increase in interest rates, as shown in Figure 5, implies a fall in output, a fall in the CPI, and an appreciation of the nominal exchange rate. An exogenous exchange rate appreciation is associated with a fall in the CPI and a reduction in the nominal interest rate, as shown in Figure 3.

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[20] 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[21], 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 or quantitative easing (QE) undertaken by the Bank of England (BoE) Monetary Policy Committee after that.[22] This allows us to avoid 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[23]. 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.

[19] We have carried out a range of robustness checks of the estimation methodology – summarized in Section VII – and found the key results remain little changed.
[20] The first and second quarter of 1993 are only used as explanatory variables in the estimation.
[21] We use the import price deflator for total imports, including all goods and services.
[22] 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).
[23] For further detail see http://www.bankofengland.co.uk/statistics/Pages/iadb/notesiadb/effective_exc.aspx

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 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.[24]

V. <u>Exchange rate pass-through to UK import prices</u>

1. <u>Shock-based metrics of exchange rate pass-through</u>

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 C, Figures C.1 through C.6, and are consistent with economic theory and the model developed in Section III. 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 focus 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 1% appreciation of sterling. 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 C. First, a positive domestic supply shock causes the exchange rate to appreciate in the median case, albeit with wide confidence bands (Figure C.1).[25] 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 Section III) and is more tightly estimated (Figure C.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

[24] For further details of the estimation procedure see Appendix B.

[25] 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).

an increase in the exchange rate due to exogenous factors both cause an appreciation – as a result of our identifying restrictions for the short-term responses (Figures C.3 and C.4, respectively).

Finally, the two global shocks generate exchange rate appreciations in the median case and both have very wide confidence bands (Figures C.5 and C.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 6 graphs the median of these ratios, as well as the pass-through profile implied by the more standard reduced-form regressions estimated in Section II (as a black dashed line). We differentiate between the effects of the four domestic and two global shocks (Figures 6.a and 6.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 C, Table C.1.

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 theoretical predictions 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 (i.e., the "rule-of-thumb") appears close to an average of the responses for the four domestic shocks. But using this rule-of-thumb 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. [26]

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 on import prices, as well as the direct exchange rate effects.

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 and without fully understanding the reason behind the movement.

[26] Given the wide confidence bands around the impulse responses in Appendix C, Figures C.1 through C.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 6 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.

Figure 6.a: Pass-through to import prices for domestic shocks

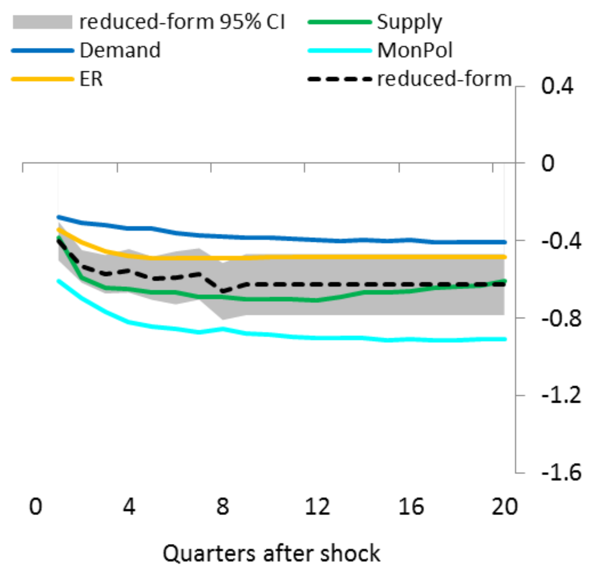
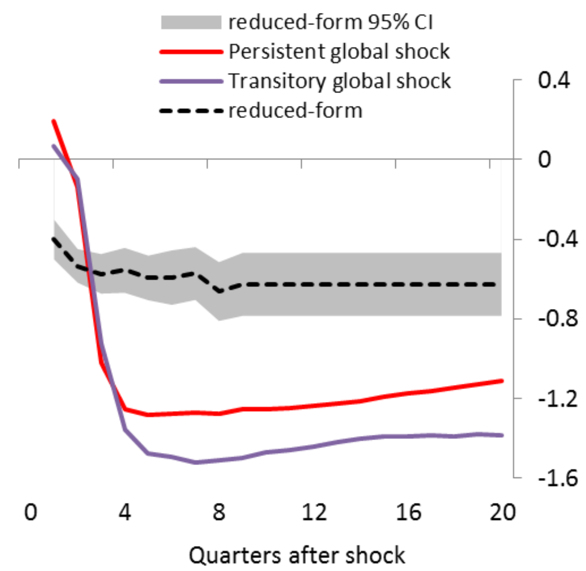


Figure 6.b: Pass-through to import prices for global shocks



Note: Pass-through is defined as the median ratio of cumulative impulse responses of import prices relative to the exchange rate. The x-axis displays quarters since a shock.

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 will 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 (and in particular the drivers of exchange rate movements) can explain changes in the observed rates of pass-through over time.

To begin, Table 4 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 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 4: Forecast error variance decomposition

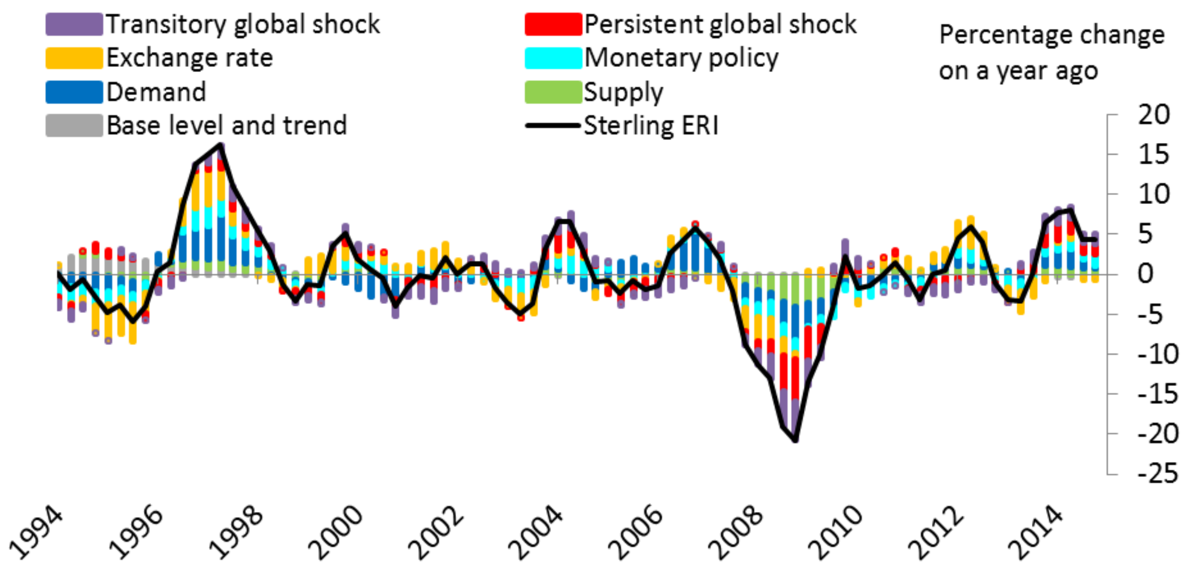
Variable		*Proportion of variance explained by shocks to:*					
	Horizon (quarters)	**Supply**	**Demand**	**Monetary policy**	**Exchange rate**	**Persistent global shocks**	**Transitory global shocks**
GDP	**1**	0.50	0.08	0.04	0.06	0.14	0.17
	20	0.47	0.05	0.03	0.04	0.28	0.13
CPI	**1**	0.14	0.15	0.17	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 index	**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 B 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 7. 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 persistent global shocks (in red) and domestic supply shocks (in green) than occurred in most other periods. Both of these types of shocks — and especially the persistent global shock — 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 most recent 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.

<u>Figure 7: Historical decomposition of year-on-year changes in nominal sterling ERI</u>



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 B for further detail on the estimation methodology.

To clarify the distinctions between these periods more formally, Table 5 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, also relative 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. Most important 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 6.a and 6.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. Most importantly, it does not control for movements in commodity prices and foreign export prices more broadly, which could be affected by the global or other shocks. Reduced form regressions estimating pass-through (such as discussed in Section II) usually control for these changes in foreign export prices, in order to isolate the effects of exchange rate movements on import prices from these other effects. To be consistent with this approach—and obtain more accurate estimates of pass-through—we also report "adjusted pass-through" coefficients at the bottom of Table 5. These coefficients cannot be directly derived from an endogenous model like ours, so it is necessary to make several additional assumptions. More specifically, we assume that 50 to 100% of changes in foreign export prices are passed-through to UK import prices.[27] As these calculations of adjusted pass-through rely on additional assumptions and are therefore not as precise as those from the structural model, we use the implied estimate ranges when forecasting how exchange rate movements will affect inflation.

