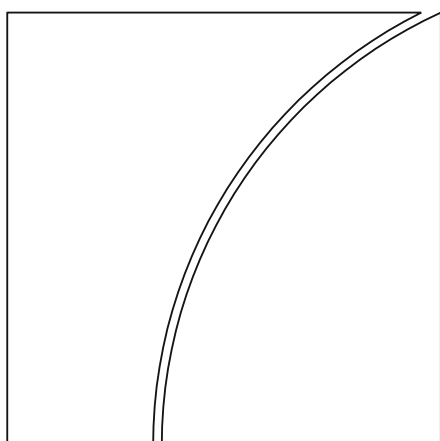




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by Hernán Rincón-Castro and Norberto Rodríguez-Niño

Monetary and Economic Department

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Keywords: Exchange rate pass-through to prices, pricing along the distribution chain, state-dependent, shock-dependent, LST-VAR, Bayesian estimation

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# Nonlinear state and shock dependence of exchange rate pass-through on prices

Hernán Rincón-Castro and Norberto Rodríguez-Niño\*

## Abstract

This paper examines the nature of the pass-through of exchange rate shocks on prices along the distribution chain, and estimates its short and long-term path. It uses monthly data from a small open economy and a smooth transition auto-regressive vector model estimated by Bayesian methods. The main finding is that exchange rate pass-through is nonlinear and state and shock dependent. There are two main policy implications of these findings. First, models used by central banks for policymaking should take into account the nonlinear and endogenous nature of the pass-through. Second, a specific rule on pass-through for monetary policy decisions should be avoided.

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# 1. Introduction

Authorities in small open economies may wish to study the impact of exchange rate shocks for at least three reasons. The first is to learn about how well the exchange rate facilitates short-term macroeconomic adjustment. If there is full pass-through from exchange rate changes to prices of imported goods, the resulting expenditure-switching effects will imply that the exchange rate will be fully stabilizing.<sup>1</sup> The full pass-through assumption is fundamental for the nominal exchange rate to bring about real short-term adjustment, even in DSGE models. If pass-through is incomplete, real short-term adjustment may require a larger change in the exchange rate or changes in other instruments, such as the domestic interest rate.<sup>2</sup> In this setting, the outcome predicted by flexible price models (ie, that when the monetary authority stabilizes prices, there is a corresponding adjustment in the output gap) would no longer be feasible (Smets and Wouters, 2002).

The second reason, which is closely related to the first, is to determine how exchange rate shocks affect inflation, and the implications for monetary policy<sup>3</sup>. If exchange rate pass-through is complete, exchange rate fluctuations, other things equal, are transmitted one-to-one to the prices of imported goods, and probably to prices of producer and consumer goods. Consequently, authorities may need to respond in order to reach their inflation goals. However, if pass-through is incomplete, this response may be neither necessary nor optimal. The reason is that it would be possible to maintain the monetary policy stance without compromising the inflation target.

A third reason is that movements in the exchange rate may affect pricing, production and consumption responses by domestic firms and households. Particularly, firms are concerned about how the exchange rate affects the local price of imported inputs, affecting production costs and expectations about future price behavior. In the case of households, exchange rate movements can alter final prices in local currency, thus altering consumption decisions from foreign to local goods or vice versa.

The purpose of this paper is to study the nature of pass-through (henceforth PT) of exchange rate shocks to prices along the distribution chain, and to estimate the short and long-term impact of these shocks. As in previous literature, a first set of estimates assumes those shocks are exogenous, but PT is nonlinear and state-dependent (section 6). Thus, for example, PT may be larger when inflation is high than when it is low.

On the other hand, in contrast to the existing literature, a second set of estimates assumes that exchange rate fluctuations are endogenous to domestic and foreign macroeconomic shocks, so that PT is nonlinear and state and shock dependent (section 7). For instance, PT may not be the same when the exchange rate depreciates by 1% than when it does by 10%, or when exchange rate movements are caused by domestic shocks compared with foreign shocks. The state of the economy is described by the behavior of CPI inflation (variation, volatility and deviation from the central bank's target), the performance of exchange rates (variation and volatility of the nominal rate and "misalignment" of the real exchange), the output gap (as a measure of the phase of the economy in the business cycle), the degree of economic openness, growth in price of commodities and a trend variable.

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1 Obstfeld and Rogoff (1995), and Obstfeld (2001).

2 Adolfson (2001), Engel (2002), Smets and Wouters (2002), and Adolfson (2007).

3 Ball (1999), Taylor (2000), Devereux and Yetman (2003), Flamini (2007), Mishkin (2008), and Forbes et al. (2015).

The analytical framework is an adjusted and augmented version of McCarthy's (2007) pricing model. The empirical model is a logistic smooth transition VAR (LST-VAR) estimated by Bayesian methods. Given the empirical methodology we will use, the historical decomposition of shocks for changes in prices will be also obtained. The paper uses monthly data from a small open economy (Colombia) along with price and trade data from its main trading partners for the period from 2002:7 to 2015:5 (ie, since the floating exchange-rate and the inflation-target regimes have been in place).

In order to provide readers with context on the Colombian economy and the shocks it may have faced along the sample, we describe some of the statistics related to the main variables of interest. Imported goods account for 30% of the Colombian producer price index while the main imported consumer goods account for 9% of the consumer price index (CPI). Lastly, the total tradable goods constitute 38% of the CPI. To illustrate some possible implications, Figure 1 illustrates the time paths of the Colombian nominal effective exchange rate (local currency units per one unit of foreign currencies weighted by trade) and aggregate prices. As can be seen, they show some co-movements, especially for import prices, and have experienced long swings throughout the sample.

This paper contributes to the literature in at least three ways. First, it models the endogenous and nonlinear nature of PT in a setup that clarifies the channels through which exogenous and endogenous exchange-rate shocks affect prices along the distribution chain (imported, producer, imported consumer, and consumer goods).

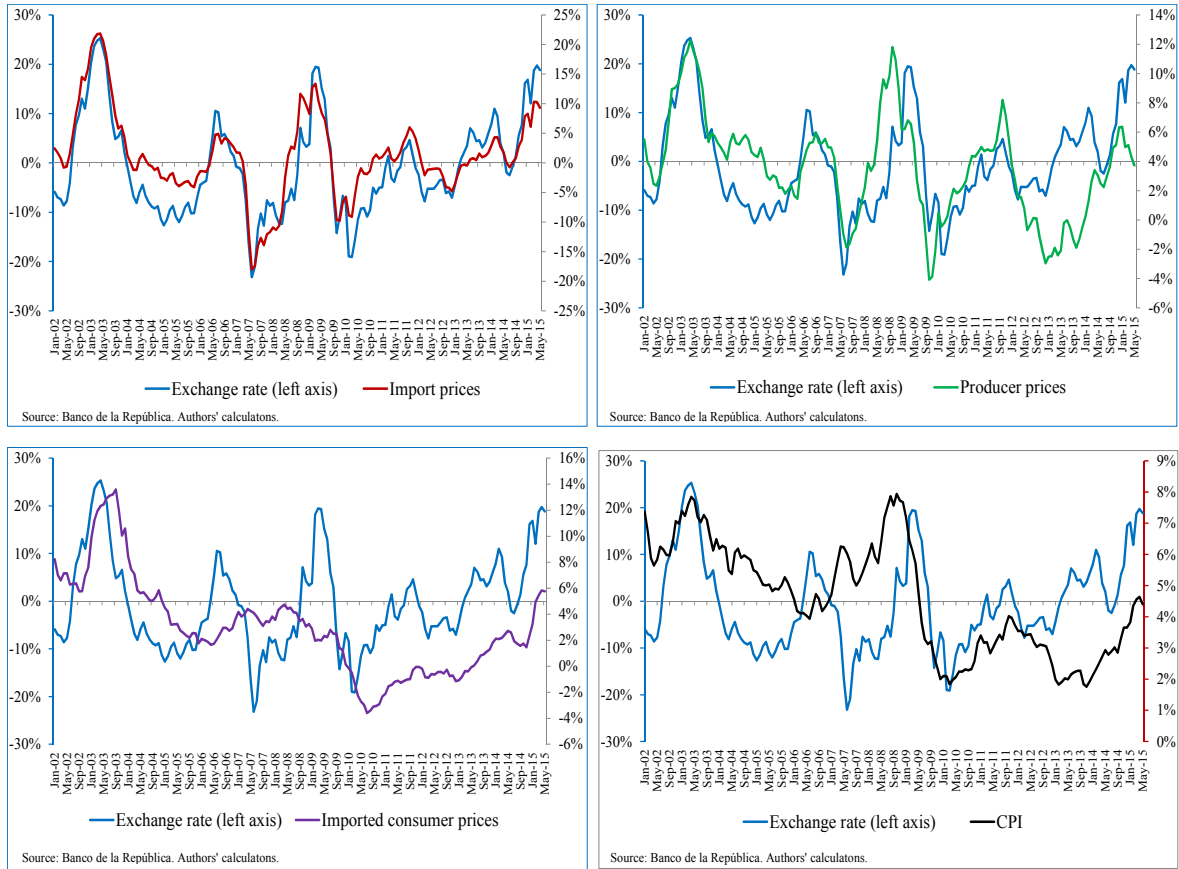
Second, it implements a Bayesian approach for estimation, inference and prediction which addresses several issues raised by "frequentist" approaches. Particularly, the Bayesian approach (i) integrates out nuisance parameters and allows joint estimation of all model parameters, thus avoiding grid-search procedures which may generate unstable estimations; (ii) it employs inference that does not depend on sample size and is based on model-averaged measures, which addresses uncertainties about model-specification; (iii) it considers "the additional uncertainty present in likelihoods that are not single-peaked in finite samples;" (iv) prediction and dynamics do not rely upon asymptotic methods, but on the different models and the observed sample (Koop and Potter, 1999, pages 259-261).<sup>4</sup>

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4    Fernández-Villaverde et al. (2014) list and neatly explain additional justifications for using Bayesian methods in economic and econometric analyses.

Figure 1: Colombian Nominal Effective Exchange Rate versus Prices

(Yearly percentage changes)



Third, it obtains a historical decomposition of shocks (HD) for the proposed LST-VAR model. This will allow us to differentiate which of the foreign and macroeconomic shocks (implicit in our LST-VAR system) were the main determinants of the behavior of prices along the distribution chain and to reveal the relative roles played by exogenous and endogenous shocks to the exchange rate. As will be clear, this will provide empirical support to Klein's (1990) seminal predictions and offer alternative evidence to the findings by Frankel et al. (2012), Shambaugh (2008), Forbes et al. (2015), and Rincón-Castro et al. (2017).<sup>5</sup>

The main finding of this paper is that pass-through is nonlinear and state and shock dependent in both the short term and long term. This in sharp contrast to the well-known findings by Campa and Goldberg (2005, 2006) for a sample of OECD countries and other results of the literature reported in this paper or listed in appendixes A.1.A and A.1.B. The historical decomposition of shocks reveals that Colombian price variations are endogenous to the different macroeconomic shocks faced by the economy and the exchange rate itself.

5 Balke (2000) and Avdjiev and Zeng (2014) employed similar methods for the credit market and economic activity, respectively.

There are several policy implications. First, models used at central banks for policymaking need to be adjusted to the endogenous and nonlinear nature of PT. Second, there is no specific rule of thumb to summarise PT to prices for policymaking, even in the short term. Third, transmission of movements in the exchange rate to prices vanishes along the distribution chain, as expected, and this behavior seems independent from any market behavior by firms, the state of the economy, or shocks. Fourth, uncertainty about PT estimates increases rapidly two years after the shock, as the shown by the bands.<sup>6</sup>

The rest of the paper is organized as follows. Section 2 reviews the Colombian and international literature. Section 3 describes the transmission channels of exchange rate shocks to imported, producer, imported consumer, and total consumer good prices. Section 4 presents an adjusted and augmented version of McCarthy's (2007) pricing model along the distribution chain, which is the analytical framework of the paper. Section 5 explains the data and introduces the regression model and Bayesian smooth transition estimation approach. Sections 6 and 7 show and analyze results for the PT estimates. Section 8 studies the historical decomposition of shocks. The last section summarizes the main conclusions. All aspects related to the implementation of the econometric methodology are left to the appendixes.

## 2. Literature review

Theoretically, the assumption of complete transmission of the exchange rate on prices arises from monetary models of the exchange rate, specifically from the assumed validity of the law of one price or its generalization (purchasing-power parity hypothesis) at all moments in time. This "law" states that prices of goods sold in a country should be equal to the prices of the goods sold abroad when measured in the same currency. In other words, any fluctuation in the exchange rate of a country's currency should be fully reflected in local inflation.

Some studies using static partial equilibrium models<sup>7</sup> and macroeconomic models<sup>8</sup> have cast doubt on the assumptions of complete or exogenous PT. In particular, it can be shown that PT may be incomplete when there are non-competitive market structures along the production or distribution chains, strategic pricing by foreign producers and exporters, or by local importers and producers,<sup>9</sup> nominal rigidities,<sup>10</sup> menu costs,<sup>11</sup> shifts in the composition of country import bundles, or increased sensitivity of tradable and non-tradable consumer goods' prices to movements in exchange rates,

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6 Notice that under Bayesian estimation the 'confidence band' or 'standard error band' terminology is changed to "credible band" or "credible interval" concepts.

7 Krugman (1986) and Dornbusch (1987).

8 Klein (1990), Engel (2000), and Engel and Rogers (2001).

9 Krugman (1986), Dornbusch (1987), Ball et al. (1988), Corsetti and Dedola (2005), Floden and Wilander (2006), and Takhtamanova (2008). For instance, some foreign firms set prices of their exports in their own currency ("producer-currency pricing", PCP), while others set prices in the importer country's currency ("local-currency pricing", LCP). In the first case, a local exchange-rate movement is expected to pass-through fully on import prices, whereas in the second it may not do so. See Engel (2002) for a deep discussion on the implications of one or another strategy on the degree of exchange rate pass-through and on the macroeconomic adjustment mechanisms.

10 Ball et al. (1988) and Corsetti et al. (2008a).

11 Floden and Wilander (2006), and Wolf and Ghosh (2001).

due mainly to a large expansion of imported input use across sectors.<sup>12</sup> As for endogeneity, it arises because PT depends on the stochastic underlying macroeconomic structure of the economy (Klein, 1990). Alternatively, because the exchange rate itself is an endogenous variable, PT and prices are jointly determined (Devereux et al., 2004; Corsetti et al., 2008a, 2008b; Engel, 2009).

The nonlinear behavior of PT is related to the size and nature (transitory versus permanent) of the exchange rate shocks, to their volatility, to price rigidities, and to the state of the economy.<sup>13</sup> Lastly, nonlinearity may arise because of an inventory management strategy or the duration of price contracts between sellers and buyers.

The international and Colombian empirical literature has concluded almost unanimously that PT is incomplete, and recently, that it is endogenous, nonlinear and asymmetric in both the short and the long terms, as shown by González et al. (2010) for Colombia and Donayre and Panovska (2016) for Canada and Mexico (a comprehensive literature review is shown in appendixes A.1.A and A.1.B).<sup>14</sup> These results are independent from the theoretical and empirical approximation used and the country, period, and data frequencies analyzed.

### 3. Transmission channels of exchange rate shocks on inflation

Exogenous or endogenous exchange rate fluctuations manifest themselves on CPI inflation through at least three channels, two of them direct and the other indirect (Figure 2). The first channel is the direct effect of exchange rate fluctuations on import prices and then on producer prices. For producers, the cost of production changes because many products use imported inputs, and, through the cost channel, so does the CPI.<sup>15</sup> The degree of transmission through this channel will depend, among others, on the importing firms' market power over the internal market, on their ability to compensate *menu costs* in price changes or their strategic management of inventories, on the nominal rigidities embedded in the economy, on the sign, size, volatility, and nature of exchange rate movements, and on the state of the economy, as was said before.

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12 Campa and Goldberg (2005), and Campa and Goldberg (2006).

