# External MPC Unit

# Discussion Paper No. 43

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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: incorporating the underlying shocks that cause exchange rate fluctuations when evaluating how these fluctuations 'pass through' into 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 develop an SVAR framework for a small open economy that relies on both short-run and long-run identification restrictions consistent with our theoretical model. Applying this framework to the United Kingdom, we find that the response of both import and consumer prices to exchange rate fluctuations depends on what caused the fluctuations. For example, exchange rate pass-through is relatively large in response to domestic monetary policy shocks, but smaller in response to domestic demand shocks. This framework helps explain why pass-through can change over time, including why sterling's post-crisis depreciation caused a sharper increase in prices than expected and sterling's recent appreciation has had a more muted effect.

**Key words:** Exchange rate pass-through, import prices, consumer prices, inflation, vector autoregression.

**JEL classification:** E31, F3, F41.

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## I.     Introduction

Exchange rates can fluctuate sharply over time. These fluctuations—and even just moderate exchange rate movements—can have sizable effects on output and prices. But unfortunately, despite substantive advances in the academic literature and forecasting models, predictions of how exchange rate fluctuations will affect output, and especially inflation, at different points in time have had only limited success.[1] This has created challenges for central banks which are forced to set monetary policy without a clear understanding of how exchange rate movements will affect inflation over the medium term.

This paper proposes a fundamental change in the current framework used to analyse and measure how exchange rate movements affect inflation (i.e., exchange rate pass-through). It suggests that instead of treating exchange rate movements as exogenous when estimating their effect on various economic variables, it is necessary to take a step back and model what caused the exchange rate to move in the first place. An application of this framework to the UK shows that this approach can explain why exchange rate movements have had such different effects at different points in time, including why exchange rate pass-through was surprisingly strong during the crisis and more muted recently. This new modelling framework could substantially improve our ability to predict the effects of exchange rate movements on variables such as inflation, thus improving policymakers' ability to conduct monetary policy in the future.

It is somewhat surprising that this approach of considering why an exchange rate moves before evaluating its impact has not yet been widely adopted. There is an extensive academic literature on the different causes of exchange rate movements, and a general appreciation that exchange rates are endogenous variables.[2] There is also an extensive literature showing that firms adjust their prices and mark-ups differently after different shocks, based on factors such as how those shocks affect their current and future marginal costs, potential competitors' prices, and demand conditions.[3] For all of these reasons, the pass-through from exchange rate movements to prices may be shock-dependent. There has been some discussion that different shocks to the exchange rate could generate different effects on the economy, such as Klein (1990) and Astley, Pain and Smith (2009). Theoretical work has also made this point, such as Corsetti, Dedola and Leduc

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[1] See Burstein and Gopinath (2014) and Gopinath (2015) for recent overviews of the academic literature and Mishkin (2008) for a discussion of the implications for monetary policy. See Forbes (2015b) for a discussion of current puzzles in exchange rate pass-through in the UK.

[2] See Clarida and Gali (1994) and Eichenbaum and Evans (1995) for early and influential examples, or Engel (2013) for a recent discussion.

[3] 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 when facing a change in the exchange rate.

(2009), which shows that the degree of pass-through varies depending on whether shocks hit upstream or downstream producers. Despite this discussion, evaluations of the impact of currency price movements generally do not incorporate what caused those movements, a 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.[4] One explanation is that researchers have been hesitant to incorporate such considerations into empirical models due to the challenges in explaining exchange rate movements with fundamentals.[5]

This limited attention to the factors behind an exchange rate movement when assessing its effects on inflation are also surprising given the evidence that has been accumulating that exchange rate pass-through can change over time within individual countries. For example, a series of papers (such as Campa and Goldberg, 2005, Marazzi *et al.*, 2005, Gagnon and Ihrig, 2004, and Gust *et al.*, 2010) documents a fall in pass-through in the United States from the 1980s to the 1990s. They attempt to explain this change through variables such as changes in the composition of imports, the monetary policy framework, or the role of China. Stulz (2007) also documents a decline in pass-through in Switzerland in the 1990s, and Mumtaz *et al.* (2006) find a decline in pass-through to import prices in the UK between 1995 and 2004. Other evidence shows pass-through can increase as well as decrease over time. Fleer, Rudolf, and Zurlinden (2015) documents a sharp increase in pass-through in Switzerland in 2010-2011, and Forbes (2015b) shows that pass-through to both import prices as well as consumer inflation has fluctuated over time in the UK.

A small number of empirical papers have highlighted that the traditional approach to estimating pass-through could suffer from endogeneity bias because fluctuations in exchange rates and prices are generally endogenous responses to other shocks. For example, Corsetti, Dedola and Leduc (2008a) find that the performance of exchange rate pass-through regression models depends on whether the shocks affecting the economy are real or nominal. They also stress the importance of controlling for the general-equilibrium effects of the shocks. An and Wang (2011) and Stulz (2007) attempt to circumvent these issues by identifying exogenous exchange rate movements within a VAR framework. This approach, however, only reveals the true degree of pass-through if it is not shock-dependent. The analysis which makes the most progress in accounting for the shock dependence of pass-through, and is closest to our approach, is Shambaugh (2008). He conjectures that a change in the type of shocks driving exchange rate fluctuations might explain the decline in estimated exchange rate pass-through in the 1990s. To test this, he identifies fundamental shocks in

a VAR and investigates their impact 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.[6]

Despite this building evidence that pass-through can change over time, and some empirical papers making initial attempts to account for the source of exchange rate fluctuations, most economic models used in policy institutions have continued to assume that pass-through is fixed over time or only changes for structural reasons.[7] This has supported the use of general "rules of thumb" that are frequently cited for how an exchange rate movement would affect inflation in the future. For example, in the US a 10% dollar appreciation has been estimated to result in a fall in US consumer prices of around 0.5% (equivalent to a pass-through coefficient of 5%).[8] In the UK, the Bank of England (BoE) has used estimates of the pass-through from exchange rate movements to UK consumer prices of around 20% to 30%.[9]

This paper proposes, however, that we move beyond these rules of thumb. When assessing how exchange rate movements pass-through to inflation, we find that it is critically important to evaluate the changes in economic conditions behind the exchange rate fluctuation and any general equilibrium effects. We develop a standard open-economy model to show that firms' decisions on how to adjust their prices in response to exchange rate movements depend on how economic conditions have changed. Then, in order to capture this empirically, we use an SVAR framework which we estimate for the UK. The framework allows us to identify separate shocks to UK demand and supply, world demand and supply, UK monetary policy, and any exogenous exchange rate shocks. We then evaluate the impact of exchange rate fluctuations caused by these different shocks on import prices (for the first stage of pass-through) and consumer prices (for overall pass-through), as well as other variables (such as output). We identify the SVAR model using a series of short-run, long-run, and sign restrictions based on the model and economic theory. Then we use this framework to investigate whether pass-through is shock-dependent and whether the drivers of exchange rate fluctuations can explain observed changes in estimated pass-through coefficients over time.

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[6] Our analysis is closest to this paper, but we explore a richer set of causes behind exchange rate fluctuations and consider the effects on more variables directly relevant to monetary policy. We also use a different set of identifying assumptions—including short-run and sign restrictions as well as long-run restrictions.

[7] One exception is Kirby and Meaning (2014), which discusses how different shocks affect the degree of exchange rate pass-through for the UK using NIESR's global structural model.

[8] See Mishkin (2008) http://www.federalreserve.gov/newsevents/speech/mishkin20080307a.htm.

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

Our results show 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 leading to the exchange rate fluctuation. For example, global shocks and monetary policy shocks that cause an appreciation (depreciation) tend to cause a greater decrease (increase) in import prices than other shocks causing comparable currency movements. These global and monetary policy shocks also tend to generate greater pass-through to consumer prices in the medium term. In contrast, domestic demand shocks tend to have smaller effects on import prices and very different effects on consumer prices. These different degrees of pass-through are consistent with the theoretical predictions and can be explained by the different ways in which firms respond to the different types of shocks causing the exchange rate to fluctuate. For example, if an exchange rate appreciation is driven by stronger domestic demand, the boost to demand supports prices and this outweighs the drag on inflation from cheaper imports. In contrast, if an exchange rate appreciation is driven by tighter monetary policy, the simultaneous contraction in demand reduces inflationary pressure and this price effect amplifies the drag on inflation from cheaper imports.

This framework of considering the shocks behind exchange rate fluctuations can help explain why the degree of exchange rate pass-through has varied 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). Our model suggests that the distribution of shocks behind this depreciation was different than behind exchange rate fluctuations on average. Negative global shocks and domestic supply shocks (which correspond to greater pass-through) were relatively important drivers of this depreciation, while negative domestic demand shocks (which correspond to less pass-through) had a relatively smaller weight. An example shows that the composition of shocks driving sterling's sharp depreciation in this period would have caused pass-through to consumer prices to roughly double relative to what occurred during 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 2013-2015Q1 is also different from the distribution of shocks driving the depreciation during the crisis. Our model predicts that this should have caused pass-through to recently fall sharply relative to that observed in the crisis period, a prediction supported by recent movements in import prices.

These findings have important implications for monetary policy. Most important, they suggest that policymakers should not assume that pass-through is constant or use rules of thumb to predict pass-through. Instead, they need to update their estimates based on the nature of the

shocks driving exchange rate fluctuations. This should substantially improve their ability to forecast how exchange rate movements will affect import prices and consumer prices, and thereby their ability to forecast inflation and set monetary policy appropriately.

The remainder of the paper is as follows. Section II sets out the theoretical foundations for the link between exchange rates and prices and analyses how pass-through depends on the shock affecting the exchange rate. Section III discusses our empirical methodology for estimating pass-through following different shocks, including the identification strategy, the data, and the estimation technique. Section IV discusses the central results on how different shocks correspond to different degrees of pass-through to import prices and to the overall price level. Section V applies the framework to investigate whether it can help us understand observed changes in pass-through in the UK since 1993. Section VI discusses some extensions and robustness checks. Section VII concludes.

## II.    Exchange rate pass-through in theory

We begin by developing a standard open-economy DSGE model in order to investigate pass-through and analyse how it depends on the underlying shocks moving the exchange rate. Our model builds on the framework used in Eggertsson *et al.* (2014) and is similar to the SIGMA model developed by Erceg *et al.* (2006).

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 each of these countries. There are two types of households in each country: households who have access to the financial markets and that we name Ricardian or optimizing households (denoted with superscript *O*); and households who do not have access to financial markets and are therefore constrained to consume their entire income every period. We name the latter households rule-of-thumb households (denoted with superscript *R*). While Ricardian consumers face complete financial markets domestically, international financial markets are incomplete in that only nominal bonds are traded across countries. Ricardian households supply differentiated labour inputs and set wages in a staggered fashion, whereas rule-of-thumb households supply a homogenous labour input taking wages as given. Firms produce differentiated traded and non-traded 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. The monetary authorities follow a persistent interest rate rule with a flexible domestic CPI inflation target. Appendix A presents the equilibrium equations for this model.

We consider the impact of six shocks in this model: changes in domestic productivity, domestic demand (preference), domestic monetary policy, shocks to the UIP condition (an exogenous exchange rate shock), global productivity and global demand (of which the last two shocks affect both countries simultaneously). 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. To take into account that there is uncertainty about the precise estimates of the structural parameters in our model and to ensure that our results do not hinge on a particular parameter combination, we allow each of the structural parameters to take on values within a range. In particular, in order to examine the impact of a shock, we simulate that shock many times while each time choosing different Home and Foreign parameter values from the specified ranges, assuming that the parameters are independently and uniformly distributed over those ranges. As a result of these simulations, we get a distribution of impulse responses to each shock which reflect different economic structures. The parameter ranges are shown in Table 1.

**Table 1: Parameter ranges**

| Description | Parameter | Range |
|---|---|---|
| Population in Home country | $n$ | 0.05 |
| Discount factor | $\beta$ | 0.99 |
| Yield sensitivity to external debt | $\delta$ | 0.01 |
| **Home/Foreign country parameters:** | | |
| Degree of openness | $op_H, op_F$ | [0.2,0.4] |
| Inverse of the Frish elasticity of labour supply | $\eta_H, \eta_F$ | [1.5,2.5] |
| Risk aversion coefficient | $\sigma_H, \sigma_F$ | [1,1.2] |
| Price stickiness parameter in sector k | $\alpha_H^k, \alpha_F^k$ | [0.25,0.9] |
| Wage stickiness parameter in sector k | $\alpha_{k,H}^w, \alpha_{k,F}^w$ | [0.25,0.9] |
| Intra-temporal elasticity of substitution in sector k | $\theta_H^k, \theta_F^k$ | [3,11] |
| Elasticity of substitution between labour inputs in sector k | $\theta_{k,H}^w, \theta_{k,F}^w$ | [3,11] |
| Elasticity of substitution between traded H and F goods | $\phi_H, \phi_F$ | [0.5,1] |
| Elasticity of substitution between traded and non-traded goods | $\varphi_H^N, \varphi_F^N$ | [0.4,1] |
| Proportion of rule of thumb households | $\lambda_H^R, \lambda_F^R$ | [0.1,0.4] |
| Proportion of firms setting export prices in their own currency (PCP) | $\gamma_H, \gamma_F$ | [0.25,0.75] |
| **Home/Foreign monetary policy rule parameters:** | | |
| Interest rate persistence | $\alpha_H^R, \alpha_F^R$ | [0.5,0.7] |
| Interest rate sensitivity to CPI inflation | $\alpha_H^\pi, \alpha_F^\pi$ | [1.1,1.3] |

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 (LCP) exporters. Some of these LCP exporters face sticky prices, and they 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.

