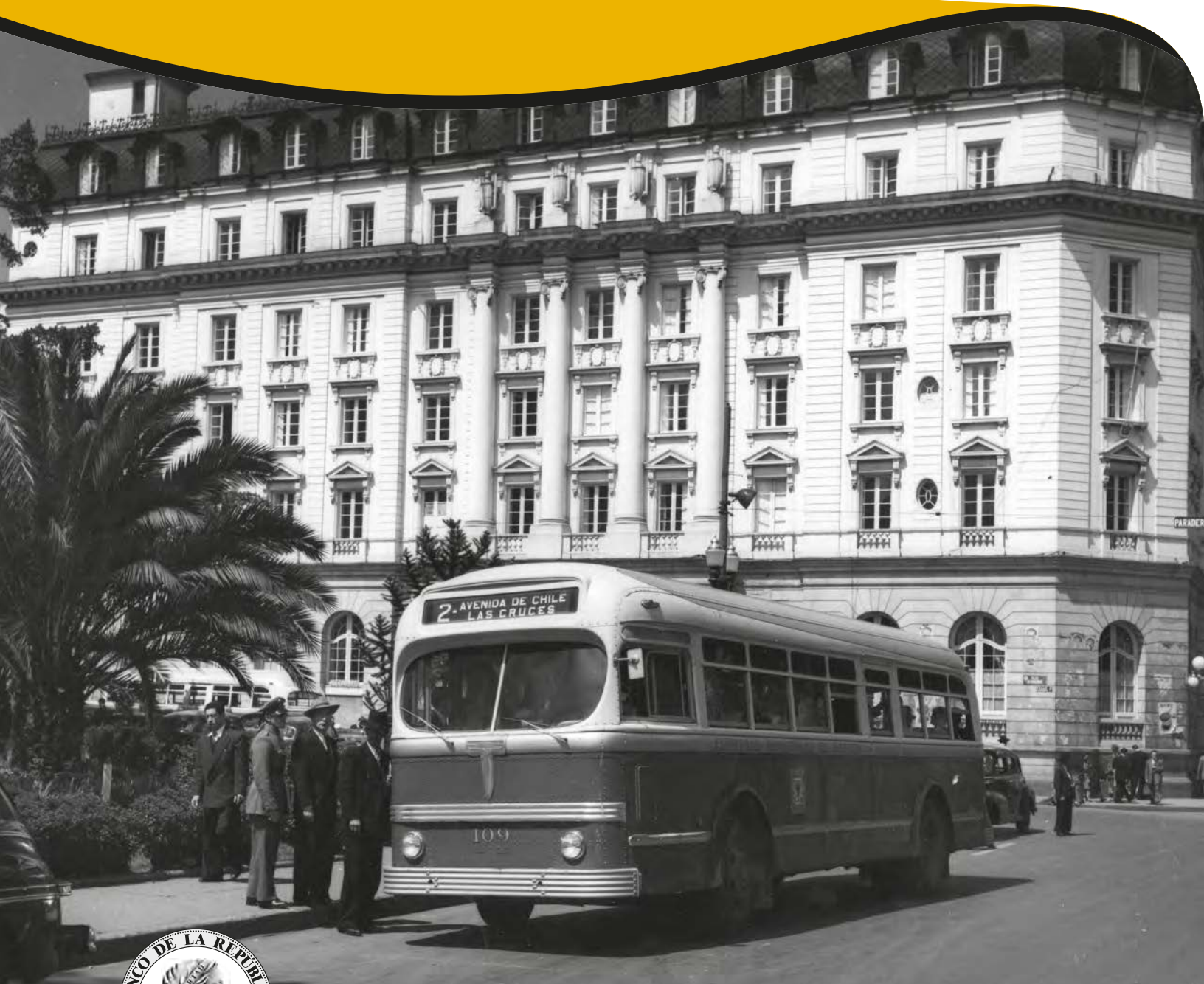


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Vector Auto-Regression with
Residual Stochastic Volatility
Approach

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Estimating the Exchange Rate Pass-Through: A Time-Varying Vector Auto-Regression with Residual Stochastic Volatility Approach*

Juan Manuel Julio-Román[†]

The conclusions and implications of this paper are the sole responsibility of its author and do not reflect the views of BANCO DE LA REPUBLICA or its JUNTA DIRECTIVA.

Abstract

The adoption of a Time-Varying Vector Auto-Regression with residual Stochastic Volatility approach to address the state and time dependency of the exchange rate pass-through, ERPT, is proposed. This procedure is employed to estimate the size, duration and stability of the ERPT to flexible relative price changes in Colombia through a fairly simple Phillips curve. For this, the generalized impulse responses, i.e. pass-throughs, from different periods of time are compared. It was found that the ERPT is bigger and faster than previous estimates for broader price indexes. It was also found that regardless of the existence of time-varying shock sizes, i.e. time varying standard deviations, the ERPT before full Inflation Targeting, IT, is marked and significantly larger before than during full IT, and also that the ERPT relates to real exchange rate volatility. The second results relates to the benefits derived from the adoption of full IT in this country. It was finally found that the output gap and flexible relative price change residual volatilities drop permanently and importantly at 1998Q3, emphasizing the role of the free float regime adoption in the success of IT in this country.

Keywords: Pass-Through, Price Stickiness, Phillips Curve.

JEL: C22, F31, F41.

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Estimando el Traspaso de la Tasa de Cambio en Colombia: Un Enfoque Vector Auto-Regresivo Tiempo-Variante con Volatilidad Estocástica[§]

Juan Manuel Julio-Román¹

Las conclusiones y recomendaciones de este artículo son responsabilidad exclusiva de su autor y no reflejan la posición del BANCO DE LA REPUBLICA o su JUNTA DIRECTIVA.

Resumen

La adopción de un enfoque de Vectores Auto-Regresivos Tiempo-Variantes con Volatilidad Estocástica residual para examinar la variación temporal y sobre el estado de la economía del Traspaso de la Tasa de Cambio, TCC, es propuesta. Este enfoque es empleado para estimar el tamaño, duración y estabilidad del TTC a los cambios de los precios relativos de los flexibles en Colombia a través de una curva de Phillips relativamente simple. Para esto, las funciones de impulso respuesta generalizadas, es decir los TTC, de diferentes periodos de tiempo son comparados. Se encontró que el TTC es más grande y rápido que estimaciones anteriores para agregados más amplios de precios. Se encontró también que a pesar del tamaño tiempo-variante de los choques, es decir las desviaciones estándar, el traspaso antes del Esquema completo de Inflación Objetivo, EIO, es marcada y significativamente más grande que el traspaso durante este, y también se halló evidencia de una relación entre el traspaso y la volatilidad de la tasa de cambio real. El segundo resultado se relaciona con los beneficios derivados de la adopción del esquema de inflación objetivo en este país. Se encontró, finalmente, que la volatilidad residual de la brecha del PIB y del cambio de los precios relativos de los flexibles cayó substancial y permanentemente en 1998Q3, enfatizando el papel del régimen de libre flotación en el éxito del EIO en este país.

Palabras Clave: Traspaso de la Tasa de Cambio, Rigideces de Precios, Curva de Phillips.

JEL: C22, F31, F41.

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1 Introduction

Precise estimates of the Exchange Rate Pass-Through, ERPT, are important for Small Open Economies, SOEs, such as Colombia because of two reasons at least. On one hand, a SOE inflation targeting, IT, central bank must tune up its response to the ERPT as exchange rate shocks affect current and future inflation. And on the other, the ERPT is key for the determination of the country's competitiveness and trade volume. As a result, monetary as well as international trade policies depend on an accurate knowledge of the dynamic features of the ERPT. See Bussiere (2013).

Previous estimates of the pass-through in Colombia suggest it is small, incomplete, takes some time to die out, display non-linear behaviour and may depend on the kind of shocks hitting the exchange rate. Earlier studies such as Rincón (2000), Rowland (2003) and Jiménez and Rendón (2009) estimated the dynamic response of import, producer and consumer prices to exchange rate changes. Later on, Rincón, Caicedo, and Rodríguez (2007), González, Rincón, and Rodríguez (2008) and Rincón and Rodríguez (2014) analysed the dependence of the ERPT on the exchange rate regime and the existence of non-linearities. More recently Rincón and Rodríguez (2016) and Rincón, Rodríguez, and Castro (2017), explored the dependence of the ERPT on the type of shock hitting the exchange rate and non-linearity.

These contributions follow the methodologies utilized in similar studies in other countries. They estimate price or Purchasing Power Parity, PPP, equations for open economies, which are estimated through different forms of Vector Auto-Regressions, VARs, Vector Error Correction Models, VECMs, simultaneous equations models and single equation models. Non-linearities and asymmetries are introduced through standard TAR, STAR, polynomial lag, small/big asymmetry dummies, logistic smooth transition, etc. More precisely, VAR and simultaneous equations models have been estimated by McCarthy (2007), Adolfson (2004) and De Walque, Smets, and Wouters (2005). In turn, VECM ERPT estimation has been implemented by Adolfson (1997) to study the ERPT to import prices, and to final prices by Heath, Roberts, Bulman, et al. (2004). In addition, non-linearities and asymmetries, especially on single equation models, has been undertaken by Kiliç (2016), Herzberg, Kapetanios, and Price (2003), Bussiere (2013), Junttila and Korhonen (2012), and Shintani, Terada-Hagiwara, and Yabu (2013).

Theoretical studies suggest a variety of sources of incomplete, small, and time and state dependent ERPTs. For instance, Aron, Macdonald, and Muellbauer (2014, pp. 103) summarize the sources of delayed and incomplete ERPT into three channels; mark-up, marginal costs and price rigidity. Furthermore, Taylor (2000), Choudhri and Hakura (2006), Gopinath and Itskhoki (2010) and Devereux and Yetman (2010), developed theoretical models that explain ERPT variation in terms of the monetary policy regime, the level of inflation and its persistence, as well as on price stickiness.

We propose to study the dynamics of the ERPP through a Time-Varying VAR with residual Stochastic Volatility, which has the following features. First, the time-varying VAR coefficient matrices lead to time-varying impulse responses, i.e. time-varying ERPTs, with their own dynamics, speed and size at every date in the sample. Second, since the coefficient matrices elements are assumed to behave as random walks, the ERPT transition between dates is allowed to be sudden as well as smooth. Third, Since the ERPT transitions along a continuous (as opposed to finite) state space, ERPT transition includes a wide variety of non-linearities among which are those related to unobserved thresholds. Fourth, stochastic volatile errors allow us to study the effect of exchange rate volatility shifts, i.e. control for the exchange rate shock size time-variation. And finally, the multivariate SV error assumption allows us to control for and address ERPT dependency on heteroskedasticity, co-volatility, and residual heavy-tailedness, some of which may lead to ERPT estimation bias when not accounted for.

As a result, this approach permits studying time and state ERPT variation in a wide variety of situations in a exploratory rather than pre-identified manner. Indeed, this approach departs from previous works as it does not require to identify ex-ante the sources of pass-through endogeneity and non-linearity, a perilous task, but embraces them all in a convenient manner. As a result, other sources of ERPT endogeneity on time or the state of the economy are likely to be discovered.

This paper contributes in many other ways to both, ERPT estimation in general as well as to Colombian ERPT results. First, instead of PPP or price equations, we follow Takhtamanova (2010) who studies the ERPT to prices in a panel data Phillips curve, and applies it to OCDE countries. This novel approach is based on a multi-country model for local and foreign firms whose optimal import prices are aggregated and explained through an open economy Phillips curve. Furthermore, this author sets-up her Phillips curve in terms on the Real Exchange Rate, RER, rather than the nominal, a choice we also adhere to in this paper. A further advantage of Takhtamanova (2010) approach is that it allows us obtaining monetary results as well. We find the Phillips curve to be advantageous to study the ERPT as the PPP and open economy price equations might not necessarily hold or display a poor fit in comparison to a Phillips curve, the workhorse of IT.

Second, we examine whether the dependence of ERPT on price stickiness heterogeneity, that has been recently established in the literature, holds in Colombia. For instance, Gopinath and Itskhoki (2010) and Devereux and Yetman (2010) found empirical evidence that, on average, items whose prices are flexible have at least twice the long-run pass-through exhibited by items whose prices are sticky. They also found that these results are consistent with theoretical models characterized for variable mark-ups. The latter author also found that the ERPT increases with inflation. Therefore, price stickiness could also be an important determinant of the ERPT in Colombia since Julio, Zárate, and Hernández (2010) and Julio (2010) found price stickiness heterogeneity among Consumer's Price Index,

CPI, items, and report that flexibility and inflation relate as well.