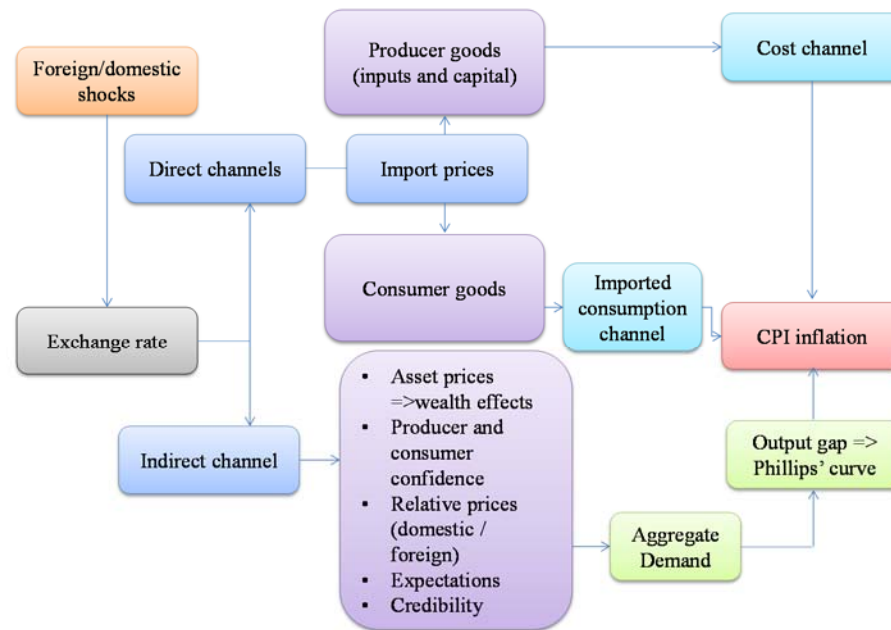
13 Borensztein and De Gregorio (1999), Taylor (2000), Smets and Wouters (2002), Devereux and Yetman (2003), Floden and Wilander (2006), Corsetti et al. (2008a), Mishkin (2008) and Bussiere (2013).

14 See Burstein and Gopinath (2013) for a recent overview of the academic literature on PT. Caselli and Roitman (2016) found PT nonlinearities and asymmetries in a sample of 28 Emerging Markets, Colombia among them.

15 Notice that CPI inflation may be affected through the cost channel not only because prices of tradable goods are changing (for instance because of prices of imported inputs used by producers), but also due to the fact that prices of non-tradable goods or services may adjust, too. For example, changes in the exchange rate may alter transportation or telecommunication prices due to adjustments in the prices of imported equipment.



Figure 2: Transmission Channels of Exchange Rate Shocks on Prices



Source: Authors' construction, based on Miller (2003) and own deductions.

The second channel is the direct effect on prices of imported consumer goods (which may also be intermediated by importers) and which directly impacts the CPI. This channel can be called the imported consumption channel. It also manifests itself in changes in the demand of domestic goods derived from price variations of the imported goods competing with them, putting upward/downward pressure on the CPI. The degree of substitutability between imported and local goods will determine the degree of transmission through this channel.

The indirect channel works through multiple means and disturbances that impact aggregate demand and the CPI through the Phillips' curve. Among these mechanisms are asset prices, inflation expectations, and credibility on the monetary authority. Therefore, this can be called the general equilibrium channel of PT.

Of course, the timing, degree and dynamics of the impact of exchange rate movements on prices at each stage are different, as will be shown later.

## 4. Analytical framework

In order to study the impact of exchange rate fluctuations on prices, this section follows McCarthy's (2007) pricing model along the distribution chain. However, we adjust and augment his model in three directions. First, we introduce marginal costs of foreign exporters of domestic imports ( $mgc^*$ ), which capture not only the impact of their non-competing behavior on the domestic inflation when the exchange rate of the domestic currency changes (as was originally pointed out and modeled by

Dornbusch (1987)), but also the effects of global supply shocks.<sup>16,17</sup> Second, we change the order of the system of equations to allow for demand shocks to affect supply, and not the other way around, in order to somehow incorporate the predictions from Neo-Keynesian DSGE models for small open economies.<sup>18</sup> Third, we differentiate import prices that affect producers from those that affect consumers directly. Thus, as we will show next, there will be four price stages: import, producer, imported consumer, and total consumer goods.

Hence, price variations at a specific distribution stage in period  $t$  have different components (see Figure 2): (1) the expected inflation at the respective stage based on all information available at period  $t-1$ ; (2) the effects of period  $t$  foreign marginal cost shock on inflation at that stage; (3) the impact of period  $t$  exchange rate shock at a particular stage; (4) the influence of period  $t$  domestic demand and supply shocks at a particular stage; (5) inflation shocks of other goods at previous stages; (6) the respective inflation shock at period  $t$ , which is nothing but the fraction or residual of inflation at each stage not explained by the other components, for instance, by shocks to mark-ups at each distribution stage, as predicted by Dornbusch's model in the case of import prices.

Therefore, the inflation rates in period  $t$  at each of the stages – import ( $m$ ), producer ( $ppi$ ), imported consumer ( $mc$ ) and total consumer ( $cpi$ ) goods – can be written as:

- (1) Foreign marginal cost:  $\Delta mgc_t^* = E_{t-1}(\Delta mgc_t^*) + \varepsilon_t^{\Delta mgc^*}$
- (2) Exchange rate:  $\Delta e_t = E_{t-1}(\Delta e_t) + \alpha_1 \varepsilon_t^{\Delta mgc^*} + \varepsilon_t^{\Delta e}$
- (3) Inflation of import prices:  $\pi_t^m = E_{t-1}(\pi_t^m) + \beta_1 \varepsilon_t^{\Delta mgc^*} + \beta_2 \varepsilon_t^{\Delta e} + \varepsilon_t^{\pi^m}$
- (4) Domestic demand:  $D_t = E_{t-1}(D_t) + \gamma_1 \varepsilon_t^{\Delta mgc^*} + \gamma_2 \varepsilon_t^{\Delta e} + \gamma_3 \varepsilon_t^{\pi^m} + \varepsilon_t^D$
- (5) Domestic supply:  $S_t = E_{t-1}(S_t) + \delta_1 \varepsilon_t^{\Delta mgc^*} + \delta_2 \varepsilon_t^{\Delta e} + \delta_3 \varepsilon_t^{\pi^m} + \delta_4 \varepsilon_t^D + \varepsilon_t^S$
- (6) Inflation of producer goods:  $\pi_t^{ppi} = E_{t-1}(\pi_t^{ppi}) + \theta_1 \varepsilon_t^{\Delta mgc^*} + \theta_2 \varepsilon_t^{\Delta e} + \theta_3 \varepsilon_t^{\pi^m} + \theta_4 \varepsilon_t^D + \theta_5 \varepsilon_t^S + \varepsilon_t^{\pi^{ppi}}$
- (7) Inflation of imported consumer goods:  $\pi_t^{mc} = E_{t-1}(\pi_t^{mc}) + \vartheta_1 \varepsilon_t^{\Delta mgc^*} + \vartheta_2 \varepsilon_t^{\Delta e} + \vartheta_3 \varepsilon_t^{\pi^m} + \vartheta_4 \varepsilon_t^D + \vartheta_5 \varepsilon_t^S + \vartheta_6 \varepsilon_t^{\pi^{ppi}} + \varepsilon_t^{\pi^{mc}}$
- (8) Inflation of total consumer goods:  $\pi_t^{cpi} = E_{t-1}(\pi_t^{cpi}) + \varphi_1 \varepsilon_t^{\Delta mgc^*} + \varphi_2 \varepsilon_t^{\Delta e} + \varphi_3 \varepsilon_t^{\pi^m} + \varphi_4 \varepsilon_t^D + \varphi_5 \varepsilon_t^S + \varphi_6 \varepsilon_t^{\pi^{ppi}} + \varphi_7 \varepsilon_t^{\pi^{mc}} + \varepsilon_t^{\pi^{cpi}}$

The exchange rate shock is pulled out from its own perturbation. As was stated in the introduction, this corresponds to an exogenous or autonomous exchange rate shock. Later on, an endogenous exchange rate fluctuation will be modeled and the corresponding PT will be estimated. The demand shock is extracted from a measure of the output gap and the supply shock from the non-core CPI, as any 'modern' central banker would do. Thus,  $\varepsilon_t^{\Delta mgc^*}$ ,  $\varepsilon_t^{\Delta e}$ ,  $\varepsilon_t^D$  and  $\varepsilon_t^S$  are the structural

16 Dornbusch models a foreign firm which optimally fixes its export price with a markup above its marginal cost. In his model, the markup is a growing function of its product market share in the domestic country. Unfortunately, we could not build a measure of the marginal cost for each of the firms or countries exporting to Colombia, due to unavailability of data. For this reason, we use their whole price index as their marginal cost proxy, once we weigh them by the respective monthly trade weight into the Colombian imports.

17 Introducing international prices in the model also tackles criticism to the empirical literature on exchange rate pass-through on inflation that did not differentiate between changes in the exchange rate vis-à-vis changes in international prices, as was pointed out by Shambaugh (2008).

18 Due to the presence of sticky prices or non-competitive behavior by producers, supply is demand-determined in the short term.

innovations to foreign marginal cost, exchange rate, domestic demand, and domestic supply, respectively. These shocks are assumed as contemporaneous, independent, and uncorrelated with every variable in the information set and with any other shock; in other words, they are assumed to be rational expectation errors.  $\varepsilon_t^{\pi^m}$ ,  $\varepsilon_t^{\pi^{ppi}}$ ,  $\varepsilon_t^{\pi^{mc}}$  and  $\varepsilon_t^{\pi^{cpi}}$  are the structural innovations to import, producer, imported consumer and total consumer inflation. It is also understood that they are contemporaneously independent and uncorrelated.  $E_{t-1}(\cdot)$  is the mathematical expectation of the respective conditional variable on all the information available and observable variables at time  $t-1$ , including past data.

The conditional expectations given in equations (1) to (8) are replaced by projections of the lags of the variables in the system. Hence, they can be expressed as a VAR system, where the vector of variables summarizing this is  $Y_t = (\Delta mgc_t^*, \Delta e_t, \pi_t^m, D_t, S_t, \pi_t^{ppi}, \pi_t^{mc}, \pi_t^{cpi})'$ , with a vector of structural shocks given by  $\varepsilon_t = (\varepsilon_t^{\Delta mgc^*}, \varepsilon_t^{\Delta e}, \varepsilon_t^{\pi^m}, \varepsilon_t^D, \varepsilon_t^S, \varepsilon_t^{\pi^{ppi}}, \varepsilon_t^{\pi^{mc}}, \varepsilon_t^{\pi^{cpi}})'$ .

## 5. Data, regression model and estimation approach

### 5.1 The Data

We use monthly data from Colombia and its main trading partners for the period 2002:7 and 2015:5. An index weighted by foreign trade was constructed to obtain a nominal effective exchange rate measure of the domestic currency (peso). Trade weights were obtained from Colombia's main trading partners. Here, a rise in the index represents a depreciation of the peso. Appendix A.2 describes the time series, their sources, and methodology.

### 5.2 The Regression Model: A Nonlinear Logistic Smooth Transition VAR Model

The estimations of PT on imported, producer, imported consumer, and total consumer goods start from the pricing model along the distribution chain given by equations (1) to (8) in section 3. This model will be specified as a logistic smooth transition VAR (LST-VAR) model,<sup>19</sup> which allows us to model and diagnose the types of endogeneities and nonlinearities of PT discussed above.<sup>20</sup> The model will be estimated by Bayesian methods, following closely the approach implemented by Gefang and Strachan (2010), and Gefang (2012). We explain the methodology step by step, as well as the robustness exercises implemented, in Appendix A.3.

Movements of imported, producer, imported consumer, and total consumer prices will depend on their own lags, lags of foreign marginal cost and their lags, lags of exchange rate movements and their lags, lags of demand and supply and their lags, and on the different shocks. Moreover, their regime changes are determined by the transition variables, whose dynamic is captured by a logistic smooth transition function. The  $p$ -lags order LST-VAR model is written as (see He et al., 2009):

19 Luukkonen, Saikkonen and Terasvirta (1988), Granger and Teräsvirta (1993), Teräsvirta (1994), Van Dijk et al. (2002).

20 We selected the transition model on the basis of the economic theory, as well as the Bayes Factors results, which suggests the use of a logistic smooth transition model in order to capture possible nonlinearities and asymmetries for extreme values of the variable that describes the transition or state of the economy, as will be shown later on.

$$(9) \quad Y_t = A(L)Y_{t-1} + F(z_{t-d}; \gamma, c)B(L)Y_{t-1} + \mu_t,$$

with  $A(L)$  and  $B(L)$  being  $p$ -order polynomial matrixes;  $L$  being the lag operator;  $F(z_{t-d}; \gamma, c)$  being a diagonal matrix whose elements  $f_j$  are transition functions, with  $f_j(\cdot) = \{1 + \exp[-\gamma(z_t - c)/\sigma_z]\}^{-1}$  representing the cumulative function of logistical probability for the  $j$ -th transition variable,  $z_t$  the vector of transition variables and  $\gamma$  the smoothing parameter for the change in the value of the logistic function ( $\gamma > 0$ ). Thus, the smoothness of the transition from one regime to the other has the following behavior: If  $\gamma$  is very large, the logistic function  $f_j(z_t; \gamma, c)$  approaches the indicator function  $I(z_t > c)$ . As a consequence, changes from 0 to 1 become instantaneous at  $z_t = c$ . When  $\gamma$  approaches zero, the logistic function becomes a constant (equal to 0.5) and the LST-VAR model reduces to a linear VAR model with parameters  $\Phi_j = A_j + \frac{B_j}{2}$ , for  $j = 0, 1, \dots, p$ .

On the other hand,  $c$  is the localization parameter and can be interpreted as the threshold between the two regimes, in the sense that the logistic function  $f_j(\cdot)$  changes monotonically from 0 to 1 as  $z_t$  increases.<sup>21</sup> Finally,  $\mu_t$  is a vector of white-noise processes. Parameters  $\gamma$  and  $c$  together with  $z_t$  govern the transition between regimes. Thus when  $\gamma \rightarrow \infty$  and  $z_t < c$  we are under the regime of  $A(L)Y_{t-1}$ , while when  $\gamma \rightarrow \infty$  and  $z_t > c$  we are then under  $[A(L) + B(L)]Y_{t-1}$ . For finite values of  $\gamma$ , one has a continuum between the two extreme regimes.

The structural shocks in equation (9) are identified by using the Cholesky decomposition. In other words, we define  $\mu_t = \mathbf{A}^{-1}\varepsilon_t$ , with  $\mathbf{A}$  being an inferior triangular matrix and  $\varepsilon$  the vector of the structural shocks, which are assumed to have the following properties:  $E[\varepsilon_t^i / \Omega_{t-1}] = 0$ ,  $E[\varepsilon_t^{i^2} / \Omega_{t-1}] = \sigma^{i^2}$ , not cross-correlated and  $\Omega_{t-1} = [y_{t-1}^i, y_{t-2}^i, \dots, y_{t-p}^i]$ , with  $i = \Delta mgc^*, \Delta e, \pi^m, D, S, \pi^{ppi}, \pi^{mc}, \pi^{cpi}$ .

But, why does this paper choose a Cholesky decomposition method, which has been critiqued in different contexts? There are several reasons. First, it does not affect the robustness of our PT estimates since they are constructed using GIRFs, which are quite robust to the ordering of the variables in VAR systems (Pesaran and Shin, 1998; Ewing, 2001).<sup>22</sup> Second, it introduces an additional identification assumption, which consists on imposing a positive PT, and conditioning the accumulated GIRFs of the numerator and denominator of equation (10) to it. This makes sense by definition and goes along with the idea of identification by sign restrictions of Canova and De Nicolò (2002). Notice that this assumption will be relaxed by the second set of estimations, which assume that the exchange-rate movements respond endogenously to shocks. Third, innovative work in the field of Bayesian nonlinear VARs (such as Gefang and Strachan, 2010; Gefang, 2012) considers that Cholesky decomposition is a good approximation of identification, which is complemented with GIRFs to overcome the issue of ordering the variables in a VAR system. Therefore, the critiques of recursive identification methods by Faust and Rogers (2003) do not hold for our estimations.<sup>23</sup>

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21 As will be shown later, parameters  $\gamma$  and  $c$  will change with each transition variable  $z$ .