The determinants of exporters' pricing decisions, namely expected marginal costs and demand conditions, 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 in the traded sector and foreign productivity $\left(\frac{W_{T,t}^*}{A_t^*}\right)$; and the mark-up over marginal costs ($mkup_t^*$). In other words,

$$P_{F,t} = s_t \, mkup_t^* \left(\frac{W_{T,t}^*}{A_t^*}\right).$$

We can then decompose any change in the import price level (relative to the level of traded prices) into changes in the terms of trade, $\frac{s_t P_{T,t}^*}{P_{T,t}}$ (which will be highly correlated with changes in the nominal exchange rate), changes in average marginal costs, and changes in the mark-up over average marginal costs:

$$\widehat{\frac{P_{F,t}}{P_{T,t}}} = \widehat{\frac{s_t P_{T,t}^*}{P_{T,t}}} + \widehat{mkup}_t^* + \widehat{\frac{W_{T,t}^*}{P_{T,t}^*}} - \hat{A}_t^* \, ,$$

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.

Using this decomposition, 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 and can therefore serve as a benchmark.[10] 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 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 red line in Figure 1 shows the estimated changes to mark-ups after such an exogenous exchange rate shock that causes a 1% appreciation.

**Figure 1: Foreign exporters' mark-up after selected shocks**
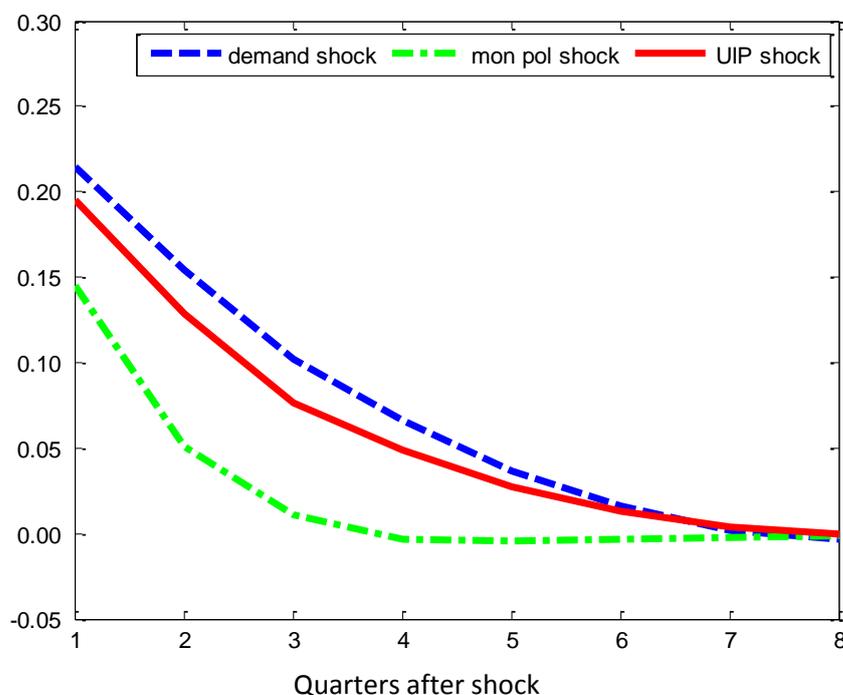


**Note:** The figure depicts the average percentage change in foreign exporters' mark-up (relative to domestic traded prices) following a shock which appreciates the exchange rate by 1%, in the median case. The picture looks similar for other percentiles of the distribution of impulse responses for the mark-up (though the magnitudes are different).

Figure 2 provides more details on the other adjustments that occur in response to this 1% appreciation caused by such an exogenous UIP shock. Import prices instantaneously fall by around 0.7% following the 1% appreciation, implying that foreign exporters' average mark-up increases following the domestic appreciation (as shown in Figure 1). Over time, import prices adjust by being

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[10] 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.

reduced in domestic currency. 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. The second stage of pass-through to the CPI is almost full after two years (i.e. the CPI has fallen by 30% of the level of the nominal exchange rate appreciation, which is the average share of imports in the parameterized model). The monetary policymakers in the model are simply assumed to follow a flexible inflation targeting rule, so that they loosen monetary policy in response to the fall in import prices and the CPI.[11]

**Figure 2: The impact of an exogenous exchange rate change on selected variables**
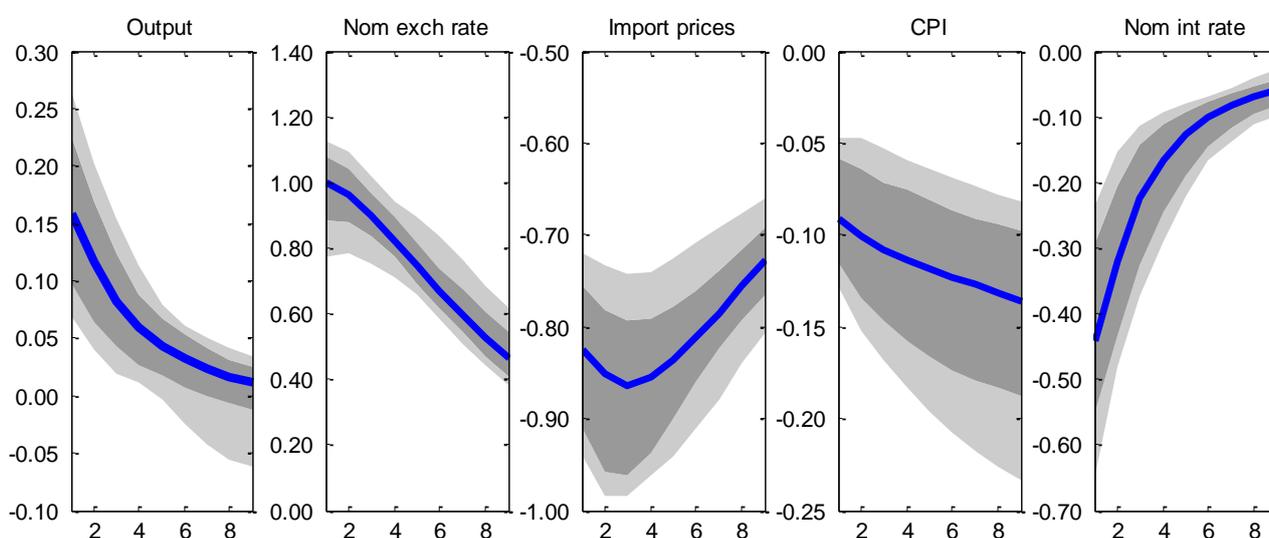


**Note:** This figure depicts the effects of an exogenous exchange rate shock causing the nominal exchange rate to appreciate by 1% in the first quarter on: the percentage change in domestic output relative to steady state, the level of the nominal exchange rate; the import price level, the CPI, and the percentage point change in the nominal interest rate. The x-axis shows the quarters following the shock which happens in quarter 1. The impulse responses are computed by solving the model 1000 times selecting all the parameters randomly from a uniform distribution over the parameter ranges specified in Table 1. From the obtained impulse responses, the figures report the median impulse response from the 1000 simulations in blue, as well as the central 90% and 68% of the distribution of impulse responses in different shades.

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. However, the extent to which the average mark-up increases (decreases) in the face of an appreciation (depreciation) 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). In a similar way, consumer prices will be determined not only

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[11] 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, which ignores other factors that are part of the monetary policy decision process.

by the change in import prices multiplied by their share of the consumption basket, but also by the impact of the exchange rate shock through other channels. Therefore, the final impact on consumer 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: domestic demand and monetary policy shocks.

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 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 3.

## **Figure 3: The impact of a demand shock on selected variables**
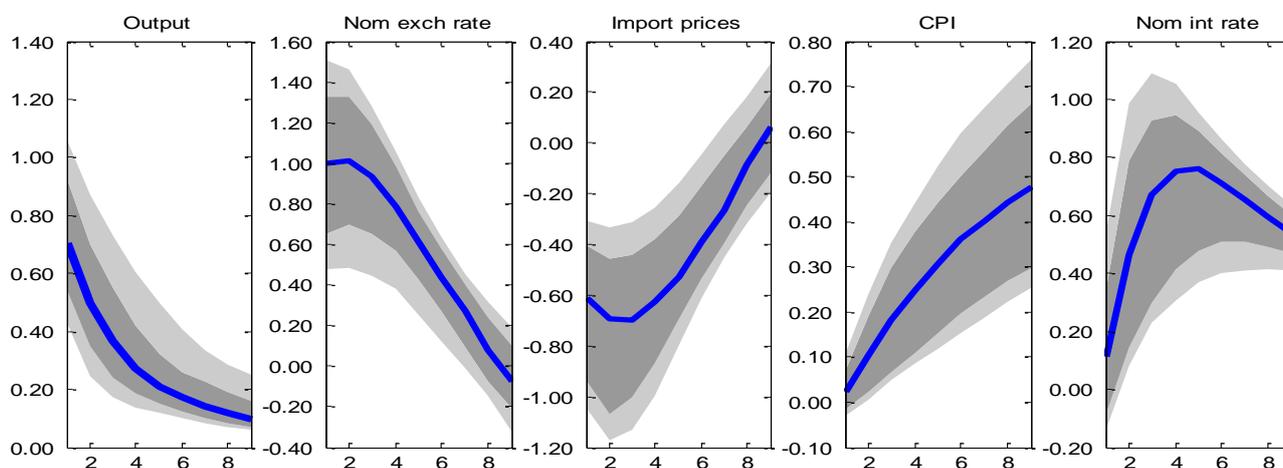


**Note:** This figure depicts the effects of a positive demand shock causing the nominal exchange rate to appreciate by 1% in the first quarter on: the percentage change in domestic output relative to steady state, the level of the nominal exchange rate; the import price level, the CPI, and the percentage point change in the nominal interest rate. The x-axis shows the quarters following the shock. The impulse responses are computed by solving the model 1000 times selecting all the parameters randomly from a uniform distribution over the parameter ranges specified in Table 2. From the obtained impulse responses, the figures report the median impulse response from the 100 simulations in blue, as well as the 90th and 68th percentiles of the distribution of impulse responses in different shades.

Figure 1 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). Most striking, 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; in contrast to our usual expectation, the CPI <u>rises</u> despite the fall in import prices.

Finally, consider a negative *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 4. Exporters will therefore more fully incorporate the exchange rate move into cheaper import prices rather than increase their margins. Indeed, Figure 1 shows that in this scenario, margins only increase by 0.15% after the appreciation— much less than in the previous two scenarios—and quickly fall back to zero. Exchange rate pass-through to import prices is complete after 4 quarters, about the half the time as in the other cases. 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 4: The impact of a monetary policy shock on selected variables**
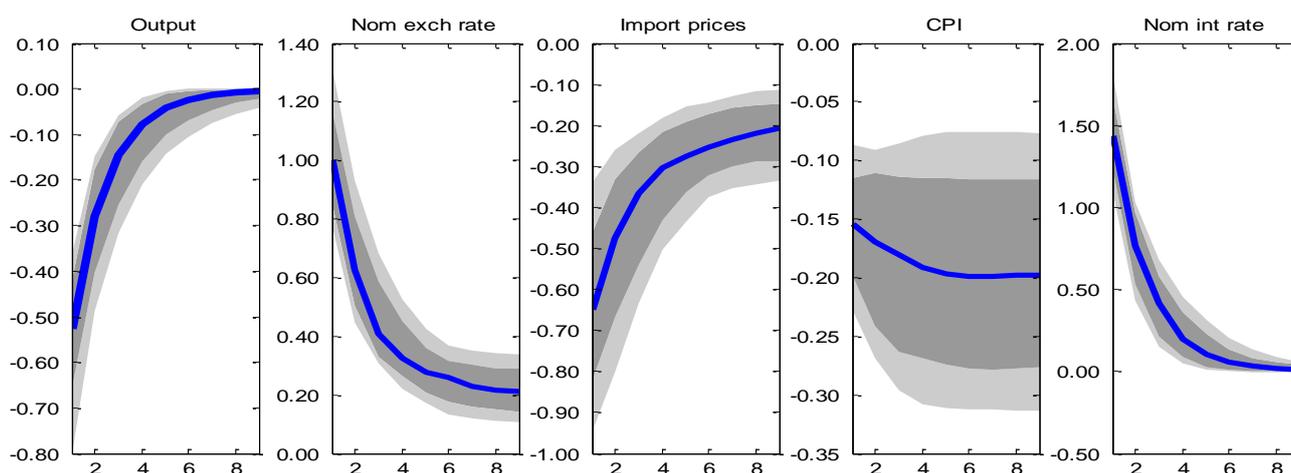


**Note:** This figure depicts the effects of a tightening of monetary policy causing the nominal exchange rate to appreciate by 1% in the first quarter on: the percentage change in domestic output relative to steady state, the level of the nominal exchange rate; the import price level, the CPI, and the percentage point change in the nominal interest rate. The x-axis shows the quarters following the shock. The impulse responses are computed by solving the model 1000 times selecting all the parameters randomly from a uniform distribution over the parameter ranges specified in Table 2. From the obtained impulse responses, the figures report the median impulse response from the 100 simulations in blue, as well as the 90th and 68th percentiles of the distribution of impulse responses in different shades.

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 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 any of these cases, theory clearly predicts that pass-through differs across shocks. Next, we propose an empirical framework for estimating pass-through which is able to take into account that pass-through may be shock-dependent.

## III.     Empirical methodology

### a. Identification strategy

Our empirical framework for studying pass-through allows us to estimate how the six domestic and global shocks incorporated in the theoretical model impact the exchange rate, as well as import and consumer prices. Specifically, we consider the impact of domestic supply, domestic demand, global supply, global demand, domestic monetary policy, and exogenous exchange rate shocks. This is a wider variety of shocks than previously considered in related literature and encompasses all shocks that could be important determinants of exchange rate movements. For example, a change in oil prices would be captured as a global supply 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 movements in monetary policy as well as exchange rates—is to use economic theory to identify the shocks of interest separately using either short-run sign restrictions or zero restrictions (in the short or long-run). The identification strategies used in the sparse 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 with different origins. 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 both import and consumer prices, we identify shocks using a combination of zero short- and long-run restrictions, as well as sign restrictions. These restrictions are consistent with the framework developed in the Section II. Their application to UK data implies the restrictions summarised in Table 2 and are based on three sets of assumptions.