Focusing on the adjusted pass-through estimates at the bottom of Table 5, 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%.

[27] 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.

Table 5: 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 5 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 led to a sharp overestimate of the impact on import price inflation.

As a check on these results, Appendix Figure C.7 shows the same decomposition for import price inflation. It highlights that after the sterling depreciation in 2007-9, import price inflation was boosted by persistent global shocks (in red) 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. These estimates agree with the above estimates for pass-through to import prices.

This series of results highlights the importance of adjusting estimates of pass-through over time to incorporate the nature of the underlying shocks instead of using “rules of thumb” for how an exchange rate movement affects inflation. 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. But the results in this section suggest that using this this “rule of thumb” 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 more recent sterling appreciation.[28] Similarly, lower pass-through from the 2013-15 appreciation episode might also not be an accurate indicator of the extent of any pass-through that will occur in the future. Instead, it is critically important to evaluate the nature of the shocks driving the currency movements when predicting how they will affect inflation. This should lead to more accurate inflation forecasts, improving policymakers’ ability to set monetary policy appropriately.

VI. <u>Exchange rate pass-through to consumer prices</u>

Even more important for monetary policy is the pass-through to consumer prices (or corresponding variable for the inflation target). This section shows that exchange rate pass-through to consumer prices is also shock-contingent. The general results on the rankings of the effects of different types of shocks are consistent with those discussed for pass-through to import prices, and, in some cases the differences across shocks are even starker.

To begin, Figure 8 plots the same measures of exchange rate pass-through as shown in Figure 6 for import prices, but this time for consumer prices. As before, we also 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 C, Table C.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 C.1, Figures 6.a and 6.b) and those for overall pass-

[28] 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.

through to consumer prices (Appendix Table C.2, Figures 8.a and 8.b) indicates that pass-through is significantly lower to final consumer prices than to import prices. This is a well-documented finding in 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 8.a and 8.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). This is still, however, somewhat shorter than has historically been found in the academic literature.[29]

Figure 8.a: Pass-through to consumer prices for domestic shocks

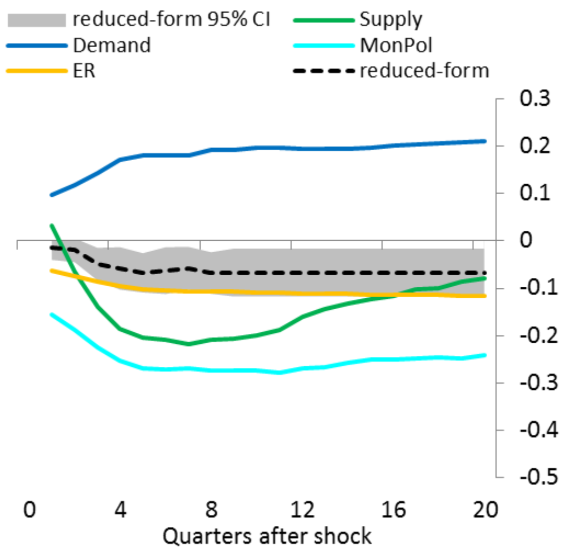
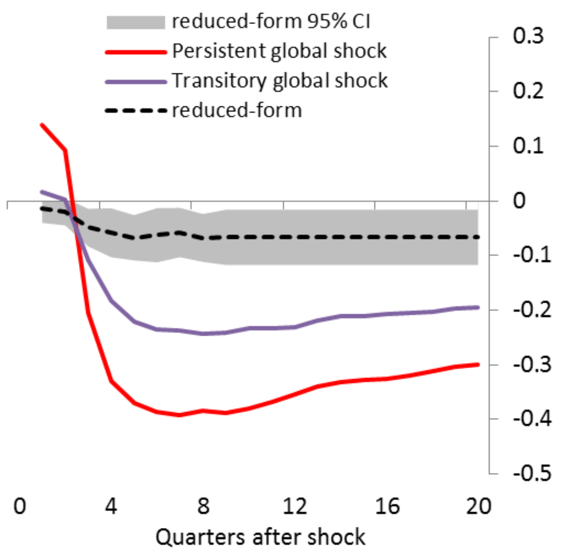


Figure 8.b: Pass-through to consumer prices for global shocks



Next, the profiles for overall exchange rate pass-through in Figure 8 reveal that appreciations driven by five of the six shocks (all except domestic demand) generate the traditional result of lower consumer prices. Monetary policy, domestic supply shocks and the two global shocks all generate large degrees of pass-through, with consumer prices falling by more than 20% of the initial exchange rate appreciation after 8 quarters. The exogenous exchange rate shock has a somewhat lower estimated pass-through. In contrast to the drag on domestic prices from these five 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 in Section III, 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 can drive up prices overall—more than counteracting the drag from import prices. In other words, appreciations resulting primarily from

[29] For example, see Rogoff (1996) for a survey of the literature on deviations of prices from PPP. More recent work, however, has suggested that full pass-through may be faster today than the roughly 3 to 5 years generally assumed in the academic literature. For example, Fisher (2015) and Forbes (2015a) discuss faster rates of pass-through in the US and UK, respectively.

positive domestic demand shocks would be expected to exhibit much less pass-through, and possibly even 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 three large moves in the sterling exchange rate generated differing degrees of pass-through to import prices. We can apply the same calculations as before to consumer prices and weigh the exchange rate pass-through profiles shown in Figure 8 by the exchange rate decompositions in Table 5 to get an "unadjusted" exchange rate pass-through coefficient for each episode. The resulting multipliers are reported in the first row of Table 6. 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%.[30] 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 the sterling 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 overestimated the effects of the exchange rate move substantially; 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.

As a final check, Appendix Figure C.8 reports the decomposition of shocks driving changes in UK consumer price inflation. The estimates support the main results above. They show the unusually large role of negative persistent global shocks and UK supply shocks in driving up inflation in the 2007-9 episode (similar to the decomposition of import prices shown in the previous section). This is consistent with the large negative global and domestic productivity shocks that occurred during this episode, as large numbers of workers became unemployed, the financial system was severely impaired, and many companies were unable to obtain access to credit. Also striking is the role of persistent as well as transitory global shocks contributing to low CPI inflation in 2015. These global shocks are estimated to be reducing CPI inflation by almost 2% in 2015—explaining almost all of the deviation in inflation from the BoE's target.

[30] Based on the latest (2010) Input-Output tables published by the UK Office of National Statistics. 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.

Table 6: Implied pass-through coefficients for consumer prices after large exchange rate movements

	1996-7 appreciation	***2007-9 depreciation***	***2013-2015q1 appreciation***	***Full sample FEVD[(b)]***
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[(c)]	***-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) 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 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.

VII. Extensions and sensitivity analysis

In order to test if the results reported above are robust to various specifications, as well as to see how the results change over various time periods and during different types of currency movements, this section summarizes a series of extensions to the main analysis. It begins by examining what our baseline results suggest for different types of exchange rate movements—appreciations versus depreciations and large exchange rate movements versus smaller ones. Then it considers if the results change when the model is estimated over different time periods, including under a very different monetary policy and exchange rate framework starting in 1980 (instead of 1993). It also tests for breaks associated with the financial crisis. The section concludes by summarizing a series of tests to evaluate if the main results are robust to different lag orders and different measures of key variables.

1. Asymmetries and nonlinearities in exchange rate pass-through

There are a number of reasons why different types of exchange rate movements could have different effects on import and consumer prices. For example, if there are "menu costs", companies may be more reluctant to adjust prices in response to small changes in the exchange rate and foreign prices. This could imply less pass-through from small exchange rate movements than large ones. Similarly, if wages are downwardly rigid, firms may be reluctant to lower prices and see a corresponding reduction in margins in response to appreciations which reduce import prices. In contrast, they might be more likely to adjust prices upward after depreciations which increase import prices, thereby leading to greater pass-through after depreciations than appreciations. The evidence on whether pass-through effects are asymmetric and/or nonlinear is only beginning to emerge. Berger and Vavra (2015) find no evidence of asymmetries in the US. Dainauskas (2015) finds that pass-through is higher for depreciations than appreciations in the UK, while Lewis (2016) finds a higher degree of pass-through for large exchange rate moves than for small ones. Rincón-Castro and Ridríguez-Nino (2016) find evidence that pass-through is asymmetric for Colombia. Caselli and Roitman (2016) find evidence of both asymmetries and non-linearities in a sample of emerging markets.