Third, our empirical strategy enables us to study Taylor (2000) hypothesis, under which the ERPT is explained in part by the level of inflation and inflation persistence. According to this author, this is due to the fact that firms facing lower inflation accompanied by low inflation persistence lose pricing power. This loss, in turn, hampers their ability to pass-through costs, among which are those originating in the exchange rate shocks. Thus, the level of local competition and inflation affect price changes and their frequency, leading the ERPT to depend on monetary policy.

Fourth, we also explore whether exchange rate volatility shifts affect the ERPT, which may result from the pricing power channel as well. Whenever a RER depreciation volatility spike arises, firms do not adjust prices as much as they would under a less uncertain environment by fear of losing market share, which ends up undermining their market power. This fact seems to hold regardless of the type of exchange rate volatility shock the firm faces, be it an exchange rate regime shift, country risk, contagion episodes, etc. Consequently, higher exchange rate volatility may reduce the ERPT. This might be the case in Colombia as well, since the sample under study contains several monetary and exchange rate regime shifts as well as volatility clustering². Hence, the move to exchange rate flotation in 1999Q3³, and the occurrence of several crises such as the 2007's sub-prime, might have affected the ERPT in this country.

To illustrate the use of this procedure, We study the dynamics of the ERPT in Colombia through a Phillips curve that explains relative flexible price changes in terms of the RER. The theoretical underpinning of this procedure follows Takhtamanova (2010) and part of the empirical strategy follows from Julio, Gómez, and Hernández (2017) and Gómez and Julio (2016)⁴. Furthermore, by relying on a stochastic volatile Phillips curve, we may also study the effect of volatility shifts on the ERPT.

Our findings summarize as follows. First, the ERPT to flexible relative price changes is comparatively larger than previous results for broader price indexes, and is also quite fast (about 80% of the long-run ERPT is transmitted within one year of the shock), and this pace is time-invariant. This size and speed is consistent with the fact that we study flexible rather than rigid or CPI prices, thus showing that ERPT depends of price stickiness. See Gopinath and Itskhoki (2010), Devereux and Yetman (2010) and Takhtamanova (2010), also.

Second, the ERPT to flexible relative price changes significantly varies across the time, and these changes seem to arise from two sources. On one hand, the ERPT is

²See Julio (2017) for evidence on the second fact.

³When the full inflation targeting was completed in Colombia according to Hammond (2012).

⁴Julio et al. (2017, Fig. B.12) found a striking relationship between RER depreciation and the change in relative flexible prices. This relationship characterizes for a positive cross-correlation function from the current RER depreciation to future relative price changes, Julio et al. (2017, Fig. B.13).

marked and significantly larger before the switch to full IT than after. And on the other, smaller but significant differences within the IT regime seem to relate to temporary RER volatility reductions. In fact, the long-run ERPT to relative flexible price changes after an one time unexpected RER depreciation shock of 1% was (i) close to 0.55% before full IT, 0.1% during IT in RER turbulent times, and 0.25% during IT but tranquil RER times.

And Third, there is a sharp and highly significant residual output gap and relative price change volatility fall precisely at the date of the adoption of the free float. This result has two implications. On one hand, it confirms the date of the biggest ERPT shift, i.e. the completion of the IT regime in this country. And on the other, reveals the success of full IT with respect to the second moments. In fact, an unbiased IT central bank minimizes its expected loss function, i.e. a linear combination of (future) inflation and output gap square deviations with respect to their targets. This procedure entails a residual output gap and flexible relative price change volatility fall at the completion of the IT regime.

We conclude that this country is reaping the benefits of full IT not only through the reduction of inflation, but also through the fall of its ERPT and the decrease of inflation and output gap volatility. As a matter of fact, regardless of the existence of time varying RER depreciation shocks, our results imply that (i) the sensitivity of flexible relative price changes to RER depreciation shocks has reduced with full IT (ii) however, periods with low exchange rate volatility may reduce these gains, and (iii) the flexible relative price change and output gap residual volatility fall that occurred after 1998 confirms the importance of the adoption of the free float regime for the success of IT in this country. However, as (Taylor, 2000) mentions, these gains “may disappear quickly if monetary policy and expectations change”. We also conclude that the ERPT depends on price stickiness heterogeneity in this country. Nonetheless, it is worth emphasizing that we do not consider cross second round effects on rigid or headline inflation.

To be precise, our results indicate that a 10% exchange rate depreciation has a long-run effect on flexible relative price changes of 1% at a time when inflation is already low and characterized for increased exchange rate volatility. Since the share of flexible prices in the CPI is 30% for the 2018 methodology, according to Equation (1), the pass-through to headline inflation becomes 0.3% in the long-run, not taking into account second round effects⁵ Furthermore, provided that 80% of the shock is transmitted within one year, this 10% depreciation translates into a 0.24% price increase in one year.

This paper is distributed into four sections, being this introduction the first one. The second describes the construction of the flexible price index for Colombia, as well as the sources of the data under analysis. The third summarizes the econometric time series technique used to obtain our results. The fourth and last, describes the results from which

⁵Julio et al. (2010, Table 1) report that rigid and flexible inflation have an approximate share of 30% of CPI each, and the remaining 40% corresponds to food and regulated prices items.

our previous conclusions follow.

2 The Data

Our dataset consists of quarterly measures of flexible and rigid price indexes, P_t^{Flex} and P_t^{Rig} , the output gap, z_t and the RER depreciation rate, ΔE_t^R , for Colombia from 1982Q2 to 2017Q2. Flexible and rigid price indexes come from Julio et al. (2017) and the remaining data comes from Banco de la República.

Julio et al. (2017) adapted the methodology proposed by Bryan and Meyer (2010) to calculate flexible and rigid price indexes for Colombia as follows. First, a total of 181 minimal CPI item classes, the highest level of CPI disaggregation publicly available in this country were used for their calculations. Second, food and price regulated items were excluded from our calculations since their most of their variations respond to factors outside the realm of monetary policy⁶. Third, the remaining minimal classes were classified as rigid or flexible by comparing their price duration with a threshold obtained from the current steady state duration distribution. This distribution was approximated from the data Julio et al. (2010) used to calculate the distributions of price durations across the time. More precisely, the median of the distribution of price durations for a period of time, in their sample, when the inflation level was similar to the current one was used as the duration threshold. This procedure led to a 10.76 months threshold.

These authors also report some of the quarterly annualized flexible and rigid inflations stylized facts, as well as the annualized quarterly flexible relative price change ones,

$$\begin{aligned}\pi_t^{Flex} &= 4 \left(\ln(P_t^{Flex}) - \ln(P_{t-1}^{Flex}) \right) \\ \pi_t^{Rig} &= 4 \left(\ln(P_t^{Rig}) - \ln(P_{t-1}^{Rig}) \right) \\ \Delta q_t^{Flex} &= 4 \left(\pi_t^{Flex} - \pi_t^{Rig} \right)\end{aligned}$$

respectively. These stylized facts summarize as follows. First, rigid inflation is the component that more likely transmits permanent shocks to inflation such as expectations, and may reveal expectation anchoring. Second, flexible inflation is the component that more likely transmits cyclical shocks such as those hitting the output gap and exchange rate. Nonetheless, the correlation between these inflations is quite low, indicating that the shocks affecting them are mostly orthogonal. Third, the change in the relative price of flexibles

⁶Similar calculations were performed by Bryan and Meyer (2010, Fig. 2), Millard and O’Grady (2012, pp 9-10), Reiff and Várhegyi (2013) and Erlandsen (2014, Fig 1b) who exclude similar items from their calculations.

with respect to rigids is dominated by cyclical frequencies. This latter fact arises by writing the core inflation, π_t^C , as the sum of rigid inflation, π_t^{Rig} , and the weighted change in relative prices, $\Delta q_t^{Flex} = (q_t^{Flex} - q_{t-1}^{Flex})$, as follows

$$\begin{aligned}\pi_t^C &= \alpha_{Rig}\pi_t^{Rig} + \alpha_{Flex}\pi_t^{Flex} + \left(\alpha_{Flex}\pi_t^{Rig} - \alpha_{Flex}\pi_t^{Rig}\right) \\ &= \pi_t^{Rig} + \alpha_{Flex}\left(q_t^{Flex} - q_{t-1}^{Flex}\right)\end{aligned}\tag{1}$$

where $\alpha_{Flex} = 1 - \alpha_{Rig}$ is the share of flexible prices into the core. Therefore, the change in relative flexible prices is the component that carries cyclical innovations to inflation, and the open economy Phillips curve might be written as follows

$$\begin{aligned}\pi_t^{FR} &= f_1\left(S_t, \pi_t^{FR,e}\right) + \epsilon_{1,t} \\ \pi_t^{Rig} &= f_2\left(z_t, \pi_t^{C,e}\right) + \epsilon_{2,t} \\ \Delta q_t^{Flex} &= f_3\left(\Delta E^R, z_t\right) + \epsilon_{3,t}\end{aligned}\tag{2}$$

where π_t^{FR} is the food and regulated inflation rate, S_t summarize the supply shocks hitting these items' prices, z_t is the output gap, ΔE^R is the RER depreciation, $\pi_t^{i,e}$ is the expected inflation, and $\epsilon_{i,t}$ are noises, for $i \in \{FR, Rig, Flex, C\}$. As a result, substantial correlation between ΔE^R and π_t^{Flex} may arise.

3 The Empirical Strategy

We follow Takhtamanova (2010) in the use of a Phillips curve to study the pass-through, using the specification in the third line of Equation (2). However, due to the possible endogeneities that may arise in single equation estimation, we transform it to a vector process.

The additive reduced-form shocks are assumed to follow a multivariate stochastic volatility process⁷. Accordingly, ERP T dependence on heteroskedasticity, volatility clustering, co-volatility and heavy error tails might be also studied, which includes several different types of non-linearities. Therefore, this assumption specifies more thoroughly

⁷SV models have important advantages over the GARCH alternatives which derive from two facts. On one hand, in SV models volatility is stochastic by definition, as opposed to the deterministic volatility in the GARCH family. That is, SV models may be subject to direct volatility shocks. And on the other, SV models have a strong relationship with the types of models used in financial economics and mathematical finance, that is, SV models are more likely to have theoretical counterparts in financial mathematics than the popular GARCH family of models. Nonetheless, GARCH models are very well adapted to measure risk. See Shephard (1996), Kim, Shephard, and Chib (1996) and Shephard (2005)

changes in policy and the structure of the transmission of shocks. See Primiceri (2005) and Del Negro and Primiceri (2015).

Finally, the estimation of this TV-VAR-SV model and its subsequent shock identification is performed, at every period of time, through generalized impulse responses. These steps are carried out by fully Bayesian methods designed by Primiceri (2005) and Del Negro and Primiceri (2015).

This section consists of three subsections. The first summarizes the specification of the Univariate Auto-Regressive SV, UAR(p)-SV model. The second describes the TV-VAR-SV model. And the last discusses the generalized impulse responses.

3.1 Univariate Auto-Regressive Model with Stochastic Volatility Noise

To determine the features of the univariate processes in our model, we start with univariate analyses of our series. We fit Univariate Auto-Regressions, AR, of order p with residual Stochastic Volatility, that is UAR(p)-SV models, which are described by the following equations

$$Y_t | \mathfrak{F}_{t-1} \sim N(\beta_0 + \beta_1 Y_{t-1} + \dots + \beta_p Y_{t-p}, \exp(h_t)) \quad (3)$$

$$h_t | h_{t-1} \sim N(\mu + \phi(h_{t-1} - \mu), \sigma_\eta^2) \quad (4)$$

for $t \in \mathbb{N}$, and

$$h_0 \sim N(\mu, \sigma_\eta^2 / (1 - \phi^2)) \quad (5)$$

where $\Theta = (\beta_0, \dots, \beta_p, \mu, \phi, \sigma_\eta)^{\prime}$ is the vector of time-invariant parameters, \mathfrak{F}_t is the information set up to time t , Y_t is the observable process, μ is the mean of the unobserved log-variance process, ϕ determines its persistence, and σ_η its variance.

The estimation of model (3), (4) and (5) is carried out by Bayesian methods. More specifically, a standard simulation technique for β_0, \dots, β_p is coupled with one specifically designed for the rest of parameters, including the unobserved log-variance. Details on the prior distributions, the simulation algorithm for the second component and its properties may be found in Kastner and Frühwirth-Schnatter (2014).