**Table 2: Identification restrictions**

| | UK supply shock | UK demand shock | UK monetary policy shock | Exogenous exchange rate shock | Global supply shock | Global demand 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 supply shocks 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),[12] and is widely used in the SVAR literature, including by Shambaugh (2008) and Erceg, Gust and Guerrieri (2005). We incorporate this identifying assumption for both the UK and the global supply shock separately— either of which can impact UK GDP in the long run. Global supply shocks can incorporate oil price shocks, as well as global technology shocks.

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, see e.g. Liu, Mumtaz and Theophilopoulou (2011) and Carriere-Swallow and Céspedes (2013). Instead, only global shocks (to either global supply or global demand) 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, and that global demand shocks also incorporate those caused by policy abroad (e.g., foreign monetary policy) as well as other transitory global 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 theoretically by the open-economy DSGE model presented in Section II. 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. [13] 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

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[12] 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.

[13] 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, Gust and Guerrieri (2005).

(forthcoming) 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. Indeed, while the global supply shock captures any global shocks which might affect UK output in the long run, the demand shock captures any transitory global shocks, e.g. global demand shocks, foreign monetary policy shocks or other temporary shocks. We also do not put any restrictions on how import prices—a key variable for pass-through—respond to any of the shocks. This combination of sign restrictions—together with the zero restrictions described previously — constitute the minimum number of economically sensible restrictions that allow us to identify the shocks of interest separately.

The impulse responses from our theoretical model presented in Section II support these key assumptions in our identification scheme. For example Figure 3 shows that a domestic demand shock implies a positive correlation between output and the CPI. It also shows that after a positive demand shock, the exchange rate appreciates, inflation increases, and monetary policy (which follows a flexible inflation-targeting interest rate rule) adjusts with an increase in the interest rate. Also consistent with our identification assumptions, a monetary policy shock that leads to an increase in interest rates, as shown in Figure 4, 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 2.

**b. 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[14] through 2015q1 on the following six variables: UK GDP, UK CPI, the UK shadow Bank Rate (Shadow BR), the Sterling Exchange Rate Index (ERI), UK Import Prices, and Foreign Export Prices. GDP is UK real GDP growth. CPI is UK Consumer Price Index inflation, 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

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[14] The first and second quarter of 1993 are only used as explanatory variables in the estimation.

or quantitative easing (QE) undertaken by the Bank of England (BoE) Monetary Policy Committee after that.[15] ERI is 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[16]. Import prices measures import price inflation by the ONS price deflator for total imports (goods and services). Finally, Foreign Export Prices is world (ex-UK) export prices (including oil prices), which is constructed by averaging the export price indices of 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.

### c. Estimation method

The SVAR model is estimated using Bayesian methods with standard Minnesota priors.[17] The standard errors, percentiles and confidence intervals reported below are based on a Gibbs sampling procedure, from which we save the final 1,000 repetitions.

We include two lags of the endogenous variables in line with the lag length preferred by the Schwarz information criterion. Because the Akaike information criteria favoured one lag, we also estimated the model with only one lag to confirm that the reported results are unchanged by our lag selection. The sign restrictions shown in Table 2 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.

## IV.    Results

### a.    Impulse responses

This section uses the identification strategy, data and estimation method discussed in the last section to estimate the impulse responses of shocks to domestic supply, domestic demand, monetary policy, the exchange rate, global supply, and global demand on GDP, the CPI, interest rates, the nominal exchange rate index, import prices, and world export prices for the UK from

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[15] 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).
[16] For further detail see http://www.bankofengland.co.uk/statistics/Pages/iadb/notesiadb/effective_exc.aspx
[17] This assumes each variable follows a random walk process and is independent from the other endogenous variables in the model. The hyperparameter values are as follows: λ1=0.2, λ2=0.5, λ3=1, λ4=10,000.

1993q1 through 2015q1. The resulting sets of six impulse responses are shown in Appendix B, Figures B.1 through B.6.

The series of impulse responses are consistent with economic theory and the model developed in Section II on the effects of the six shocks in our model. They also respect the short- and long-run restrictions we have imposed. We will not discuss each set of impulse responses in detail here. Instead, we will 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 import and consumer prices relative to the exchange rate.

A crucial feature of these impulse responses is the behaviour of the exchange rate in response to the different shocks and nature of the shock that causes the initial 1% appreciation. These exchange-rate paths are used as the denominators in calculating the implied profiles of pass-through to import and consumer prices in the following section and are shown in the graphs in Appendix B for each respective shock. First, a positive domestic supply shock causes the exchange rate to appreciate in the median case, albeit with wide confidence bands (Figure B.1).[18] 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 II, and is more tightly estimated (Figure B.2). It is worth noting that, also in line with the theoretical model, this appreciation is associated with a less than one-for-one fall in import prices and a rise in consumer prices. Third, a shock from tighter monetary policy or an increase in the exchange rate due to exogenous factors both cause an appreciation – as a result of our identifying restrictions for the short-term responses (Figures B.3 and B.4, respectively).

Finally, the two global shocks generate exchange rate appreciations in the median case and both have very wide confidence bands (Figures B.5 and B.6). The global supply shock could be interpreted as a positive global productivity shock or a fall in oil or other commodity prices. The negative global demand shock could be interpreted generally as a transitory shock that has a negative effect on global prices, such as a 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 supply and demand shocks having

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[18] 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 (Corsetti *et al.*, 2008b).

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.

b. **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 and consumer price inflation 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 and consumer 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 5 graphs the median of these ratios of the impulse responses for import prices (Figures 5.a and 5.b) and consumer prices (Figures 5.c and 5.d) for the 20 quarters following the shocks. We differentiate between the effects of the four domestic and two global shocks in order to highlight that the import price movements corresponding to global shocks also incorporate the effect of the global shocks on foreign export prices—as well as any exchange rate effects as occurs with the domestic shocks. Different percentiles of the ratios at selected horizons are also reported in Appendix B, Table B.1 for the first stage of pass-through to import prices and in Table B.2 for the overall pass-through to consumer prices.

Before examining these results in detail, however, it is useful to begin by assessing if the overall patterns agree with basic results on pass-through documented widely in the literature and in the microeconomic data. A quick comparison between the estimates for the first-stage of pass-through (Appendix Table B.1, Figures 5.a and 5.b) and those for overall pass-through to consumer prices (Appendix Table B.2, Figures 5.c and 5.d) 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 fairly rapid and largely complete within around a year after the initial shock. Figures 5.c and 5.d suggest that pass-through to consumer prices is somewhat slower, as would be expected, with the full impact more often around six to eight quarters after the initial shock. This is still, however, somewhat shorter than has historically been found in the academic literature.[19]

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[19] 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

Next, the results on the first-stage of pass-through in Figures 5.a and 5.b (and Appendix Table B.1) clearly indicate that different exchange-rate shocks corresponding to a 1% appreciation after 1 year have different effects on import prices. Of the domestic shocks, monetary policy shocks lead to the highest observed degree of pass-through. The magnitude is large—with import prices falling by almost 70% of the appreciation in two quarters (and by 85% by quarter six). As noted in our theoretical framework in Section II, this likely reflects the fact that the increase in interest rates exerts some additional downward pressure on import prices by supressing domestic demand. At the other extreme, the domestic demand shock has the lowest degree of first-stage pass-through—with less than 40% of the exchange rate appreciation being passed through to import prices after 5 quarters. This weaker effect is also intuitive; importers facing an appreciation linked to stronger domestic demand would have less incentive to reduce prices as much; increasing domestic prices gives them some leeway to increase margins without losing market share. These findings are consistent with the theoretical predictions. 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. 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 foreign shocks, as well as the direct exchange rate effects, on import prices.

Moving to the results on overall pass-through to consumer prices, exchange rate appreciations driven by five of the six shocks (all except domestic demand) generate the traditional result of lower consumer prices (see Figures 5.c and 5.d and Appendix Table B.2). The shocks to global supply, monetary policy, global demand, and domestic supply all generate large degrees of pass-through, with consumer prices falling by greater than 20% of the initial exchange rate appreciation after 8 quarters. The pass-through corresponding to the global supply shock is the greatest (at nearly 40% after 8 quarters), although this also incorporates effects of the global supply shock on foreign export prices. The effect of the domestic supply shock is the most short-lived (declining to about 10% after 20 quarters). The strong pass-through from monetary policy shocks (the second most powerful) is worth highlighting. It suggests that central banks need to consider the larger effects on prices after monetary policy shocks than would occur from exchange rate movements related to other types of shocks. Of the five shocks that exert downward pressure on prices, the exogenous exchange rate shock has the lowest estimated pass-through, with a 10% appreciation corresponding to less than a 1% fall in the CPI after 2 years. This smaller effect may

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academic literature. For example, Fisher (2015) and Forbes (2015a) discuss faster rates of pass-through in the US and UK, respectively.

reflect that an exogenous exchange rate shock is expected to be less permanent, thereby making firms with sticky prices more hesitant to lower prices.

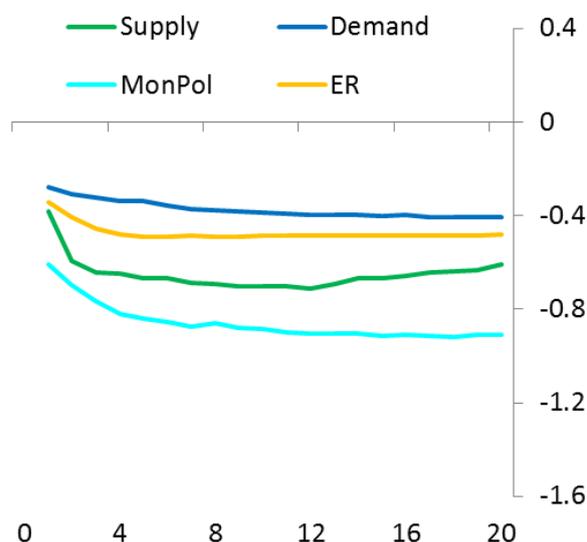**Figure 5.a: Pass-through to import prices for domestic shocks**



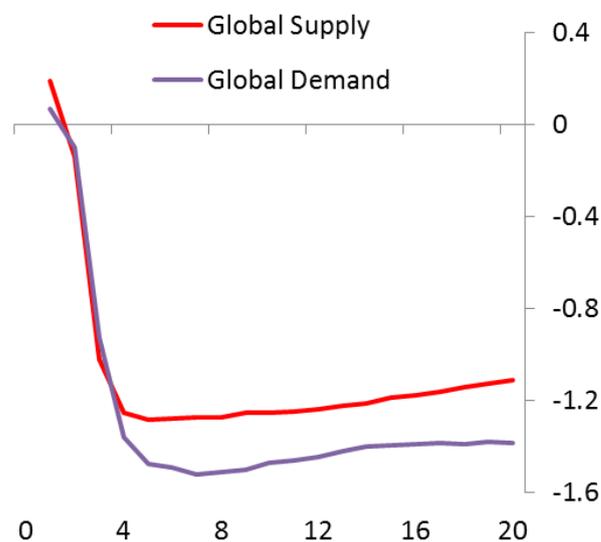**Figure 5.b: Pass-through to import prices for global shocks**



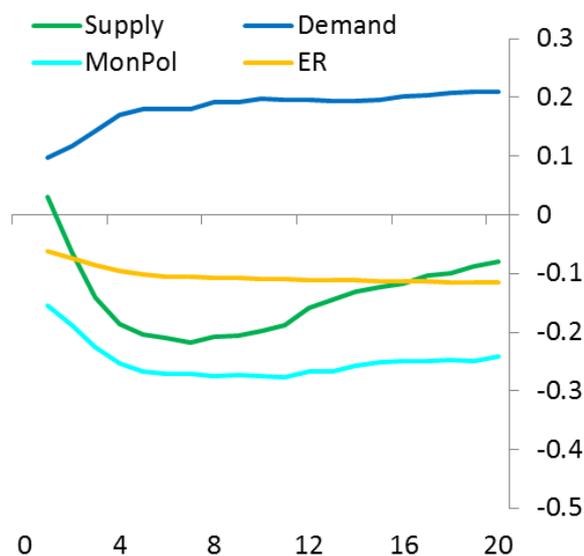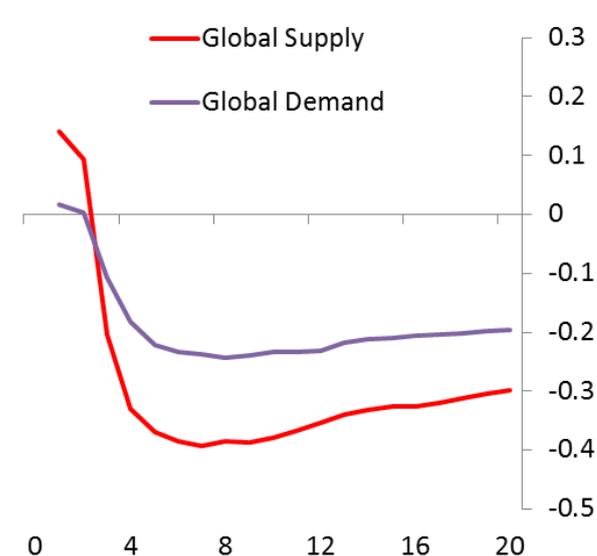**Figure 5.c: Pass-through to consumer prices for domestic shocks**



**Figure 5.d: Pass-through to consumer prices for global shocks**



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

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 <u>positive</u> pass-through 'coefficient'. This is consistent with the previous results; 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 positive domestic demand shocks would be expected to exhibit very different degrees of pass-through, and possibly even no decline in overall inflation. This is a sharp distinction to the effects of appreciations driven by other types of shocks.

To summarise, the impulse responses from our SVAR suggest that exchange rate movements corresponding to different economic shocks are associated with very different relative movements in the exchange rates and UK prices. A given appreciation or depreciation could have very different effects on import prices and overall inflation depending on what caused the initial currency movement. 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, especially without fully understanding the reason behind the movement.