The model used to estimate pass-through in this paper is linear and symmetric, however, and does not explicitly allow us to test for nonlinear effects or asymmetries based on the direction of the exchange rate movement. It is possible, however, to focus on specific periods based on the magnitude or direction of the exchange rate movement to see if the nature of the shocks tends to differ for different types of exchange rate movements. For example, if domestic demand shocks have historically played a greater role in driving appreciations than depreciations, when combined with the evidence in Figures 6 and 8 that domestic 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 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 in 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 more associated with a particular type of exchange rate movement, and whether that implies a different degree of exchange rate pass-through.[31] Table 7 shows the resulting shock decompositions of these different types of exchange rate movements on the left, and the implied pass-through coefficients on the right. We focus on unadjusted exchange rate pass-through coefficients here, so it is important to bear in mind that a greater role for the two global shocks might imply higher pass-through due to the simultaneous direct effect on foreign export prices.

The first two rows of Table 7 show that the shocks driving large (relative to small) exchange rate movements are broadly similar.[32] Some of the minor differences, however, appear intuitive. For instance, the exogenous exchange rate shock explains a greater share of small fluctuations in sterling compared to large ones, which makes sense given that this shock is less related to economic

[31] Ideally, we would have liked to re-estimate our SVAR model using just those periods, but this approach leaves us with very small samples, making robust estimation difficult. Work in progress is extending this analysis for a panel of small-open economies, which might provide more observations and allow us to test for differential effects of different types of exchange rate moves.
[32] This similarity in the types of shocks corresponding to the different types of exchange rate movements agrees with the micro-level analysis reported in Lewis (2016).

fundamentals and might not be expected to be as persistent. On the other hand, domestic supply shocks and persistent global shocks – which should capture slow-moving technological changes and both have larger effects on medium-term exchange rate movements – play a greater role in explaining larger exchange rate fluctuations. The different types of shocks may drive slightly higher pass-through from large exchange rate moves (relative to smaller moves) to both import and consumer price, but given the small number of large exchange rate movements in the sample, it is impossible to know if this difference is systematic or purely coincidental.

The results from comparing the shocks and corresponding pass-through resulting from sterling appreciations relative to depreciations (both larger than 3%) are shown in the bottom two rows of Table 7. The implied pass-through coefficients to both import and consumer prices are quite similar for major appreciations and depreciations, even if the mix of corresponding shocks is somewhat different. Again, it is difficult to draw strong conclusions given the limited number or episodes.

Table 7: Historical decompositions of different types of exchange rate moves[(a)] and implied pass-through

	Shocks						Implied pass-through to:	
	Supply	Demand	Monetary policy	Exchange rate	Persistent global shock	Transitory global shock	Import prices	CPI
Large moves	11%	24%	15%	19%	16%	15%	-0.86	-0.13
Small moves	8%	25%	18%	26%	10%	12%	-0.80	-0.11
Appreciations	12%	20%	24%	14%	15%	25%	-0.90	-0.15
Depreciations	18%	9%	19%	22%	19%	13%	-0.91	-0.18

Note: Estimated using SVAR model described in Section III. Implied-pass-through is for 8 quarters after the shock.
(a) Specifically, the table reports the average shock contributions to quarterly changes in the sterling ERI of different shocks.

Overall, these results do not suggest that pass-through varies significantly between small relative to large sterling moves, or between appreciations relative to depreciations. Our framework is not well suited to test this formally, however, as the type of shocks moving the exchange rate is the only driver of changes in pass-through over time rather than the size or direction of the exchange rate move itself.

2. Different time periods and monetary policy frameworks

One approach to address this challenge of having limited episodes to examine differences in pass-through around certain types of exchange rate movements could be to consider a longer time period for the analysis. For example, over our baseline period starting in 1993, there was only 1 episode in which the exchange rate depreciated by over 10% on an annual basis, while starting the analysis in 1980 would yield six episodes.[33] We do not focus on this longer time period in our main analysis, however, because the framework for monetary and exchange rate policy has changed substantially over this longer window. For example, sterling was basically pegged when it was part of the European Exchange Rate Mechanism (ERM) from October 1990 through September 1992. We begin our main analysis in 1993, which is when sterling left the ERM, began to float, and an inflation target was adopted. This is the same central framework that remains in place today. Nonetheless, estimating our model for the period starting before 1993 could still provide useful information on whether the distribution of shocks affecting the exchange rate and extent of pass-through has changed over time.

For this extension, we estimate the SVAR on data from 1980 to 2015q1. Even the earlier part of this sample covers periods with very different monetary policy frameworks. For example, UK monetary policy targeted various monetary aggregates between 1976 and 1987, switched to exchange rate targeting between 1987 and 1992, and joined the ERM in 1989.[34] We use the same framework as discussed in Sections V and VI to estimate shock-dependent pass-through. Table 8 reports the average forecast error variance decomposition for the exchange rate over the first eight quarters (in the first six rows). The bottom two rows report the unadjusted pass-through 'coefficients' implied by this decomposition and the impulse responses of the exchange rate, import prices and consumer prices. The column on the left summarizes our main results for our base sample starting in 1993, with the second column reporting results for the longer time period.

Starting with the similarities, domestic demand and exchange rate shocks continue to explain similar and substantial shares of exchange rate movements in both the shorter period since 1993 and the longer one since 1980. On the other hand, the three shocks with notably different weights between the two sample periods are the domestic monetary policy shocks and the two global shocks. Monetary policy shocks explain a much larger proportion of the exchange rate variance in the longer period, while global shocks explain much less. The estimated impulse responses (not shown for

[33] Defined as periods with consecutive quarters when the year-on-year change in the exchange rate was greater than the 10% threshold.
[34] For further detail see https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221567/ukecon_mon_policy_framework.pdf

brevity) suggest that monetary policy shocks have a greater impact on the exchange rate during the longer sample, but this is associated with less pass-through to prices. This explains much of the lower estimated pass-through to both import and consumer prices in the longer sample. These findings seem intuitive; the exchange rate targeting regime in the first part of the sample might generate greater sensitivity of the exchange rate to monetary policy surprises, while the less credible monetary policy regime, especially in the 1980s, might have led agents to doubt the persistence of exchange rate movements caused by monetary policy shocks and therefore be less willing to adjust prices in response. Turning to the two global shocks, these contribute much less to the variance in the exchange rate in the longer period, which is not surprising since the UK economy has become more open since the early 1980s. All in all, these differences support our priors that there were substantial changes in the UK monetary policy regime in the 1990s, so it makes sense to focus on the more recent period in order to better understand pass-through today.

We also checked if our findings were robust to starting the sample in 1998 (rather than 1993), which was when the BoE became independent. The resulting variance decompositions and implied pass-through ratios are reported in the third column of Table 8. These results are quite close to those using 1993 as the start date. The implied pass-through for the period starting in 1998 is slightly higher than that starting in 1993, which could result from the major global shocks that occurred after the mid- and late-2000s receiving greater weight in the shorter sample. Most important, our main conclusions about the sources of shocks and corresponding degrees of pass-through during the key periods of interest are unchanged. For example, the sharp sterling depreciation in 2007-9 continues to be driven more by global and domestic supply shocks, and less by domestic demand and monetary policy shocks, than occurs on average over the full period or during other periods of sharp exchange rate movements.

A final question related to whether our main results change over time is whether there was a structural change in our more recent sample associated with the global financial crisis and sharp recession between 2007 and 2009. Unfortunately, we do not have enough data after the crisis to split our baseline estimation sample (1993-2015q1) along these dimensions. As an alternative test of a structural change after 2007, however, we re-estimate our model with data from 1993 until the end of 2007. Then we test whether the 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.[35] The results suggest no evidence of a structural change in the data or estimated relationships during and after the financial crisis. As an additional check, we also

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

re-estimate the model over the baseline 1993-2015q1 period with a dummy for the period from 2007. Our key results, reported in the last column of Table 8, remain little changed.

Table 8: Forecast error variance decompositions of the exchange rate and implied pass-through over different samples

	Estimation period:			
	Baseline: 1993-2015q1	**1980-2015q1**	**1998-2015q1**	**1993-2015q1 with post-2007 dummy**
Supply	10%	5%	12%	10%
Demand	25%	18%	21%	21%
Monetary policy	17%	45%	15%	15%
Exogenous exchange rate	21%	23%	22%	25%
Persistent global shock	14%	4%	17%	17%
Transitory global shock	13%	5%	14%	12%
Implied pass-through to:				
Import prices	***-0.79***	***-0.49***	***-0.94***	***-0.85***
Consumer prices	***-0.13***	***-0.06***	***-0.17***	***-0.11***

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

3. 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 our lag order or measures for key variables. More specifically, we have also estimated the model using one and three lags of the endogenous variables and found no notable differences compared to our baseline results obtained with two lags. In the remainder of this section, we discuss the results from estimating our baseline specification (with two lags and sample period from 1993 to 2015q1) using different measures of domestic prices (PPI and core-CPI, instead of CPI) and interest rates.