22 The methodological appendixes will explain how the GIRF functions are calculated.

23 Regarding long-term restrictions, as done for instance by Blanchard and Quah (1989), two aspects are worth noting. First, we would not know how to justify that PT is completed in the long term (that is, PPP holds), since theory (see, for instance, Engel, (2000)) and most of the empirical literature has generally shown that it is incomplete, even for long periods, in spite of the fact that for DSGE models it is a standard assumption. Second, even if one assumes that PPP holds, one has to impose additional restrictions (usually Cholesky on short and long-term parameters) that make economic sense and allow one to recover the structural errors from the nonlinear model implemented. Accordingly, such restrictions must be proven to ensure that they are validated by the data and are statistically significant across the different regimes of the transition variables, which have not yet been formulated by theory in the context of nonlinear models estimated by Bayesian methods. Additionally, the complexity involved in calculating Generalized Impulse Response Functions under

One possibility to know the  $p$ -order of the system, to choose the transition variables  $V$ , and to know the lag delay  $d$  of the transition variables and the values of the parameters  $\gamma$  and  $c$  is to have a range of models and then choose the best one using a criterion, for example, the maximization of the likelihood function. This is commonly done by the applied literature on nonlinear models, for instance by Winkelried (2003), González et al. (2010) and Mendoza (2012), who use data from Latin American small open economies.

An alternative, as presented in this paper, is to use Bayesian methods to formally compare among different model specifications (remember that under the Bayesian approach models become random variables). Specifically, we calculate the Bayes factor from the Savage–Dickey density ratios (SDDR) for many combinations of the arguments and compute posterior model probabilities to select the dominant model for inference.<sup>24,25</sup> This allows us to account for model specification and coefficient uncertainties, as well as for the driving forces of the nonlinearities. From there we construct GIRF and then trace out the dynamics of PT coefficients.<sup>26</sup>

Based on the theory presented above, the transition variables are: Variation of the CPI inflation ( $\Delta\pi^{cpi}$ ), volatility of inflation ( $V(\pi^{cpi})$ ), and deviation of the CPI inflation from the central bank's target ( $D\pi$ ), as an effort to differentiate a "high" inflation regime from a "low" one. Also, variation of the exchange rate change ( $\Delta(\Delta e)$ ), volatility of the exchange rate ( $V(\Delta e)$ ), and a measurement of misalignment of the real exchange rate ( $Mq$ ) are analyzed. It is worth noting that we use the volatility of the exchange rate of the Colombian peso as a measure of the nature of its changes: if the volatility is high, we suppose that foreign exporters (or local importers) perceive such changes as transitory, while if it is low, we assume they perceive such changes as permanent.<sup>27</sup>

The other transition variables are the output gap ( $Gy$ ), the degree of economic openness (*Openness*), growth in price of commodities ( $\Delta P_{comm}$ ), the interbank interest rate, or operational instrument of the monetary policy (*IBR*), as well as a trend variable as a "time ordering" variable (*Trend*). The operational interest rate aims to condition PT on the behavior of the main monetary policy instrument of the Colombian monetary authority.

Thus, theory predicts that PT should be larger when inflation is high, PT increases, and is less volatile, because firms may gain price-fixing power (in the first two cases) and cause expectations that those changes may be long-lasting so they cannot stand to keep prices unchanged; the exchange

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such restrictions in the framework of nonlinear models puts them outside of the scope of this paper, rather an open research agenda.

- 24 Keep in mind that the Bayes factor is the posterior odds of the null hypothesis; i.e., the degree to which we favor a null hypothesis over an alternative one after observing the data, given the prior probabilities on the null and alternative. Details on how to calculate the Bayes factors are explained, for instance, in Koop (2003) and Gefang (2012, Appendix A).
- 25 The Savage–Dickey density ratio is a computational strategy to calculate the Bayes factor, and then, if needed, the posterior odds ratio for nested models comparison. The SDDR numerator is calculated with the draws from the Gibbs Sampler and the denominator is evaluated just with the priors at the restricted parameters, with some coefficients equal to zero in the current application (see Koop (2003)).
- 26 As is stated by some authors (Koop, Pesaran and Potter, 1996; Koop and Potter, 1999), impulse response functions of nonlinear models are history and shock dependent. "This contrasts with the traditional impulse response analysis in a linear VAR in which positive and negative shocks are treated symmetrically and independent... [of state of the economy]" (Gefang and Strachan, 2010, page 19).
- 27 Pollard and Coughlin (2003) state that the effect of the exchange rate volatility on the pass-through will depend on whether prices are set in the exporter's. Thus, under PCP, pass-through is lower when exchange rate volatility increases, because firms do not update prices. On the contrary, under LCP pass-through rises because the updating frequency of firms' pricing increases.

rate depreciation/appreciation increases and its volatility is low, as firms perceive those movements as long-lasting or permanent and, by the same token, they rapidly transmit movements in the exchange rate to prices; the real exchange rate is undervalued, since the further from above the real exchange rate is from its equilibrium, the larger the transmission of nominal depreciation on prices should be in order to restore such equilibrium. Conversely, the further from below the real exchange rate is from its equilibrium, the lower or more neutral the transmission of nominal depreciation on prices should be; the output gap is positive, as demand pressures on inflation are higher (as predicted nowadays by any Neo-Keynesian DSGE model); economic openness is larger because the more tradable the goods of the economy are, the more responsive should prices be to exchange rate changes (this assumption has been recently challenged by Forbes (2015)). As for commodity prices and trend, it is difficult to make a general prediction. Finally, it is expected that the higher the interbank interest rate (ie, the tighter the monetary policy), the lower the PT should be.

The PT coefficient for a period  $\tau$  is calculated as follows:<sup>28</sup>

$$(10) \quad PT_{\tau}^n = \frac{\sum_{j=0}^{\tau} \frac{\partial \pi_{t+j}^n}{\partial \varepsilon_t^{\Delta e}}}{\sum_{j=0}^{\tau} \frac{\partial \Delta e_{t+j}}{\partial \varepsilon_t^{\Delta e}}}, \quad n = m, ppi, mc, cpi,$$

where  $0 \leq PT_{\tau}^n \leq 100$ . That is to say, PT measures the change in accumulated inflation up to moment  $\tau$  following an exogenous shock in the exchange rate in period 0, relative to accumulated changes between 0 and  $\tau$  of the exchange rate in response to the same exchange rate shock. Upon correcting for this last effect, the possibility of overestimating the degree of PT is avoided. We describe how we estimate PT coefficients under the Bayesian approach step by step in Appendix A.4.

## 6. Results: an exogenous exchange rate shock

### 6.1 Model comparison and selection

Table 1 shows the natural logarithms of the Bayesian factors (BF) for each of the models to a restricted zero-lag model (a model with only one constant term).<sup>29</sup> It is assumed as independent, (ie, we assign the same prior weight to each of the candidate models). Hence, the table reports the best alternative combinations of VAR-lag or LST-VAR-lag and delay for each candidate transition variable (denominators) when compared to the restricted model (numerator). Hence, the closer the estimated BF is to zero, the more preferable the unrestricted model will be. In other words, the more negative "Ln(BF)" is, the better the specification obtained. The results (last column) show strong support for the nonlinear specification for all transition variables.

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28 Goldfajn and Werlang (2000), Winkelried (2003), Mendoza (2004), González et al. (2010), Mendoza (2012), Rincón and Rodríguez (2015), and Donayre and Panovska (2016).

29 We present natural logs of BF because of computational approximation problems with the BF.

Table 1. Bayes Factor for selected Models

Model	Transition variable	p-lag	d-lag	Ln(BF)
VAR	$\Delta(\pi^{cpi})$	3	NA	-1220.2
LST-VAR	$\Delta(\pi^{cpi})$	3	2	-20101.2
VAR	$V(\pi^{cpi})$	3	NA	-2002.7
LST-VAR	$V(\pi^{cpi})$	3	1	-19237.8
VAR	$D\pi$	3	NA	-1015.8
LST-VAR	$D\pi$	3	1	-20179.8
VAR	$\Delta(\Delta e)$	3	NA	-1888.3
LST-VAR	$\Delta(\Delta e)$	3	2	-19540.5
VAR	$V(\Delta e)$	4	NA	-2901.7
LST-VAR	$V(\Delta e)$	4	2	-19429.2
VAR	$Mq$	3	NA	-1098.3
LST-VAR	$Mq$	3	1	-20350.9
VAR	$Gy$	3	NA	-2916.1
LST-VAR	$Gy$	3	1	-20000.0
VAR	<i>Openness</i>	3	NA	-4315.4
LST-VAR	<i>Openness</i>	3	2	-21615.7
VAR	$\Delta(Pcomm)$	3	NA	-1170.3
LST-VAR	$\Delta(Pcomm)$	3	1	-20731.3
VAR	<i>IBR</i>	3	NA	-1586.6
LST-VAR	<i>IBR</i>	3	2	-20764.2
VAR	<i>Trend</i>	3	NA	-6254.1
LST-VAR	<i>Trend</i>	3	2	-22065.7

Source: Authors' calculations. "BF" means 'Bayes factor', Ln: natural logarithm and "NA" means 'Not Applicable'.

Therefore, data seem to validate an endogenous and nonlinear dynamics of the exchange rate shocks on the price variations of imported, producer, imported consumer, and total consumer goods. Accordingly, the generalized impulse response functions and estimates of the PT coefficients reported below will be based upon the results reported in Table 1.

## 6.2 Estimations of transition functions and their parameters

The estimation of the regression model given by equation (9) is done by the Gibbs sampler scheme described in Appendix A.3, which requires initial values. For the localization parameter  $c_j$ , the search is limited to the percentile range of  $16\%=c_{min}$  to  $84\%=c_{max}$  of the transition variable under consideration. As said before, the importance of parameter  $c$  is that it allows the regimes to be cataloged based on the values of the transition variables, for instance, highs and lows, or as rises and falls, etc.

The results reported in Table 2 first indicate that the estimated  $c$  is located fairly at the center of the distribution of the  $j$ th transition variable, except for the variation of the exchange rate change ( $\Delta(\Delta e)$ ) and the increase in the prices of commodities ( $\Delta P_{comm}$ ).<sup>30</sup> For example, when the transition variable is the volatility of CPI inflation, the  $c$  estimate is 0.44 and the threshold is 0.53, and the number of observations classified in the low regime is 99 and in the high, 53. That is to say, the volatility of CPI inflation has been in the low regime in 65% of the cases along the sample.

Table 2: Estimated Parameters for the selected Models

Transition variable	Estimated parameters		# obs. per regime		Threshold	$p$ -lag	$d$ -lag
	$\gamma$	$c$	Low	High			
$\Delta(\pi^{CPI})$	32.11	-12.67	78	74	0.07	3	2
$V(\pi^{CPI})$	1.10	0.44	99	53	0.53	3	1
$D\pi$	6.76	-1.92	87	65	0.29	3	1
$\Delta(\Delta e)$	5.03	-120.69	85	67	0.0	3	2
$V(\Delta e)$	6.92	3.34	86	65	5.72	4	2
$Mq$	2.23	-11.38	87	65	0.00	3	1
$Gy$	2.30	-1.35	81	71	0.00	3	1
Openness	5.69	26.37	79	73	36.31	3	2
$\Delta(P_{comm})$	2.10	-30.65	72	80	5.75	3	1
IBR	1.13	4.31	78	74	5.80	3	2
Trend	4.27	225.10	76	76	275.50	3	2

Source: Authors' calculations.

In order to achieve a better comprehension of the form of the asymmetric effects and the dynamics of the transition variables and the estimated logistic transition functions, we plot the time series of the transition variables (top), their smooth transition functions (center), and the time profile of the smooth transition functions (below), for the variation of the CPI inflation only (Appendix A.5).<sup>31</sup>

As the figure shows, the transition between one regime and another is very smooth (central plot). Not only the trajectory of the variable (top), but also its historical transition function (lower) show three critical moments throughout the sample. The first one may be related to the cycle on the international price of commodities, which impacted severely at world level, and volatility of inflation around 2007. The second one could be due to the inflationary impact of the high and rapid depreciation of the Colombian peso around 2009 as a consequence of the collapse of Lehman-Brothers in September 2008 and the deepening of the international financial crisis. The third one, at the end of the sample, has been caused mainly by the domestic positive shock in the price of the

30 A possible reason for the result is its high volatile of both series.

31 Results for the other transition variables are available upon request.



agricultural products and the high, rapid, and volatile changes of domestic currency (Rincón-Castro et al., 2017).

In summary, the transition functions seem to corroborate that the logistic smooth transition model and the transition variables we selected are most likely to capture the nonlinear behavior of PT embedded in the data.

### 6.3 Estimations of the degree and dynamics of PT

Tables 3.1 and 3.2, 4.1 and 4.2, 5.1 and 5.2, and 6.1 and 6.2 display the degree and dynamics of PT coefficients on import, producer, imported consumer, and total consumer prices as defined by equation (10), respectively. Thus, tables show the median of the accumulated PT estimates (in percentage points) on prices at each stage conditional on each of the identified regimes of transition variables, in the presence of exogenous positive (depreciation) and negative (appreciation) shocks of 1% and 10% to the variation of the nominal effective exchange rate of the local currency. Notice that we took the median of PT rather than the mean because is a more robust measure to extreme values and preferred in cases where parameter distribution is asymmetric, as is the current case.

In addition, Appendix A.6 shows the median of the time path of the accumulated PT coefficients for CPI when there is a positive 10% shock to the exchange rate change for both regimes and only three of the transition variables: Interbank interest rate (*IBR*), *Trend*, and output gap (*Gy*). From those figures the reader can notice both the endogenous and nonlinear nature of PT estimates of the state of the economy and of the behavior of the exchange rate and CPI inflation. The other figures are available upon request.

The first conclusion that can be extracted from tables 3.1 and 3.2 to 6.1 and 6.2 is that the degree of PT is incomplete for the data analyzed both in the short and long terms, even for import prices, which are the most connected prices to the exchange rate. This shows evidence against a complete exchange rate transmission even for import prices in the long term, as predicted by the purchasing-power parity hypothesis embedded in most of DSGE models. Thus, when a positive or negative exogenous shock to the exchange rate takes place, it is not fully passed-through to prices, and this finding is independent of the size and sign of the shock and the state of the economy. Notice that, by the definition given by equation (10), the estimated PT is always positive, no matter the sign of the shock. This does not mean that when there is a negative shock (eg, an appreciation of the peso), the import prices rise. Instead, *ceteris paribus*, these prices fall by PT estimates reported on the right-hand side of the tables.

Table 3.1 Median Estimates of PT on Prices of Imported Goods

(Percentage points)

Transition Variable	Shock %Points	Positive shock to the exchange rate change				Negative shock to the exchange rate change			
		1 month	6 months	1 year	4 years	1 month	6 months	1 year	4 years
$\Delta(\pi^{CPI})$		<i>CPI inflation increases</i>							
	1	50	62	65	68	49	62	65	69
	10	50	62	62	64	50	62	63	65
		<i>CPI inflation decreases</i>							
	1	49	62	65	68	49	62	64	67
	10	50	62	62	65	50	62	62	65
$V(\pi^{CPI})$		<i>High Volatility of CPI Inflation</i>							
	1	49	66	67	71	49	67	69	71
	10	50	67	68	70	50	68	68	70
		<i>Low Volatility of CPI Inflation</i>							
	1	51	59	62	74	49	57	62	76
	10	51	58	60	74	50	57	59	74
$D\pi$		<i>"High" CPI inflation</i>							
	1	50	62	65	71	50	62	65	71
	10	50	61	63	66	50	62	63	66
		<i>"Low" CPI inflation</i>							
	1	51	62	65	70	50	61	66	70
	10	50	61	63	65	51	62	63	65
$\Delta(\Delta e)$		<i>Depreciation / appreciation of the peso increases</i>							
	1	49	62	65	72	50	63	66	74
	10	51	63	63	70	51	62	63	69
		<i>Depreciation / appreciation of the peso decreases</i>							
	1	50	62	64	72	51	62	65	72
	10	51	63	63	68	51	63	63	68
$V(\Delta e)$		<i>High volatility of the exchange rate</i>							
	1	50	60	62	64	51	61	63	64
	10	50	62	60	61	50	61	60	62
		<i>Low volatility of the exchange rate</i>							
	1	48	60	64	66	50	60	63	64
	10	49	59	61	64	49	60	62	65
$Mq$		<i>Undervalued real exchange rate</i>							
	1	48	64	65	72	48	64	64	72
	10	49	65	65	73	49	65	65	72
		<i>Overvalued real exchange rate</i>							
	1	48	62	62	64	49	62	62	64
	10	48	61	60	60	49	62	60	61

Source: Authors' calculations.