**V.        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 new framework can help understand the link between movements in sterling and in UK import and consumer 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, import prices and consumer 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 3 reports 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 the six shocks to UK supply, UK demand, UK monetary policy, the exchange rate, global supply and global demand. 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 have been 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 global demand and supply shocks over the longer term (accounting for 15% and 17% of the exchange rate variation, respectively, at five years).

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 at any time period to be precise. Therefore, treating all exchange rate fluctuations as exogenous exchange rate shocks might not adequately capture the underlying dynamics, especially if the mix of shocks driving the exchange rate varies over time.

**Table 3: Forecast error variance decomposition**

| *Variable* | | *Proportion of variance explained by shocks to:* | | | | | |
|---|---|---|---|---|---|---|---|
| **GDP** | *Horizon (quarters)* | **Supply** | **Demand** | **Monetary policy** | **Exchange rate** | **Global supply** | **Global demand** |
| | 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 Section III.c for further detail on the estimation methodology.

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 6. A quick glance at the figure suggests that there are significant differences in the sources of exchange rate movements at different points in time. For example, the large depreciation during the 2007-2009 crisis was associated with larger global supply shocks (in red) and domestic supply shocks (in green) than occurred in most other periods. Both of these shocks — and especially the global supply shock — generate relatively higher degrees of exchange rate pass-through to both import and final consumer 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 degrees of pass-through. Providing yet another contrast, the most recent appreciation from 2013-2015 is associated with a relatively greater role of global shocks (to both supply and demand). These are correlated with large movements in import prices, but make it necessary to differentiate the direct impact on foreign export prices from global shocks separately from the effects of the exchange rate.

**Figure 6: Historical decomposition of year-on-year changes in nominal sterling ERI**
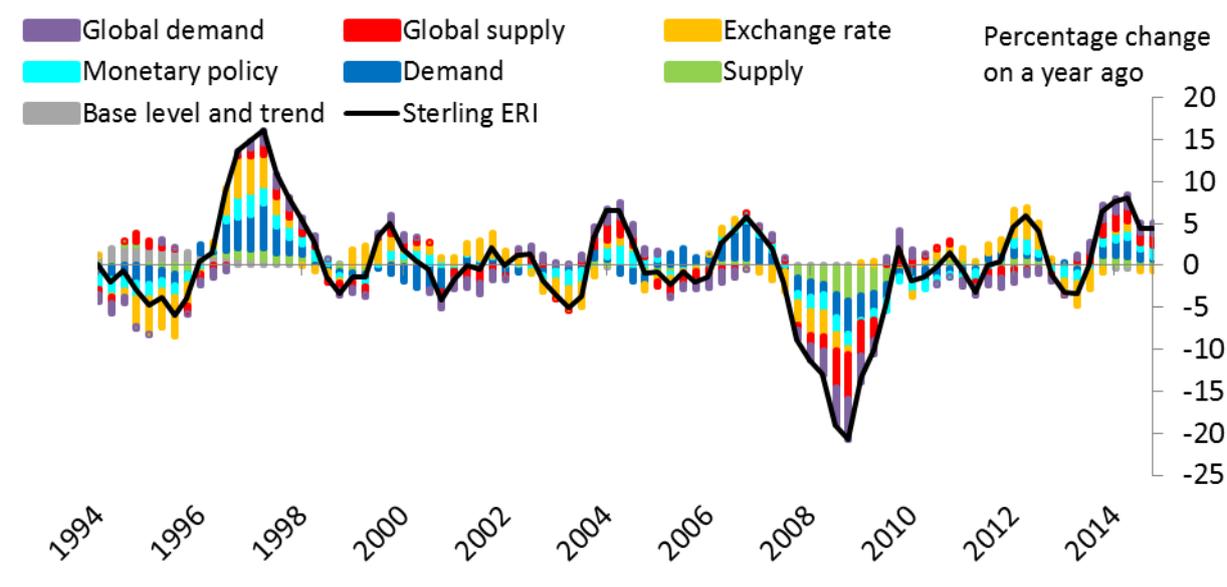


**Note:** The figure depicts the contribution of each of the six shocks to y/y changes in the ERI, in percent. The presented historical decompositions of the variables in the SVAR are the averages of the 1,000 historical decompositions obtained from the saved iterations of the estimation algorithm. See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

To clarify the distinctions between these periods, Table 4 decomposes the movements in sterling into the corresponding average contributions from the six shocks during these three episodes when sterling has recently 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 its historical average, but also relative to the 2007-9 depreciation. In contrast, global supply and global demand shocks play a substantially greater role in driving the 2007-9 episode, also both relative to their historical averages and relative to the earlier episode. Shocks to domestic supply are also very important in driving the 2007-9 episode, more so than the historical average as well as other periods of sharp exchange rate movements. Turning to the most recent sterling appreciation, global shocks are identified as the two most important contributors – even more so than during the 2007-9 depreciation. The fact that the contributions from different shocks varies across these episodes of sharp exchange rate movements indicates that the resulting exchange rate pass-through might also differ across episodes.

To better understand what these shock decompositions might imply for changes in pass-through over time, we can use our model estimates of the pass-through ratios shown in Figures 5a through 5d. 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 changes in global supply and demand or other shocks. Reduced form regressions estimating pass-through 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. In order 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 4. These coefficients cannot be directly derived from an endogenous model like ours, so it is necessary to make several additional assumptions. More specifically, for the first-stage of pass-through we assume that 50 to 100% of changes in foreign export prices are passed-through to UK import prices.[20] For the second-stage to consumer prices, we assume full pass-through from import prices and an import intensity of the CPI basket of around 30%.[21] 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.

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[20] This range is consistent with values obtained from simple time-series regressions of the pass-through from foreign export prices to UK import prices.

[21] 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 as that from the exchange rate but using constant import-intensity estimates and assuming 100% pass-through from import prices to consumer prices is a commonly applied approach (see Gopinath, 2015).

**Table 4: Shock decomposition of sterling exchange rate changes[a] and implied pass-through coefficients 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% |
| **Global supply** | 6% | 18% | 25% | 14% |
| **Global demand** | 8% | 17% | 23% | 13% |
| | | | | |
| *Unadjusted pass-through to import prices (not controlling for foreign export prices)* | *-0.67* | *-0.86* | *-0.99* | *-0.79* |
| *Unadjusted pass-through to consumer prices (not controlling for foreign export prices)* | *-0.08* | *-0.16* | *-0.18* | *-0.13* |
| *Adjusted pass-through to import prices[c]* | *-0.69 to -0.71* | *-0.89 to -0.92* | *-0.40 to -0.69* | |
| *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) Both of the "adjusted pass-through" measures assume 50% to 100% pass-through from world export prices. The measure for consumer prices also assumes a 30% CPI import intensity. These 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.

Focusing on the adjusted pass-through estimates at the bottom of Table 4, 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% and the CPI by at most 1%. In contrast, using the decomposition from the 2007-9 episode, the same 10% exchange rate movement would cause import prices to adjust by 9% and the CPI by around 2%. 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 about 20% and on the CPI by 100% !

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 4 suggests that a 10% exchange rate appreciation would have caused import prices to fall by 4% - 7%, and the CPI by 0.1% to 1%. These estimates are less precise due to the large movements in commodity prices

that occurred during this period and the uncertainty about how much of the changes in import prices reflected movements in commodity prices or effects of sterling's appreciation. But even using this broad range of estimates, pass-through has fallen substantively compared to that following the 2007-9 depreciation.

Additional details supporting this analysis are available in a similar decomposition of the shocks driving import price inflation, consumer price inflation, GDP growth, the shadow Bank Rate, and foreign export prices in the UK over the same period (Appendix Figures B.7 – B.11).[22] For example, Appendix Figure B.7 highlights that after the sterling depreciation in 2007-9, import price inflation was boosted by negative global supply 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. Global demand shocks appear to have consistently played an important role in affecting import prices over the full period (as also shown in Table 3), and global supply and demand both played a key role in the most recent decline in import prices since 2013. Similarly, the decomposition showing which shocks have driven changes in UK consumer price inflation (in Appendix Figure B.8) supports these results. It shows the unusually large role of negative global supply and UK supply shocks in driving up inflation in the 2007-9 episode (as well as affecting the exchange rate as documented above). 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. Particularly striking is the role of global supply and demand 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.

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 if this rule of thumb was used today, it would lead to inaccurate estimates of the extent of pass-through from recent fluctuations in sterling due to the different shocks driving these two large exchange rate movements. More specifically, this rule-of-thumb would generate forecasts predicting a greater drag on import prices

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[22] Some of these decompositions are not as directly relevant to our analysis of pass-through, but useful to understand the predictions of the framework developed in this paper.

and consumer price inflation than is likely to occur today.[23] But similarly, lower pass-through from the 2013-2015 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.    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.

### a.    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 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

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[23] The Bank of England recently adjusted its assumptions about the extent of exchange rate pass-through to import prices from the higher levels 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.

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 Figure 5.a. and 5.c. 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.[24] Table 5 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 5 show that the shocks driving large (relative to small) exchange rate movements are broadly similar.[25] 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 fundamentals and might not be expected to be as persistent. On the other hand, domestic and global supply shocks – which should capture slow-moving technological changes and might be more persistent – 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.

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[24] 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.

[25] This similarity in the types of shocks corresponding to the different types of exchange rate movements agrees with micro-level analysis performed at the Bank of England. This research has shown that there is little significant difference in pass-through from appreciations relative to depreciations, although it does find some evidence of bigger effects from large currency movements than small movements (Forbes, 2014).

The results from comparing the shocks and corresponding pass-through resulting from sterling appreciations relative to depreciations (both larger than 3%) are also similar. These results are shown in the bottom two rows of Table 5. 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.

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.

**Table 5: 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 | Global supply | Global demand | 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.

b. **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.[26] 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

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[26] Defined as periods with consecutive quarters when the year-on-year change in the exchange rate was greater than the 10% threshold.

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.[27] We use the same framework as discussed in Section V, and Appendix C shows the resulting estimates of the pass-through 'coefficients' for each of the six shocks to import and consumer prices. Table 6 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.

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. Domestic supply shocks are somewhat more important in the shorter sample, but generate lower pass-through to consumer prices in the base model, so that their contribution to overall implied pass-through to consumer prices is broadly similar.

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) suggest that monetary policy shocks have a greater impact on the exchange rate during the longer sample, but this associated with less pass-through to prices (see Appendix C, Figures C.1 and C.3). 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

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[27] For further detail see
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221567/ukecon_mon_policy_framework.pdf

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. The two global shocks also appear to have different effects on UK variables across the two sample periods (Appendix C, Figures C.2 and C.4). 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 6. 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-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.[28] 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 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 6, remain little changed.

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

**Table 6: Forecast error variance decompositions of the exchange rate and implied pass-through over different samples**

| | Baseline: 1993-2015q1 | 1980-2015q1 | 1998-2015q1 | 1993-2015q1 with post-2007 dummy |
|---|---|---|---|---|
| | | Estimation period: | | |
| Supply | 10% | 5% | 12% | 10% |
| Demand | 25% | 18% | 21% | 21% |
| Monetary policy | 17% | 45% | 15% | 15% |
| Exogenous exchange rate | 21% | 23% | 22% | 25% |
| Global supply | 14% | 4% | 17% | 17% |
| Global demand | 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.

### c. 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 7 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 CPI across all six shocks but their signs are unchanged (negative for all shocks except the domestic demand shock).

**Table 7: 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% |
| Global supply | 14% | 15% | 18% | 12% |
| Global demand | 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 7, 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. This lower degree of pass-through to core-CPI relative to CPI applies for all six shocks in our model.

Next, we replaced the shadow Bank Rate with the one-year instantaneous forward UK government bond yield as our measure of domestic interest rates.[29] 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

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[29] Using interest rates of longer maturity seemed unsuitable in our set-up as these are often driven by term premia to a larger extent 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.

monetary policy surprises[30]. This lowers the implied overall degree of pass-through slightly compared to our baseline specification.

## VII.    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. But unfortunately, although the academic literature has made noteworthy strides in improving our understanding of different degrees of pass-through across countries and industries, we have a more limited understanding of why currency movements can have such different effects at different times—even within one 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 a new 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, but instead begin by trying to 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 consumer prices in ways that are not only different in magnitude and duration, but even in 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,

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[30] 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.

and the monetary policy framework.[31] 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 to analysing exchange rate pass-through.

The results indicate that adding this new dimension to the framework for assessing the impact of currency fluctuations on prices 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 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 recent appreciation has been more muted. This clearer understanding of the past should improve our ability to predict the impact of currency movements on inflation, as well as to better understand the effects of central banks own actions on exchange rates and inflation in their own economies. As a result, it will hopefully improve the ability of central banks to set monetary policy appropriately in the future.

### Appendix A. DSGE model equilibrium equations

Details of a version of this model with all firms setting prices in their own currency figure in Hjortsoe, Weale and Wieladek (forthcoming).