3.2 The time-varying Vector Auto-Regressive Model with Stochastic Volatility

The dynamic relationship between our variables has usually been studied through single equation estimation methods on fixed parameterizations that account for regressors endogeneity. However, a less restrictive approach might be to employ a TV-VAR-SV model,

which is given by

$$\mathbf{Y}_t = \mathbf{c}_t + \sum_{j=1}^k \mathbf{B}_{jt} \mathbf{Y}_{t-j} + \mathbf{u}_t \quad t \in \mathbb{Z} \quad (6)$$

where \mathbf{B}_{jt} for $j = 1, 2, \dots, k$ are $n \times n$ unknown time-varying parameter matrices, \mathbf{Y}_t is a vector of observable processes, \mathbf{c}_t is a vector of unknown time-varying intercepts, and \mathbf{u}_t is the unobserved reduced form heteroskedastic vector of shocks, such that \mathbf{u}_t are independently distributed $(\mathbf{0}, \boldsymbol{\Omega}_t)$ for $t \in \mathbb{Z}$, and $\boldsymbol{\Omega}_t$ satisfies

$$\mathbf{A}_t \boldsymbol{\Omega}_t \mathbf{A}_t' = \boldsymbol{\Sigma}_t \boldsymbol{\Sigma}_t' \quad (7)$$

for a lower triangular matrix

$$\mathbf{A}_t = \begin{bmatrix} 1 & 0 & 0 & \dots & 0 \\ \alpha_{21,t} & 1 & 0 & \dots & 0 \\ \alpha_{31,t} & \alpha_{32,t} & 1 & \dots & \vdots \\ \vdots & \vdots & \vdots & \ddots & 0 \\ \alpha_{n1,t} & \alpha_{n2,t} & \dots & \alpha_{n,n-1,t} & 1 \end{bmatrix} \quad (8)$$

and a diagonal matrix

$$\boldsymbol{\Sigma}_t = \begin{bmatrix} \sigma_{1,t} & & \\ & \ddots & \\ & & \sigma_{n,t} \end{bmatrix} \quad (9)$$

both of these matrices containing unknown time-varying parameters. See Primiceri (2005) and Del Negro and Primiceri (2015) for more details.

For an observed time series $\{\mathbf{Y}_t\}_{t=1}^T$ Primiceri (2005) and Del Negro and Primiceri (2015) write this model in a familiar way as follows

$$\mathbf{Y}_t = \mathbf{X}_t' \mathbf{B}_t + \mathbf{A}_t^{-1} \boldsymbol{\Sigma}_t \boldsymbol{\epsilon}_t \quad (10)$$

$$\mathbf{B}_t = \mathbf{B}_{t-1} + \boldsymbol{\nu}_t \quad (11)$$

$$\boldsymbol{\alpha}_t = \boldsymbol{\alpha}_{t-1} + \boldsymbol{\zeta}_t \quad (12)$$

$$\log \boldsymbol{\sigma}_t = \log \boldsymbol{\sigma}_{t-1} + \boldsymbol{\eta}_t \quad (13)$$

where $\boldsymbol{\epsilon}_t = \mathbf{A}_t^{-1} \boldsymbol{\Sigma}_t \mathbf{u}_t$ for $t = 1, 2, \dots, T$, \mathbf{B}_t are all the parameters to the right hand side of Equation (10) stacked in a vector

$$\mathbf{X}_t = \mathbf{I}_n \otimes [1, \mathbf{Y}_{t-1}', \dots, \mathbf{Y}_{t-k}'] ,$$

$\boldsymbol{\alpha}_t$ is a vector containing the unknown elements in \mathbf{A}_t , $\boldsymbol{\sigma}_t$ contains the diagonal elements in $\boldsymbol{\Sigma}_t$, and $\boldsymbol{\nu}_t$, $\boldsymbol{\zeta}_t$ and $\boldsymbol{\eta}_t$ are vectors of unobserved noises. Finally, all residuals in model

(10)-(13) have a variance co-variance matrix

$$\mathbf{V} = \text{Var} \begin{bmatrix} \epsilon_t \\ \nu_t \\ \zeta_t \\ \eta_t \end{bmatrix} = \text{diag}(\mathbf{I}_n, \mathbf{Q}, \mathbf{S}, \mathbf{W}) \quad (14)$$

where \mathbf{S} is usually assumed to be block diagonal, and Equation (13) is known as a geometric random walk process.

Given the sample information, estimation is carried out by Bayesian methods. Several issues prevent the use of standard procedures in this setting. On one hand, the dimension of this system is high as Equations (11), (12) and (13) determine the stochastic behaviour of an important number of unobserved time-varying components, to which an important number of time-invariant parameters have to be added. And on the other, Equations (10)-(13) define a non-linear system. The high dimensionality and non-linearity in this problem pose important obstacles to standard estimation techniques such as the Kalman filter. Hence, the estimation of the unobserved states (Equations (11), (12) and (13), as well as the parameters in matrix \mathbf{V} , Equation (14)) must be carried out by sequential simulation. See Primiceri (2005) and Del Negro and Primiceri (2015). More rigorously, the posteriors of the state elements are simulated from the smoothing rather than the filtering density⁸. For a detailed description of the assumptions on the prior distributions, the simulation algorithm and its properties see Primiceri (2005) and Del Negro and Primiceri (2015).

Equation (2) suggests the inclusion of several variables into the TV-VAR-SV model among them the annualized quarterly change of relative flexible prices Δq_t^{Flex} , the annualized quarterly RER depreciation ΔE_t^R , and the output gap z_t . We intentionally keep the number of variables small in order to reduce the dimensionality of our system.

As a result, we fit the TV-VAR-SV model to the vector

$$\mathbf{Y}_t = \begin{bmatrix} \Delta E_t^R \\ z_t \\ \Delta q_t^{Flex} \end{bmatrix}$$

3.3 Impulse Response Analysis

We perform impulse responses analyses to summarize the dynamic joint behaviour of the RER depreciation, the output gap and the change in relative flexible prices. To overcome the drawbacks of commonly employed identification schemes such as orthogonalization, we

⁸Del Negro and Primiceri (2015) cite Sims (2001) who argues that “filtered estimates are inappropriate estimates of the state evolution as they contain transient,[i.e. time idiosyncratic,] variation”.

employ Pesaran and Shin (1998) generalized impulse responses. The scaled generalized response of \mathbf{Y}_{t+n} , to a impulse in Y_{jt} is defined as

$$\psi_j^g(n) = \sigma_{jj}^{-1/2} \mathbf{A}_n \boldsymbol{\Sigma} \mathbf{e}_j \quad (15)$$

where $\sum_{n=0}^{\infty} \mathbf{A}_n L^n = (\sum_{n=0}^{\infty} \mathbf{B}_n L^n)^{-1}$, and \mathbf{e}_j is a vector full of zeros except at position j where it is one, and L is the lag operator. The main advantage of this identification approach is that it does not require orthogonalization and is, thus, invariant to the ordering of the variables in the VAR. See Pesaran and Shin (1998) for further details.

To compare the time-varying responses of the output gap and flexible relative price change to RER depreciation shocks at different periods of time, the shock sizes might be assumed constant. Primiceri (2005) and Del Negro and Primiceri (2015) set the diagonal residual VCV matrices at their average sample values, and allow the off diagonal values assuming their corresponding values at every date.

And in order to account for RER depreciation heteroskedastity, i.e. time-varying RER depreciation average shock sizes, the ERPT from these shocks are also compared. In fact, it is widely known that the Colombian RER depreciation rate heteroskedastic due to exchange policy shifts and external as well as internal vulnerabilities. By performing this comparison we determine whether these time-varying shock sizes overturn the conclusions about the ERPT obtained from time invariant shocks.

4 Results

The results are organized in three subsections as follows. The first describes the unit root, heteroskedasticity and volatility persistence properties of the univariate processes, where we set the stage for the estimation of the TV-VAR-SV model. These analyses are performed by fitting UAR(2)-SV models to our three series. In the second, we summarize the results of the TV-VAR-SV model estimation, where we focus on the time-varying residual standard deviations. Finally, the third sub-section contains the main results, i.e. the time-varying generalized impulse responses.

To motivate our results, we perform our analysis on a set of dates chosen accordingly to the following criteria. These dates correspond to (i) before the inflation targeting regime was completed, 1994Q1 and 1995Q1, (ii) after this regime was adopted, but characterized by excess local exchange rate volatility, 2004Q1, (iii) after this event but with comparatively lower exchange rate volatility, 2005Q4, and (iv) the latest date in the sample, 2017Q2, when the highest exchange rate volatility occurred.

However, our final results follow from the impulse response estimates at all effective dates available. At this point it is worth noticing that ten years plus the number of lags,

k , are lost from the initial data available in order to estimate the hyper-parameters for the prior distributions and conditioning.

4.1 Integration Order, Heteroskedasticity and Volatility Persistence in the Univariate Processes

Aside from the integration order of the variables in our VAR, the more important concerns about the univariate processes in the system are the presence of heteroskedasticity, volatility persistence and heavy tails. To document these facts we fitted Univariate Auto-Regressions of order two with residual Stochastic Volatility, UAR(2)-SV, to each of our series. The existence of a unit root may be checked using the Highest Probability posterior Density, HPD, of $\beta_1 + \beta_2$, while the level of volatility persistence can be obtained from ϕ 's HPD. Heavy tailedness, however, is not a major concern in our sample since it is inversely proportional to the sampling interval, and it is known to reduce substantially for quarterly data⁹.

Figures B.1 and B.2 depict the data under analysis. From these figures we may unquestionably conclude that the flexible relative price change is heavily heteroskedastic, especially when the periods before and after the adoption of full flotation are compared. Figure B.1, in turn, may suggest episodic excess volatility in the output gap between 1998 and 2001, and volatility reduction episodes close to 1995, 2007, near the end of the sample and between 1987 and 1989. In a similar manner, Figure B.2 reveals a permanent RER depreciation volatility shift at 1998, a clear result the adoption of the free exchange rate float regime.

4.1.1 Unit Root, Volatility Persistence and Heteroskedasticity for RER Depreciation

The existence of a unit root in the RER is a minor concern as we analyse the rate of depreciation. Economists propose two hypothesis on the existence of a unit root in RER levels. Whenever the RER is $I(1)$, non-stationarity relates to existence of two components; a unit root and heteroskedastic innovations. But if the RER does not posses a unit root, only the second component arises. Regardless, the first difference transformation, ΔE_t^R , reduces the unit root whenever the RER is $I(1)$, and induces a unit root in the moving average component when it is $I(0)$. Therefore, the existence of unit root in RER depreciation is not a concern but its innovations are likely heteroskedastic.

Regarding time-invariant UAR-SV parameters estimation, Figures B.3 and B.4 show convergence of the simulation samples to the corresponding marginal posterior. These

⁹Julio (2017) showed that this is true for nominal exchange rates in several LatinAmerican countries.

Figures show the posterior marginal simulations after thinning the first nine out each ten iterations to get rid of auto-correlation (left panels), and the corresponding estimated posterior density (right panels), for each of the parameters in the model. The fact that these simulations seem to show no mean or variability shifts suggest that the distribution from which they were drawn has already converged to the steady state distribution, i.e. the marginal posterior. The posteriors at the right hand side confirm this convergence as they are uni-modal and lack important tail bumps.

Moreover, the RER depreciation residual volatility process looks highly persistent, and RER depreciation is stationary. As a matter of fact, the results in Table A.1 show that the HPD upper limit for ϕ is one, a feature of highly persistent volatility, but the HPD upper limit for $\beta_1 + \beta_2$ is just 0.5591, showing that RER depreciation does not have a unit root.

More interestingly, the residual RER depreciation volatility is significantly time-varying. In fact, the top panel of Figure B.9, which depicts the mean and 16% and 84% percentiles of the posterior of the log volatility process at each period of time, shows that it is significantly increasing until 1998 when it reaches a plateau. After this plateau a temporary RER depreciation reduction is observed between 2010 and 2015. The former result suggests that the period before the adoption of the free float is peculiarly different from the period after.

Finally, the top panel of Figure B.10 suggests that the standardized residual tails behave normally, thus discarding the existence of heavy tails. Indeed, the frequency of standardized residuals above two standard deviations, 2, does not look higher than expected with respect to standard normal tails.

4.1.2 Unit Root, Volatility Persistence and Heteroskedasticity for the Output gap

The output gap is a stationary and persistent process by definition, that is, it has a big but not unit root. However, it may exhibit some degree of volatility clustering and volatility jumps due possibly to structural shifts and crises in the sample.