First, using producer (PPI) rather than consumer prices in the estimation leads to very similar conclusions in terms of the effects of the identified shocks on the other variables in the SVAR. Table 9 shows that the decomposition of the exchange rate when the model is estimated with the PPI (in column 2) is almost unchanged relative to the baseline model estimated using the CPI (column 1). The one notable difference between the two is the higher implied exchange rate pass-through to producer 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 it 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. We find that the absolute value of pass-through 'coefficients' to the PPI is higher than to the CPI across all six shocks, but their signs are unchanged (negative for all shocks except the domestic demand shock).

Table 9: Forecast error variance decompositions of the exchange rate and implied pass-through with alternative domestic prices and monetary policy measures

	SVAR estimated with:			
	Baseline: CPI	**PPI**	**Core CPI**	**1-year forward gilt yield**
Supply	10%	8%	11%	10%
Demand	25%	23%	22%	25%
Monetary policy	17%	19%	15%	24%
Exchange rate	21%	23%	22%	21%
Persistent global shock	14%	15%	18%	12%
Transitory global shock	13%	12%	12%	9%
Implied pass-through to:				
Import prices	***-0.80***	***-0.79***	***-0.86***	***-0.66***
Consumer prices	***-0.14***	***-0.25***	***-0.03***	***-0.10***

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

Second, the results from estimating our model with core-CPI (excluding energy, food and non-alcoholic beverages, also adjusted for VAT changes) also remain little changed from our baseline (shown in Table 9, column 3). Again, the main notable difference is the different degree of pass-through to final prices than found for the CPI. Since core-CPI excludes some highly import-intensive goods (such as oil and food) and assigns greater weight to services, this is not surprising.

Next, we replaced the shadow Bank Rate with the one-year instantaneous forward UK government bond yield as our measure of domestic interest rates.[36] The main results are little changed, except for the higher proportion of variance attributable to the monetary policy shock and the smaller proportion attributed to the two global shocks. The monetary policy shock estimated with the one-year yield has a lower pass-through, possibly due to the measure's greater volatility compared to the shadow policy rate and the fact that it probably captures factors other than just monetary

[36] 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.

policy surprises[37]. This lowers the implied overall degree of pass-through slightly compared to our baseline specification.

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, we have 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 fact recognized in some papers but not yet operationalized. Instead, we should explicitly model and understand what drives the exchange rate movement. Different types of shocks causing an appreciation (or depreciation) could have different effects on the economy—even if the shocks are scaled to 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 based on whether they result 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

[37] 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.

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. 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. It also shows why pass-through from sterling's 2013-15 appreciation has been more muted. Utilizing this framework 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.

Appendix A. DSGE model equilibrium equations

The equilibrium is a set of stationary processes

$$\left\{\begin{array}{c} Y_{H,t} Y_{F,t}, C_t, C_t^*, L_t, L_t^*, C_{H,t}, C_{H,t}^*, C_{F,t}, C_{F,t}^*, Q_t, \left(\frac{B_{F,t}}{P_t}\right), i_t, i_t^* \\ \left(\frac{P_{H,t}}{P_t}\right), \left(\frac{P_{F,t}}{P_t}\right), \left(\frac{P_{H,t}^{PCP}}{P_{H,t}}\right), \left(\frac{P_{H,t}^{LCP}}{P_{H,t}}\right), \left(\frac{P_{F,t}^{LCP}}{P_{F,t}}\right), \left(\frac{P_{F,t}^*}{P_t^*}\right), \left(\frac{P_{H,t}^*}{P_t^*}\right), \left(\frac{P_{F,t}^{PCP*}}{P_{F,t}^*}\right), \left(\frac{P_{H,t}^{LCP*}}{P_{H,t}^*}\right), \left(\frac{P_{F,t}^{LCP*}}{P_{F,t}^*}\right), \\ \pi_{H,t}, \pi_{H,t}^{PCP}, \pi_{H,t}^{LCP}, \pi_{H,t}^{LCP*}, \pi_{F,t}^* \pi_{F,t}^{PCP*}, \pi_{F,t}^{LCP*}, \pi_{F,t}^{LCP}, \left(\frac{W_t}{P_t}\right), \left(\frac{W_t^*}{P_t^*}\right), \\ x_{1,t}^{PCP}, x_{2,t}^{PCP}, x_{1,t}^{LCP}, x_{1,t}^{LCP*}, x_{2,t}^{LCP}, x_{2,t}^{LCP*}, x_{F,1,t}^{PCP}, x_{F,2,t}^{PCP}, x_{F,1,t}^{LCP}, x_{F,1,t}^{LCP*}, x_{F,2,t}^{LCP}, x_{F,2,t}^{LCP*} \end{array}\right\} \text{ for } t \geq 0$$

which satisfy the 46 equilibrium equations described in this appendix (denoted 1A-46A) given the shock processes for $\{\gamma_t^C, \gamma_t^{C*}, \gamma_t^I, \gamma_t^{I*}, \gamma_t^C, \gamma_t^{UIP}\}_{t=0}^{\infty}$ and the initial conditions consisting of the variables above for $t < 0$.

Price equations

We rewrite the pricing equations in a recursive form by engaging in the following transformations. Focusing first on the PCP firms' maximisation problem, we rewrite the following pricing equation

[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 (2015) 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.

$$\frac{p_t^{PCP}(h)}{P_{H,t}^{PCP}} = \frac{\theta_H}{(\theta_H - 1)(1-\tau_H)} \frac{E_t \sum_{s=0}^{\infty}(\beta\alpha_H)^s P_{t+s}^{-1} U_{C,t+s} W_{t+s}\, y_{t,t+s}^{PCP}(h)}{E_t \sum_{s=0}^{\infty}(\beta\alpha_H)^s P_{H,t}^{PCP} P_{t+s}^{-1} U_{C,t+s} y_{t,t+s}^{PCP}(h)}$$

as

$$\frac{p_t^{PCP}(h)}{P_{H,t}^{PCP}} = \frac{x_{1,t}^{PCP}}{x_{2,t}^{PCP}}$$

where $x_{1,t}^{PCP} \equiv \frac{\theta_H}{(\theta_H-1)} E_t \sum_{s=0}^{\infty}(\beta\alpha_H)^s P_{t+s}^{-1} U_{C,t+s} W_{t+s}\, y_{t,t+s}^{PCP}(h)$

$$= \frac{\theta_H}{(\theta_H-1)} C_t^{-\sigma} \frac{W_t}{P_t} p_{H,t}^{PCP-\theta_H} \left\{C_{H,t} + \frac{1-n}{n} p_{H,t}^{-\theta_H} Q_t^{\theta_H} p_{H,t}^{*\,\theta_H} C_{H,t}^*\right\} + (\beta\alpha_H)\pi_{H,t}^{PCP\,\theta_H} x_{1,t+1}^{PCP} \quad (1A)$$

and $x_{2,t}^{PCP} \equiv (1-\tau_H) E_t \sum_{s=0}^{\infty}(\beta\alpha_H)^s P_{H,t}^{PCP} P_{t+s}^{-1} U_{C,t+s}\, y_{t,t+s}^{PCP}(h)$

$$= (1-\tau_H) C_t^{-\sigma} p_{H,t} p_{H,t}^{PCP1-\theta_H} \left\{C_{H,t} + \frac{1-n}{n} p_{H,t}^{-\theta_H} Q_t^{\theta_H} p_{H,t}^{*\,\theta_H} C_{H,t}^*\right\} + (\beta\alpha_H)\pi_{H,t}^{PCP\,\theta_H-1} x_{2,t+1}^{PCP} \quad (2A)$$

where $p_{H,t} \equiv \left(\frac{P_{H,t}}{P_t}\right)$, $p_{H,t}^{PCP} \equiv \left(\frac{P_{H,t}^{PCP}}{P_{H,t}}\right)$, and $p_{H,t}^* \equiv \left(\frac{P_{H,t}^*}{P_t^*}\right)$.