The equilibrium is a set of stationary processes

$$\left\{ \begin{array}{c} Y_t, Y_t^*, Y_{H,t} Y_{F,t}, C_t, C_t^*, C_{N,t}, C_{N,t}^*, C_{T,t}, C_{T,t}^*, L_{T,t}^O, L_{N,t}^O, L_{T,t}^{O*}, L_{N,t}^{O*}, C_t^R, C_t^{R*}, C_t^O, C_t^{O*}, C_{H,t}, C_{H,t}^*, C_{F,t}, C_{F,t}^*, L_{T,t}^R, L_{T,t}^{R*}, L_{N,t}^R, L_{N,t}^{R*}, \\[4pt] L_{T,t}, L_{T,t}^*, L_{N,t}, L_{N,t}^* \left(\frac{P_{H,t}}{P_{T,t}}\right), \left(\frac{P_{F,t}^*}{P_{T,t}^*}\right), \left(\frac{P_{F,t}^{LCP}}{P_{T,t}}\right), \left(\frac{P_{F,t}^{LCP*}}{P_{T,t}^*}\right), \left(\frac{P_{H,t}^{total}}{P_{T,t}}\right), \left(\frac{P_{H,t}^{total*}}{P_{T,t}^*}\right), \left(\frac{P_{T,t}}{P_t}\right), \left(\frac{P_{T,t}^*}{P_t^*}\right), \left(\frac{P_{N,t}}{P_t}\right), \left(\frac{P_{N,t}^*}{P_t^*}\right), \left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right), Q_t, \left(\frac{B_{F,t}}{P_t}\right), \\[4pt] \pi_{H,t}, \pi_{F,t}^* \pi_{H,t}^*, \pi_{F,t}, \pi_{N,t}, \pi_{N,t}^*, \left(\frac{W_{T,t}}{P_{T,t}}\right), \left(\frac{W_{T,t}^*}{P_{T,t}^*}\right), \left(\frac{W_{N,t}}{P_t}\right), \left(\frac{W_{N,t}^*}{P_t^*}\right), \pi_{H,t}^W, \pi_{F,t}^{W*}, \pi_{N,t}^W, \pi_{N,t}^{W*}, Disp_t, Disp_t^N, Disp_t^*, Disp_t^{N*}, \\[4pt] x_{1,t}, x_{1,t}^*, x_{2,t}, x_{2,t}^*, x_{1,t}^{LCP}, x_{1,t}^{LCP*}, x_{2,t}^{LCP}, x_{2,t}^{LCP*}, x_{1,t}^N, x_{1,t}^{N*}, x_{2,t}^N, x_{2,t}^{N*}, x_{1,t}^W, x_{1,t}^{W*}, x_{2,t}^W, x_{2,t}^{W*}, x_{1,t}^{WN}, x_{1,t}^{WN*}, x_{2,t}^{WN}, x_{2,t}^{WN*}, i_t, i_t^* \end{array} \right\}$$

for $t \geq 0$ which satisfy the 83 equilibrium equations below given the processes for

$\left\{ A_t, A_t^*, B_t^*, B_t^*, UIP_t, \psi_t^I, \psi_t^{I*} \right\}_{t=0}^{\infty}$ and the initial conditions consisting of the variables above for $t < 0$.

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[31] See Gopinath (2015) for the role of currency invoicing and Stulz (2007) for the role of monetary policy expectations. Also see Fleer, Rudolf and Zurlinden (2015), who show that sectors with a high price-change dispersion tend to have larger pass-through than sectors with low price dispersion.

$Y_t, Y_t^*$ denote Home and Foreign GDP, $Y_{H,t} Y_{F,t}$ denote Home and Foreign tradable output, $C_t$, $C_t^*, C_{N,t}, C_{N,t}^*, C_{T,t}, C_{T,t}^*$ denote total consumption, consumption of non-traded goods and consumption of traded goods respectively in the Home and Foreign countries. $L_{T,t}^O, L_{N,t}^O, L_{T,t}^{O*}, L_{N,t}^{O*}$ and

$L_{T,t}^R, L_{T,t}^{R*}, L_{N,t}^R, L_{N,t}^{R*}$ denote labour supplied by respectively Ricardian and Rule-of-thumb consumers to the traded and non-traded sectors in each country while $C_t^R, C_t^{R*}, C_t^O, C_t^{O*}$ denote their respective consumption. $C_{H,t}, C_{H,t}^*$ denote consumption of traded goods produced in country H by Home households and by Foreign households while $C_{F,t}, C_{F,t}^*$ denote consumption of traded goods produced in country F by respectively Home and Foreign households.

All other variables refer to relative prices.

$A_t, A_t^*, B_t^I, B_t^*, UIP_t, \psi_t^I, \psi_t^{I*}$ denote the country-specific productivity shocks, preference shocks, the exogenous exchange rate shock and the monetary policy shocks.

Equilibrium equations:

Aggregate demand for traded output:

$$Y_{H,t} = a_H \left(\frac{P_{H,t}}{P_{T,t}}\right)^{-\varphi} C_{T,t} + \frac{1-n}{n}(1-a_F)\left[\gamma_H \left(\frac{P_{H,t}^{LCP*}}{P_{T,t}^*}\right)^{-\varphi} + (1-\gamma_H)\left(\frac{P_{H,t}}{P_{T,t}}\right)^{-\varphi}\left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)^{\varphi}\right] C_{T,t}^*$$

$$Y_{F,t} = \frac{n}{1-n}(1-a_H)\left[\gamma_F \left(\frac{P_{F,t}^{LCP}}{P_{T,t}}\right)^{-\varphi} + (1-\gamma_F)\left(\frac{P_{F,t}^*}{P_{T,t}^*}\right)^{-\varphi}\left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)^{-\varphi}\right] C_{T,t} + a_F \left(\frac{P_{F,t}^*}{P_{T,t}^*}\right)^{-\varphi} C_{T,t}^*$$

GDP:

$$Y_t = \left(\frac{P_{H,t}}{P_{T,t}}\right)\left(\frac{P_{T,t}}{P_t}\right)C_{H,t} + \frac{1-n}{n}(1-a_F)\left(\frac{P_{H,t}^{total*}}{P_{T,t}^*}\right)\left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)\left(\frac{P_{T,t}}{P_t}\right)C_{H,t}^* + \left(\frac{P_{N,t}}{P_t}\right)C_{N,t}$$

$$Y_t^* = \left(\frac{P_{F,t}^*}{P_{T,t}^*}\right)\left(\frac{P_{T,t}^*}{P^*}\right)C_{F,t}^* + \frac{n}{1-n}(1-a_H)\left(\frac{P_{F,t}^{total}}{P_{T,t}}\right)\left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)^{-1}\left(\frac{P_{T,t}^*}{P^*}\right)C_{F,t} + \left(\frac{P_{N,t}^*}{P_t^*}\right)C_{N,t}^*$$

Consumption demand:

$$C_{T,t} = a_T \left(\frac{P_{T,t}}{P_t}\right)^{-\varphi_H^N} C_t$$

$$C_{N,t} = (1-a_T)\left(\frac{P_{N,t}}{P_t}\right)^{-\varphi_H^N} C_t$$

$$C_{T,t}^* = a_T^* \left(\frac{P_{T,t}^*}{P_t^*}\right)^{-\varphi_H^N} C_t^*$$

$$C_{N,t}^* = (1 - a_T^*) \left(\frac{P_{N,t}^*}{P_t^*}\right)^{-\varphi_H^N} C_t^*$$

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

$$C_{F,t} = (1 - a_H) \left[ \gamma_F \left(\frac{P_{F,t}^{LCP}}{P_{T,t}}\right)^{-\varphi_H} + (1 - \gamma_F) \left(\frac{P_{F,t}^*}{P_{T,t}^*}\right)^{-\varphi_H} \left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)^{-\varphi_H} \right] C_{T,t}$$

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

$$C_{H,t}^* = (1 - a_F) \left[ \gamma \left(\frac{P_{H,t}^{LCP*}}{P_{T,t}^*}\right)^{-\varphi_H} + (1 - \gamma) \left(\frac{P_{H,t}}{P_{T,t}}\right)^{-\varphi_H} \left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)^{\varphi_H} \right] C_{T,t}^*$$

Price equations for PCP firms:

$$\frac{x_{1,t}}{x_{2,t}} = \left(\frac{1 - \alpha_H^T \pi_{H,t+1}^{\theta_H^T - 1}}{1 - \alpha_H^T}\right)^{\frac{1}{1 - \theta_H^T}}$$

$$x_{1,t} = \frac{\theta_H^T}{(\theta_H^T - 1)} \left(\frac{P_{H,t}}{P_{T,t}}\right)^{-\varphi} \left[ a_H C_{T,t} + \frac{1-n}{n}(1 - a_F) \left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)^{\varphi} C_{T,t}^* \right] C_t^{O-\sigma_H} \frac{W_{T,t}}{P_{T,t}} \frac{P_{T,t}}{P_t}$$
$$+ \alpha_H^T \beta \pi_{H,t+1}^{\theta_H^T} x_{1,t+1}$$

$$x_{2,t} = (1 + \tau_H^T) \left(\frac{P_{H,t}}{P_{T,t}}\right)^{-\varphi} \left[ a_H C_{T,t} + \frac{1-n}{n}(1 - a_F) \left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)^{\varphi} C_{T,t}^* \right] C_t^{O-\sigma_H} \frac{P_{H,t}}{P_{T,t}} \frac{P_{T,t}}{P_t}$$
$$+ \alpha_H^T \beta \pi_{H,t+1}^{\theta_H^T - 1} x_{2,t+1}$$

$$Disp_t = (1 - \alpha_H^T) \left(\frac{1 - \alpha_H^T \pi_{H,t}^{\theta_H^k - 1}}{1 - \alpha_H^T}\right)^{\frac{-\theta_H^T}{1 - \theta_H^T}} + \alpha_H^T \pi_{H,t}^{\theta_H^T} Disp_{t-1}$$

$$\frac{x_{1,t}^*}{x_{2,t}^*} = \left( \frac{1 - \alpha_F^T \pi_{F,t+1}^{*\theta_F^T-1}}{1 - \alpha_F^T} \right)^{\frac{1}{1-\theta_F^T}}$$

$$x_{1,t}^* = \frac{\theta_F^T}{(\theta_F^T - 1)} Y_{F,t} \, C_t^{O*-\sigma_H} \frac{W_{T,t}^*}{P_{T,t}^*} \frac{P_{T,t}^*}{P_t^*} + \alpha_F^T \beta \pi_{F,t+1}^{*\theta_F^T} x_{1,t+1}^*$$

$$x_{2,t}^* = (1 + \tau_F^T) Y_{F,t} \, C_t^{O*-\sigma_H} \frac{P_{F,t}^*}{P_{T,t}^*} \frac{P_{T,t}^*}{P_t^*} + \alpha_F^T \beta \pi_{F,t+1}^{*\theta_F^T-1} x_{2,t+1}^*$$

$$Disp_t^* = (1 - \alpha_H^T) \left( \frac{1 - \alpha_H^T \pi_{H,t}^{\theta_H^k-1}}{1 - \alpha_H^T} \right)^{\frac{-\theta_H^T}{1-\theta_H^T}} + \alpha_H^T \pi_{H,t}^{\theta_H^T} Disp_{t-1}$$

Price equations for LCP firms:

$$\frac{x_{1,t}^{LCP}}{x_{2,t}^{LCP}} = \left( \frac{1 - \alpha_H^T \pi_{H,t+1}^{*\theta_H^T-1}}{1 - \alpha_H^T} \right)^{\frac{1}{1-\theta_H^T}}$$

$$x_{1,t}^{LCP} = \frac{\theta_H^T}{(\theta_H^T - 1)} \frac{1-n}{n} (1 - a_F) \left( \frac{P_{H,t}^{*LCP}}{P_{T,t}^*} \right)^{-\varphi} C_{T,t}^* C_t^{O-\sigma_H} \frac{W_{T,t}}{P_{T,t}} \frac{P_{T,t}}{P_t} + \alpha_H^T \beta \pi_{H,t+1}^{\theta_H^T} x_{1,t+1}^{LCP}$$

$$x_{2,t}^{LCP} = (1 + \tau_H^T) \frac{1-n}{n} (1 - a_F) \left( \frac{P_{H,t}^{*LCP}}{P_{T,t}^*} \right)^{1-\varphi} C_{T,t}^* C_t^{O-\sigma_H} \left( \frac{s_t P_{T,t}^*}{P_{T,t}} \right) \frac{P_{T,t}}{P_t} + \alpha_H^T \beta \pi_{H,t+1}^{\theta_H^T-1} x_{2,t+1}^{LCP}$$

$$\pi_{H,t}^* = \left( \frac{P_{H,t}^{*LCP}}{P_{T,t}^*} \right) \left( \frac{P_{H,t-1}^{*LCP}}{P_{T,t-1}^*} \right)^{-1} \left( \frac{P_{F,t-1}^*}{P_{T,t-1}^*} \right) \left( \frac{P_{F,t}^*}{P_{T,t}^*} \right)^{-1} \pi_{F,t}^*$$

$$\left( \frac{P_{H,t}^{total*}}{P_{T,t}^*} \right) = \gamma_H \left( \frac{P_{H,t}^{*LCP}}{P_{T,t}^*} \right) + (1 - \gamma_H) \left( \frac{P_{H,t}}{P_{T,t}} \right) \left( \frac{s_t P_{T,t}^*}{P_{T,t}} \right)^{-1}$$

$$\frac{x_{1,t}^{LCP*}}{x_{2,t}^{LCP*}} = \left( \frac{1 - \alpha_F^T \pi_{F,t+1}^{\theta_F^T-1}}{1 - \alpha_F^T} \right)^{\frac{1}{1-\theta_F^T}}$$

$$x_{1,t}^{LCP*} = \frac{\theta_F^T}{(\theta_F^T - 1)} \frac{n}{1-n} (1 - a_H) \left( \frac{P_{F,t}^{LCP}}{P_{T,t}} \right)^{-\varphi_H} C_{T,t} C_t^{O*-\sigma_F} \frac{W_{T,t}^*}{P_{T,t}^*} \frac{P_{T,t}^*}{P_t^*} + \alpha_F^T \beta \pi_{F,t+1}^{\theta_F^T} x_{1,t+1}^{LCP*}$$

$$x_{2,t}^{LCP*} = (1 + \tau_F^T) \frac{n}{1-n} (1 - a_H) \left( \frac{P_{F,t}^{LCP}}{P_{T,t}} \right)^{1-\varphi_H} C_{T,t} C_t^{O*-\sigma_F} \left( \frac{s_t P_{T,t}^*}{P_{T,t}} \right)^{-1} \frac{P_{T,t}^*}{P_t^*} + \alpha_F^T \beta \pi_{F,t+1}^{\theta_F^T-1} x_{2,t+1}^{LCP*}$$

$$\pi_{F,t} = \left(\frac{P_{F,t}^{LCP}}{P_{T,t}}\right)\left(\frac{P_{F,t-1}^{LCP}}{P_{T,t-1}}\right)^{-1}\left(\frac{P_{H,t-1}}{P_{T,t-1}}\right)\left(\frac{P_{H,t}}{P_{T,t}}\right)^{-1}\pi_{H,t}$$

$$\left(\frac{P_{F,t}^{total}}{P_{T,t}}\right) = \gamma_F\left(\frac{P_{F,t}^{LCP}}{P_{T,t}}\right) + (1-\gamma_F)\left(\frac{P_{F,t}^*}{P_{T,t}^*}\right)\left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)$$