The time-invariant parameter estimation results suggest the existence of mistaken temporary mean output gap shift related to a prolonged crisis. The top panels of Figure B.5 show that convergence issues arise in the simulation from the posterior distribution of μ , which shows a marked bump on its left hand side tail. This finding suggests that μ is not identified because of the sharp output gap drop of 1998 and its subsequently long recovery. That Figure along with Figure B.6 show that the remaining parameters distributions simulations converged to the desired posterior.

Consistently, Table A.2 shows evidence of highly persistent but not integrated volatility and, not surprisingly, the presence of a unit root. In fact, the HPD for ϕ is well within the unit interval but the posterior probability that $\beta_1 + \beta_2 \geq 1$ is non-negligible as its HPD is [0.65, 1.19]. This result clearly arises from the prolonged 1998 crisis that was mistakenly taken as a mean shift.

Furthermore, the middle panel in Figure B.9 shows that the estimated residual volatility has been falling since 1998, and suggests episodic but significant excess volatility. Finally, no significant heavy tailedness was found in the standardized residuals, as the middle panel of Figure B.10 suggests.

4.1.3 Unit Root, Volatility Persistence and Heteroskedasticity for Flexible Relative Price Changes

The stochastic behaviour of flexible and rigid prices in a non-hyper-inflation country are at most $I(1)$ with perhaps some breaks¹⁰. As a result, the relative price, q_t^{Flex} is at most a $I(1)$ process and its difference Δq_t^{Flex} is, consequently, stationary. Hence, the change in the relative price of flexibles is at most $I(0)$ with some structural breaks.

Time-invariant parameter estimation results show that no convergence issues to the true posteriors arise, Figures B.7 and B.8.

Furthermore, the flexible relative price change is stationary and has a high volatility persistence. The results in Table A.3 confirm that the log volatility process is highly persistent as its HPD upper limit for ϕ is exactly the unit. In addition, the posterior of $\beta_1 + \beta_2$ might cover the unit with a very low probability as its HPD upper limit reaches just 0.9271, thus rejecting the presence of a unit root.

In addition, an important flexible relative price change volatility reduction near 1998 took place, which seems to coincide with the adoption of the free float exchange rate regime, Figure B.9. This figure also reveals that there is a non-significant but important volatility increase between 1987-1988 and a non-significant reduction near 2015. In addition, flexible relative price change volatility has been reducing since the early 1990's.

Finally, Figure B.10 reveals that aside from the model doing a poor job in estimating a mean trend shift before 1998, there does not seem to be un-normally big standardized residuals.

¹⁰For instance, Julio (1995) showed that the Colombian inflation process is stationary but subject to a few trend breaking events related to structural monetary policy changes and exchange rate crises.

4.2 TV-VAR-SV Estimation Results

To determine how the inclusion of all the process in a single system affects the time-varying residual standard deviation estimation, we start by comparing the volatility estimates of the multivariate model, Figure B.11 with those of the univariate ones, Figure B.9. From these Figures we conclude the following. First, the mean volatility reduces importantly for the output gap, the relative price change and the RER depreciation rate, in this order, when compared to the UAR(2)-SV residual volatility estimates. Second, the estimated volatilities from the multivariate model are smoother than those of the univariate UAR(2)-SV ones, and display spikes of smaller size at similar dates as the later. Moreover, because of this smoothing, RER depreciation residual volatility becomes borderline heteroskedastic. And third, and more importantly, the output gap estimated residual volatility reduces quite importantly around 1998. This behaviour mimics closely the estimated volatility of flexible relative price changes, thus suggesting that the time before adoption of the free float was peculiarly different from the full IT regime.

The later results seems to confirm the success of the IT regime in Colombia. As a matter of fact, under IT unbiasedness, the central bank target is achieved by minimizing its expected loss function, i.e. a expected linear combination of (future) inflation and output gap square deviations with respect to their targets. In other words, the IT central bank minimizes a linear combination of the standard deviations of (future) inflation and output gap with respect to their targets. These standard deviations, under the steady state, become the volatilities we estimated in B.11. As a result, the output gap and flexible relative price change 1998 volatility fall shows the success of full IT through the second moments.

4.3 Impulse Responses

Our conclusions follow from four pieces of statistical evidence. First, the generalized responses of flexible relative price changes to a time-invariant RER depreciation shock. Second, the comparison of these responses between dates. Third, the comparison of cumulative generalized response of flexible relative price changes. And fourth, the comparison of the generalized responses to an one standard deviation RER depreciation shock estimated at each date in the sample. The later piece of evidence takes into account that the ERPT depends not only on the response to time-invariant RER depreciation shocks but also to the average size of the shock at each particular date.

4.3.1 The Effect of Time (State) Variation on ERPTs

Before we start, it might be useful to determine what type of results we might have obtained had we followed the standard time-invariant homoskedastic VAR approach. For this, we compare the responses of flexible relative price change to one standard deviation RER depreciation shock at 2017Q2 from an ordinary VAR(2) and our SV-VAR(2)-TV model. To make these responses comparable, we set the shock to the average estimated residual SD for the later model. This comparison is summarized in Figure B.12. The dashed line represents the response under the ordinary VAR, while the posterior median and credibility bands are those of the TV-VAR-SV.

Figure B.12 reveals remarkable ERPT differences along the time, which are both, economically important and statistically significant. On impact the ERPT from the ordinary VAR is significantly greater than the one arising from the TV-VAR(2)-SV model, and the former remains non-significantly above the later at the remaining lags of the horizon. This result implies that the long-run ERPT from the ordinary VAR is not only bigger, but also faster than the one derived from the TV-VAR(2)-SV model. These results suggest that regime shifts, crises, heteroskedasticity and contagion, among many other factors may play a key role on the estimated responses to RER depreciation shocks for this sample.

4.3.2 The ERPT to Flexible Relative Price Changes and the Output Gap

4.3.2.1 The ERPT to Flexible Relative Price Changes

Figure B.13 displays the responses of the flexible relative price change to a time-invariant RER depreciation shock, at the chosen dates. These responses are significant and positive during a time invariant length of time, and then converge, either smoothly or raggedly, to zero. At 1994Q1, 1995Q1 and 2011Q1 they seem to differ both drastically and significantly from the ones obtained at the remaining three dates as the former are significantly different from zero up to a year and a half after the shock, while the later is significant during the first quarter only. Furthermore, the responses at 1994Q1 and 1995Q1 are substantially bigger than the responses at the remaining dates, which are below 1 after the second quarter.

These results are confirmed in Figure B.14 where the cumulative ERPTs at each of the six dates chosen are shown. Before 1998 the long-run ERPT is sharply different from the ones after, and during the second sub-period an increase long-run ERPT arises at 2011Q2. This Figure reveals, furthermore, that the ERPT is fast, reaching up to 80% of its long-run transmission in less than one year, which is consistent with the fact that it relates to flexible rather than rigid or headline prices as in Takhtamanova (2010) and Gopinath and Itskhoki (2010). More interestingly, the ERPT transmission speed is time invariant. As a result, important behaviour differences in the flexible relative price change

responses arise at different periods of time, the ERPT transmission speed seems to be fast and time-invariant, and the ERPT to flexible prices is big but incomplete.

More precisely, a 10% exchange rate depreciation increases 1% the flexible relative price change in the long-run whenever inflation is low and the exchange rate is volatile. Since the share of flexible within the CPI is 30%, from Equation (1) the long-run pass-through to headline inflation becomes 0.3%, not considering second round effects. Additionally, since 80% of the pass-through happened within one year, a 10% depreciation would lead to a 0.24% increase of prices one year ahead.

In order to establish the statistical significance of these ERPT differences, Figure B.15 depicts the pairwise posterior flexible relative price difference between all pairs of dates considered. This figure reveals the existence of three significantly different groups of dates. The first group contains 1994Q1 and 1995Q1, the second only has 2011Q2, and the third 2004Q1, 2005Q4 and 2017Q2. These results suggest that the period before 1998 is conspicuously different from the period after, and that within the IT regime the response at 2011Q2 is different as well. The former differences seem to arise from the completion of the IT regime in Colombia, while the latter seems to relate to a temporary RER depreciation volatility reduction around that date, top panel of Figure B.10.

These results provide the background to analyse Figure B.16 which show the cumulative response of the flexible relative price change to a standard deviation of the date for all dates in the effective sample. This figure confirms our previous results with the caveat; that the transition between the responses at consecutive dates are smooth rather than sudden. This smoothness is clearly the result of employing the smoothing rather than the filtering distribution to estimate the VAR parameters.

Furthermore, combining these results with the residual volatility shifts in the bottom panels of Figure B.11, a much clearer picture emerges; (i) the time before full IT is noticeably and significantly different from the full IT period, (ii) there is an important temporary reversion around 2011Q2, which seems to relate to an episodic RER depreciation volatility reduction, and (iii) the flexible relative price change volatilities exhibit a clear cut and highly significant reduction at 1998, suggesting that the adoption of the free float causes these shifts.

4.3.2.2 Accounting for RER Depreciation Heteroskedasticity

To determine whether an increasing RER depreciation residual volatility alters our previous results, Figure B.17 shows the comparison of the responses to the average RER depreciation residual standard deviation (from which our previous results follow), and the responses to the RER depreciation residual standard deviation at each date. From this figure we conclude that the differences between these responses are small and do not change our

results.

Furthermore, the figures from which significance response differences among dates may be obtained are extremely similar to Figures B.15 and B.16, and, thus, are not shown here.

As a result, accounting for RER depreciation heteroskedasticity does not change our previous results.

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Appendixes

A Tables

Table A.1 – Bayesian Estimation Results SV-AR(2) fit to Quarterly Annualized RER Depreciation^a

	Parameter						
	μ	ϕ	σ	β_0	β_1	β_2	$\beta_1 + \beta_2$
16% Perc. ^b	-11.094	0.999	0.1337	-0.1736	0.2146	-0.1969	0.0177
Median	-9.0658	0.9997	0.2151	1.3794	0.3007	-0.1059	0.1948
84% Perc.	-6.9558	0.9999	0.3222	2.832	0.3914	-0.0167	0.3747
Mean	-9.0284	0.9995	0.2282	1.3478	0.3013	-0.1066	0.1948
Lower HPD ^c	-12.9096	0.9982	0.0566	-1.8674	0.1397	-0.2731	-0.1334
Upper HPD	-4.8482	1	0.4173	4.1597	0.4837	0.0754	0.5591

^a *Source:* Author's Calculations

^b Perc. is Percentile

^c HPD is the Highest Probability Density

Table A.2 – Bayesian Estimation Results SV-AR(2) fit to the Output Gap^a

	Parameter						
	μ	ϕ	σ	β_0	β_1	β_2	$\beta_1 + \beta_2$
16% Perc. ^b	-8.9046	0.8782	0.3736	-0.0497	1.4832	-0.6984	0.7848
Median	-5.341	0.9822	0.4925	-0.0239	1.5547	-0.6269	0.9278
84% Perc.	-2.6021	0.9953	0.6495	0.0032	1.6245	-0.5578	1.0667
Mean	-5.6854	0.9461	0.5099	-0.0234	1.5541	-0.6271	0.9269
Lower HPD ^c	-10.8094	0.7853	0.2558	-0.074	1.4147	-0.7614	0.6533
Upper HPD	-1.8123	0.9999	0.7878	0.0303	1.684	-0.4933	1.1907

^a *Source:* Author's Calculations

^b Perc. is Percentile

^c HPD is the Highest Probability Density

Table A.3 – Bayesian Estimation Results SV-AR(2) fit to the Quarterly Annualized Relative Price Change^a

	Parameter						
	μ	ϕ	σ	β_0	β_1	β_2	$\beta_1 + \beta_2$
16%	-10.7554	0.9979	0.2039	-0.6483	0.1341	0.3173	0.4514
50%	-8.6600	0.9991	0.2726	-0.3745	0.2149	0.3930	0.6079
84%	-6.5071	0.9997	0.3611	-0.0846	0.2965	0.4718	0.7683
mean	-8.6212	0.9988	0.2835	-0.3711	0.2159	0.3935	0.6094
lower HPD	-12.9460	0.9964	0.1400	-0.9449	0.0594	0.2459	0.3053
upper HPD	-4.4001	1.0000	0.4482	0.1838	0.3810	0.5461	0.9271