Table 3.2 Median Estimates of PT on prices of Imported Goods

(Percentage points)

Transition Variable	Shock %Points	Positive shock to the exchange rate change				Negative shock to the exchange rate change			
		1 month	6 months	1 year	4 years	1 month	6 months	1 year	4 years
Gy	1	<i>Positive</i>							
		49	58	55	47	53	60	56	47
	10	51	59	55	43	52	61	56	52
		<i>Negative</i>							
	1	49	57	54	45	50	57	55	45
	10	50	59	55	43	50	59	55	44
Openness	1	<i>High economic openness</i>							
		50	65	66	64	51	66	65	64
	10	51	65	63	62	51	65	63	63
		<i>Low economic openness</i>							
	1	50	65	67	75	50	65	66	74
	10	51	65	67	76	50	65	66	75
$\Delta(Pcomm)$	1	<i>High</i>							
		49	62	63	69	50	63	63	70
	10	51	62	61	66	50	62	61	67
		<i>Low</i>							
	1	51	63	64	70	49	63	63	70
	10	50	62	61	67	50	62	61	67
IBR	1	<i>"High"</i>							
		49	60	63	56	50	59	63	56
	10	49	61	64	54	50	61	64	54
		<i>"Low"</i>							
	1	50	60	60	66	50	60	59	66
	10	50	59	57	65	50	59	57	64
Trend	1	<i>From April 2009</i>							
		50	64	65	65	51	65	66	65
	10	51	65	64	64	51	65	64	64
		<i>Before April 2009</i>							
	1	51	66	67	74	53	67	67	74
	10	51	65	66	72	52	66	66	72

Source: Authors' calculations.

Table 4.1 Median Estimates of PT on prices of Producer Goods

(Percentage points)

Transition Variable	Shock %Points	Positive shock to the exchange rate change				Negative shock to the exchange rate change			
		1 month	6 months	1 year	4 years	1 month	6 months	1 year	4 years
$\Delta(\pi^{cpi})$	<i>CPI inflation increases</i>								
	1	22	31	33	43	22	32	33	43
	10	15	23	22	32	15	23	22	31
	<i>CPI inflation decreases</i>								
	1	20	30	33	43	21	31	33	43
	10	15	23	22	33	16	23	22	32
$V(\pi^{cpi})$	<i>High Volatility of CPI Inflation</i>								
	1	21	29	31	59	18	28	30	56
	10	16	22	21	45	15	22	22	44
	<i>Low Volatility of CPI Inflation</i>								
	1	22	32	36	57	21	32	36	56
	10	16	24	26	50	16	24	26	50
$D\pi$	<i>"High" CPI inflation</i>								
	1	21	30	33	48	19	29	33	49
	10	14	22	23	37	14	23	24	37
	<i>"Low" CPI inflation</i>								
	1	21	30	34	48	19	29	32	45
	10	15	22	23	34	15	22	23	35
$\Delta(\Delta e)$	<i>Depreciation / appreciation of the peso increases</i>								
	1	21	30	33	46	23	32	35	47
	10	16	23	23	34	16	23	23	34
	<i>Depreciation / appreciation of the peso decreases</i>								
	1	23	33	34	44	23	32	33	45
	10	15	23	23	33	15	23	23	33
$V(\Delta e)$	<i>High volatility of the exchange rate</i>								
	1	23	33	35	63	20	28	27	45
	10	18	24	24	40	16	22	22	35
	<i>Low volatility of the exchange rate</i>								
	1	23	38	46	58	21	35	43	57
	10	17	29	33	47	17	29	36	48
$Mq$	<i>Undervalued real exchange rate</i>								
	1	22	30	28	30	21	29	28	29
	10	15	21	20	24	15	22	20	23
	<i>Overvalued real exchange rate</i>								
	1	22	30	32	41	23	33	35	42
	10	16	23	23	30	17	24	23	31

Source: Authors' calculations.

Table 4.2 Median Estimates of PT on prices of Producer Goods

(Percentage points)

Transition Variable	Shock %Points	Positive shock to the exchange rate change				Negative shock to the exchange rate change			
		1 month	6 months	1 year	4 years	1 month	6 months	1 year	4 years
Gy		<i>Positive</i>							
	1	27	33	29	43	25	31	30	42
	10	16	22	21	32	17	24	23	42
		<i>Negative</i>							
	1	21	28	30	33	21	30	28	30
	10	15	22	20	23	16	23	21	26
Openness		<i>High economic openness</i>							
	1	23	32	32	30	21	31	30	28
	10	15	22	21	22	17	24	21	22
		<i>Low economic openness</i>							
	1	25	31	35	43	24	30	33	44
	10	17	23	25	35	17	22	25	35
$\Delta(Pcomm)$		<i>High</i>							
	1	25	33	32	44	24	32	31	43
	10	17	23	22	34	17	24	22	34
		<i>Low</i>							
	1	24	32	31	44	25	32	31	45
	10	17	24	22	33	17	23	22	34
IBR		<i>"High"</i>							
	1	19	27	27	35	17	25	26	33
	10	14	22	22	33	14	22	22	32
		<i>"Low"</i>							
	1	22	30	32	65	21	29	32	63
	10	16	22	24	58	17	22	24	56
Trend		<i>From April 2009</i>							
	1	17	28	28	27	23	34	35	28
	10	15	23	21	20	16	24	23	21
		<i>Before April 2009</i>							
	1	24	30	33	42	24	30	33	43
	10	17	22	25	33	17	22	24	33

Source: Authors' calculations.

The tables summarize the minimum and maximum historical degree of the accumulated transmission of an exogenous exchange rate shock on prices at each of the distribution stages and at any time-period  $\tau$  (see equation (10)). Thus, the accumulated PT on import prices of a 1% positive shock ranges (across the transition variables) from 48% to 52% (proportional to the size of the shock) in the first month and from 55% to 67% in the first year. The equivalent figures on producer, imported consumer, and total consumer prices range from 18% to 27%, 8% to 14%, 6% to 11% in the first month, respectively, and from 27% to 46%, 19% to 42%, and 13% to 21% in the first year. Finally, the maximum accumulated PT at four years on import, producer, imported consumer, and total consumer prices corresponds to 75%, 65%, 68%, and 40%, respectively.

A number of points may be made. First, the estimates show how the degree of transmission vanishes along the distribution chain, as shown by Frankel et al. (2012) for a sample of 76 developed, emerging market, and developing economies.<sup>32</sup>

Second, the estimates reported in the tables show overwhelming evidence and statistical support for the endogeneity of the PT coefficient to the state of the economy, which causes it to be quantitatively different across states and change over time.

Third, the evidence indicates the nonlinear nature of the degree of PT. For example, when exchange rate volatility is low, a 1% depreciation of the peso results in a pass-through to the CPI of 9% in one month and 20% in one year (fifth part of Table 6.1). When exchange rate volatility is high, PT falls from 7% to 18% in the same period. For another example for the CPI, when the interbank interest rate is high, a 1% depreciation results in PT of 13% after one year (fourth part of Table 6.2). When the interbank interest rate is low, PT reaches 19%. Finally, it is worth mentioning that the size of PT on the CPI estimated in this paper is higher than reported by the Colombian literature cited in the introduction (among them, those results from our own research), which may be explained by the size and highly persistent nature of the latest exchange rate shock.

Certainly, the nonlinear nature of PT is more evident when we increase the size of the exchange rate shock. The results show that the larger the shock, the smaller the PT, except for import prices that depend on the state (transition) variable. This is a puzzling result for which we have no answer in this paper, but which could be solved using micro-data. However, notice that our findings do not mean that the impact of a larger exchange rate shock on prices is smaller. For example, let us take the import prices when the transition variable is the change of the CPI inflation and it increases (first part of Table 3.1). A 1% exchange rate shock has an accumulated impact on producer prices of 65 basis points (bp) ( $1\% \times 65\% = 65$  bp) in the first year. On the other hand, a 10% exchange rate shock has an accumulated impact on the same prices of 620 basis points ( $10\% \times 62\% = 620$  bp) in the same period.

Therefore, our findings for import prices partially confirm, for instance, those by Floden and Wilander (2006), who state that a greater depreciation of the local currency increases the opportunity cost of keeping prices fixed so that the transmission on import prices will be larger.<sup>33</sup> On the other hand, our results for the CPI certainly differ from Caselli and Roitman's (2016), since they found that

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32 The reader can repeat the same exercise for the cases of a 10% positive shock or 1% and 10% negative shocks.

33 Since Colombia cannot be characterized as a dollarized economy, the findings of Carranza et al. (2009) do not seem to apply to our results. These authors conclude that depreciations have a negative impact on the degree of PT when economies are dollarized "because higher internal demand and imported inflation can be offset or diminished by both the larger financial costs and the balance-sheet effect."

the greater the exchange rate shock, the larger the PT.<sup>34</sup> They use local projection techniques to estimate the exchange-rate transmission on CPI for a sample of 28 emerging markets, Colombia among them. Caselli and Roitman show that for depreciations greater than 10 and 20 percent, pass-through on the CPI is equal to 18 and 25 percent, respectively, after one month (and 6% in the linear case). Moreover, they find that for depreciations greater than 20% and that last for more than 3 months, the pass-through on CPI touches 32% after 3 months.

Fourth, PT does not seem to respond differently to the sign of the exchange rate shock; in other words, PT appears to be symmetric, since the degree of asymmetry is quite low if one compares the sizes of PT estimates. The reader can review findings on asymmetry of PT in Floden and Wilander (2006) for artificial data, Bussiere (2013) for the G-7 economies, and Caselli and Roitman (2016) for a sample of emerging markets.<sup>35</sup>

Four interesting results can be emphasized, and they have to do with PT when the transition variables are the volatility of the exchange rate, the degree of misalignment of the real exchange rate, the degree of economic openness, and the variable *Trend*.

Regarding the first variable, the degree of the accumulated PT is almost unanimously higher for all prices and for the short and long terms when the exchange rate volatility is low. This means that firms transmit exchange rate changes to prices more rapidly and to a higher degree when they expect changes to be of long duration. This result is completely opposite to that by Campa and Golberg (2005), for instance, who found that “countries with higher rates of exchange rate volatility have higher pass-through elasticities.” As for the second variable, our findings disagree with the prediction—except for import prices—that the degree of PT should be higher when the real exchange rate is undervalued. Indeed, a positive structural shock to the nominal exchange rate should pass-through to inflation rapidly so that prices act as a correction mechanism, allowing for the real exchange rate to appreciate, *ceteris paribus*.

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34 Notice, however, that our definition of PT is very different than Floden and Wilander’s and Caselli and Roitman’s since they neither ‘correct’ PT by the endogenous response of the exchange rate to its own shock (review our equation (10)), nor do they calculate the accumulated PT.

35 According to Bussiere, when “the exchange rate depreciates, exporters increase their export prices more than they decrease them when there is an appreciation. This also means that depreciations have a larger effect than appreciations on import prices.”

Table 5.1 Median Estimates of PT on prices of Imported Consumer Goods

(Percentage points)

Transition Variable	Shock %Points	Positive shock to the exchange rate change				Negative shock to the exchange rate change			
		1 month	6 months	1 year	4 years	1 month	6 months	1 year	4 years
$\Delta(\pi^{cpi})$	1	CPI inflation increases							
		11	23	30	55	11	22	30	54
	10	4	14	22	45	4	14	22	45
		CPI inflation decreases							
$V(\pi^{cpi})$	1	11	23	31	55	10	21	28	53
		10	5	14	22	47	4	14	22
	High Volatility of CPI Inflation								
	1	11	21	31	58	11	21	31	60
10		4	14	23	51	4	13	23	51
	Low Volatility of CPI Inflation								
1	10	22	34	66	10	22	33	66	
	10	4	16	27	64	4	16	27	62
$D\pi$	"High" CPI inflation								
	1	12	24	33	61	11	22	32	61
		10	5	14	23	51	5	14	23
	"Low" CPI inflation								
1	10	22	31	58	11	23	32	59	
	10	4	14	22	50	5	14	23	50
$\Delta(\Delta e)$	Depreciation / appreciation of the peso increases								
	1	12	22	32	58	11	23	33	59
		10	4	15	24	49	5	15	24
	Depreciation / appreciation of the peso decreases								
1	11	22	32	56	12	23	33	57	
	10	5	15	24	46	4	14	24	47
$V(\Delta e)$		High volatility of the exchange rate							
	1	8	18	25	36	8	22	29	42
		10	4	14	21	32	4	13	21
	Low volatility of the exchange rate								
1	10	21	28	53	9	20	27	53	
	10	4	14	22	46	4	14	22	44
$Mq$	Undervalued real exchange rate								
	1	10	21	28	48	11	20	27	48
		10	4	13	19	37	5	13	19
	Overvalued real exchange rate								
1	11	21	30	49	10	21	30	48	
	10	4	13	22	38	4	14	22	38

Source: Authors' calculations.



Table 5.2 Median Estimates of PT on prices of Imported Consumer Goods

(Percentage points)

Transition Variable	Shock %Points	Positive shock to the exchange rate change				Negative shock to the exchange rate change			
		1 month	6 months	1 year	4 years	1 month	6 months	1 year	4 years
Gy		<i>Positive</i>							
	1	11	20	28	57	12	20	27	53
	10	5	10	16	49	4	15	24	55
		<i>Negative</i>							
	1	11	17	21	48	12	17	21	45
	10	5	10	14	42	4	10	14	42
Openness		<i>High economic openness</i>							
	1	8	15	21	42	10	16	22	44
	10	4	10	16	34	3	10	16	37
		<i>Low economic openness</i>							
	1	9	25	35	53	8	25	35	51
	10	4	18	28	45	4	18	28	44
$\Delta(P_{comm})$		<i>High</i>							
	1	9	21	32	60	11	22	33	61
	10	4	16	26	55	4	16	26	55
		<i>Low</i>							
	1	11	22	32	61	11	22	32	60
	10	4	16	26	55	5	16	26	56
IBR		<i>"High"</i>							
	1	14	17	20	31	12	15	19	32
	10	5	9	11	27	5	8	11	27
		<i>"Low"</i>							
	1	11	27	42	68	10	25	42	68
	10	4	21	37	67	4	21	38	66
Trend		<i>From April 2009</i>							
	1	9	14	19	32	8	14	19	33
	10	3	9	14	25	3	9	13	24
		<i>Before April 2009</i>							
	1	9	22	32	44	9	22	31	43
	10	4	16	25	36	4	17	25	36

Source: Authors' calculations.

Table 6.1 Median Estimates of PT on prices of Total Consumer Goods

(Percentage points)

Transition Variable	Shock %Points	Positive shock to the exchange rate change				Negative shock to the exchange rate change			
		1 month	6 months	1 year	4 years	1 month	6 months	1 year	4 years
$\Delta(\pi^{cpi})$	1	CPI inflation increases							
		8	13	16	28	8	13	16	28
	10	3	6	7	17	3	6	7	17
		CPI inflation decreases							
	1	8	13	15	29	8	12	15	27
		10	3	6	7	18	3	6	7
$V(\pi^{cpi})$	1		High Volatility of CPI Inflation						
		8	12	15	38	8	12	15	39
	10	3	6	8	25	3	6	8	24
		Low Volatility of CPI Inflation							
	1	6	12	17	40	7	13	18	43
		10	3	6	10	33	3	6	10
$D\pi$	1		"High" CPI inflation						
		9	13	16	32	8	13	16	33
	10	3	6	8	20	3	6	8	20
		"Low" CPI inflation							
	1	8	12	15	30	8	13	16	32
		10	3	6	8	18	3	6	8
$\Delta(\Delta e)$	1		Depreciation / appreciation of the peso increases						
		8	14	17	32	8	13	17	33
	10	3	6	8	18	3	6	8	19
		Depreciation / appreciation of the peso decreases							
	1	8	13	16	29	9	14	17	31
		10	3	6	8	18	3	7	8
$V(\Delta e)$	1		High volatility of the exchange rate						
		7	13	18	36	9	13	15	23
	10	3	7	8	19	3	6	8	17
		Low volatility of the exchange rate							
	1	9	15	20	36	8	14	18	37
		10	3	8	10	23	3	7	9
$Mq$	1		Undervalued real exchange rate						
		8	11	13	27	8	12	14	28
	10	3	5	6	18	3	5	6	18
		Overvalued real exchange rate							
	1	7	12	15	30	8	12	16	31
		10	3	6	8	17	3	6	8

Source: Authors' calculations.