Price equations for non-tradable firms:

$$\frac{x_{1,t}^N}{x_{2,t}^N} = \left(\frac{1 - \alpha_H^N \pi_{N,t+1}^{\theta_H^N-1}}{1-\alpha_H^N}\right)^{\frac{1}{1-\theta_H^N}}$$

$$x_{1,t}^N = \frac{\theta_H^N}{(\theta_H^N-1)}C_{N,t}\,C_t^{O-\sigma_H}\frac{W_{N,t}}{P_t} + \alpha_H^N\beta\pi_{N,t+1}^{\theta_H^N}x_{1,t+1}^N$$

$$x_{2,t}^N = (1+\tau_H^N)C_{N,t}\,C_t^{O-\sigma_H}\frac{P_{N,t}}{P_t} + \alpha_H^N\beta\pi_{N,t+1}^{\theta_H^N-1}x_{2,t+1}^N$$

$$Disp_t^N = (1-\alpha_H^N)\left(\frac{1-\alpha_H^N\pi_{N,t}^{\theta_H^N-1}}{1-\alpha_H^N}\right)^{\frac{-\theta_H^T}{1-\theta_H^T}} + \alpha_H^N\pi_{N,t}^{\theta_H^N}Disp_{t-1}^N$$

$$\frac{x_{1,t}^{N*}}{x_{2,t}^{N*}} = \left(\frac{1-\alpha_F^N\pi_{N,t+1}^{*\theta_F^N-1}}{1-\alpha_F^N}\right)^{\frac{1}{1-\theta_F^N}}$$

$$x_{1,t}^{N*} = \frac{\theta_F^N}{(\theta_F^N-1)}C_{N,t}^*\,C_t^{O*-\sigma_H}\frac{W_{N,t}^*}{P_t^*} + \alpha_F^N\beta\pi_{N,t+1}^{*\theta_F^N}x_{1,t+1}^{N*}$$

$$x_{2,t}^{N*} = (1+\tau_F^N)C_{N,t}^*\,C_t^{O*-\sigma_F}\frac{P_{N,t}^*}{P_t^*} + \alpha_F^N\beta\pi_{F,t+1}^{*\theta_F^N-1}x_{2,t+1}^{N*}$$

$$Disp_t^{N*} = (1-\alpha_F^N)\left(\frac{1-\alpha_F^N\pi_{N,t}^{*\theta_F^N-1}}{1-\alpha_F^N}\right)^{\frac{-\theta_F^N}{1-\theta_F^N}} + \alpha_F^N\pi_{N,t}^{\theta_F^N}Disp_{t-1}^{N*}$$

$$\pi_{N,t} = \frac{P_{N,t}}{P_t}\frac{P_{t-1}}{P_{N,t-1}}\frac{P_{H,t-1}}{P_{T,t-1}}\frac{P_{T,t}}{P_{H,t}}\frac{P_{T,t-1}}{P_{t-1}}\frac{P_t}{P_{T,t}}\pi_{H,t}$$

$$\pi_{N,t}^* = \frac{P_{N,t}^*}{P_t^*}\frac{P_{t-1}^*}{P_{N,t-1}^*}\frac{P_{F,t-1}^*}{P_{T,t-1}^*}\frac{P_{T,t}^*}{P_{F,t}^*}\frac{P_{T,t-1}^*}{P_{t-1}^*}\frac{P_t^*}{P_{T,t}^*}\pi_{F,t}^*$$

Wage equations:

$$\frac{x_{1,t}^W}{x_{2,t}^W} = \left(\frac{1 - \alpha_H^W \pi_{H,t}^{W\theta_H^W - 1}}{1 - \alpha_H^W}\right)^{\frac{1+\theta_H^W \eta_H}{1-\theta_H^W}}$$

$$\frac{x_{1,t}^{WN}}{x_{2,t}^{WN}} = \left(\frac{1 - \alpha_{HN}^W \pi_{N,t}^{W\theta_{HN}^W - 1}}{1 - \alpha_{HN}^W}\right)^{\frac{1+\theta_{HN}^W \eta_H}{1-\theta_{HN}^W}}$$

$$x_{1,t}^W = \frac{\theta_H^W}{(\theta_H^W - 1)}\left(\frac{L_{T,t}^O}{a_T}\right)^{1+\eta_H} + \alpha_H^W \beta \pi_{H,t+1}^{W\theta_H^W(1+\eta_H)} x_{1,t+1}^W$$

$$x_{1,t}^{WN} = \frac{\theta_{HN}^W}{(\theta_{HN}^W - 1)}\left(\frac{L_{N,t}^O}{1 - a_T}\right)^{1+\eta_H} + \alpha_{HN}^W \beta \pi_{N,t+1}^{W\theta_{HN}^W(1+\eta_H)} x_{1,t+1}^{WN}$$

$$x_{2,t}^W = (1 - \tau_H^W) C_t^{O-\sigma_H} \frac{W_{H,t}}{P_{T,t}} \frac{P_{T,t}}{P_t}\left(\frac{L_{T,t}^O}{a_T}\right) + \alpha_H^W \beta \pi_{H,t+1}^{W\theta_H^W - 1} x_{2,t+1}^W$$

$$x_{2,t}^{WN} = (1 - \tau_{HN}^W) C_t^{O-\sigma_H} \frac{W_{N,t}}{P_t}\left(\frac{L_{N,t}^O}{1 - a_T}\right) + \alpha_{HN}^W \beta \pi_{N,t+1}^{W\theta_{HN}^W - 1} x_{2,t+1}^{WN}$$

$$\pi_{H,t}^W = \frac{W_{H,t}}{P_{T,t}} \frac{P_{T,t-1}}{W_{H,t-1}} \frac{P_{H,t-1}}{P_{T,t-1}} \frac{P_{T,t}}{P_{H,t}} \pi_{H,t}$$

$$\pi_{N,t}^W = \frac{W_{N,t}}{P_t} \frac{P_{t-1}}{W_{N,t-1}} \frac{P_{N,t-1}}{P_{t-1}} \frac{P_t}{P_{N,t}} \pi_{N,t}$$

$$\frac{x_{1,t}^{W*}}{x_{2,t}^{W*}} = \left(\frac{1 - \alpha_F^W \pi_{F,t}^{W*\theta_F^W - 1}}{1 - \alpha_F^W}\right)^{\frac{1+\theta_F^W \eta_F}{1-\theta_F^W}}$$

$$\frac{x_{1,t}^{WN*}}{x_{2,t}^{WN*}} = \left(\frac{1 - \alpha_{FN}^W \pi_{N,t}^{W*\theta_{FN}^W - 1}}{1 - \alpha_{FN}^W}\right)^{\frac{1+\theta_{FN}^W \eta_F}{1-\theta_{FN}^W}}$$

$$x_{1,t}^{W*} = \frac{\theta_F^W}{(\theta_F^W - 1)}\left(\frac{L_{T,t}^{O*}}{a_T^*}\right)^{1+\eta_F} + \alpha_F^W \beta \pi_{F,t+1}^{W*\theta_F^W(1+\eta_F)} x_{1,t+1}^{W*}$$

$$x_{1,t}^{WN*} = \frac{\theta_{FN}^{W}}{(\theta_{FN}^{W} - 1)} \left(\frac{L_{N,t}^{O*}}{1 - a_T^*}\right)^{1+\eta_F} + \alpha_{FN}^{W} \beta \pi_{N,t+1}^{W*\theta_{FN}^{W}(1+\eta_F)} x_{1,t+1}^{WN*}$$

$$x_{2,t}^{W*} = (1 - \tau_F^{W}) C_t^{O*-\sigma_H} \frac{W_{F,t}^*}{P_{T,t}^*} \frac{P_{T,t}^*}{P_t^*} \left(\frac{L_{T,t}^{O*}}{a_T^*}\right) + \alpha_H^{W} \beta \pi_{H,t+1}^{W\theta_H^{W}-1} x_{2,t+1}^{W*}$$

$$x_{2,t}^{WN*} = (1 - \tau_{FN}^{W}) C_t^{O*-\sigma_F} \frac{W_{N,t}^*}{P_t^*} \left(\frac{L_{N,t}^{O*}}{1 - a_T^*}\right) + \alpha_{FN}^{W} \beta \pi_{N,t+1}^{W*\theta_{FN}^{W}-1} x_{2,t+1}^{WN*}$$

$$\pi_{F,t}^{W*} = \frac{W_{F,t}^*}{P_{T,t}^*} \frac{P_{T,t-1}^*}{W_{F,t-1}^*} \frac{P_{F,t-1}^*}{P_{T,t-1}^*} \frac{P_{T,t}^*}{P_{F,t}^*} \pi_{F,t}^*$$

$$\pi_{N,t}^{W*} = \frac{W_{N,t}^*}{P_t^*} \frac{P_{t-1}^*}{W_{N,t-1}^*} \frac{P_{N,t-1}^*}{P_{t-1}^*} \frac{P_t^*}{P_{N,t}^*} \pi_{N,t}^*$$

Ricardian households:

$$\beta B_t \ E_t \frac{C_{t+1}^{O-\sigma_H}}{C_t^{O-\sigma_H}} \frac{(1 + i_t)}{\pi_{t+1}} = 1$$

$$\beta B_t \ E_t \frac{C_{t+1}^{O-\sigma_H}}{C_t^{O-\sigma_H}} \frac{(1 + i_t^*)}{\pi_{t+1}} \frac{Q_{t+1}}{Q_t} = \frac{1}{\Phi\left(\frac{s_t B_{F,t}}{P_t}\right)} UIP_t$$

$$\beta B_t^* E_t \frac{C_{t+1}^{O*-\sigma_F}}{C_t^{O*-\sigma_F}} \frac{(1 + i_t^*)}{\pi_{t+1}^*} = 1$$

Rule-of-thumb households:

$$C_t^{R} = a_T \left(\frac{W_{T,t}}{P_t}\right)^{\frac{1+\eta_H}{\eta_H}} + (1 - a_T) \left(\frac{W_{N,t}}{P_t}\right)^{\frac{1+\eta_H}{\eta_H}}$$

$$\frac{\left(\frac{L_{k,t}^{R}}{a_k}\right)^{\eta_H}}{C_t^{R-\sigma}} = \frac{W_{k,t}}{P_t}, \qquad k = T, N$$

$$C_t^{R*} = a_T^* \left(\frac{W_{T,t}^*}{P_t^*}\right)^{\frac{1+\eta_F}{\eta_F}} + (1 - a_T^*) \left(\frac{W_{N,t}^*}{P_t^*}\right)^{\frac{1+\eta_F}{\eta_F}}$$

$$\frac{\left(\frac{L_{k,t}^{R*}}{a_k^*}\right)^{\eta_F}}{C_t^{R*-\sigma}} = \frac{W_{k,t}^*}{P_t^*}, \qquad k = T, N$$

Aggregation across households:

$$L_{k,t} = (1 - \lambda_H^R)L_{k,t}^O + \lambda_H^R L_{k,t}^R, \qquad k = T, N$$

$$C_t = (1 - \lambda_H^R)C_t^O + \lambda_H^R C_t^R$$

$$L_{k,t}^* = (1 - \lambda_F^R)L_{k,t}^{O*} + \lambda_F^R L_{k,t}^{R*}, \qquad k = T, N$$

$$C_t^* = (1 - \lambda_F^R)C_t^{O*} + \lambda_F^R C_t^{R*}$$

Price indices:

$$P_t = \left[a_T P_{T,t}^{1-\varphi_H^N} + (1 - a_T)P_{N,t}^{1-\varphi_H^N}\right]^{\frac{1}{1-\varphi_H^N}}$$

$$P_t^* = \left[a_T^* P_{T,t}^{*1-\varphi_F^N} + (1 - a_T^*)P_{N,t}^{*1-\varphi_F^N}\right]^{\frac{1}{1-\varphi_F^N}}$$

$$P_{T,t} = \left[a_H P_{H,t}^{1-\varphi_H} + (1 - a_H)P_{F,t}^{total1-\varphi_H}\right]^{\frac{1}{1-\varphi_H}}$$

$$P_{T,t}^* = \left[a_F P_{F,t}^{*1-\varphi_F} + (1 - a_F)P_{H,t}^{total*1-\varphi_F}\right]^{\frac{1}{1-\varphi_F}}$$

Exchange rate definition:

$$Q_t = \left(\frac{s_t P_{T,t}^*}{P_{T,t}}\right)\left(\frac{P_{T,t}}{P_t}\right) \ \left(\frac{P_{T,t}^*}{P_t^*}\right)^{-1}$$

Production functions:

$$Disp_{T,t}Y_{H,t} = A_t \ L_{T,t}$$

$$Disp_{T,t}^*Y_{F,t}^* = A_t^* L_{T,t}^*,$$

$$Disp_{N,t}C_{N,t} = L_{N,t}$$

$$Disp_{N,t}^*C_{N,t}^* = L_{N,t}^*$$

Resource constraint:

$$C_t \ + \frac{s_t B_{F,t}}{P_t(1 + i_t^*)\Phi\left(\frac{s_t B_{F,t}}{P_t}\right)} = Y_t \ + \frac{s_t B_{F,t-1}}{P_t}$$

Monetary policy rules:

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

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

## Appendix B: Impulse responses and additional output from SVAR

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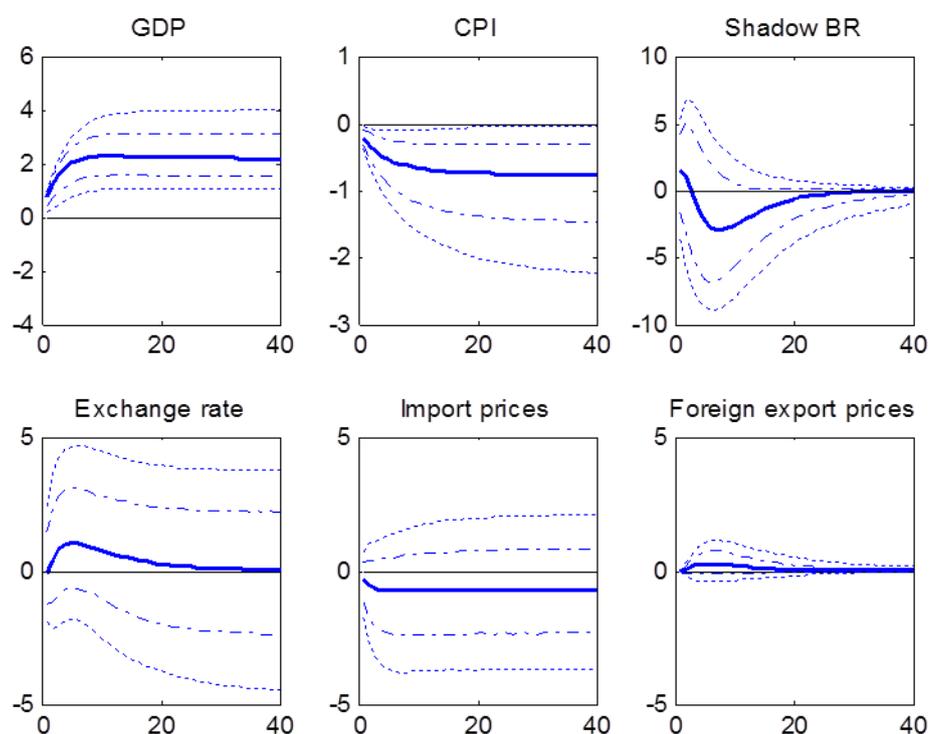


**Note:** These graphs report the median impulse responses (in solid lines) along with confidence bands at the 68% threshold (dashed lines) and 90% threshold (dotted lines) for all six variables to the respective shock. The responses for all variables except the interest rate – which is already expressed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

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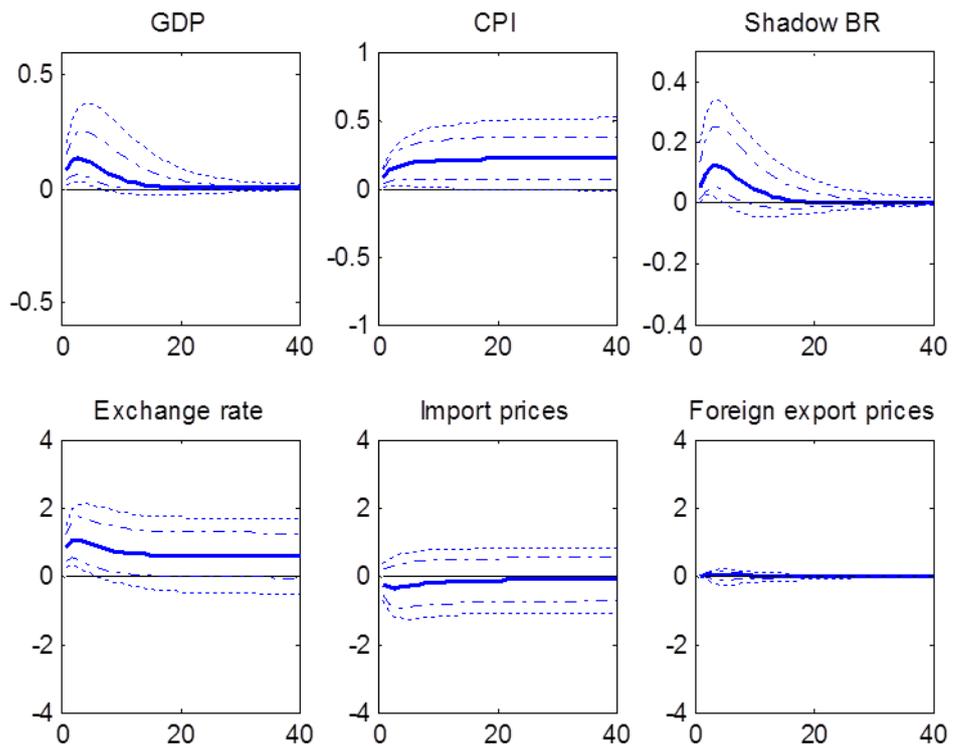


**Note:** See note to Figure B.1.

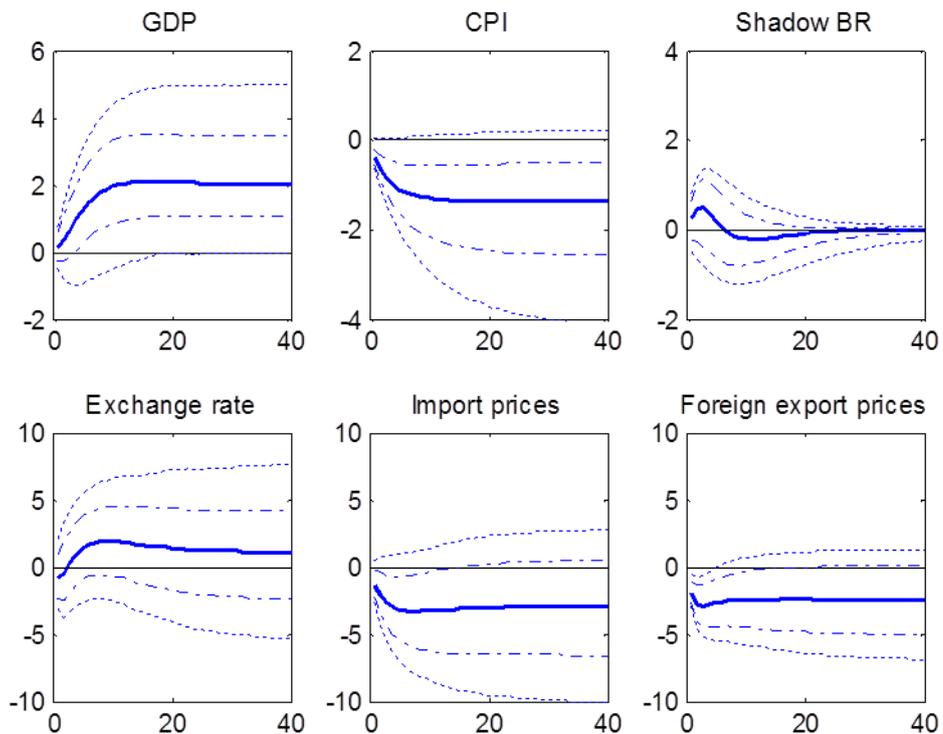**Figure B.3: Impulse responses to a UK monetary policy shock**
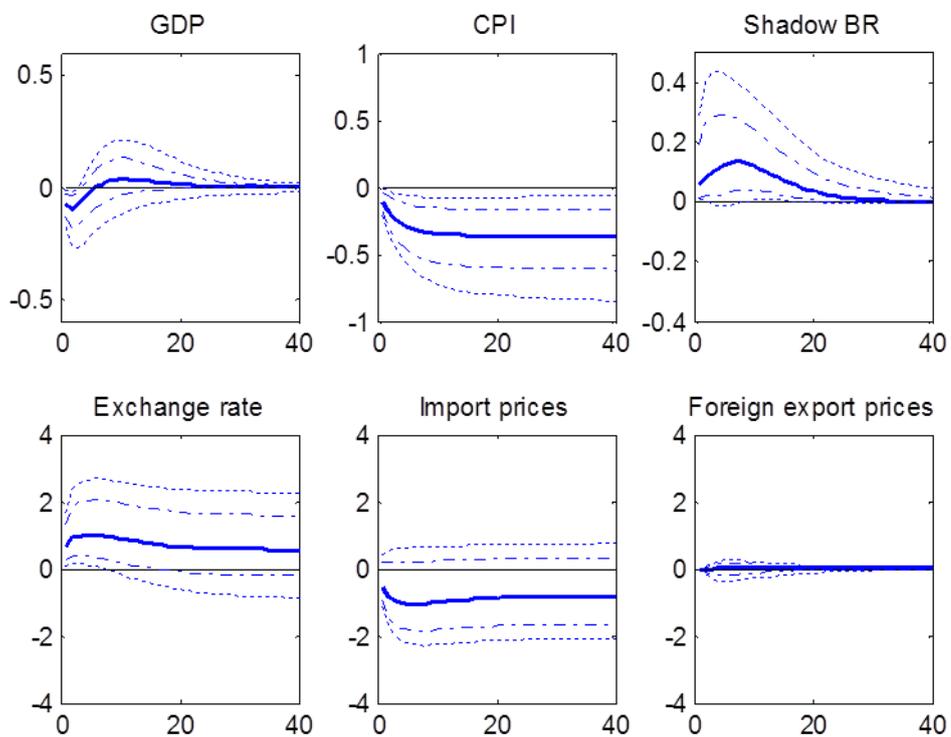


**Note:** See note to Figure B.1.

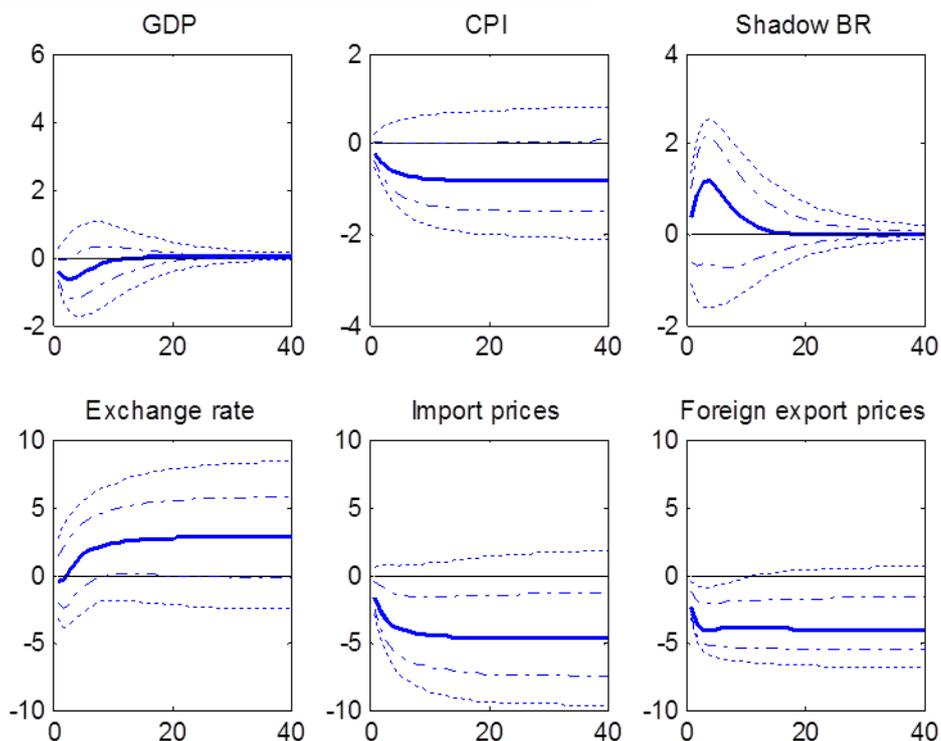**Figure B.4: Impulse responses to a UK exchange rate shock**
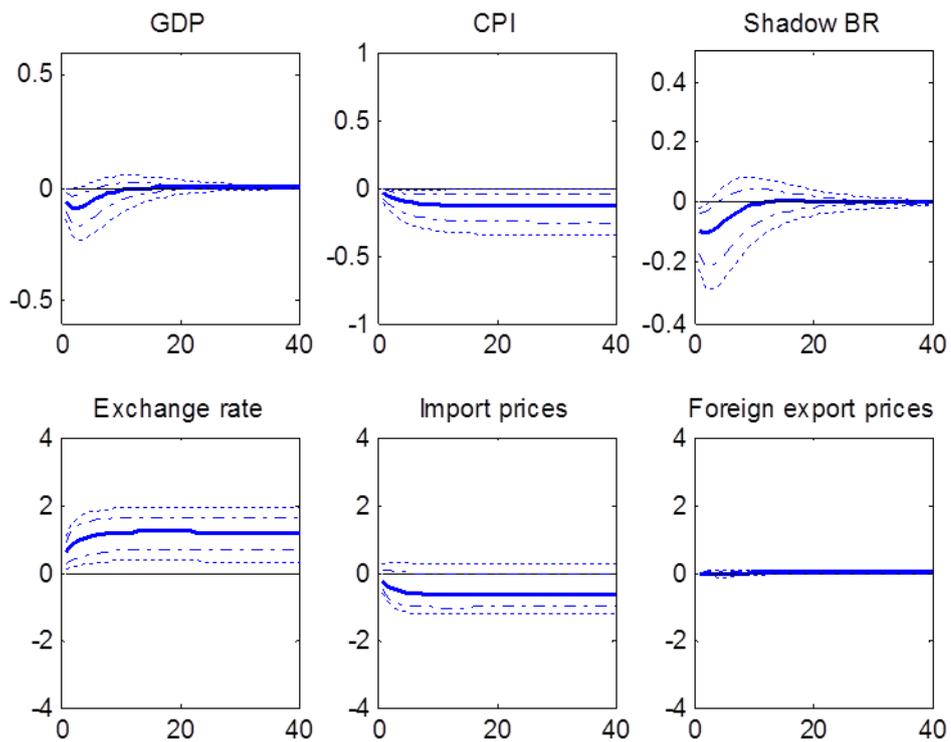