Then, we note that

$$P_{H,t}^{PCP} = \left[\alpha_H^k P_{H,t-1}^{PCP1-\theta_H} + (1-\alpha_H^k) p_t^{PCP}(h)^{1-\theta_H}\right]^{\frac{1}{1-\theta_H}}$$

can be rewritten as

$$1 = \alpha_H^k \left(\frac{P_{H,t-1}^{PCP}}{P_{H,t}^{PCP}}\right)^{1-\theta_H} + (1-\alpha_H^k)\left(\frac{p_t^{PCP}(h)}{P_{H,t}^{PCP}}\right)^{1-\theta_H}$$

So that

$$\frac{p_t^{PCP}(h)}{P_{H,t}^{PCP}} = \left[\frac{1-\alpha_H^k\left(\pi_{H,t}^{PCP}\right)^{\theta_H-1}}{(1-\alpha_H^k)}\right]^{\frac{1}{1-\theta_H}}$$

Implying that

$$\left[\frac{1-\alpha_H^k\left(\pi_{H,t}^{PCP}\right)^{\theta_H-1}}{(1-\alpha_H^k)}\right]^{\frac{1}{1-\theta_H}} = \frac{x_{1,t}^{PCP}}{x_{2,t}^{PCP}} \quad (3A)$$

Now, turning to LCP firms, we can rewrite the pricing equation for domestic prices as before to obtain:

$$\left[\frac{1-\alpha_H^k\left(\pi_{H,t}^{LCP}\right)^{\theta_H-1}}{(1-\alpha_H^k)}\right]^{\frac{1}{1-\theta_H}} = \frac{x_{1,t}^{LCP}}{x_{2,t}^{LCP}} \quad (4A)$$

where $x_{1,t}^{LCP} \equiv \frac{\theta_H}{(\theta_H-1)} E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s P_{t+s}^{-1} U_{C,t+s} W_{t+s}\, y_{t,t+s}^{LCP}(h)$

$$= \frac{\theta_H}{(\theta_H-1)} C_t^{-\sigma} \frac{W_t}{P_t} p_{H,t}^{LCP-\theta_H}\, C_{H,t} + (\beta\alpha_H) \pi_{H,t}^{LCP\ \theta_H} x_{1,t+1}^{LCP} \tag{5A}$$

and $x_{2,t}^{LCP} \equiv (1-\tau_H) E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s P_{H,t}^{LCP} P_{t+s}^{-1} U_{C,t+s}\, y_{t,t+s}^{LCP}(h)$

$$= (1-\tau_H) C_t^{-\sigma} p_{H,t} p_{H,t}^{LCP1-\theta_H} C_{H,t} + (\beta\alpha_H) \pi_{H,t}^{LCP\ \theta_H - 1} x_{2,t+1}^{LCP} \tag{6A}$$

The pricing equation for exported goods amounts to:

$$\left[\frac{1-\alpha_H^k (\pi_{H,t}^{LCP*})^{\theta_H-1}}{(1-\alpha_H^k)}\right]^{\frac{1}{1-\theta_H}} = \frac{x_{1,t}^{LCP*}}{x_{2,t}^{LCP*}} \tag{7A}$$

where $x_{1,t}^{LCP*} \equiv \frac{\theta_H}{(\theta_H-1)} E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s P_{t+s}^{-1} U_{C,t+s} W_{t+s}\, y_{t,t+s}^{LCP*}(h)$

$$= \frac{\theta_H}{(\theta_H-1)} C_t^{-\sigma} \frac{W_t}{P_t} p_{H,t}^{LCP*-\theta_H}\, C_{H,t}^{*} + (\beta\alpha_H) \pi_{H,t}^{LCP*\ \theta_H} x_{1,t+1}^{LCP*} \tag{8A}$$

and $x_{2,t}^{LCP*} \equiv (1-\tau_H) E_t \sum_{s=0}^{\infty} (\beta\alpha_H)^s s_{t+s} P_{H,t}^{LCP*} P_{t+s}^{-1} U_{C,t+s}\, y_{t,t+s}^{LCP*}(h)$

$$= (1-\tau_H) C_t^{-\sigma} p_{H,t}^{*} Q_t p_{H,t}^{LCP*1-\theta_H} C_{H,t}^{*} + (\beta\alpha_H) \pi_{H,t}^{LCP*\ \theta_H-1} x_{2,t+1}^{LCP*} \tag{9A}$$

where $p_{H,t}^{LCP*} = \frac{P_{H,t}^{LCP*}}{P_{H,t}^{*}}$.

Similar equations hold for the Foreign LCP and PCP firms, so that there are in total 18 pricing equations.

Consumption demand:

$$C_{H,t} = a_H \left(\frac{P_{H,t}}{P_t}\right)^{-\varphi_H} C_t, \tag{19A}$$

$$C_{F,t} = (1-a_H) \left(\frac{P_{F,t}}{P_t}\right)^{-\varphi_H} C_t, \tag{20A}$$

$$C_{H,t}^{*} = (1-a_F) \left(\frac{P_{H,t}^{*}}{P_t^{*}}\right)^{-\varphi_F} C_t^{*}, \tag{21A}$$

$$C_{F,t}^{*} = a_F \left(\frac{P_{F,t}^{*}}{P_t^{*}}\right)^{-\varphi_F} C_t^{*} \tag{22A}$$

Labour supply:

$$\frac{{L_t}^{\eta}}{\gamma_t^C C_t^{-\sigma}} = \frac{W_t}{P_t}, \tag{23A}$$

$$\frac{L_t^{*\eta}}{\gamma_t^{C*} C_t^{*-\sigma}} = \frac{W_t^*}{P_t^*}, \quad (24A)$$

Consumption Euler equations:

$$\beta E_t \frac{\gamma_{t+1}^C C_{t+1}^{-\sigma}}{\gamma_t^C C_t^{-\sigma}} \frac{(1+i_t)}{\pi_{t+1}} = 1 \quad (25A)$$

$$\beta E_t \frac{\gamma_{t+1}^C C_{t+1}^{-\sigma}}{\gamma_t^C C_t^{-\sigma}} \frac{(1+i_t^*)}{\pi_{t+1}^*} \frac{Q_{t+1}}{Q_t} = \frac{1}{\Phi\left(\frac{s_t B_{F,t}}{P_t}\right)} \gamma_t^S \quad (26A)$$

$$\beta E_t \frac{\gamma_{t+1}^{C*} C_{t+1}^{*-\sigma}}{\gamma_t^{C*} C_t^{*-\sigma}} \frac{(1+i_t^*)}{\pi_{t+1}^*} = 1 \quad (27A)$$

where $\pi_t \equiv \frac{P_t}{P_{t-1}} = \frac{p_{H,t-1}}{p_{H,t}} \pi_{H,t}$ denotes CPI inflation in the Home country and $\pi_t^* \equiv \frac{p_{F,t-1}^*}{P_{F,t}^*} \pi_{F,t}^*$ denotes CPI inflation in the Foreign economy.

Price indices:

$$1 = a_H \left(\frac{P_{H,t}}{P_t}\right)^{1-\varphi_H} + (1 - a_H) \left(\frac{P_{F,t}}{P_t}\right)^{1-\varphi_F} \quad (28A)$$

$$1 = a_F \left(\frac{P_{F,t}^*}{P_t^*}\right)^{1-\varphi_F} + (1 - a_F) \left(\frac{P_{H,,t}^*}{P_t^*}\right)^{1-\varphi_H} \quad (29A)$$

$$1 = \gamma_H^{PCP} \left(\frac{P_{H,t}^{PCP}}{P_{H,t}}\right)^{1-\theta_H} + (1 - \gamma_H^{PCP}) \left(\frac{P_{H,t}^{LCP}}{P_{H,t}}\right)^{1-\theta_H} \quad (30A)$$

$$1 = \gamma_H^{PCP} \left(\frac{P_{H,t}^{PCP}}{P_{H,t}} \frac{P_{H,t}}{P_t} \frac{P_t}{s_t P_t^*} \frac{P_t^*}{P_{H,t}^*}\right)^{1-\theta_H} + (1 - \gamma_H^{PCP}) \left(\frac{P_{H,t}^{LCP*}}{P_{H,t}^*}\right)^{1-\theta_F} \quad (31A)$$

$$1 = \gamma_F^{PCP} \left(\frac{P_{F,t}^{PCP*}}{P_{F,t}^*}\right)^{1-\theta_F} + (1 - \gamma_F^{PCP}) \left(\frac{P_{F,t}^{LCP*}}{P_{F,t}^*}\right)^{1-\theta_F} \quad (32A)$$

$$1 = \gamma_F^{PCP} \left(\frac{P_{F,t}^{PCP*}}{P_{F,t}^*} \frac{P_{F,t}^*}{P_t^*} \frac{s_t P_t^*}{P_t} \frac{P_t}{P_{F,t}}\right)^{1-\theta_F} + (1 - \gamma_F^{PCP}) \left(\frac{P_{F,t}^{LCP}}{P_{F,t}}\right)^{1-\theta_F} \quad (33A)$$