Table 6.2 Median Estimates of PT on prices of Total Consumer Goods

(Percentage points)

Transition Variable	Shock %Points	Positive shock to the exchange rate change				Negative shock to the exchange rate change			
		1 month	6 months	1 year	4 years	1 month	6 months	1 year	4 years
Gy		<i>Positive</i>							
	1	8	17	20	32	7	14	18	29
	10	3	8	10	23	3	10	13	27
		<i>Negative</i>							
	1	11	15	17	29	10	14	15	25
	10	3	7	8	20	3	7	9	21
Openness		<i>High economic openness</i>							
	1	8	11	12	28	8	11	14	25
	10	3	5	6	17	3	5	6	15
		<i>Low economic openness</i>							
	1	7	15	21	34	7	15	21	34
	10	3	9	13	24	3	9	13	24
$\Delta(P_{comm})$		<i>High</i>							
	1	7	12	15	30	8	12	15	30
	10	2	6	8	20	2	6	9	20
		<i>Low</i>							
	1	7	12	14	30	7	12	15	30
	10	2	6	8	20	2	6	8	20
IBR		<i>"High"</i>							
	1	10	12	12	23	9	11	11	20
	10	3	5	5	21	3	5	5	19
		<i>"Low"</i>							
	1	7	14	19	33	6	14	19	33
	10	2	8	12	26	2	8	12	27
Trend		<i>From April 2009</i>							
	1	8	12	14	21	8	11	15	23
	10	2	5	6	13	3	5	6	12
		<i>Before April 2009</i>							
	1	7	15	21	35	7	15	21	35
	10	3	9	13	24	3	9	12	23

Source: Authors' calculations.

As for the third transition variable (*Openness*), one would expect, according to the theory, that if the economy is more open, the transmission should be higher; however, we consistently found that it happens the other way around. What explains this result? Is it a problem with the measurement of the degree of economic openness? Is this finding a result of a very complex strategic behavior of fixing prices by firms when the economy is more open? Is it an issue of competitiveness? We do not have an answer for this riddle. The last result is that PT is consistently lower when the variable *trend* is located after April 2009. Is it related to a structural change in the relationship between prices and exchange rates produced by the 2007-2009 international financial crises? Or is this behavior related with the strengthening of the inflation targeting regime, started in Colombia in the 2000s, as shown by Mishkin and Klaus Schmidt-Hebbel (2007) for a sample of developed and emerging markets, by Bouakez and Rebei (2008) for Canada, and by Coulibaly and Kempf (2010) and Caselli and Roitman (2016) for samples of emerging markets?

In summary, tables 3.1 to 6.2 show that PT is incomplete, endogenous, and nonlinear. In general, PT is larger when the CPI inflation increases (mainly in the short term), is high and its volatility is low; depreciation increases and the volatility of the exchange rate is low; the output gap is positive; and the interbank interest rate is low (Table 7).

Table 7. When has PT been higher?

(1% positive exchange rate shock)

Transition variable	Regimen	Prices							
		Import		Producer		Imported consumer		Total consumer	
		1 year	4 years	1 year	4 years	1 year	4 years	1 year	4 years
$\Delta(\pi^{CPI})$	Increases	✓		✓	✓			✓	
	Decreases		✓			✓	✓		✓
$V(\pi^{CPI})$	High	✓			✓				
	Low		✓	✓		✓	✓	✓	✓
$D\pi$	High inflation		✓		✓	✓	✓	✓	✓
	Low inflation	✓		✓					
$\Delta(\Delta e)$	Increases	✓	---		✓	✓	✓	✓	✓
	Decreases		---	✓					
$V(\Delta e)$	High				✓				
	Low	✓	✓	✓		✓	✓	✓	✓
$Mq$	Undervalued	✓	✓						
	Overvalued			✓	✓	✓	✓	✓	✓
$Gy$	Positive	✓			✓	✓	✓	✓	✓
	Negative		✓	✓					
Openness	High								
	Low	✓	✓	✓	✓	✓	✓	✓	✓
$\Delta(P^{comm})$	High					✓		✓	---
	Low	✓	✓	✓	✓		✓		---
IBR	High	✓							
	Low		✓	✓	✓	✓	✓	✓	✓
Trend	From April 2009								
	Before April 2009	✓	✓	✓	✓	✓	✓	✓	✓

Source: Tables 3.1-6.2. The symbol "---" means that PT estimates are equal.

## 7. Results: an endogenous exchange rate movement

Up to now, it has been assumed that exchange-rate fluctuations are exogenous, as most of the literature does. Now it is assumed that exchange-rate movements are endogenous to macroeconomic shocks. In other words, PT will now depend on the "initial" economic conditions and the type of shock the economy is facing. In the latter case, as implemented by Shambaugh (2008), Forbes et al. (2015) and Rincón-Castro et al. (2017), but for the linear case.

Hence, this section re-estimates the nonlinear model given by equation (9) by Bayesian methods using the same data but redefining equation (10). PT is estimated for the CPI, conditional on the high and low regimes of *CPI inflation*, *depreciation/appreciation of the peso* and *output gap*, only.

The shocks are assigned to domestic demand ( $\varepsilon^D$ ) (measured by the output gap), domestic supply ( $\varepsilon^S$ ) (measured by non-core inflation),<sup>36</sup> and foreign supply ( $\varepsilon^{mgc^*}$ ) (captured by the marginal costs of foreign producers of domestic imports).

Thus, in order to capture the endogeneity of the exchange-rate movements to the macroeconomic shocks, and as a consequence of PT, equation (10) is redefined as:

$$(11) \quad PT_{\tau} = \frac{\sum_{j=0}^{\tau} \frac{\partial \pi_{t+j}^{cpi}}{\partial \varepsilon_t^i}}{\sum_{j=0}^{\tau} \frac{\partial \Delta e_{t+j}}{\partial \varepsilon_t^i}}, \quad i = D, S, mgc^*.$$

How are macroeconomic shocks transmitted to the exchange rate? According to predictions from Neo-Keynesian DSGE models, such as some of those referenced above, particularly those developed by Gali (1999) and Blanchard and Gali (2007), they can impact the exchange as follows:

In the case of the domestic demand shock, for instance, by introducing a change in preferences or an increase in disposable income of households, aggregate demand expands. This raises the demand for production factors including labor, resulting in an increase in real wages and thus on inflation and interest rates. Then, according to the uncovered interest parity, the increasing domestic interest rate leads to an increase in depreciation expectations (assuming that the foreign interest rate and the country risk remains constant), which require an initial appreciation of the local currency.

We now describe the domestic supply shock, for example, because the total factor productivity falls. This increases marginal costs, reduces supply, and increases inflation, assuming that if potential GDP decreases relatively more than the observed GDP, then the output gap becomes positive). Accordingly, the central bank acts increasing the interest rate. As in the case of a demand shock, an increasing domestic interest rate leads to an increase in depreciation expectations (assuming that the foreign interest rate and country risk remains constant), which require an initial appreciation of the local currency.

As for the foreign supply shock, no exact prediction can be obtained directly because the multiple channels through which it can have an impact on the local currency. For example, a foreign supply shock can affect domestic inflation of imported goods, productivity differentials between home and abroad, import and exports quantities, capital inflows and outflows, etc., and each them may have a different impact on the local currency, ie, they may appreciate or depreciate it.

Of course, the empirical analysis and results developed in this paper are limited to the estimation of the reduced system given by equations (9) and (11), and do not develop a structural model, which would be another paper by itself.

Figure 3 shows the median of accumulated PT estimates for the CPI over time following domestic demand and supply and 1% foreign shocks, conditional on the two regimes of each of the transition variables mentioned.<sup>37</sup> Results reveal that PT is both state and shock dependent. Their sizes are quite similar to those reported in Table 1 in Shambaugh (Ibid, page 575). Consequently, for

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36 Conversely to the Shambaugh (2008)'s supply shock -a productivity shock- which reduces inflation, here a supply shock increases inflation.

37 The equivalent tables to tables 2 and 3 are available upon request.

instance, when the economy faces a supply shock and the exchange rate responds endogenously to it, the PT on CPI rises from around 40% in the first month to approximately 60% at year four.

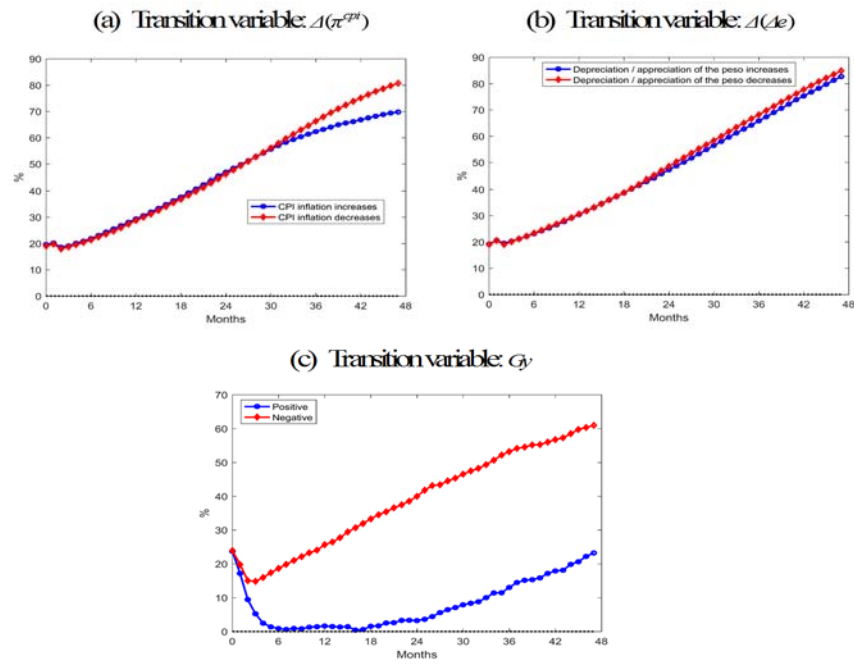
The corresponding median GIRFs defined by equation (11) show that they are generally not statistically significant, however, as their 68% and 80% most credible intervals show, except for the supply shock (Appendix A.7).<sup>38</sup> Unfortunately, given the method we use to estimate PT, which involves the calculation of generalized impulse responses (see Appendix A.4), the estimations could not normalize the size of the shocks in order to produce an identical exchange-rate movement at time  $\tau$ , as was done originally by Shambaugh (*Ibid*) for the linear case. This difficulty may also explain the larger amplitude of the credible intervals.

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38 The figures for the other shocks are available upon request. Notice that the GIRFs are the medians of the 25,000 impulse-response functions of the numerators and denominators of equation (11) obtained by such number of iterations of an estimation algorithm for each of the endogenous variables of the LST-VAR system and to each disturbance. Responses are accumulated so that figures show the impact at the level of each variable in time.

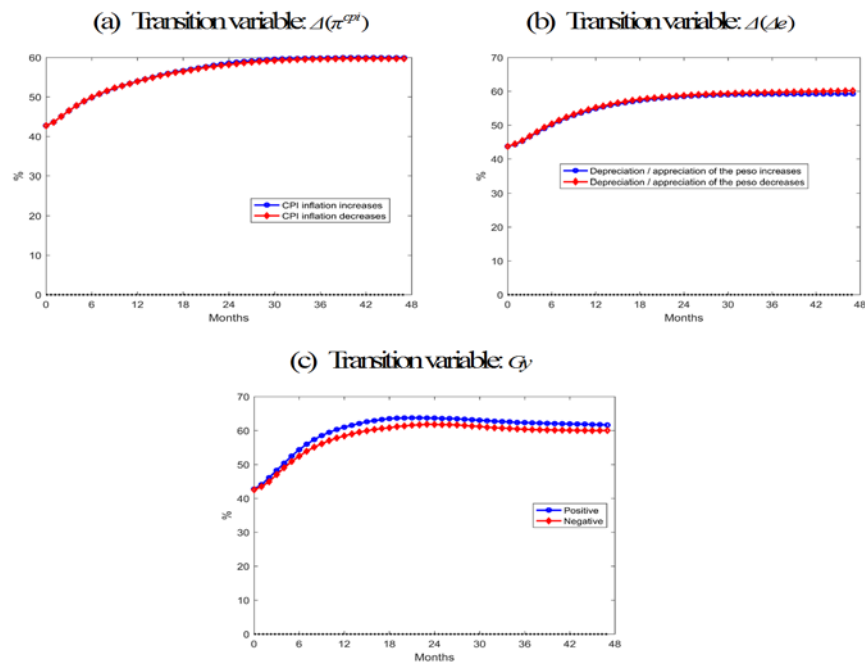
Figure 3: Macroeconomic Shocks and PT Estimates for the CPI

### Demand shock



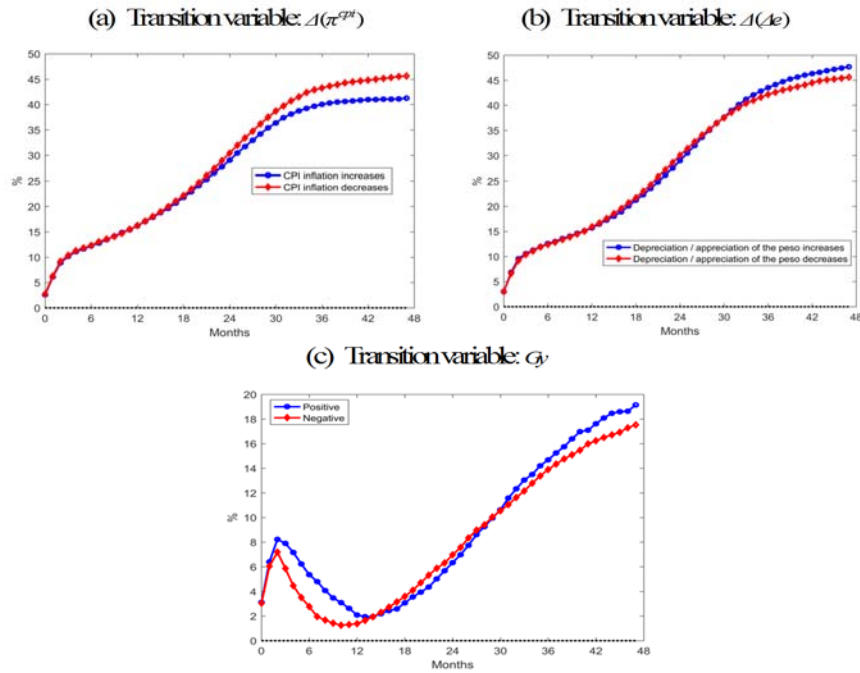
Source: Authors' calculations.

### Supply Shock



Source: Authors' calculations.

## Foreign Marginal Cost Shock



## 8. Historical decomposition of shocks

In this section, we show and analyze the historical decomposition of shocks (HD) for the LST-VAR model given by equation (9). Remember that HD allows estimating the magnitude of the contribution of each shock to the unpredicted values of the prices at each period of time. Thus, HDs allow to differentiate which of the structural shocks were the main determinants of the behavior of the endogenous variables at each time period (in our case, the determinants of the different inflation rates along the distribution chain) and to reveal the relative role played by the exogenous shocks to the exchange rate. Accordingly, as we stated in the introduction, the HDs add further evidence to support our conclusions and complement the results reported in sections 5 and 6.

For multivariate models such as the one considered in this paper and under some structure for the identification of shocks (eg, Cholesky decomposition), the results of impulse-response functions are valid only under static (or non regime-change) scenarios during the sample period, despite the fact that one averages all the answers at each regime of the transition variable. Therefore, it is important to analyze the responses of the endogenous variables to exogenous shocks of different magnitudes at different times. The HD of shocks is employed for this purpose in linear VAR and (linearized) DSGE models. Notice that in these cases, the HD is completed (exact),<sup>39</sup> but this may not be the case for nonlinear models such as LST-VARs. The missing part is called "remainder," which could be significant.