**Note:** See note to Figure B.1.

**Figure B.5: Impulse responses to a global supply shock**



**Note:** See note to Figure B.1.

**Figure B.6: Impulse responses to a global demand shock**



**Note:** See note to Figure B.1.

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

| Period | Percentile | Supply | Demand | Monetary policy | Exchange rate | Global supply | Global demand |
|---|---|---|---|---|---|---|---|
| 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 B.2: Pass-through to consumer prices by shock (ratio of consumer prices response to exchange rate response)**

| Period | Percentile | Supply | Demand | Monetary policy | Exchange rate | Global supply | Global demand |
|---|---|---|---|---|---|---|---|
| 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 B.7: Historical decomposition of year-on-year changes in UK import prices**
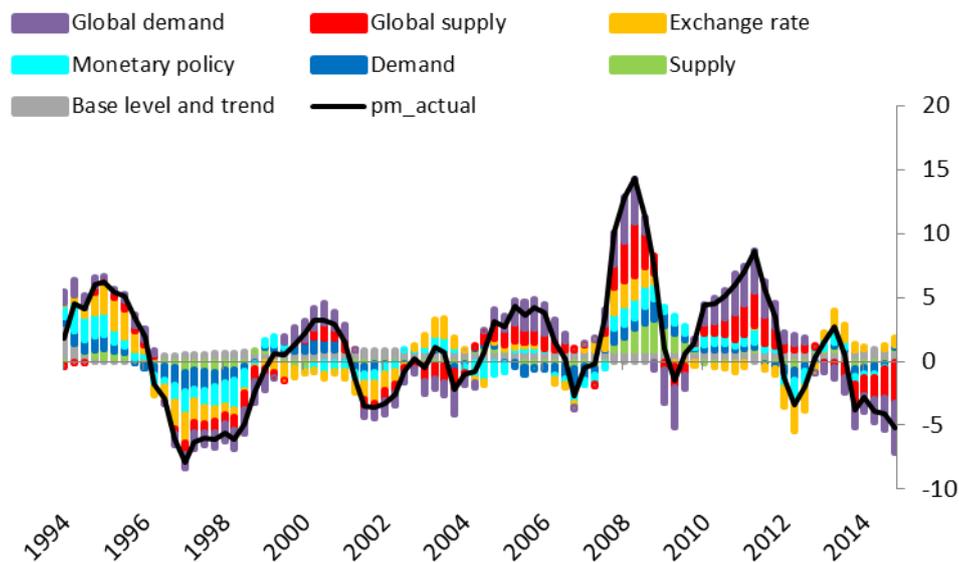


**Note:** See note to Figure 6.

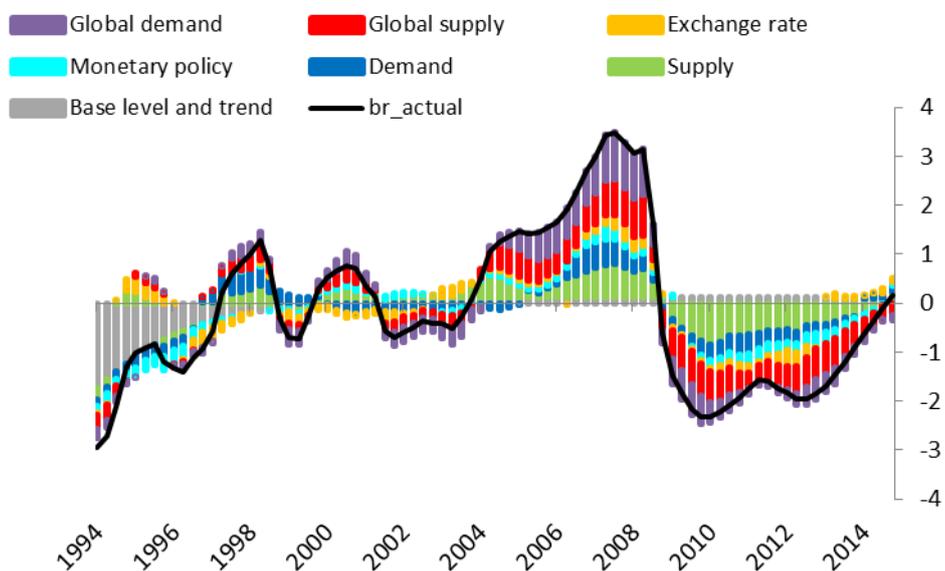**Figure B.8: Historical decomposition of year-on-year changes in consumer prices (excl. VAT changes)**
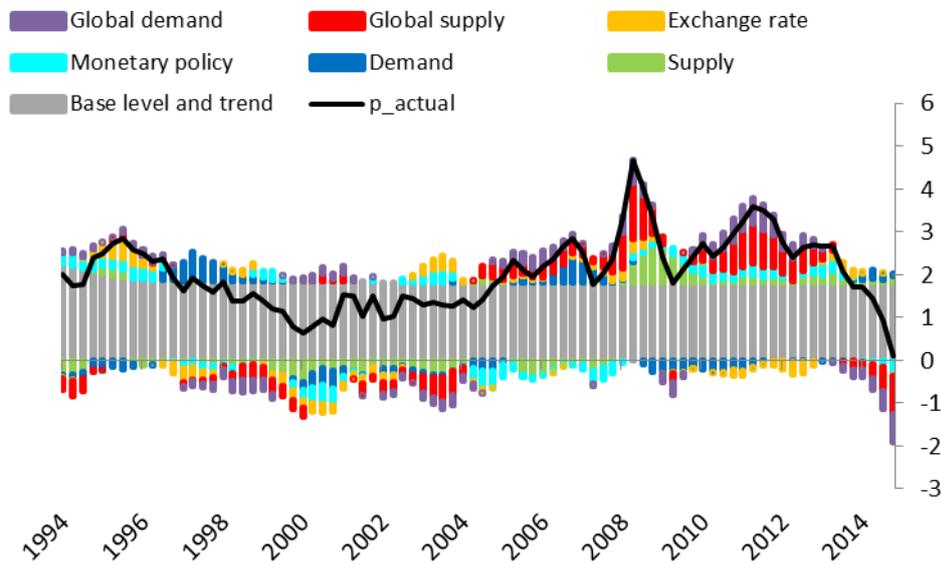


**Note:** See note to Figure 6.

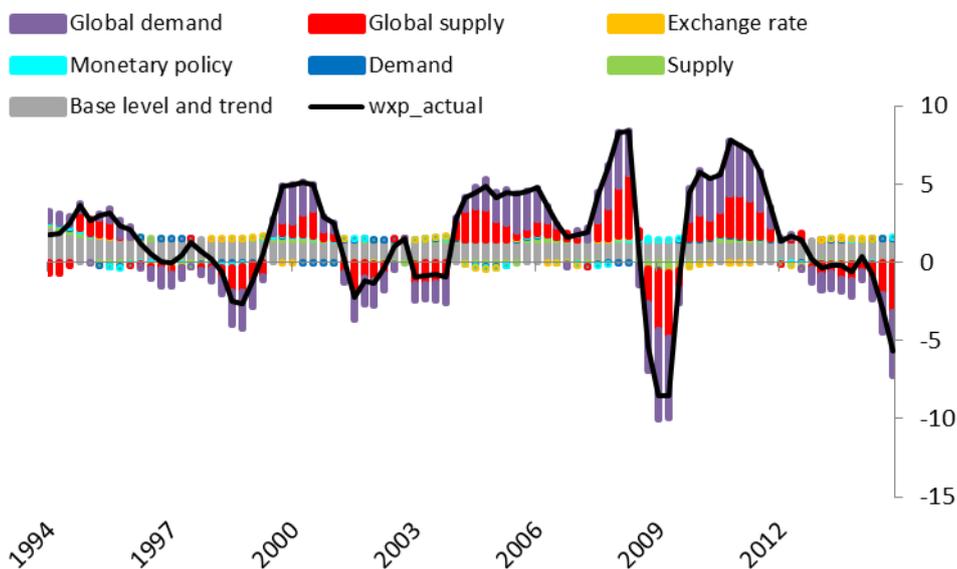**Figure B.9: Historical decomposition of year-on-year GDP growth**
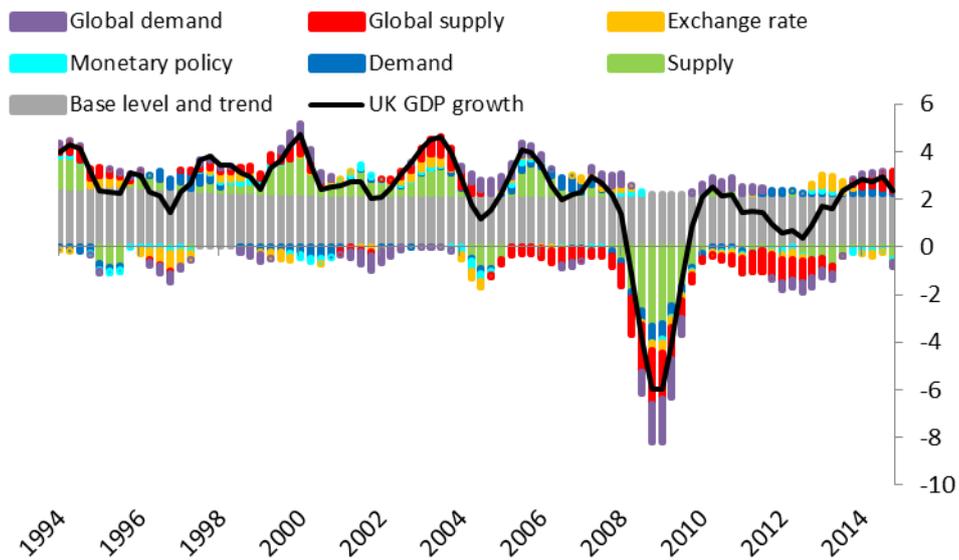


**Note:** See note to Figure 6.

**Figure B.10: Historical decomposition of detrended shadow Bank Rate**



**Note:** See note to Figure 6.

**Figure B.11: Historical decomposition of year-on-year changes in foreign export prices**



**Note:** See note to Figure 6.

**Appendix C: Results from Extending the SVAR Model for the 1980 – 2015 period**

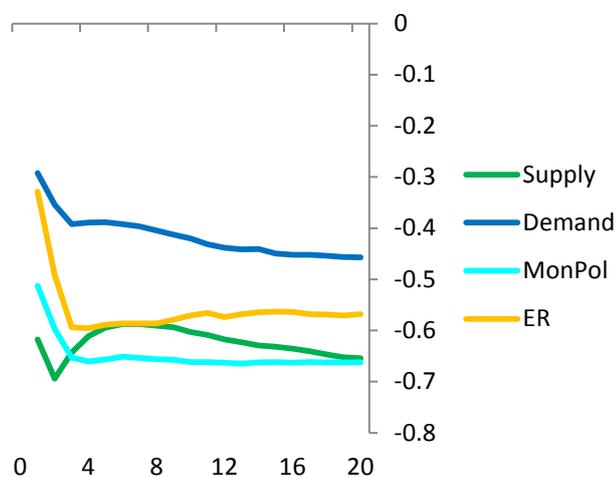**Figure C.1: Pass-through to import prices for domestic shocks**
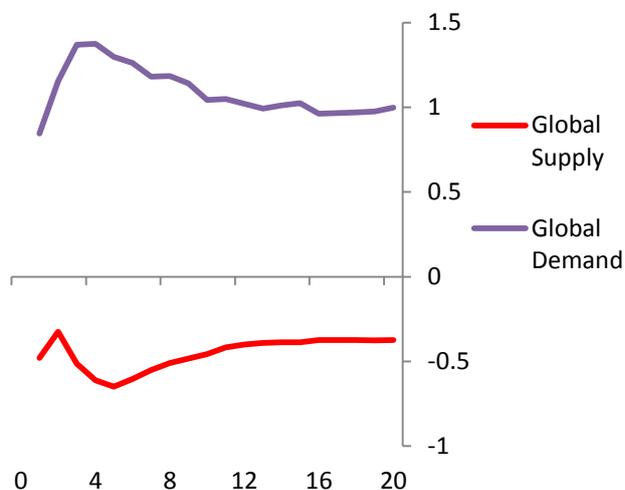


**Figure C.2: Pass-through to import prices for global shocks**



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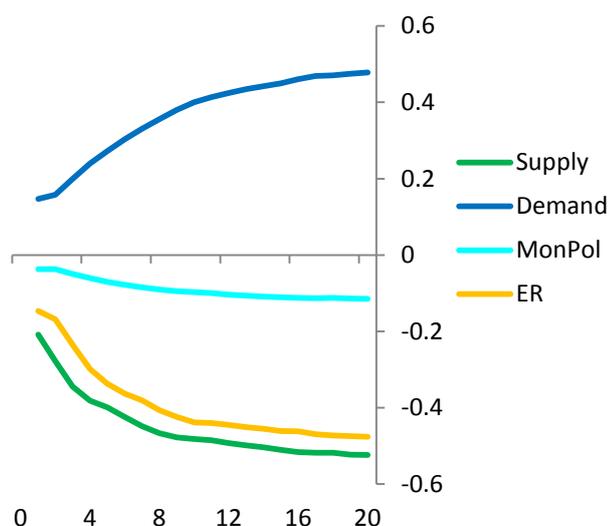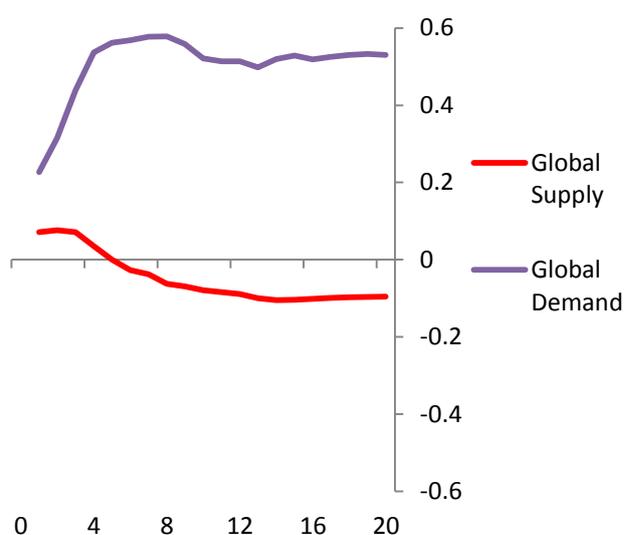


**Figure C.4: Pass-through to consumer prices for global shocks**



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