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Explaining the Exchange Rate Pass-Through in Different Prices

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Abstract

This paper examines the performance of different new open economy macroeconomic models in explaining the exchange rate pass-through in a wide range of prices. Quantitative versions of different models are used to derive the dynamic response of various prices to an exchange rate shock. Predicted responses are compared with the evidence based on VAR models to examine how well different models fit the data. The results show that the best-fitting model incorporates a number of features highlighted by different strands of the literature: sticky prices, sticky wages, distribution costs, and a combination of local and producer currency pricing.

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Keywords: Exchange rate pass-through; Prices; New open economy macroeconomic models

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I. INTRODUCTION

Recently, there has been a revival of interest in understanding how changes in the exchange rate pass through to prices. The pass-through process has been explored within the new open economy macroeconomic framework based on optimizing behavior. One issue that has received much attention is why exchange rate changes have little effect on consumer prices. A number of explanations have emerged to explain this phenomenon.[2] One strand in the literature (Betts and Devereux (1996, 2000), for example) assumes that import prices in each market are temporarily rigid in local currency. This type of nominal rigidity can block the transmission of exchange rate changes to consumer prices in the short run. Another strand in the literature follows the assumption in Obstfeld and Rogoff (1995) that prices are sticky in producer's currency, but considers imports as intermediate goods that need to go through production or distribution processes before they are consumed by households.[3] The production or distribution channels can dampen the effect of exchange rate changes on consumer prices.

The issue of whether prices are set in producer or local currency has important policy implications. Models based on producer currency pricing (PCP) support the traditional case for exchange rate flexibility while models with local currency pricing (LCP) raise doubts about the desirability of flexible exchange rates.[4] A promising test for discriminating between these hypotheses is provided by the evidence on the relationship between the exchange rate and the international prices of traded goods. The LCP and PCP models imply different degrees of exchange rate pass-through to import and export prices. These differences are especially pronounced in the simple case (typically assumed in theoretical models) where prices are predetermined for one period. In this case, the elasticity of the import price with respect to the exchange rate in the short run equals zero under LCP and equals one under PCP. These implications of LCP and PCP are reversed for the pass-through to export prices (in home currency).[5] Empirical evidence suggests that the pass-through to

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[2] See Engel (2002) for a review of these explanations.

[3] McCallum and Nelson (1999) model imports as raw materials in the production process. The importance of distribution services is discussed by Burstein, Neves, and Rebelo (2001).

[4] The choice of PCP versus LCP could influence the parameters of the monetary policy rule and thus directly affect monetary policy. This choice would also affect the response of the volume of trade to exchange rate changes (see Obstfeld (2002) for a further discussion of this issue).

[5] A related test proposed by Obstfeld and Rogoff (2000a) is that the sign of the correlation between the exchange rate (expressed as the price of foreign currency) and the terms of trade is positive under LCP and negative under PCP. They also provide evidence that the terms of trade tend to be negatively correlated with the exchange rate for a large sample of industrial countries, in accordance with the PCP hypothesis.

import and export prices tends to be somewhere between zero and one and this evidence does not appear to support either model.[6]

The evidence on the pass-through to international prices, however, is not necessarily inconsistent with more general models based on LCP or PCP, which incorporate more realistic price dynamics and richer models of international price discrimination.[7] Under staggered price adjustment, for example, prices of some imported or exported goods would be adjusted in each period and would be able to respond to exchange rate changes. In this case, LCP would imply that the pass-through coefficient is greater than zero in the short run for import prices and less than one for export prices. Also, if the degree of international price discrimination is influenced by the exchange rate, the short-run import (export) price elasticity could be less than one (greater than zero) under PCP.

The compatibility of the generalized versions of LCP and PCP models with the empirical evidence on exchange rate pass-through to various prices has not been adequately investigated. A number of quantitative applications of new open economy macroeconomics (e.g., Chari, Kehoe and McGrattan (2001), Bergin and Feenstra (2001), Kollmann (2001)) have examined the performance of LCP models with staggered wage-price setting in explaining certain empirical regularities, but the ability of these models to explain the exchange rate pass-through to various prices remains unexplored.[8] Bergin (2002) evaluates the relative performance of LCP and PCP models in fitting selected macroeconomic data for three countries. His data set, however, includes only one price index (CPI) and thus his tests do not address the question of how well LCP or PCP assumptions explain the behavior of other price indexes, especially import and export prices (or the terms of trade).

This paper explores the ability of different new open economy macroeconomic models to explain the exchange rate pass-through to a broad set of prices that includes key domestic and international prices. For this purpose, the paper develops a general small-economy model that nests LCP and PCP, and can incorporate a number of different

[6] See Goldberg and Knetter (1997) for a review. They find that the degree of pass-through to international prices over a year is typically around 0.5. See also Campa and Goldberg (2002), who test the simple versions of the LCP and PCP hypotheses for the pass-through to import prices and find that both hypotheses are rejected for most countries in their sample of member countries of the Organization for Economic Cooperation and Development (OECD).

[7] Corsetti and Dedola (2002) develop a model where the price elasticity of demand in a market depends on local distribution costs and is thus sensitive to the exchange rate. Deviations from the law of one price can occur in this model even under flexible prices. Faruqee (1995) also discusses a model of international price discrimination based on market-specific costs.