<sup>39</sup> That is, the components add up to the forecast error at each time period.



Before showing the results, it is worth mentioning the main differences between variance decomposition, which is the standard procedure used by the literature, and historical decomposition. The first thing one can think of is that the former is a hypothetical exercise, while the latter is an approximate description of the history of a time series.

Under the understanding that both are based on the same model for the same data set and the same specification, variance decomposition calculates the variance of the prediction error of each of the endogenous variables for several upcoming periods (eg from periods 1 to K). This indicates the percentage share of the prediction error for each of the endogenous variables in the whole prediction error (from 1 to K). In this case, the identification structure of the errors does not matter. Moreover, as one is working with variances and they are always non-negative, participation is calculated as the variance of the particular variable relative to the sum of the variances of all endogenous variables in the system.

On the other hand, HD is an accounting exercise that explains the prediction within the sample as a function of the errors for each period. It can be done well with a reduced or not identified form, or with structural or identified shocks. Furthermore, because in a dynamic model errors have lagged effects, there is a need to accumulate the discounted effects from previous mistakes. Finally, the prediction error is broken down under HD, not the variance; hence, it can be less than zero.

Therefore, we calculate the HDs for the price movements of imported, producer, imported consumer, and total consumer goods, conditional on each of the state variables, so that we have 44 HDs. Here we will show results for each of the prices, but only for five transition variables: variation of the CPI inflation ( $\Delta\pi^{cpi}$ ), variation of the exchange rate change ( $\Delta(\Delta e)$ ), volatility of the exchange rate ( $V(\Delta e)$ ), variation of commodity prices ( $\Delta P_{comm}$ ), and the interbank interest rate ( $IBR$ ) (the other figures are available upon request). The interpretation of the HD figures is the following: a positive bar value of a particular variable indicates that the shock pushed the  $n$ -th inflation upward in that period; otherwise, an inverse interpretation applies.<sup>40</sup>

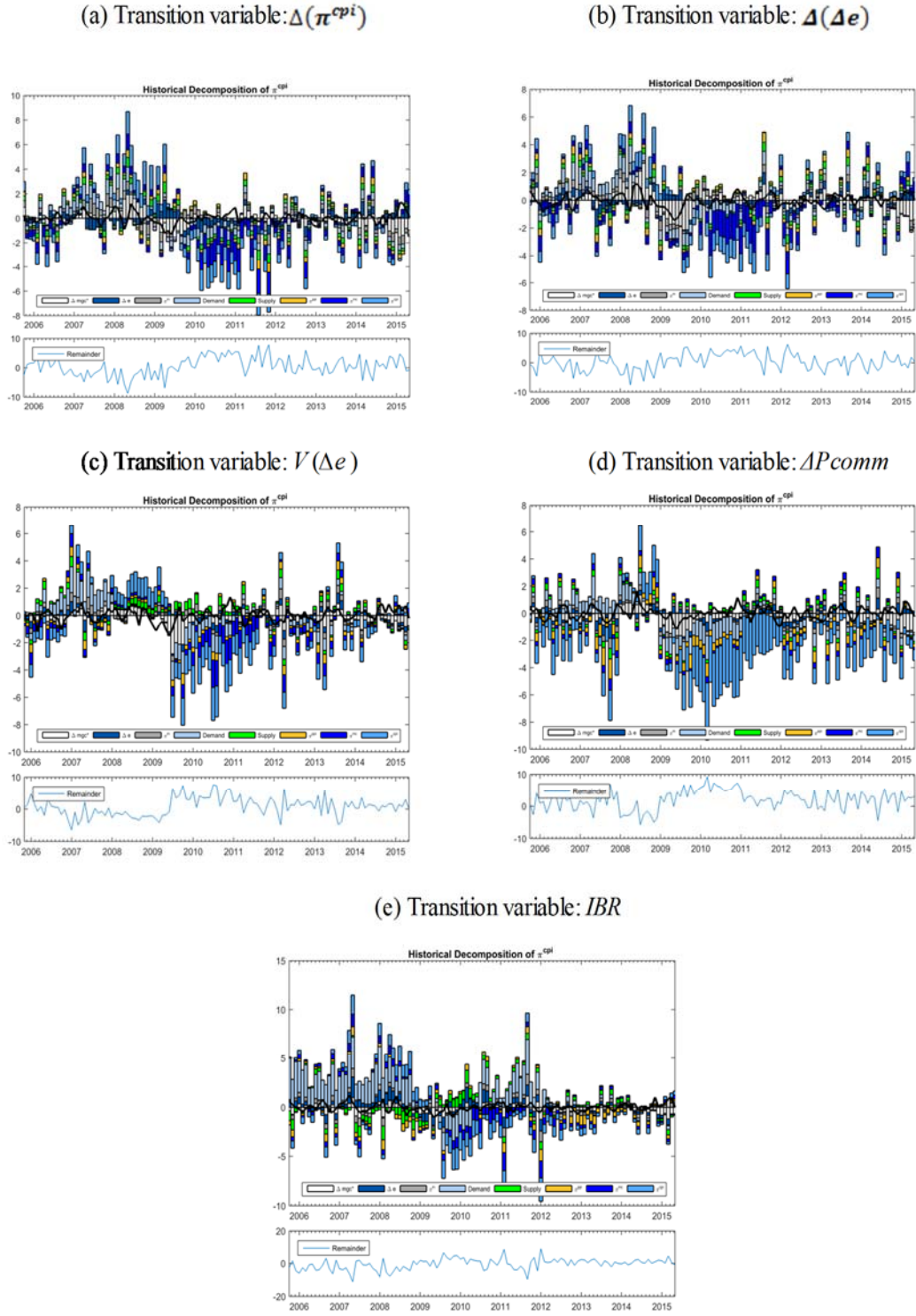
To illustrate our findings, figure 4 displays the HDs only for CPI inflation and explains the results for the last part of the sample (year 2015).<sup>41</sup> Of course, the same reconstruction of their history can be done for each of the prices at each period.

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40 Since the methodology requires to define a forecast horizon, we use K=36 months. As a result, we cannot predict or at least not break down the forecast error for the first K-months.

41 Results for the other prices are available upon request.

Figure 4. HDs for  $\pi^{cpi}$



Source: Authors' calculations.

Thus, figure 4 shows that when the transition variable is the variation of inflation (plot (a)), one of the most important upward drivers of inflation is the exchange-rate shock ( $\Delta e$ ), which acts directly and through the different channels explained in the introduction (costs and imported consumption channels). A second main driver is the inflation's own persistence shock ( $\pi^{cpi}$ ), which is related to positive shocks to the indexation of prices of goods and services by past inflation. Supply and demand shocks appear at the end of the sample as upward drivers. On the other hand, the shock to the external marginal costs ( $\Delta m_{gc}^*$ ) pressured inflation downwards. Notice that this shock may also explain the negative pressure coming from the import price shock.

When the transition variable is the variation of the exchange rate change (plot (b)), or the increase in the prices of commodities (plot (d)), the results seem to confirm the upward role played by most of the shocks and the downward role enacted by the external marginal cost shock. Nevertheless, note that the size of the impact of each of the shocks on inflation depends on the transition variable in place. Finally, when the transition variable is the interbank interest rate (plot (e)), supply and demand shocks exert negative pressure on the exchange rate and inflation. On the other hand, the inertial component of inflation exerts positive pressure on it.

Accordingly, the HD exercises show that the role played by each of the shocks on the determination of price variations along the distribution chain depends very much on the state of the economy, a finding that is not uncovered by linear variance decomposition procedures. Also, they reveal that the final impact of exchange-rate shocks on price variations is determined by or is endogenous to other shocks that the economy and the exchange rate itself may be facing, which agrees with Klein (1990) and the findings by Shambaugh (2008), Forbes et al. (2015), and Rincón-Castro and Rodríguez-Niño (2017) for the linear case.

## 9. Conclusions

Exchange rate movements are of interest to authorities, as well as to firms and households. For authorities, such movements can clarify the role of the exchange rate as a short-term macroeconomic adjustment mechanism, and the possible risks to the inflation target when they pass-through to prices. For firms, exchange rate movements impact production costs by changing the domestic price of imported inputs. For consumers, changes in the exchange rate can disturb consumption decisions if they lead to changes in the final prices of goods in local currency.

This paper has analyzed the nature of the pass-through of exchange rate shocks to prices along the distribution chain and quantified historically their short and long-term impacts. To tackle this task we used a model of pricing as an analytical framework. Using Bayesian methods on monthly data from a small open economy, we then estimated a nonlinear logistic smooth transition VAR (LST-VAR) model.

The findings are as follows. First, the exchange rate pass-through is incomplete, even for import prices. This result is evidence against the hypothesis of purchasing power parity, and implies that nominal exchange rate changes will not be fully reflected in adjustments in the price of tradable goods in the short and long term. It also implies that nominal exchange rate movements may have long-lasting effects on the real exchange rate.

Second, PT is nonlinear and depends on the state of the economy and on the type of shock that the economy and the exchange rate itself are facing. For an exogenous exchange rate shock, PT

is larger when the CPI inflation increases (mainly in the short term), is high and its volatility is low; depreciation increases and the volatility of the exchange rate is low; the output gap is positive; and the interbank interest rate is low.

The analysis changes when model specification accounts for the fact that exchange rate movements are endogenous<sup>42</sup>. Price variations then depend very much on the state of the economy and the shocks it faces and the final impact of exchange-rate movements on prices is determined by other macroeconomic shocks that the economy and the exchange rate itself may be facing. For example, a historical decomposition for the year 2015 shows that one of the most important upward drivers of inflation is the exchange-rate shock which acts directly and through costs and imported consumption channels.

Third, the transmission of exchange-rate movements to prices vanishes along the distribution chain, as expected, and this behavior seems independent from any market behavior by firms, the state of the economy, or shocks.

Fourth, uncertainty about PT increases rapidly over time after the shock.

Two policy implications for central bank policy or related analysis may be highlighted: first, models used by central banks for policymaking should take into account the nonlinear and endogenous nature of the pass-through. Second, a specific rule on pass-through for monetary policy decisions should be avoided.

Given the importance of evaluating the inflationary effects of movements in exchange rates for making monetary policy decisions, the methodology implemented in this paper can be extended and applied to almost any country with very good data and computational capacities.

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42 See section 7. This is accomplished by estimating PT for the CPI, conditional on the high and low regimes of CPI inflation, depreciation/appreciation of the peso and output gap. The shocks are assigned to domestic demand (measured by the output gap), domestic supply (measured by non-core inflation), and foreign supply (captured by the marginal costs of foreign producers of domestic imports).

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## Appendix A1.A International Literature on PT

Authors	Year	Freq. <sup>1</sup>	Sample	Countries	Econ. model	Approach <sup>2</sup>	Variables <sup>3</sup>	Inflation <sup>4</sup>
Marazzi et. al.	2005	Q	1972-04	USA	Single equation	L	Diff	↓
Campa & Goldberg	2006	Q	1975-04	18	5 categories	L	Diff	CPI: ↑ Pm: ↓
Gaytan & G.	2006	M	1992-05	Mexico	MS-VAR	NL	Diff	↓
Otani et. al.	2006	M	1980-03	Japan	Eight categories	L	Diff	↓
Rodríguez et. al.	2006	M	1994-05	Paraguay	Single equation	L	Diff	NA
Sekine	2006	Q	1974-04	G7	Single equation	DC	Diff	↓
De Bandt et. al.	2007	M	1995-05	Euro Zone	4 categories	NL	L	Pm: ↑
Ito & Sato	2008	M	1993-05	East Asian	VAR	L	Diff	CPI: ↑ Pm: ↑
Nogueira Júnior & Ledesma	2008	M	1983-05	Emerg. & Developed.	STR	NL	Diff	CPI: ↑
Al-Abri & Goodwin	2009	Q	1975-02	16 OECD	VAR-TVEC	L and NL	L & Diff	Pm: ↑
Mihailov.	2009	M	1979-02	USA-Ger-Jap	OLS-TSLS-VAR	LR	L & Diff	CPI: _ Pm: ↓
Kilic	2010	Q	1975-09	OECD	LSTM	NL	Diff	Pm: ↑ CPI: ↑
Berner	2010	M	1988-08	Germany	OLS, Weight, OLS	LR	Diff	Pm: ↑
Capistrán et al.	2011	M	1997-10	Mexico	VAR	L	Diff	Pm: ↑ CPI: ↑
An & Wang	2012	M	1980-07	OECD	VAR	L	L	Pm: ↑
Ben Cheikh.	2012	Q	1975-10	Euro Zone	STM	NL.	Diff	CPI: ↑
Frankel et al.	2012	M-Y	1990-01	& USA	ECM	L	L & Diff	Pm: ↑
Shintani et al.	2013	M	1975-07	76	STAR	NL.	Diff	CPI: ↑
Aleem & L.	2014	M	1994-09	USA	TVAR	NL.	L	CPI: ↑
Beckmann et al.	2014	M	1995-12	Mexico	VEC-DOLS-SSM	L	Diff	Pm: _
				Germany	Panel-Kalman Filter			
Ozkan & Erden	2015	M	1980-13	88	DCCGARCH-Panel threshold	L	L & Diff	CPI: ↑
Donayre & Panovska	2016	M	2001-13	Canada & Mexico	TVAR	NL	Diff	CPI, Pm, Pm, WPI, IPI, CPI:↑

Source: Authors' compilation.

<sup>1</sup> Q: Quarterly; M: Monthly; Y: Yearly. <sup>2</sup> NL: Nonlinear; L: Linear; DC: Dynamic coefficient. <sup>3</sup> L: Levels; Diff: Differences. <sup>4</sup> ↑: pass-through increases; ↓: pass-through decreases; \_: pass-through is stable; ---: ambiguous result; Pm: Import price index; WPI: Producer Price Index; IPI: Intermediate good prices; CPI: Consumer Price Index; NA: not applicable.

## Appendix A1.B Colombian Literature on PT

Authors	Year	Freq. <sup>1</sup>	Sample	Econometric model	Econometric Approach <sup>2</sup>	Variables <sup>3</sup>	Inflation <sup>4</sup>
<b>Rincón</b>	<b>2000</b>	M	1980-1998	VEC	LR	L and Diff	Pm; Px; CPI
<ul style="list-style-type: none"> <li>- First elaborate study written on exchange rate pass-through in Colombia.</li> <li>- Paper showed that PT was incomplete. This result forever changed the monetary view of the local monetary authorities on the degree of transmission of exchange-rate fluctuations on inflation.</li> <li>- The estimated long-term elasticities on import and export prices to a change in the exchange rate were 0.84 and 0.61 respectively. The long-term elasticity on consumer prices was found to be 0.1.</li> </ul>							
<b>Rowland</b>	<b>2003</b>	M	1983-2002	VAR, VEC	LR	L and Diff	Pm; W; CPI
<ul style="list-style-type: none"> <li>- Paper found that PT was incomplete.</li> <li>- Import prices responded quickly to an exchange rate shock and 0.8 of it was passed onto prices of imports within 12 months. The corresponding transmission for producer prices was 0.28, and for consumer prices less than 0.15.</li> <li>- According to the author, an exchange rate shock had little impact on consumer price inflation.</li> </ul>							
<b>Rincón et al.</b>	<b>2005</b>	M	1995-2002	VEC	LR	Diff	Pm
<ul style="list-style-type: none"> <li>- Paper made a disaggregate analysis and estimated the PT for import prices of a sample of the sectors in the Colombian manufacturing industry.</li> <li>- It found clear evidence of heterogeneity in the degree of PT across sectors as well as in the incomplete transmission of the exchange rate both in the short and long terms.</li> <li>- The degree of estimated PT was located between 0.1 and 0.7 for the short term, and 0.1 and 0.8 for the long term. In spite of the fact that they did not develop it, they made explicit the possible presence of nonlinearities in the relationship between the exchange rates and prices in the Colombian case.</li> </ul>							
<b>Ramírez<sup>5</sup></b>	<b>2005</b>	M	1980-2004	ARDL, RR	LR	Diff	Pm; W
<ul style="list-style-type: none"> <li>- Paper compares PT estimates of Colombia and other Latin American countries.</li> <li>- It found evidence of a decline in PT after different types of events had taken place: central bank independence, floating exchange rate and adoption of the inflation-targeting regime.</li> <li>- Paper showed that the country for which the clearest evidence of changes in PT induced by IT was Brazil.</li> </ul>							
<b>Parra</b>	<b>2010</b>	Y	1994-2005	Calibration	Elasticity	L	Pm; Pt; Pnt; CPI
<ul style="list-style-type: none"> <li>- Paper shows the disconnection between the nominal exchange rate and domestic inflation, which is explained by the presence of margins of distribution and marketing on the imported goods.</li> <li>- It concludes that on average a 1% nominal devaluation of the local currency would imply a 0.28 increase in the CPI.</li> </ul>							
<b>González et al.</b>	<b>2010</b>	Q	1985-2007	LST-VAR	NL	Diff	Pm
<ul style="list-style-type: none"> <li>- It showed that the PT on whole import prices was incomplete not only in the short term, but also in the long term.</li> <li>- Estimations showed that the PT coefficient was between 0.06 and 0.58.</li> <li>- Paper also found that the degree and dynamics of PT were endogenous and asymmetrical to the behavior of the exchange rate and to the state of the economy.</li> <li>- PT was greater when the economy was booming and more open, the devaluation/appreciation of the exchange rate accelerates and was less volatile, the real exchange rate was overvalued, and the inflation rate was high and less volatile, and it decelerated.</li> </ul>							
<b>Rincón and Rodríguez</b>	<b>2015</b>	Q	1985-2014	LST-VAR	LR	Diff	Pm; W; CPI
<ul style="list-style-type: none"> <li>- It concludes that PT on CPI was 0.04 in the first year, using a linear VAR model.</li> </ul>							

Source: Authors' review.