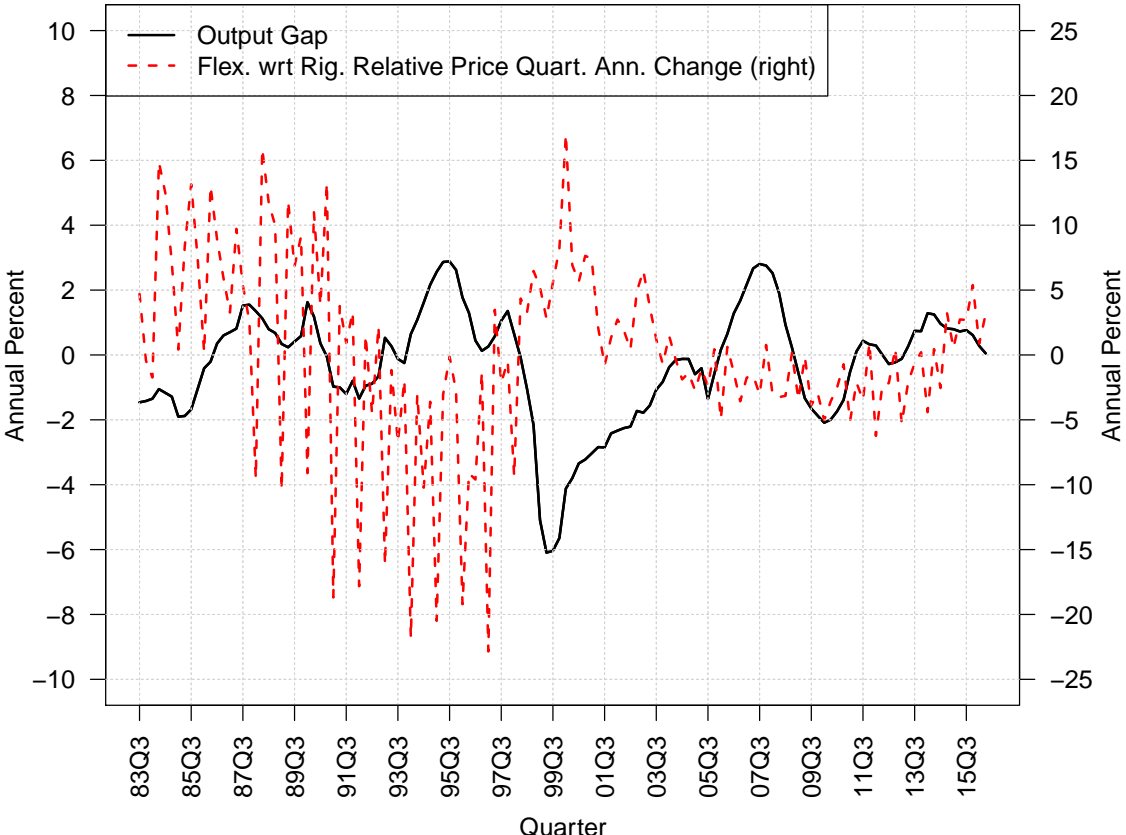
^a *Source:* Author's Calculations

^b Perc. is Percentile

^c HPD is the Highest Probability Density

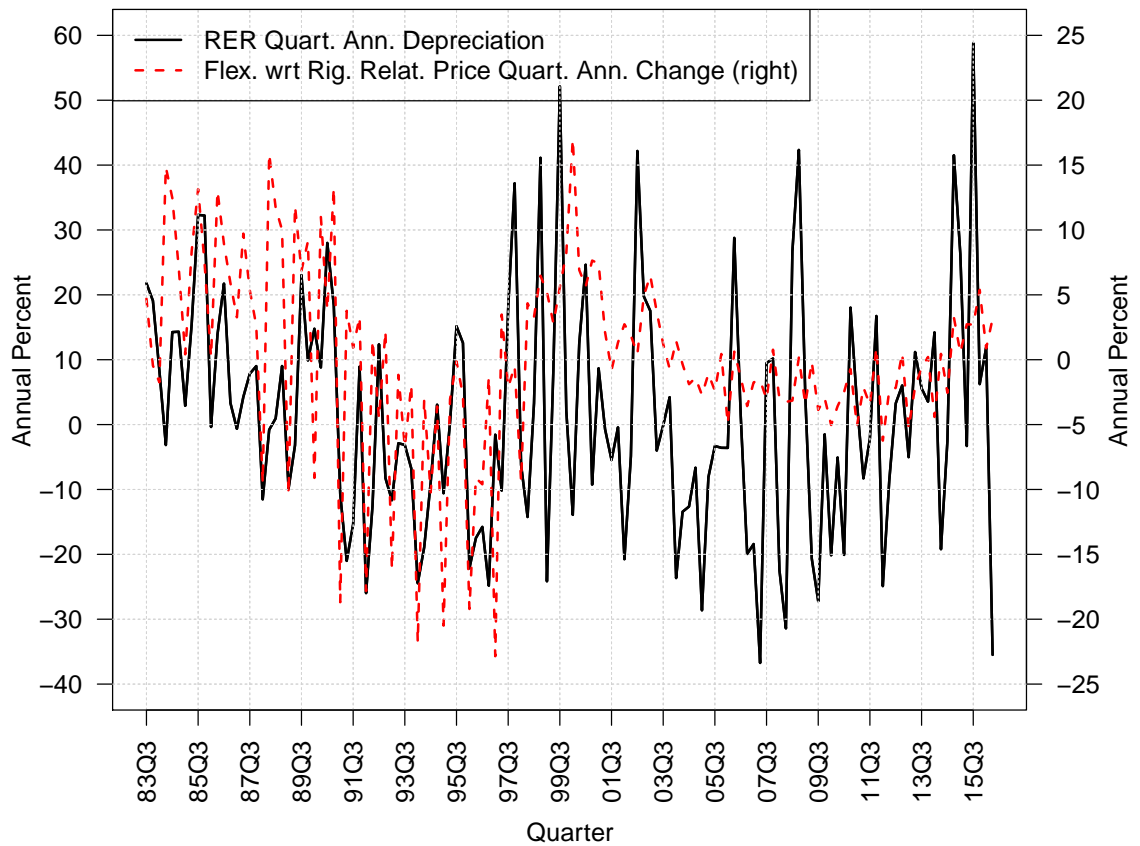
B Figures

Figure B.1 – Quarterly Annualized Change of the Relative Price of Flexible/Rigid and the Output Gap



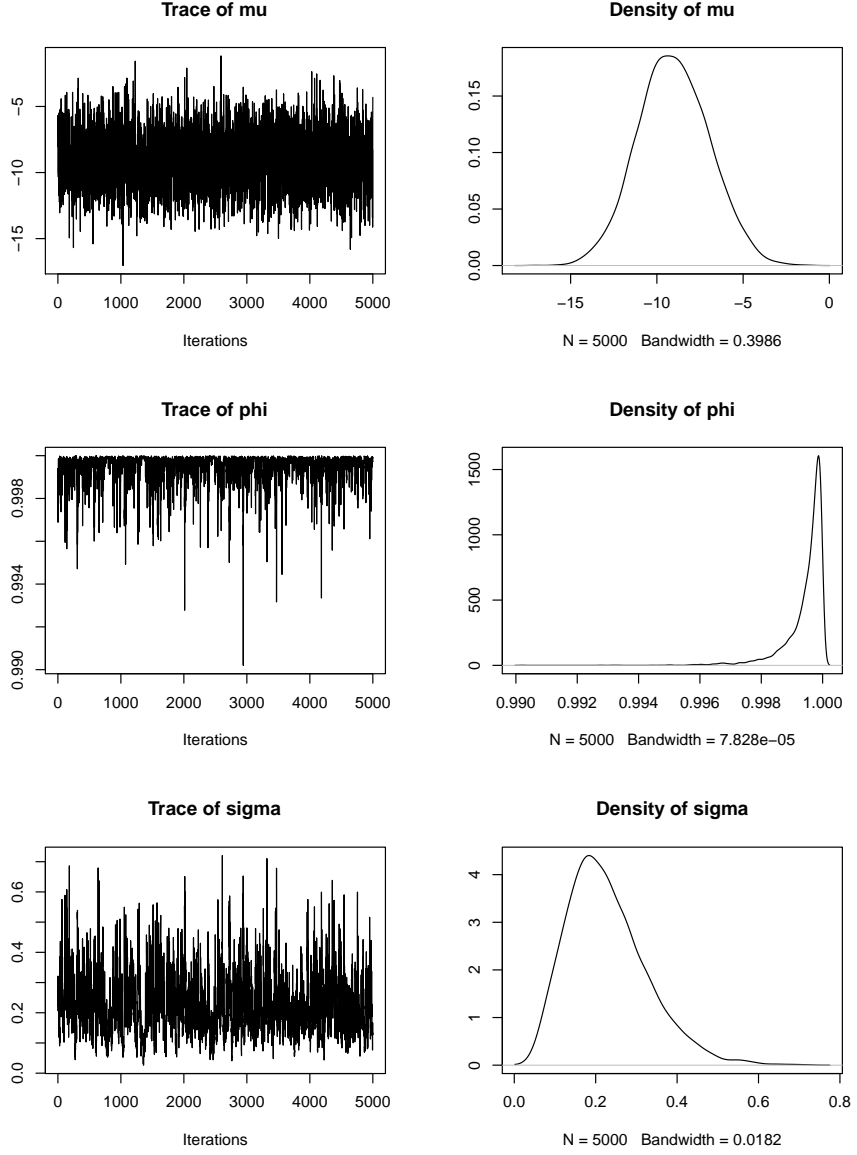
Source: Author's Calculations.

Figure B.2 – Quarterly Annualized Change of the Relative Price of Flexible/Rigid and Quarterly Annualized RER Depreciation



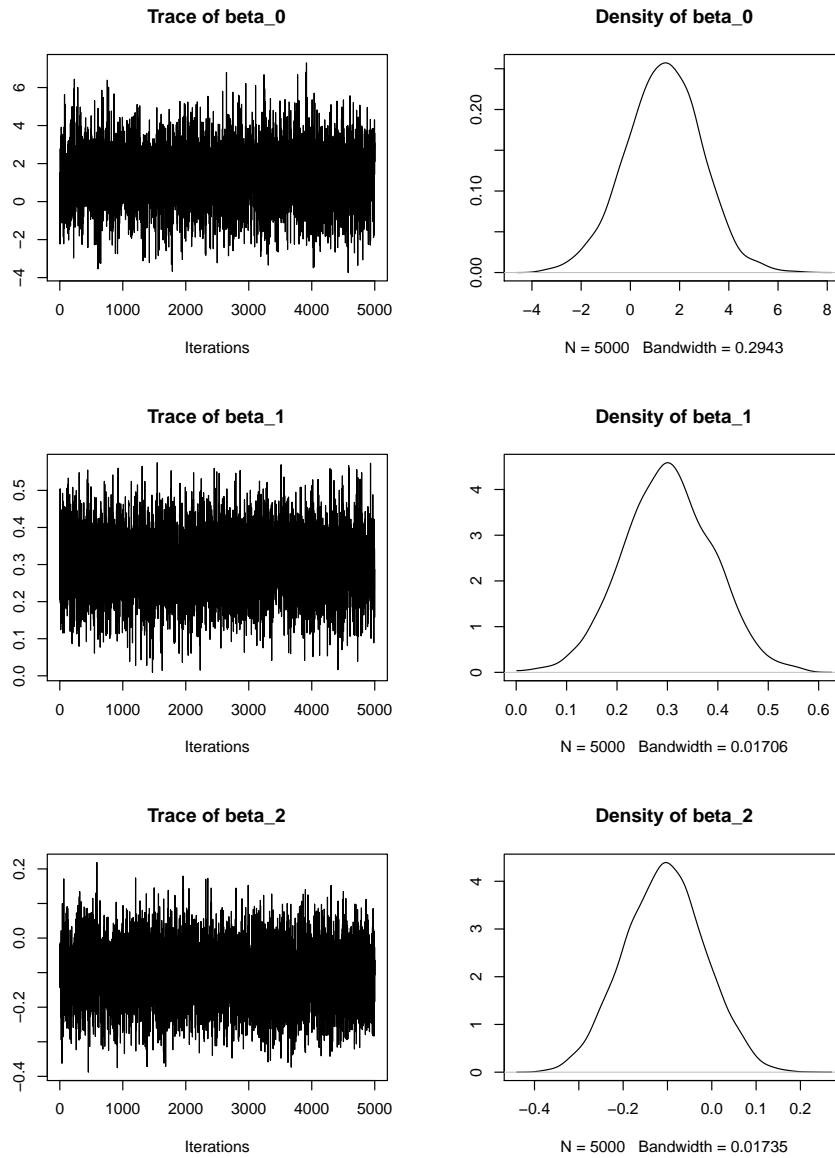
Source: Author's Calculations.