Definition of inflation rates:

$$\pi_{H,t}^{PCP} = \frac{P_{H,t}^{PCP}}{P_{H,t}} \frac{P_{H,t-1}}{P_{H,t-1}^{PCP}} \pi_{H,t} \quad (34A)$$

$$\pi_{F,t}^{PCP*} = \frac{P_{F,t}^{PCP*}}{P_{F,t}^*} \frac{P_{F,t-1}^*}{P_{F,t-1}^{PCP*}} \pi_{F,t}^* \quad (35A)$$

$$\pi_{H,t}^{LCP} = \frac{P_{H,t}^{LCP}}{P_{H,t}} \frac{P_{H,t-1}}{P_{H,t-1}^{LCP}} \pi_{H,t} \qquad (36A)$$

$$\pi_{H,t}^{LCP*} = \frac{P_{H,t}^{LCP*}}{P_{H,t}^{*}} \frac{P_{H,t-1}^{*}}{P_{H,t-1}^{LCP*}} \frac{P_{H,t}^{*}}{P_{t}^{*}} \frac{P_{t-1}^{*}}{P_{H,t-1}^{*}} \frac{P_{F,t-1}^{*}}{P_{t-1}^{*}} \frac{P_{t}^{*}}{P_{F,t}^{*}} \pi_{F,t}^{*} \qquad (37A)$$

$$\pi_{F,t}^{LCP*} = \frac{P_{F,t}^{LCP*}}{P_{F,t}^{*}} \frac{P_{F,t}^{*}}{P_{F,t-1}^{LCP*}} \pi_{F,t}^{*} \qquad (38A)$$

$$\pi_{F,t}^{LCP} = \frac{P_{F,t}^{LCP}}{P_{F,t}} \frac{P_{F,t-1}}{P_{F,t-1}^{LCP}} \frac{P_{F,t}}{P_{t}} \frac{P_{t-1}}{P_{F,t-1}} \frac{P_{t}}{P_{H,t}} \frac{P_{H,t-1}}{P_{t-1}} \pi_{H,t} \qquad (39A)$$

<u>Production functions:</u>[39]

$$Y_{H,t} = L_t \qquad (40A)$$

$$Y_{F,t}^{*} = L_t^{*} \qquad (41A)$$

<u>Resource constraint:</u>

The resource constraint is $C_t + \frac{s_t B_{F,t}}{P_t (1+i_t^*) \Phi\left(\frac{s_t B_{F,t}}{P_t}\right)} = Y_t + \frac{s_t B_{F,t-1}}{P_t}$ which we can rewrite as:

$$C_t + \frac{Q_t (B_{F,t}/P_t^*)}{(1+i_t^*) \Phi\left(Q_t (B_{F,t}/P_t^*)\right)} = Y_t + \frac{Q_t (B_{F,t-1}/P_{t-1}^*)}{\pi_t^*} \qquad (42A)$$

<u>Monetary policy rules:</u>

$$\log\left(\frac{i_t}{\bar{\imath}}\right) = \alpha_H^R \log\left(\frac{i_{t-1}}{\bar{\imath}}\right) + \alpha_H^{\pi} \log\left(\frac{\pi_t}{\bar{\pi}}\right) + \gamma_t^I \qquad (43A)$$

$$\log\left(\frac{i_t^*}{\bar{\imath}}\right) = \alpha_F^R \log\left(\frac{i_{t-1}^*}{\bar{\imath}}\right) + \alpha_F^{\pi} \log\left(\frac{\pi_t^*}{\bar{\pi}}\right) + \gamma_t^{I*} \qquad (44A)$$

<u>Goods market equilibrium:</u>

$$Y_{H,t} = a_H \left(\frac{P_{H,t}}{P_t}\right)^{-\varphi} C_t + \frac{1-n}{n} (1-a_F) \left(\frac{P_{H,t}}{P_t}\right)^{-\varphi} Q_t^{\varphi} C_t^{*} \qquad (45A)$$

$$Y_{F,t} = \frac{n}{1-n} (1-a_H) \left(\frac{P_{F,t}^*}{P_t^*}\right)^{-\varphi} Q_t^{-\varphi} C_t + a_F \left(\frac{P_{F,t}^*}{P_t^*}\right)^{-\varphi} C_t^{*} \qquad (46A)$$

[39] For simplicity, we here do not account for the impact of price dispersion on output. Given that price dispersion does not play a role in first order approximations of the equilibrium, this does not have any consequences for our results.

Appendix B: 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.[40] ε is a matrix of white noise 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 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[41] 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:[42]

i. We specify our prior for the coefficient matrix *beta* by setting all coefficients 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 for a

[40] 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.
[41] This assumption is problematic in the type of structural analysis undertaken here (Kadiyala and Karlsson, 1997).
[42] For a more thorough explanation of the simulation technique refer to Canova (2007) pp. 361-367.

relatively loose prior on the VAR coefficients.[43] 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.

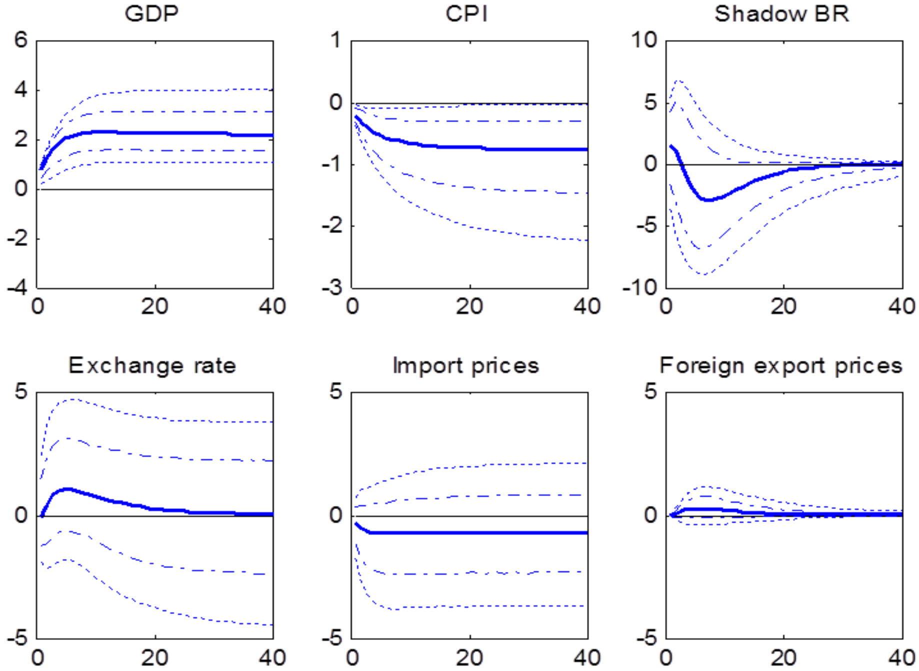
iii. We obtain an orthogonal decomposition of the resulting covariance matrix that satisfies the sign and zero restrictions and produces uncorrelated structural shocks by applying the algorithm suggested by Rubio-Ramirez *et al.* (2010) and extended by Binning (2013) for under-identified models.

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 4. This provides more robust results than using one single model.

[43] We set the hyperparameter determining the tightness of our prior about coefficients on exogenous variables to 10,000 (implying an unformed 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.

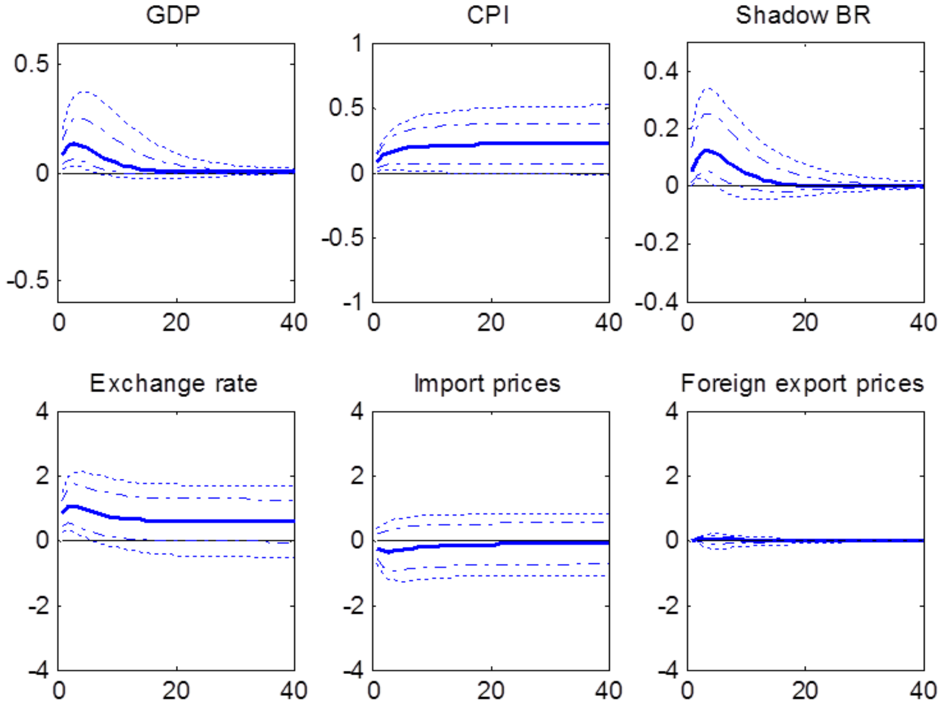
Appendix C: Impulse responses and additional output from SVAR