<sup>1</sup> Q: Quarterly; M: Monthly; Y: Yearly. <sup>2</sup> NL: Nonlinear; LR: Linear; RR: Rolling regression. <sup>3</sup> L: Levels; Diff: Differences.

<sup>4</sup> Pm: Imported producer goods; W: Producer goods; Px: Exported goods; CPI: Consumer goods; Pt: Tradable goods; Pnt: Non-tradable goods. <sup>5</sup> Brazil, Chile, Colombia and Mexico.

## Appendix A.2. Data and Sources

Sample: 2002:06 – 2015:5

Frequency: Monthly

-  $Mgc^*$ : Trade-weighted measure of the foreign countries' marginal costs. Foreign countries are the main exporters to Colombia: USA, Canada, Japan, UK, Germany, Netherlands, Spain, France, Italy, Belgium, Switzerland, Sweden, Mexico, Panama, Venezuela, Ecuador, Peru, Brazil, Chile, and Argentina. The monthly producer price index of each of these countries was used as their marginal cost proxy. Then, the price indexes were weighted by the respective monthly import weight in Colombian imports. Source: Banco de la República, International Financial Statistics (IMF) and home pages from the respective central banks (unpublished statistics).

-  $E$ : Nominal effective exchange rate index. It is weighted using imports from Colombia's main trading partners. Source: *Banco de la República* (unpublished statistics).

-  $P^m$ : Price index of imported goods. Not seasonally adjusted (2014=100). Source: *Banco de la República* (<http://www.banrep.gov.co/es/ipp>).

-  $S$ : Non-core CPI. Source: *Banco de la República* (unpublished statistics).

-  $P^{ppi}$ : Producer price index (2014=100). Not seasonally adjusted. Source: *Banco de la República* (<http://www.banrep.gov.co/es/ipp>).

-  $P^{mc}$ : Main imported goods of the Consumer Price Index. Not seasonally adjusted. Source: *Banco de la República* (unpublished statistics).

-  $P^{cpi}$ : Consumer Price Index (2008=100). Not seasonally adjusted. Source: *Banco de la República* (<http://www.banrep.gov.co/es/ipc>).

- Annualized monthly inflation ( $\pi_t^I$ ) =  $\ln(I_t) - \ln(I_{t-12})$ ,  $I = P^m, P^{ppi}, P^{mc}, P^{cpi}$ . Source: Own calculations.

-  $\Delta\pi_t^{cpi}$ : Change of the annualized monthly CPI inflation =  $(\pi_t^{cpi} / \pi_{t-1}^{cpi}) - 1$ . Source: Own calculations.

-  $V(\pi_t^{cpi})$ : Volatility of the annualized monthly CPI inflation. It is calculated as the standard deviation of  $\pi_t$  using a moving window of twelve months. Source: Own calculations.

-  $D\pi_t$ : Deviations of the annualized monthly CPI inflation from central bank's CPI inflation target. Source: Own calculations.

-  $\Delta e_t$ : Annualized monthly variation of the exchange rate =  $\ln(E_t) - \ln(E_{t-12})$ . Source: Own calculations.

-  $\Delta(\Delta e_t)$ : Change of the Annualized monthly variation of the exchange rate =  $(\Delta e_t / \Delta e_{t-1}) - 1$ . Since the series presented outliers, we adjusted it taking centered moving averages of order three. Source: Own calculations.

-  $V(\Delta e_t)$ : Volatility of the exchange rate. It is calculated as the standard deviation of  $\Delta e$  using a moving window of twelve months. Source: Own calculations.

-  $Mq$ : Measurement of misalignment of the real exchange rate: It is calculated as the difference between the quarterly real exchange-rate index taken from the statistics of the central bank (as it increases, it depreciates) and the quarterly estimated "equilibrium real exchange rate" produced by the Real Exchange Rate Team of the central bank's Research Department. The latter is a quarterly simple average of four estimates of the equilibrium real exchange rate: i) the filtered value of the real exchange rate using the Hodrick and Prescott filter; ii) the fitted value of a structural VEC model of

the real exchange rate on real variables such as net foreign assets, terms of trade and an indicator of the Colombian trade openness; iii) the fitted value of a VEC model of the real exchange rate on real variables such as net foreign assets, terms of trade, public expenditures and relative productivity between Colombia and USA; and iv) the estimation of the “fundamental equilibrium exchange rate” according to the methodology developed by the International Monetary Fund. To obtain the monthly series, we interpolated the quarterly “misalignment” series using the “DISAGGREGATE.SRC” procedure (by Tom Doan, Estima). Source: Banco de la República and own estimations (unpublished statistics). [http://www.banrep.gov.co/es/series-estadisticas/see\\_ts\\_cam\\_itcr.htm%23itcr](http://www.banrep.gov.co/es/series-estadisticas/see_ts_cam_itcr.htm%23itcr)

- Gy: Measurement of the output gap. It is the average of five models that are estimated and updated quarterly for the Colombian Inflation Report. These are: A simple HP filter; a survey data based on principal component estimates; two Neo-Keynesian models, one with adaptive expectations and the other with rational expectations; and a production function approach. All estimates that rely on statistical filters include out-of-sample forecasts to ameliorate the problem of optimal filtering end of the sample. The average serves as a prior at several points of time for a HP filter, in order to take all estimates to quarterly frequency. The centered moving average of this HP filter with priors is the official output gap estimate, which feeds the forecasting and policy analysis models. To obtain the monthly series, we interpolated the quarterly “output gap” series using the “DISAGGREGATE.SRC” procedure (by Tom Doan, Estima). Source: *Banco de la República* and own estimations (unpublished statistics).

- Openness: Indicator of the country’s trade openness. It is calculated as the ratio between total monthly imports plus exports and the GDP. Sources: National Department of Statistics (DANE), *Banco de la República*, and own calculations (unpublished statistics).

- Pcomm: Commodity price index. Correspond to CRB BLS Spot Index (1967=100)-PRICE INDEX (CRBSPOT). Source: Datastream.

- IBR: Colombian interbank interest rate (TIB). Source: *Banco de la República* <http://www.banrep.gov.co/es/tib>.

## Appendix A.3. Bayesian Econometric Method

The Bayesian analysis requires the likelihood function of the model, the prior distribution, and at least an approximation to the posterior distribution. We follow closely Koop (2003), Gefang and Strachan (2010) and Gefan (2012) and reproduce parts of their derivations here.

### A3.1 Likelihood function

Write model (11) in a compact form as

$$(A3.1.1) \quad Y = X^\theta B + E.$$

where  $B = (A_0, A_1, \dots, A_p, B_0, B_1, \dots, B_p)'$  and  $x^\theta = I_n \otimes X^\theta$ ,  $X^\theta = [x_1^\theta, \dots, x_T^\theta]'$ , with  $x_t^\theta = [x_t' F(z_{t-d}) x_t']$  and  $\theta = (\gamma, c)'$ . But model (A3.1.1) can be vectored and transformed into,

$$(A3.1.2) \quad y = x^\theta b + e,$$

where  $y = \text{vec}(Y)$ ,  $b = \text{vec}(B)$  and  $e = \text{vec}(E)$ . Given that errors terms are assumed to be Gaussian white-noise processes, the likelihood function of the model can be expressed as

$$(A3.1.3) \quad L(b, \Sigma, \gamma, c) \propto |\Sigma|^{-T/2} \exp \left\{ -\frac{1}{2} e' (\Sigma^{-1} \otimes I_T) e \right\}.$$

Now notice that the term in the exponent of (A3.1.3) can be rewritten as

$$(A3.1.4) \quad e' (\Sigma^{-1} \otimes I_T) e = s^2 + (b - \hat{b})' V^{-1} (b - \hat{b})$$

where  $s^2 = y' M_V y$ ,  $M_V = \Sigma^{-1} \otimes (I_T - X^\theta (X^{\theta'} X^\theta)^{-1} X^{\theta'})$ ,  $\hat{b} = \text{vec}((X^{\theta'} X^\theta)^{-1} X^{\theta'} Y)$  and  $V = \Sigma \otimes (X^{\theta'} X^\theta)^{-1}$ .

Therefore, the likelihood function of the model is

$$(A3.1.5) \quad L(b, \Sigma, \gamma, c) \propto |\Sigma|^{-T/2} \exp \left\{ -\frac{1}{2} [s^2 + (b - \hat{b})' V^{-1} (b - \hat{b})] \right\}$$

whose kernel, which depends on  $b$  and the rest of parameters, has the familiar multivariate conjugate posterior normal form.

### A3.2 Prior distributions

In order to choose the prior distributions (as long as one needs to calculate posterior model probabilities (Bayes Factors) to compare across different models), and given that the dimension of  $b$  changes across different model specifications, one should not use (complete) flat priors for  $b$  to avoid meaningless Bayes factors (Koop, 2003). Thus, we use a weakly informative conditional proper prior for  $b$ , as done by Gefang (2012). Thus, the prior for  $b$  is assumed as Normal with zero mean and covariance matrix  $\underline{V} = \eta^{-1} I_{nk}$ , where  $\eta$  is a shrinkage prior distributed as Gamma with mean  $\underline{\mu}_\eta$  (equal 5.6) and degrees of freedom  $\underline{\nu}_\eta$  (0.25). Additionally, an Inverse-Wishart prior is specified for the variance-covariance matrix  $\Sigma$ .

Now, the identification problem when  $\gamma = 0$  is tackled by setting its prior distribution as nearly non-informative as possible, then a Gamma distribution with mean  $\underline{\mu}_\gamma$  (equal 2) and degree of freedom  $\underline{\nu}_\gamma$  (equal 0.1). As for the prior of  $c$ , and to avoid just one regime with few histories, we elicit the prior of  $c$  as uniformly distributed between the upper and lower limits of the middle 68% of the observed transition variables.

As required by formal Bayesian analysis, we implemented robustness exercises on the priors. Since the most sensitive one is the prior distribution for  $\eta$ , the parameters  $\underline{\mu}_\eta$  and  $\underline{\nu}_\eta$  were calibrated so that they yielded suitable acceptance rates of the Metropolis algorithm, as well as that the simulated PTs met the restriction  $0 \leq PT_t \leq 100$  in most of the draws.

In addition, as the degrees of freedom  $\underline{\nu}_\eta$  play an important role on both the acceptance rates and on meeting the size restriction of the simulated PTs, we decided to assign them values consistent with an uninformative prior distribution, as recommended by Gefang (2012), since results were sensitive to their variations up to the order of  $10^{-4}$ .

On the other hand, the coefficients that characterize prior distributions of the variance-covariance matrix  $\Sigma$ , the smoothing parameter  $\gamma$ , and the location parameter  $c$  fail to have great influence on the acceptance rates or the PT estimates.

### A3.3 **Computations of the posterior distributions**

As is recalled by Gefang and Strachan (2010, page 7), the combination of equations (A3.1.3) and the previous equations yields the conditional distribution for  $\Sigma$  as the inverted Wishart with scale matrix  $E'E$  and degrees of freedom  $T$  and the conditional posterior distribution for the vector  $b$  as normal with mean  $\bar{b} = \bar{V}V^{-1}\hat{b}$  and variance  $\bar{V} = (V^{-1} + \eta I_{nk})^{-1}$ . Since no close form is obtained for  $c$  and  $\gamma$ , we use the Metropolis within Gibbs strategy for these parameters.

The Gibbs sampling scheme is used to compute the outputs from the posteriors, as follows (Ibid, page 8),

1. Initialize  $(b, \Sigma, \gamma, c, \eta) = (b^0, \Sigma^0, \gamma^0, c^0, \eta^0)$ ;
2. Draw  $\Sigma/b, \gamma, c, \eta, x, y$  from  $IW(E'E, T)$ ;
3. Draw  $b/\Sigma, \gamma, c, \eta, x, y$  from  $N(\bar{b}, \bar{V})$ ;
4. Draw  $\gamma/b, \Sigma, c, \eta, x, y$  through a Metropolis-Hastings method;
5. Draw  $c/b, \Sigma, \gamma, \eta, x, y$  from a uniform  $(c_{min}, c_{max})$ ;
6. Draw  $\eta/b, \Sigma, \gamma, c, x, y$  from  $G(\underline{\mu}_\eta, \underline{\nu}_\eta)$ ;
7. Repeat step 2 to 6 for a suitable number of replications, say B.

To avoid the draws from Metropolis-Hastings simulator from getting stuck in a local mode, we also tried different starting values for the sampler. Convergence diagnostics indicated that 25,000 effective draws were enough to attain convergence, after 5,000 burnings. The hyper-parameters  $\underline{\mu}_\eta$  and  $\underline{\nu}_\eta$  were calibrated per each transition variable in order to obtain the best acceptance rates.