Figure B.3 – Bayesian Estimation Results for AR(2)-SV Model for Quarterly Annualized RER Depreciation



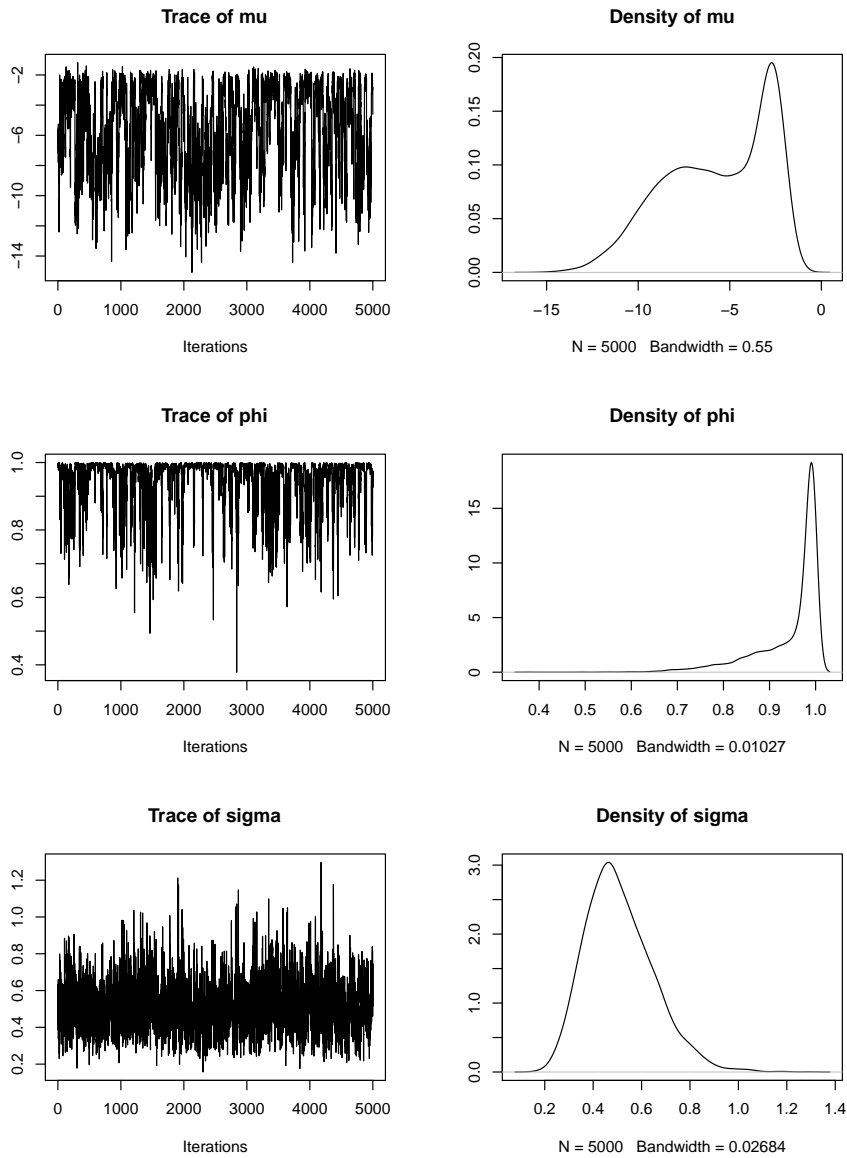
Source: Author's Calculations.

Figure B.4 – Bayesian Estimation Results for AR(2)-SV Model for Quarterly Annualized RER Depreciation (continued)



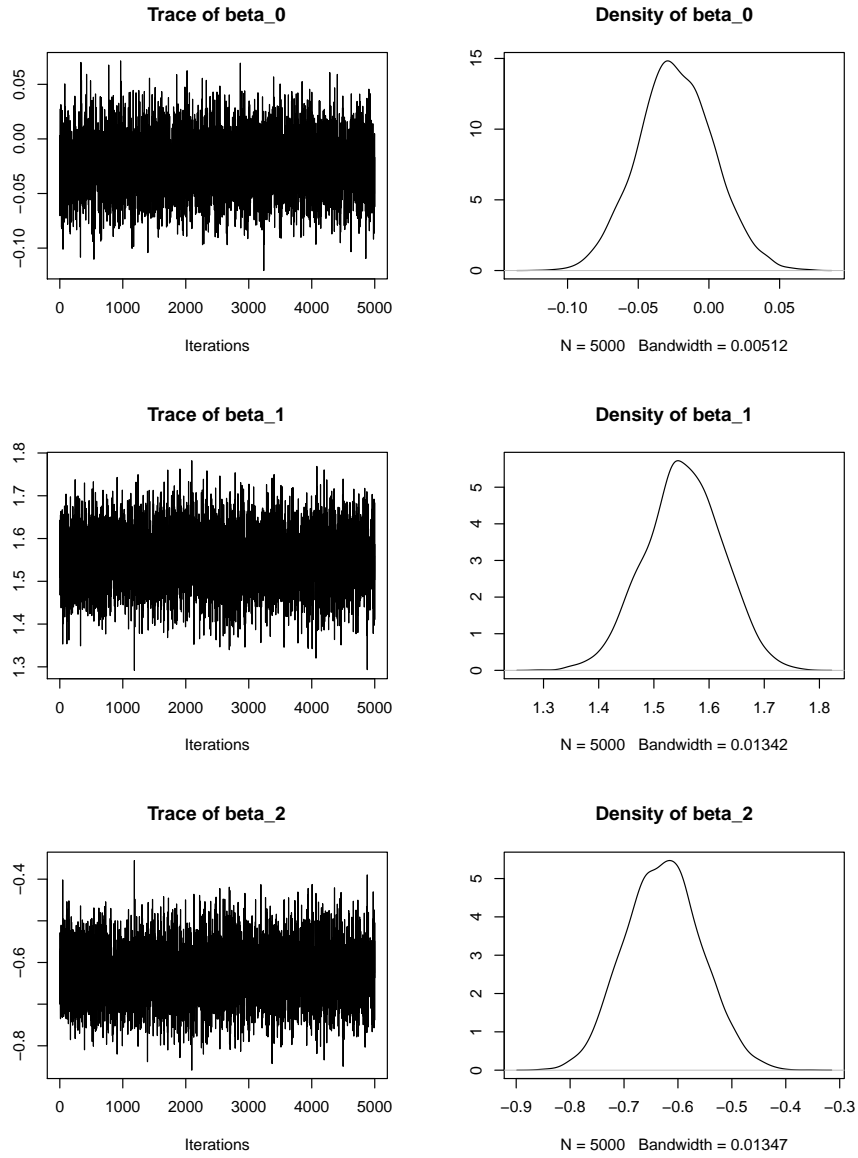
Source: Author's Calculations.

Figure B.5 – Bayesian Estimation Results for AR(2)-SV Model for the Output Gap



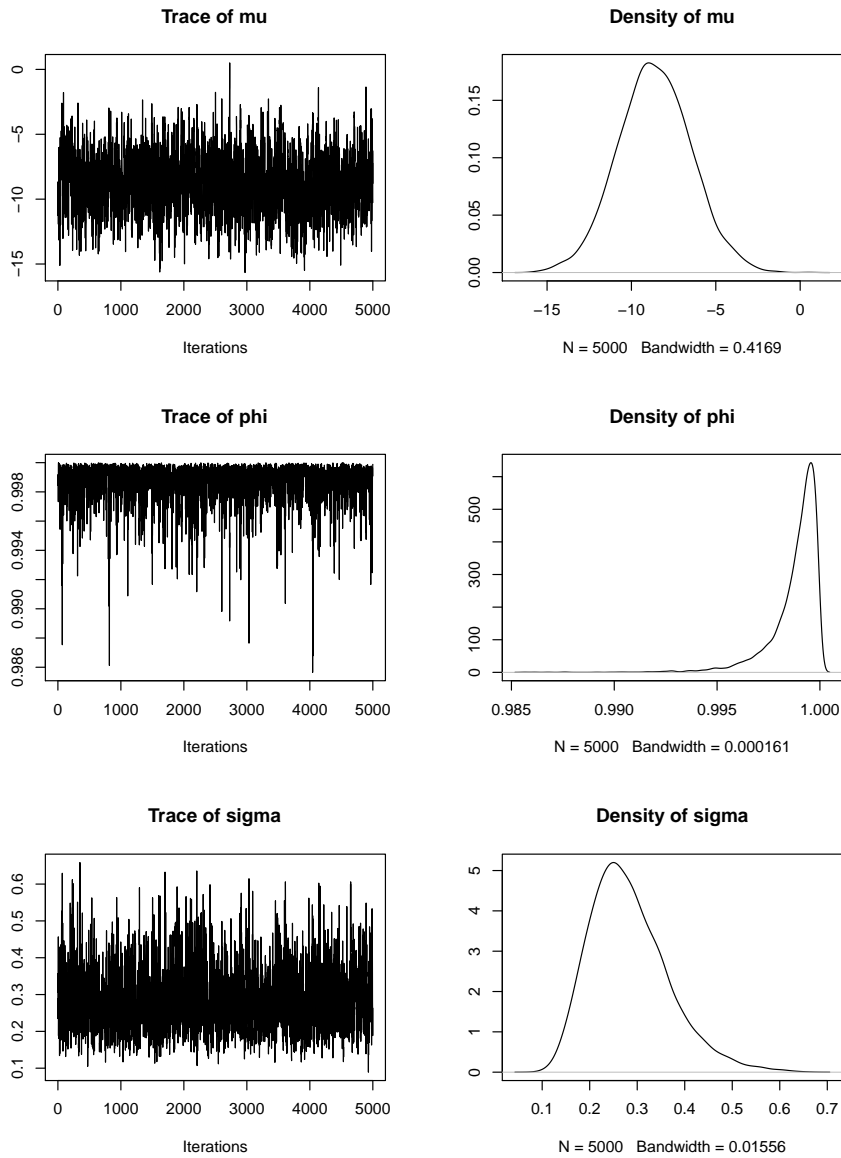
Source: Author's Calculations.

Figure B.6 – Bayesian Estimation Results for AR(2)-SV Model for the Output Gap (continued)



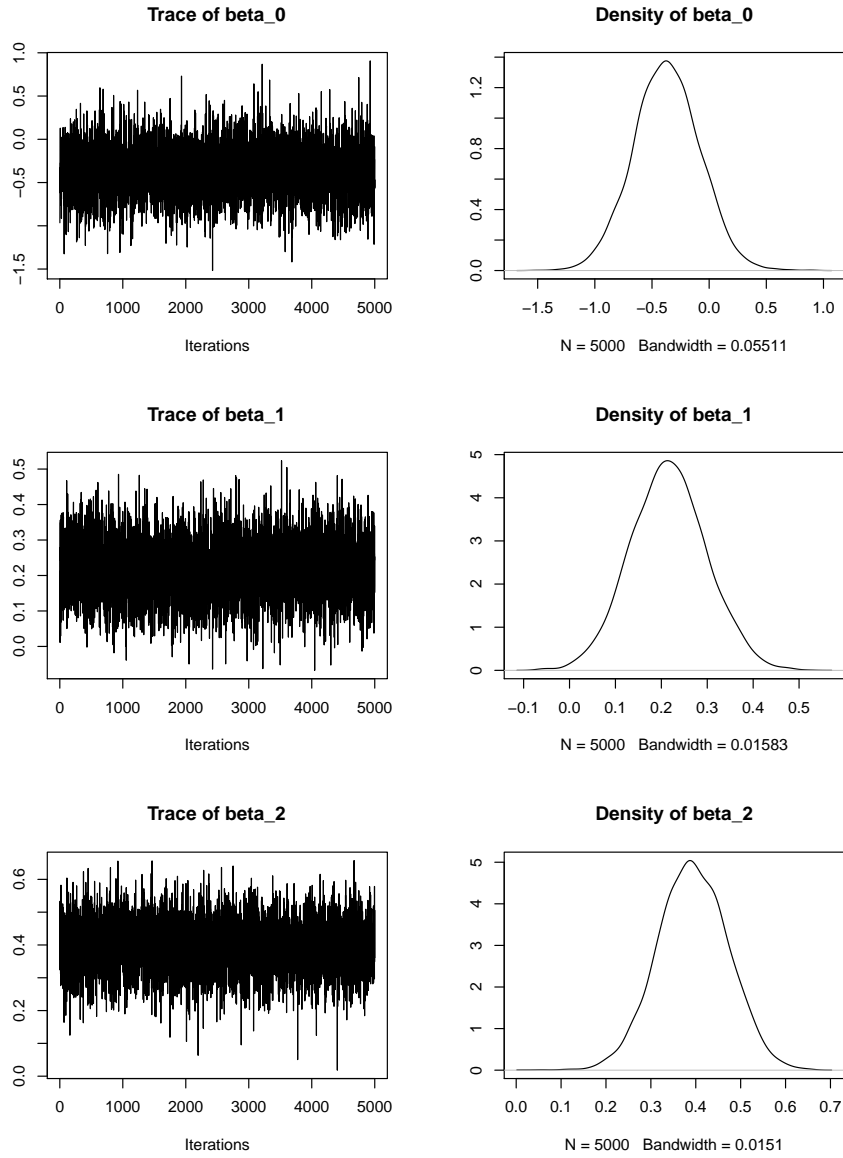
Source: Author's Calculations.