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



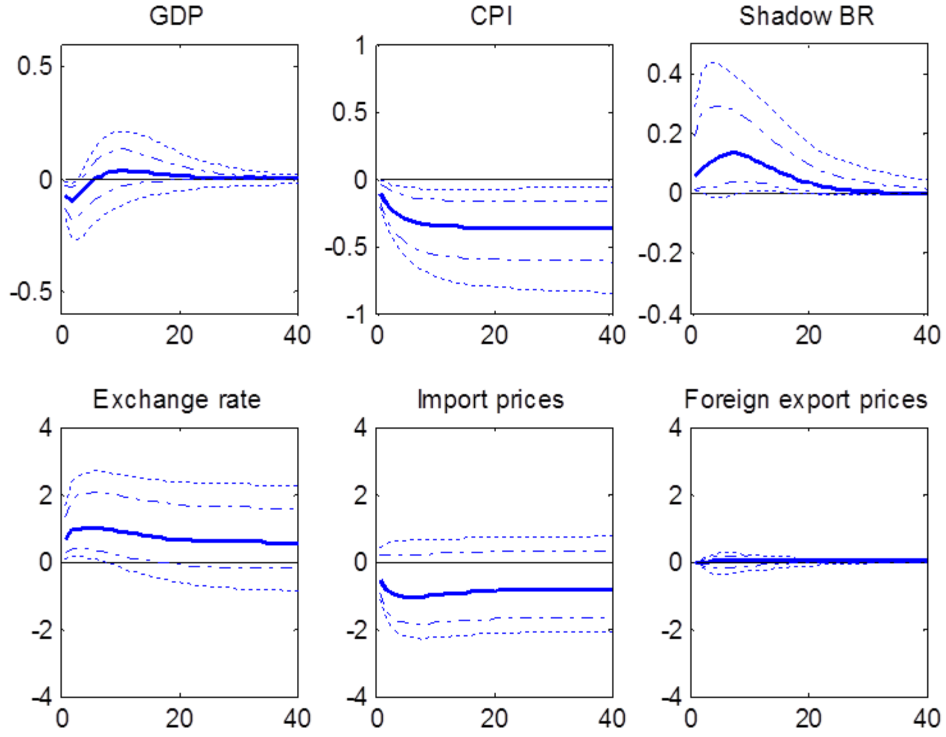
Note: These graphs report the median impulse responses (in solid lines) along with confidence bands at the 68% threshold (dashed lines) and 90% threshold (dotted lines) for all six variables to the respective shock. The responses for all variables except the interest rate – which is already expressed 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 C.2: Impulse responses to a UK demand shock



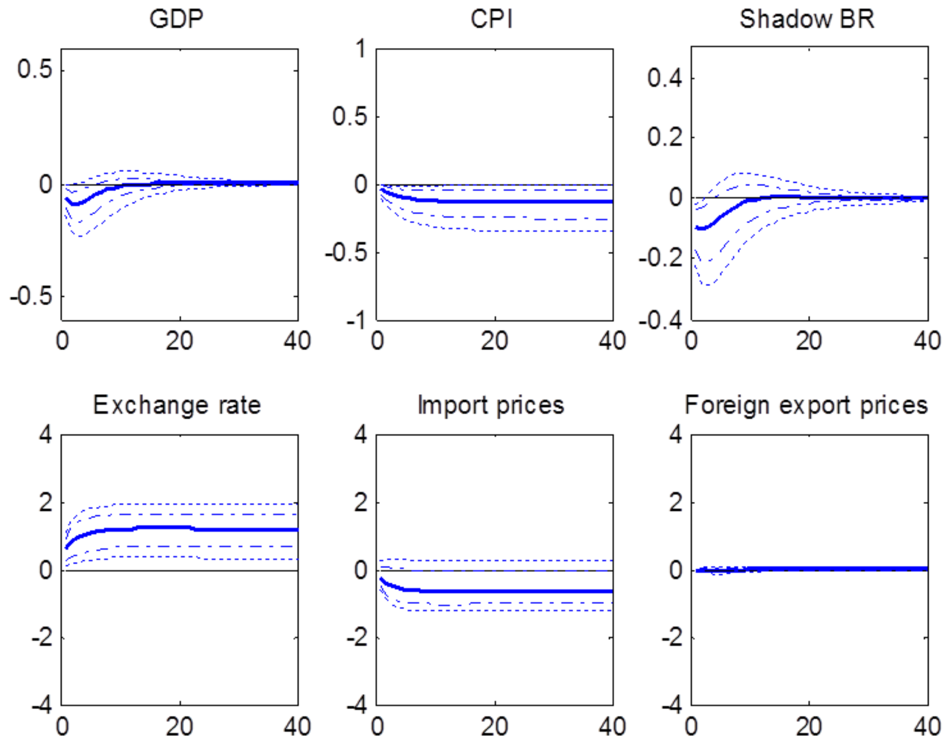
Note: See note to Figure C.1.

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



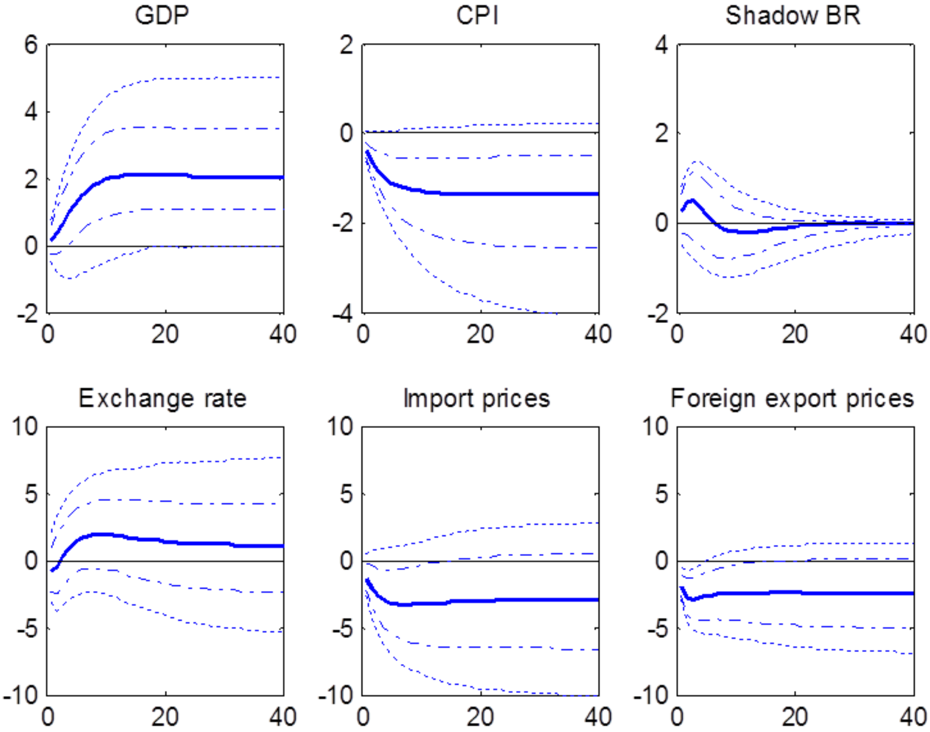
Note: See note to Figure C.1.