### Appendix A.4 **Estimation of the PT Coefficient by means of Bayesian Techniques**

This appendix summarizes the most important details of the methodology in order to estimate the effect of a shock to the exchange rate on the different price indexes in the stated nonlinear system (see details, for instance, in Koop (2003) and Lo and Morley (2015)) as stated by equations (9) and (10). The generalized impulse response function (GIRF) is defined as the expected deviation caused by a shock on the model's predicted values. Formally, if

$$(A4.1) \quad Y_t = A(L)Y_{t-1} + B(L)Y_{t-1}F(z_{t-d}; \gamma, c) + \mu_t,$$

in the presence of a shock of magnitude  $s$  to the  $k^{th}$ -element of the perturbations vector  $\mu_t$ , the result is:



$$(A4.2) \quad G(j, s, W_{t-1}) = E[Y_{t+j} | \mu_{k,t} = s, W_{t-1}] - E[Y_{t+j} | \mu_{k,t} = 0, W_{t-1}],$$

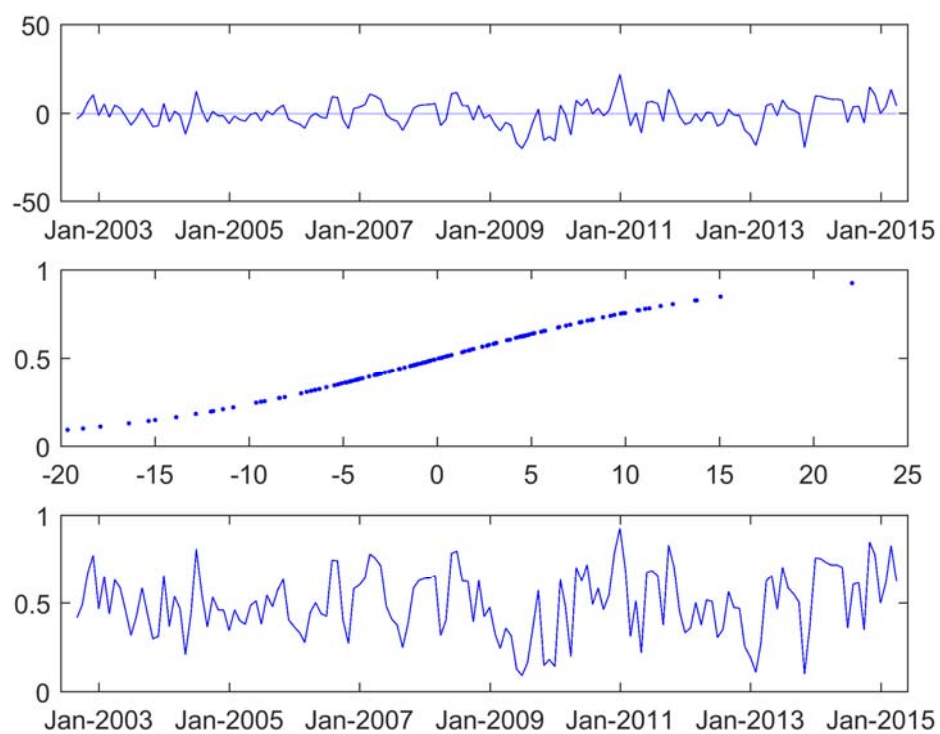
where  $W_{t-1}$  denotes the initial conditions (the history or state of the economy). Thus,  $G(\cdot)$  is the expected deviation of expected value of  $Y_{t+j}$  caused by a shock  $s$  from the expected value of  $Y_{t+j}$  conditional on the history at time  $t$ ,  $W_{t-1}$ . Then, the PT on a  $\tau$  horizon is calculated by means of the following procedure (notice we are interested in knowing the degree of PT under the  $z_{t-d} < \text{Threshold}$ , where  $\text{Threshold}$  is the value of parameter  $c$ ):

1. Randomly choose a point in the sample where the  $z_{t-d} < \text{Threshold}$  is met. The number of these points will be written  $N_{\text{lower}}$ .
2. For this point, forecast the model for  $T$  periods ahead through simulation, while considering the respective history for the elements of vector  $z_{t-d}$  and the observed values brought forward. This forecast is built by using the Bayesian estimates on each effective step of the Gibbs sampler. With that forecast we get  $E[Y_{t+j} | \mu_{k,t} = 0, W_{t-1}]$  for  $j = 0, 1, \dots, T$ .
3. Simulate the model for  $T$  periods ahead considering the same history for the elements of vector  $z_{t-d}$  from step 2, after subjecting the second element of  $z_t$  (corresponding to the devaluation) to a shock (add  $s$  in  $j=0$  period). With that you get for  $E[Y_{t+j} | \mu_t = s, W_{t-1}]$  for  $j = 0, 1, \dots, T$ . We considered different values of  $s$ .
4. Calculate  $G(\cdot)$  in accordance with (A4.2).
5. Compute the PT estimates by equation (10).
6. Return to step 1 each time, use the Gibbs sampler (following the steps stated in Appendix A3.2) and generate a new set of parameters.

With this procedure, there is a resulting total of  $N$  trajectories of the PT estimates, considering  $z_{t-d} < \text{Threshold}$  as initial conditions (for example, that the economy is in a regime of "high" inflation or in recession). To study the  $z_{t-d} > \text{Threshold}$  case, the procedure should be repeated by taking this new criteria as the initial condition (step 1). In the simulations presented, shocks were orthogonalized by the *Cholesky decomposition* method, maintaining the order of the variables given by vector  $Y$  (see definition in the text). That is, the foreign marginal cost is the most exogenous variable and CPI inflation the most endogenous one.

By drawing randomly from histories at each regime and averaging across them, we obtain an estimate and then the median of the PT, which is conditional upon the current state of the economy. Notice that for each of the inflation series, we present two sets of paths for  $G(\cdot)$  and PT median estimates, that is, whether the transition variable exhibits a "high" or "low" regime. For instance, whether the Colombian real exchange rate was overvalued or undervalued, or the inflation rate was "high" or "low." Additionally, we report the estimated path of  $G(\cdot)$  and PT when the shock to the exchange rate was a negative one or ten percent.

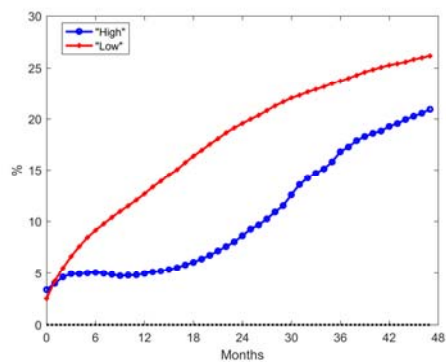
## Appendix A.5 Transition Variable, Smooth Transition Function, and Time Profile for $\Delta(\pi^{cpi})$



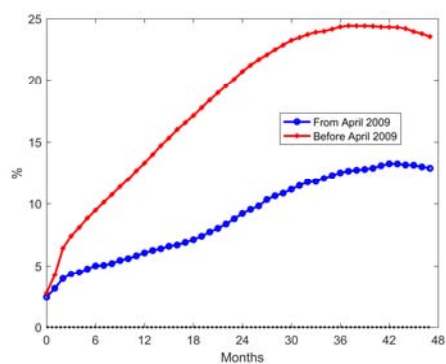
Source: Authors' calculations.

## APPENDIX A.6 Path of PT on CPI

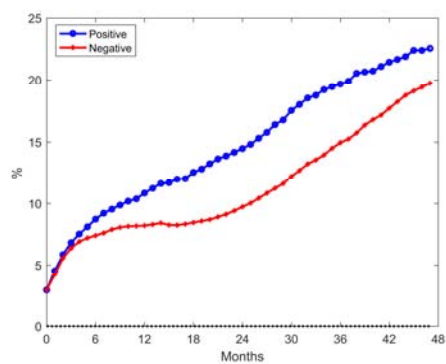
Transition variable: Interbank interest rate (*IBR*)



Transition variable: Trend (*Trend*)



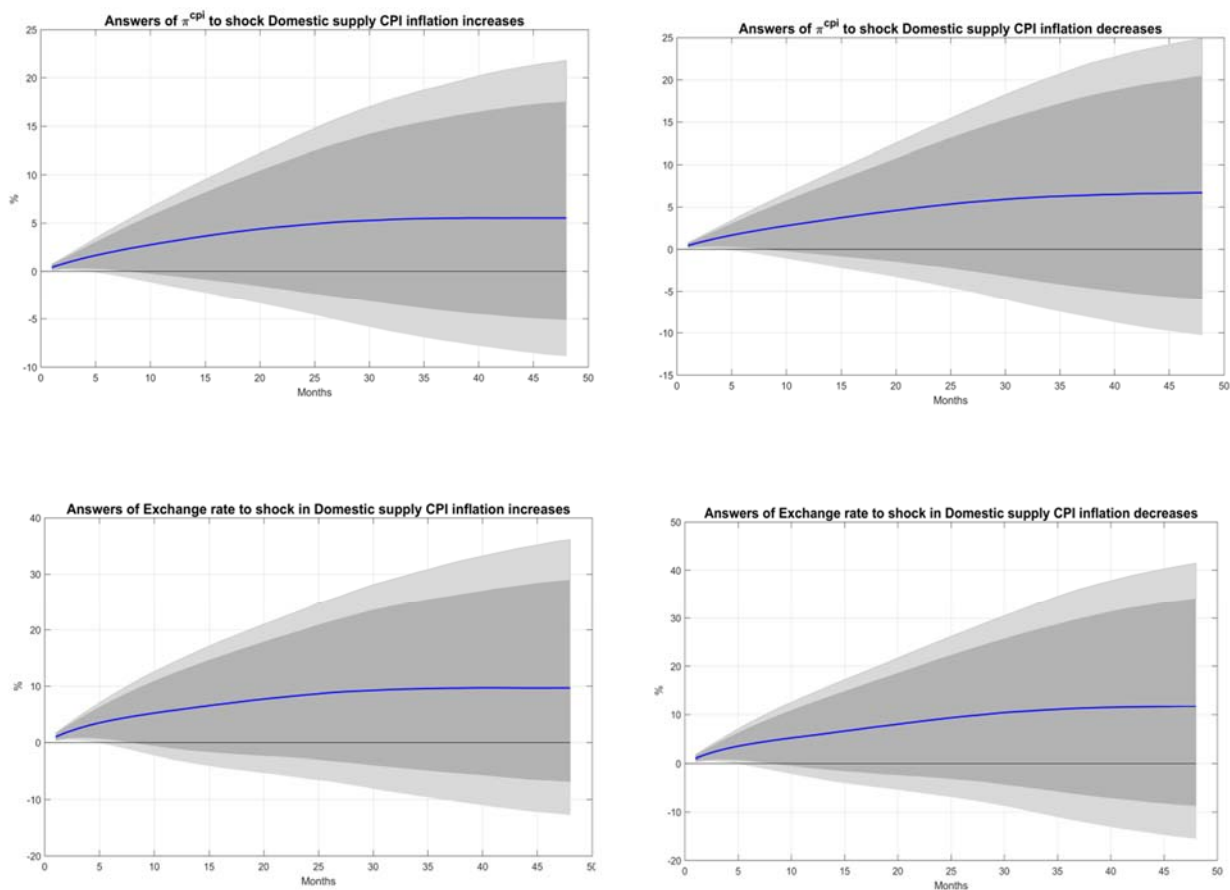
Transition variable: Output gap (*Gy*)



Source: Authors' calculations.

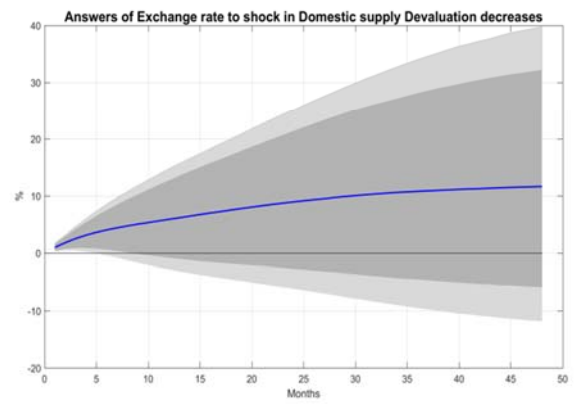
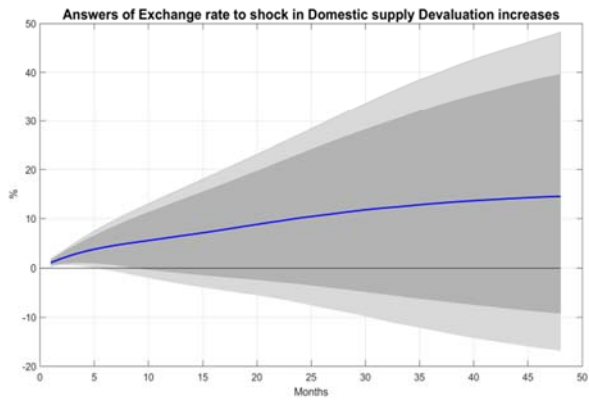
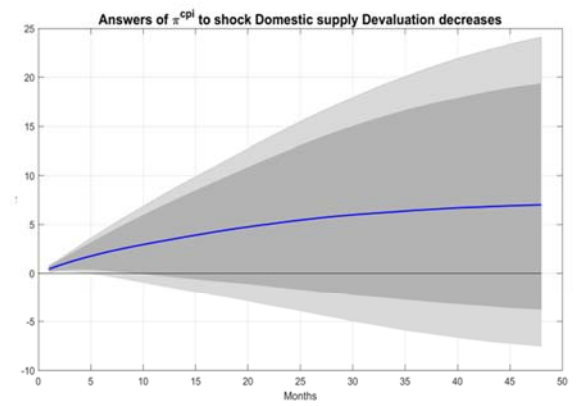
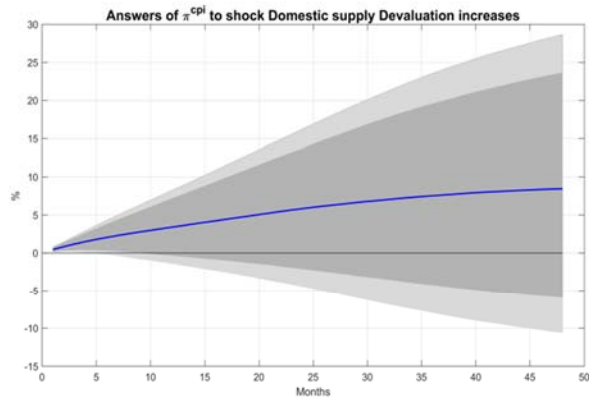
## Appendix A.7 Generalized Impulse-Response Functions: Supply shock

(a) Transition variable:  $\Delta(\pi^{cpi})$



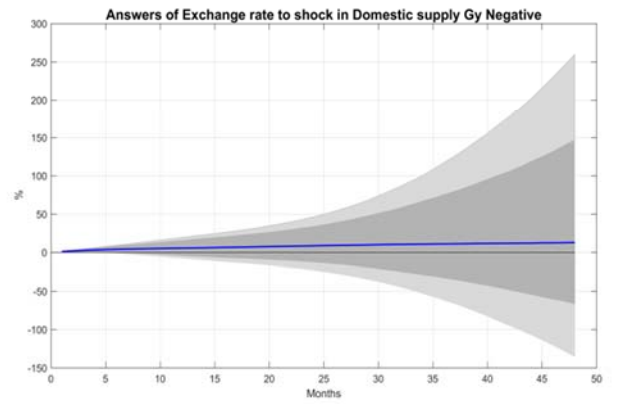
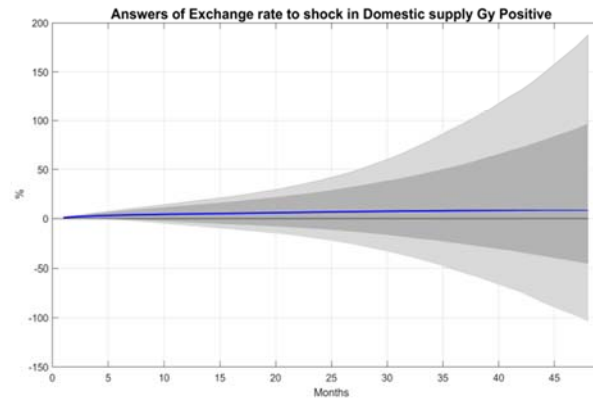
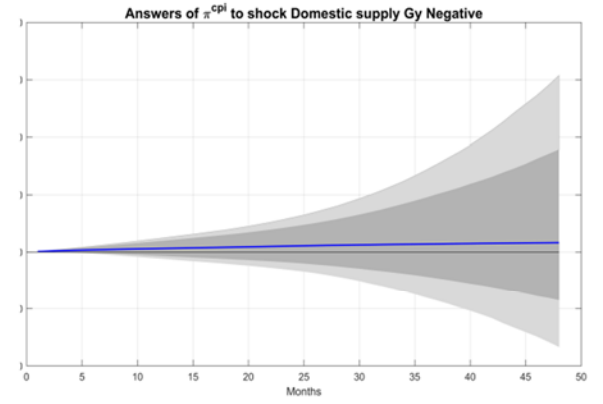
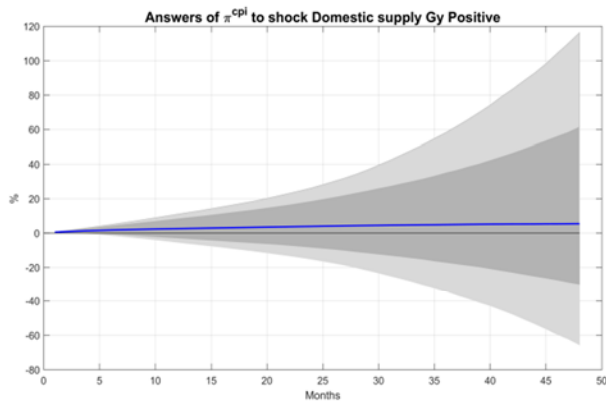
Source: Authors' calculations.

(b) Transition variable:  $\Delta(\Delta e)$



Source: Authors' calculations.

(c) Transition variable:  $G_y$



Source: Authors' calculations.

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