Figure B.7 – Bayesian Estimation Results for AR(2)-SV Model for Quarterly Annualized Change of the Relative Price of Flexible/Rigid



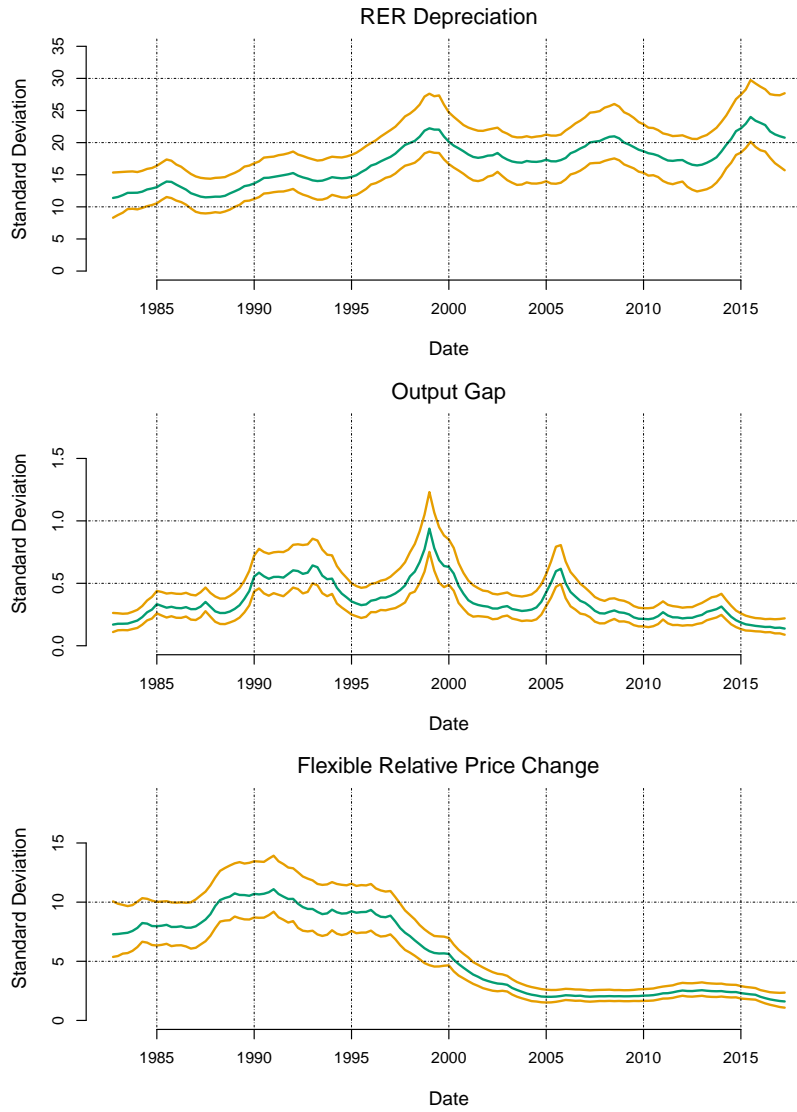
Source: Author's Calculations.

Figure B.8 – Bayesian Estimation Results for AR(2)-SV Model for Quarterly Annualized Change of the Relative Price of Flexible/Rigid (continued)



Source: Author's Calculations.

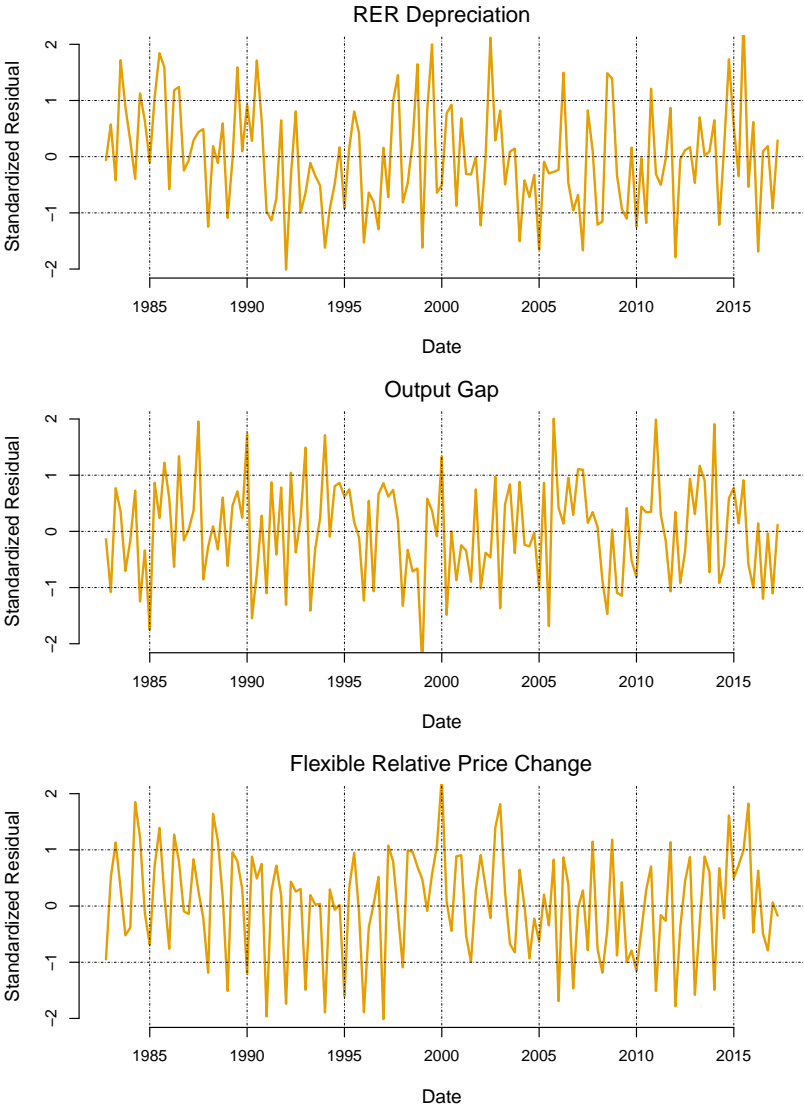
Figure B.9 – Filtered Standard Deviation from Univariate AR(2)-SV Models



Source: Author's Calculations.

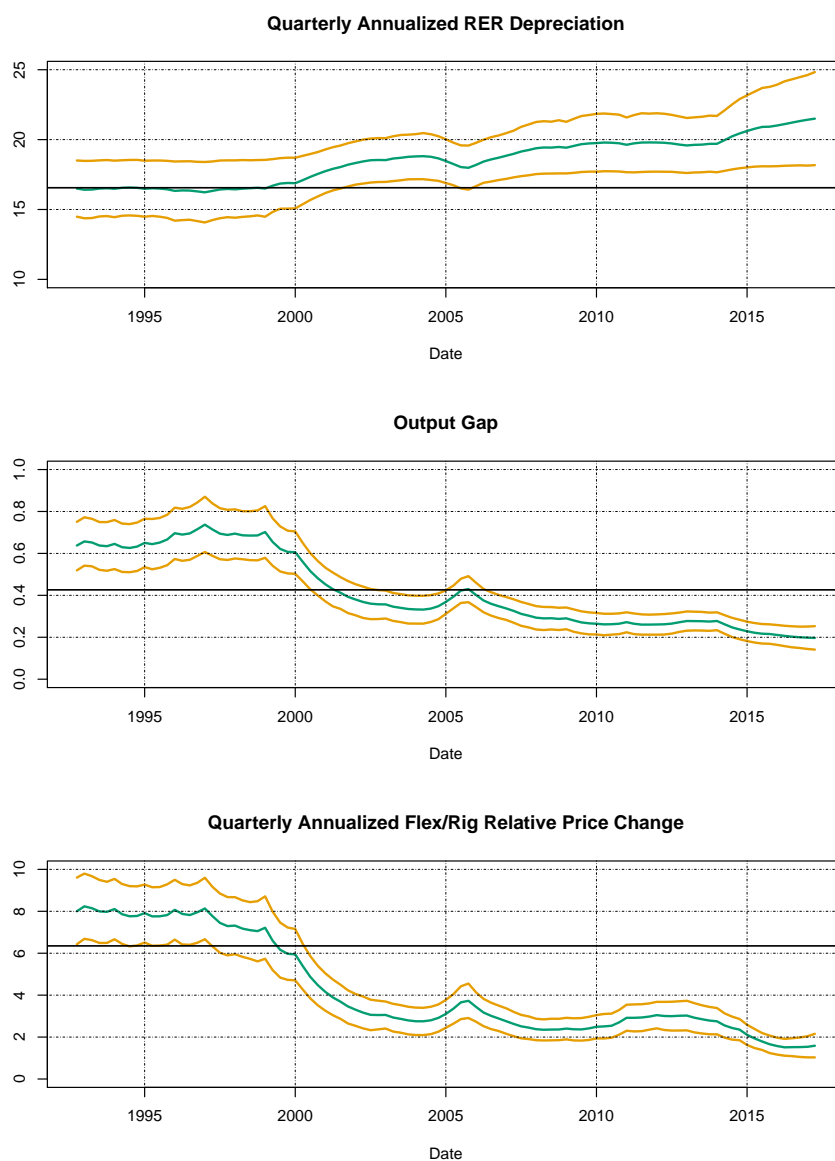
Orange lines are 16% and 84% posterior percentiles.

Figure B.10 – Standardized Residuals from Univariate AR(2)-SV Models



Source: Author's Calculations.

Figure B.11 – Filtered Standard Deviations from TV-VAR(2)-SV Model

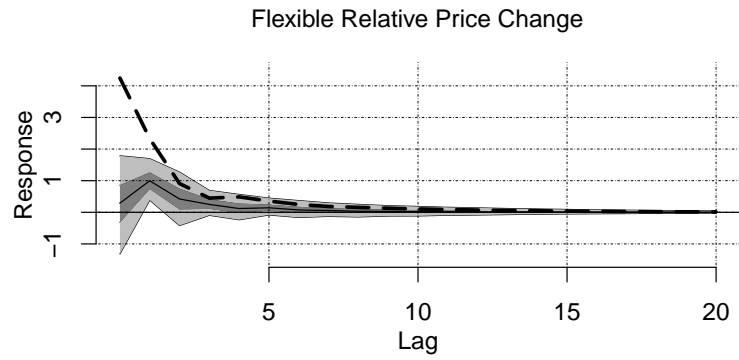


Source: Author's Calculations.

Orange lines are 16% and 84% posterior percentiles.