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



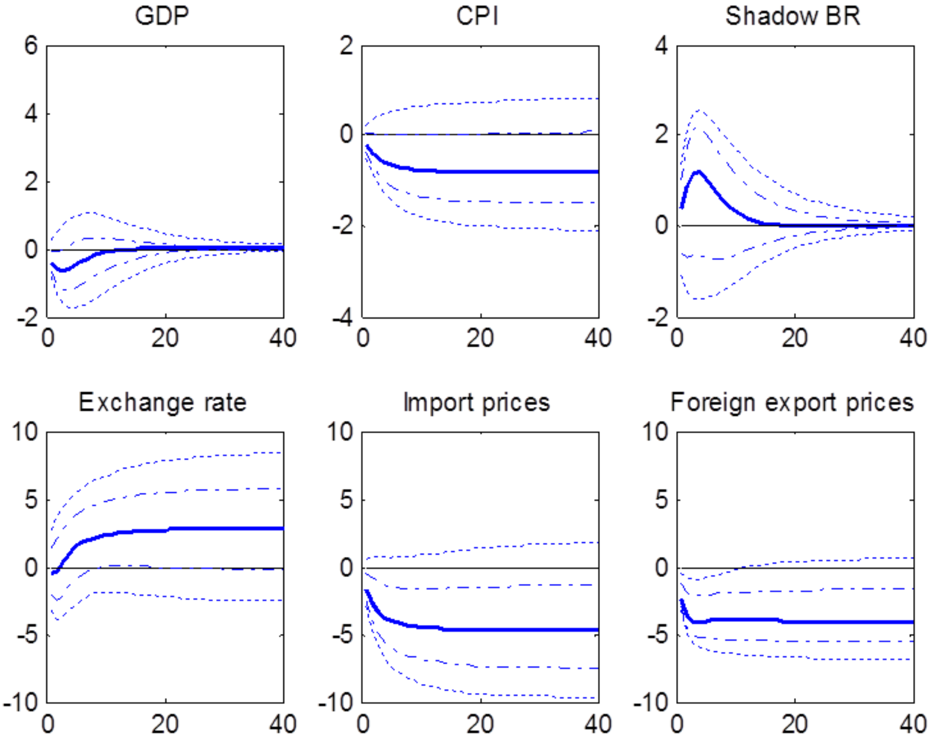
Note: See note to Figure C.1.

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



Note: See note to Figure C.1.

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



Note: See note to Figure C.1.

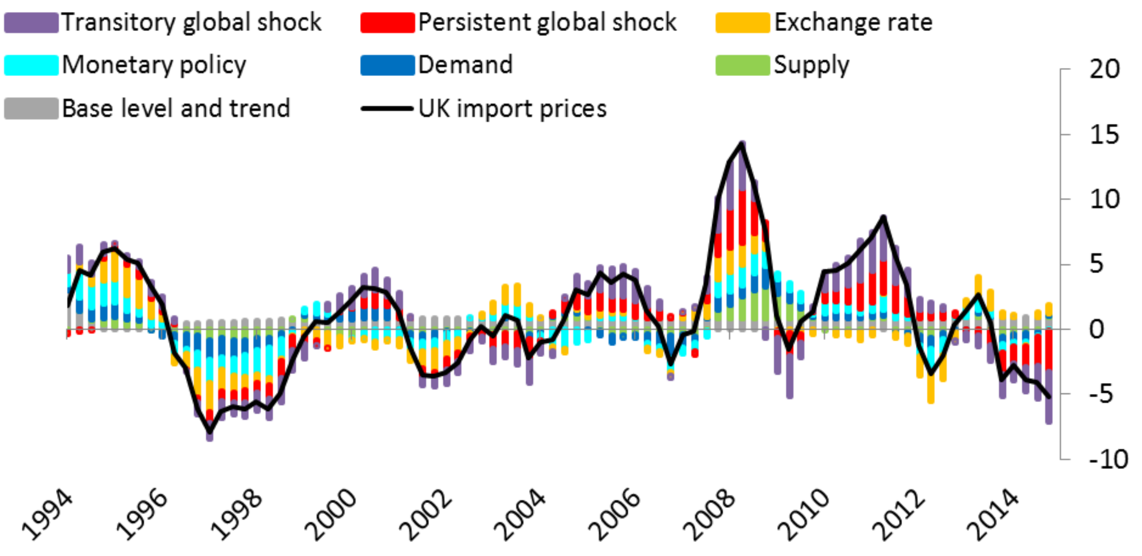
Table C.1: Pass-through to import prices by shock (ratio of import prices response to exchange rate response)

Period	Percentile	Supply	Demand	Monetary policy	Exchange rate	Persistent global shock	Transitory global shock
1	**50**	**-0.4**	**-0.3**	**-0.6**	**-0.3**	**0.2**	**0.1**
	16	*-1.2*	*-0.5*	*-1.4*	*-0.7*	*-2.0*	*-2.1*
	68	*-0.1*	*-0.1*	*-0.2*	*-0.1*	*0.8*	*0.9*
5	**50**	**-0.67**	**-0.34**	**-0.84**	**-0.49**	**-1.28**	**-1.48**
	16	*-1.26*	*-0.70*	*-1.58*	*-0.76*	*-2.94*	*-3.19*
	68	*-0.43*	*-0.03*	*-0.46*	*-0.31*	*-0.83*	*-0.94*
20	**50**	**-0.61**	**-0.41**	**-0.91**	**-0.48**	**-1.11**	**-1.38**
	16	*-1.47*	*-1.00*	*-2.14*	*-0.74*	*-2.66*	*-2.55*
	68	*-0.29*	*-0.06*	*-0.39*	*-0.32*	*-0.55*	*-1.03*

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

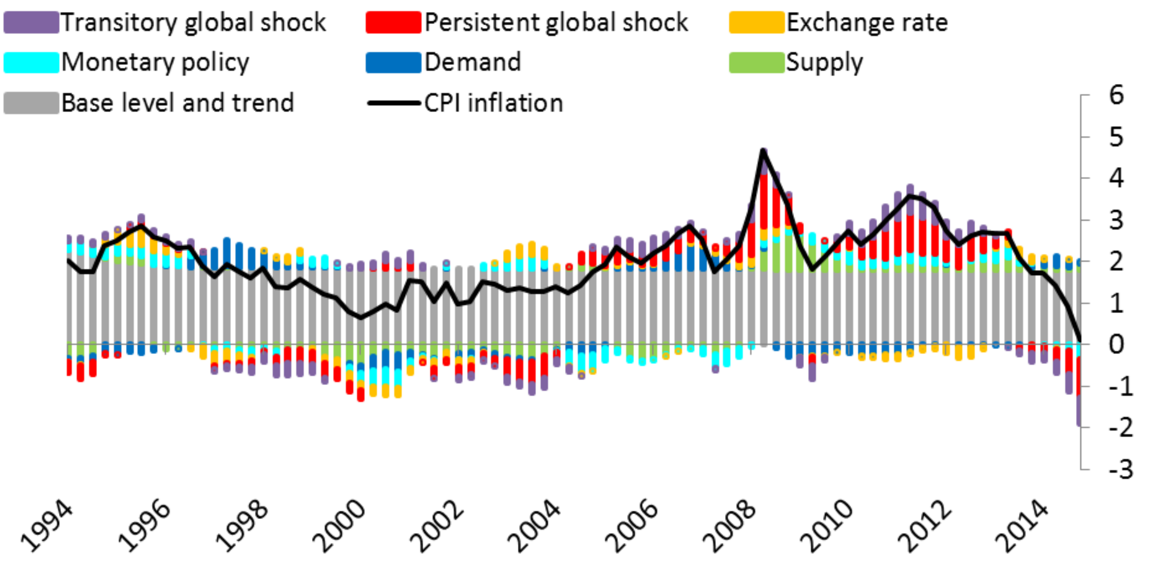
Period	Percentile	Supply	Demand	Monetary policy	Exchange rate	Persistent global shock	Transitory global shock
1	**50**	**0.0**	**0.1**	**-0.2**	**-0.1**	**0.1**	**0.0**
	16	*-0.4*	*0.0*	*-0.6*	*-0.2*	*-0.5*	*-0.3*
	68	*0.2*	*0.1*	*-0.1*	*0.0*	*0.3*	*0.1*
5	**50**	**-0.20**	**0.18**	**-0.27**	**-0.10**	**-0.37**	**-0.22**
	16	*-0.79*	*0.05*	*-0.86*	*-0.27*	*-1.05*	*-0.66*
	68	*-0.06*	*0.31*	*-0.14*	*-0.06*	*-0.19*	*-0.08*
20	**50**	**-0.08**	**0.21**	**-0.24**	**-0.12**	**-0.30**	**-0.20**
	16	*-0.97*	*-0.08*	*-1.22*	*-0.29*	*-1.14*	*-0.60*
	68	*0.30*	*0.38*	*-0.12*	*-0.07*	*0.13*	*-0.07*

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



Note: See note to Figure 7.

Figure C.8: Historical decomposition of year-on-year changes in consumer prices (excl. VAT changes)



Note: See note to Figure 7.

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