Bold horizontal line is ordinary VAR(2) estimated residual standard deviation

Figure B.12 – Generalized Response of the Relative Price Change (top panel) and the Output Gap (bottom panel) to one SD residual innovation in RER Depreciation at 2017Q2 from TV-VAR(2)-SV Model Compared to the One Obtained from an Ordinary VAR(2)



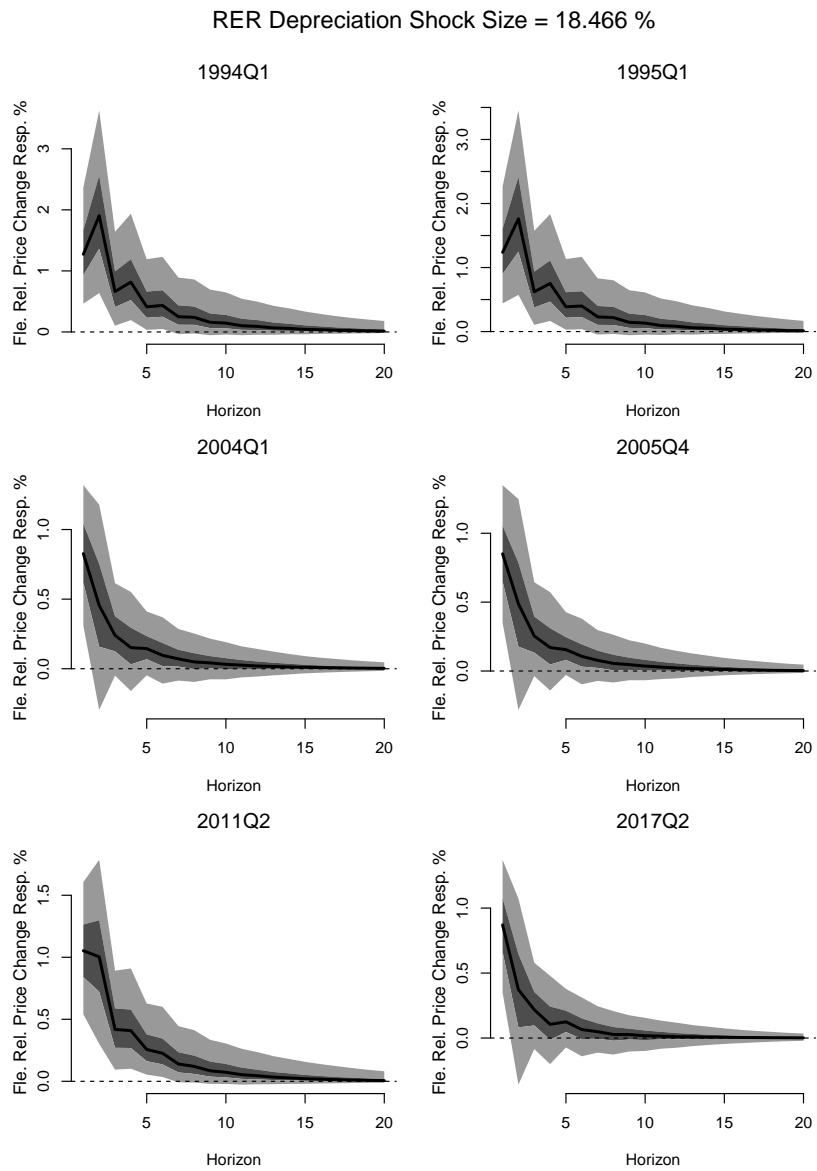
Source: Author's Calculations.

Inner bands are posterior 25% and 75% percentiles

Outer bands are posterior 5% and 95% percentiles

Bold dashed line is ordinary VAR(2) impulse response function

Figure B.13 – Generalized Response of the Flexible Relative Price Change to a 1 Average Standard Deviation of the RER Depreciation Rate

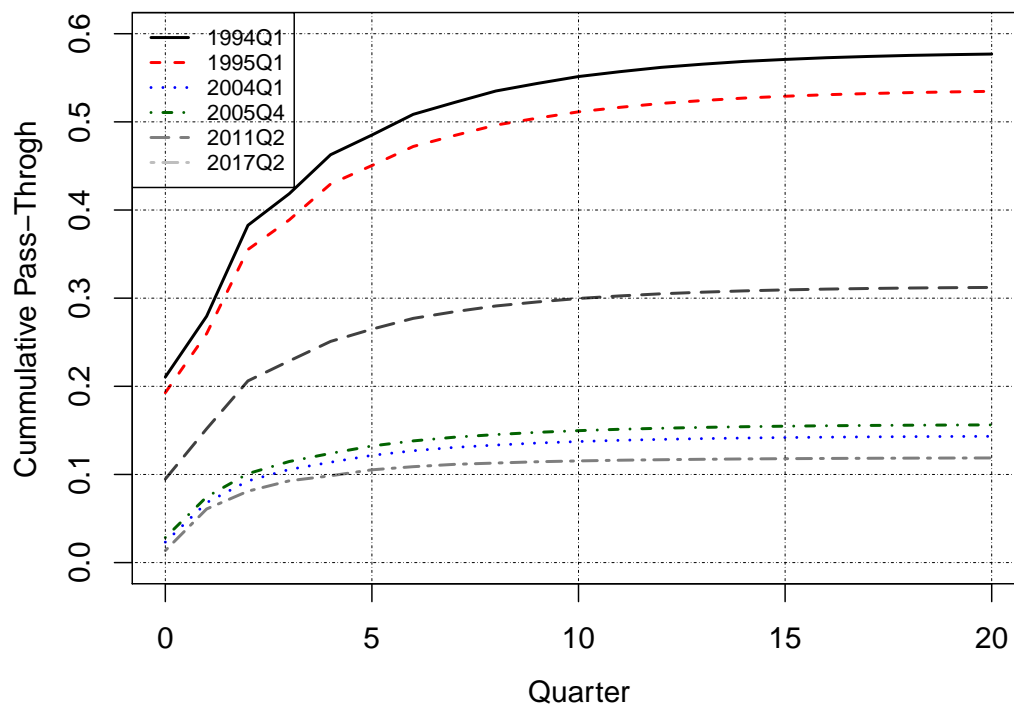


Source: Author's Calculations.

Inner bands are posterior 25% and 75% percentiles

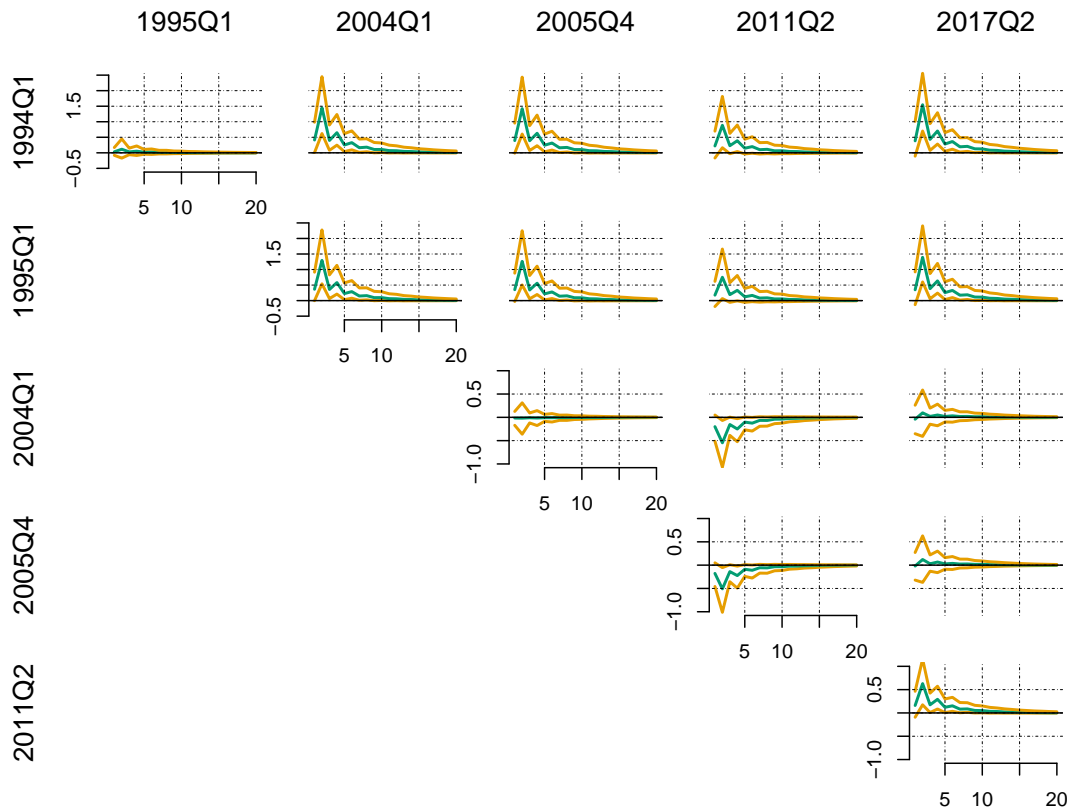
Outer bands are posterior 5% and 95% percentiles

Figure B.14 – Cumulative Pass-Through to Flexible Relative Price Changes to an Unexpected 1% Increase in the RER Depreciation Rate



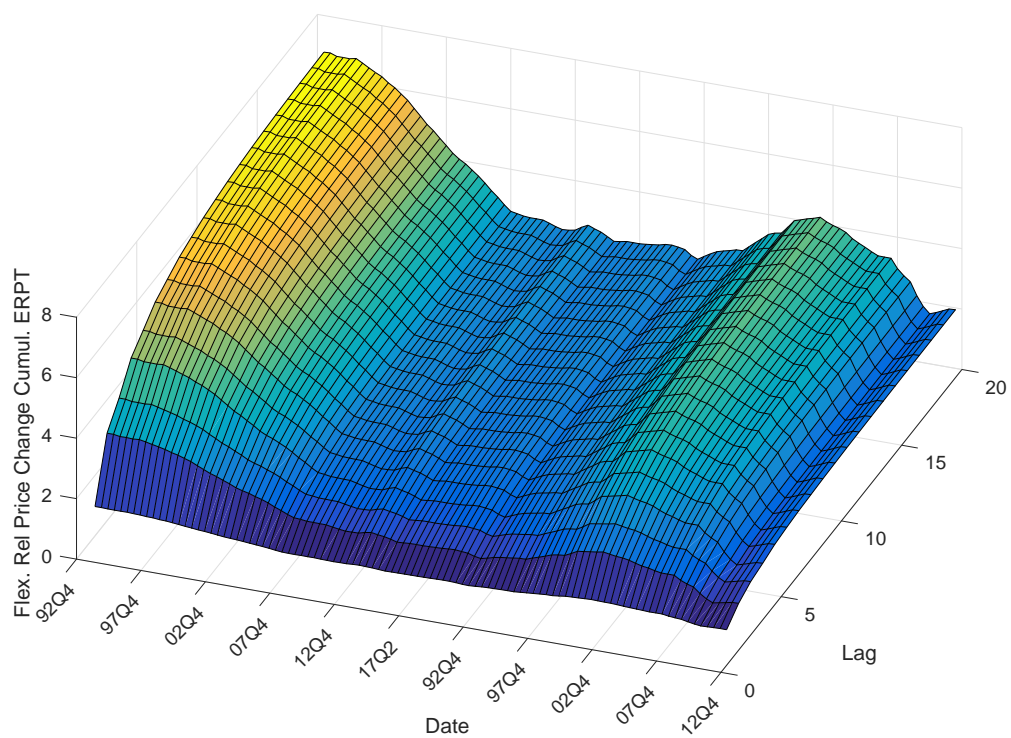
Source: Author's Calculations.

Figure B.15 – Significance of the Difference in Pass-Throughs to Flexible Relative Price Changes Between Dates



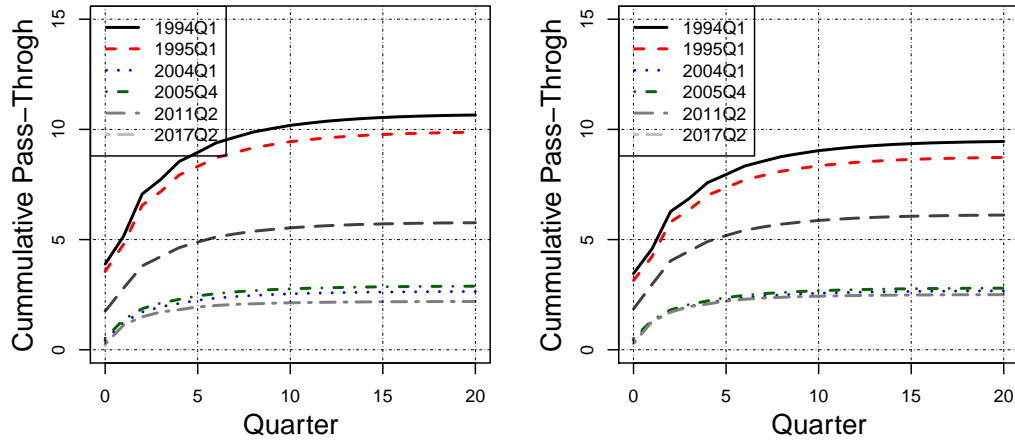
Source: Author's Calculations.

Figure B.16 – Cumulative Pass-Through from an One Standard Deviation at the Date Increase of the RER Depreciation to Flexible Relative Price Changes at all Dates



Source: Author's Calculations.

Figure B.17 – Comparison of the Responses to the Average RER Depreciation Residual SD (left panels) and to the Time-Varing RER Depreciation Residual SDs (right panels)



Source: Author's Calculations.