[8] McCallum and Nelson (2001) explore the capability of a PCP–based model to explain the correlations between (current and lagged) exchange rate depreciations and price changes, but they focus only on changes in the consumer price index.

specifications of wage-price dynamics along with international price discrimination based on distribution costs. A number of interesting variants of LCP and PCP models can be distinguished as special cases of the general model. The model assumes two differentiated goods, a traded intermediate and a nontraded final consumer good, and one differentiated primary factor, labor. This simple structure gives rise to five price indexes for the home economy: the consumer price index, the producer and export price indexes (based on the home and foreign prices of the home intermediate good), the import price index and the wage index (based on prices of labor services). A quantitative version of the model is used to derive the dynamic response of the five prices to an exchange rate shock for different variants of the model.[9] Predicted responses are compared with the evidence on the pass-through of exchange rate shocks to examine how well different variants fit the data.

The evidence on the pass-through of exchange rate shocks to different prices is based on impulse response functions derived form VAR models.[10] We focus on a sample of major industrial countries represented by G-7 countries. As our small-economy model is designed for economies with exogenously determined foreign variables, we do not include the United States in our basic sample. For the non-U.S. G-7 economies, we estimate a VAR model that includes the five price indexes highlighted in our model. The impulse response functions are then estimated from this model using a scheme to identify exchange rate shocks, which is consistent with the theoretical model.[11]

The evidence based on the impulse response analysis of VAR models is presented in Section II. Section III develops a general model that combines features highlighted by different approaches and distinguishes a number of models of interest as special cases of the general model. The relative performance of these models in matching the VAR data is discussed in Section IV. Concluding remarks are offered in Section V.

[9] The exchange rate shock is defined as a shock to the uncovered interest parity relation and is motivated by the presence of noise traders as suggested by Devereux and Engel (2001) and Jeanne and Rose (2000).

[10] Estimates of the pass-through of exchange rate changes to a price index are often based on regression models that relate the price index to current and past exchange rates. This approach, however, does not isolate the effect of exogenous shocks to the exchange rate and is thus difficult to relate to our theoretical analysis.

[11] For a number of industrial countries, McCarthy (2000) provides VAR-based estimates of the pass-through of exchange rate shocks to consumer, producer, and import prices. These estimates, however, use a procedure for identifying exchange rate shocks based on a model of pricing along a distribution chain, which is not compatible with the new open economy macroeconomic framework considered in this paper.

II. Evidence

This section presents evidence on the exchange rate pass-through to different prices for non-U.S. G-7 countries, based on the impulse response functions derived from a VAR model. The basic VAR model includes data on seven endogenous and two exogenous variables. The endogenous variables consist of: the interest rate (R), the exchange rate (S), the import price index (P_M), the export price index (P_X), the producer price index (P_Y), the consumer price index (P_C), and the wage rate (W). The exogenous variables are the foreign interest rate (R^*) and the foreign consumer price index (P_C^*). As our focus is on predicting the behavior of prices, the basic VAR model does not include an indicator of real economic activity. Our sensitivity analysis shows, however, that adding real output to the basic model does not make much difference to the main results.

The data for all variables are seasonally adjusted quarterly series at annual rates.[12] The sample period ranges from 1979:1 to 2001:3. The interest rates are measured by the three-month treasury bill rate or an equivalent money market rate. The import and export price indexes are expressed in home currency and based on unit values. The exchange rate represents the nominal effective exchange rate (expressed as the price of a currency basket in terms of the home currency) based on trade weights. The series on the foreign interest rate and the foreign price level are constructed using the same trade weights as those in the effective exchange rate. With the exception of interest rates, all series are in logs.

We assume that all series except interest rates are I(1), in accordance with our theoretical model discussed below. Tests of unit roots and stationarity are broadly consistent with this assumption.[13] The VAR model was estimated in the following form:

$$\mathbf{y}_t = \mathbf{c} + A(L)\mathbf{y}_{t-1} + B(L)\mathbf{x}_t + \mathbf{u}_t,$$

where $\mathbf{y}_t = [R_t, \Delta\log S_t, \Delta\log P_{Mt}, \Delta\log P_{Xt}, \Delta\log P_{Yt}, \Delta\log P_{Ct}, \Delta\log W_t]$ is the vector of endogenous variables, $\mathbf{x}_t = [R_t^*, \Delta\log P_t^*]$ is the vector of exogenous variables, $\mathbf{c}$ is a vector of constants, $A(L)$ and $B(L)$ are matrix polynomials in the lag operator L, and $\mathbf{u}_t$ is a

[12] The data for import and export unit values and the wage rate are from OECD's Analytical Database. Series on the consumer price index and the nominal effective exchange rate are obtained from IMF's Information Notice System. The IMF's *International Financial Statistics* is the source of all other data.

[13] For price indexes and the exchange rate, augmented Dickey-Fuller tests do not generally reject the null of unit root while the Kwiatkowski-Philips-Schmidt-Shin tests mostly reject the null of stationarity. The results of these tests for the interest rate are mixed and are not in strong conflict with our assumption that this variable is stationary.

vector of residuals.[14] Our main objective is to obtain evidence on how exchange rate shocks affect different prices over time. We thus do not attempt to identify all structural disturbances, but introduce minimal restrictions that are sufficient to identify the dynamic response of each variable to the exchange rate shock. Our identifying restrictions are based on plausible assumptions that are consistent with the theoretical framework. However, we also consider alternative identification schemes and examine the sensitivity of our results to the use of alternative schemes.

Express the structural model as

$$G(L)\mathbf{y}_t = \mathbf{c} + H(L)\mathbf{x}_t + \mathbf{e}_t,$$

where $\mathbf{e}_t$ is a vector of structural shocks, $G(L)$ and $H(L)$ are matrix polynomials in the lag operator L, and all elements on the diagonal in the coefficient matrix on L^0 in $G(L)$ equal unity. The first two equations represent, respectively, the relations determining the interest rate and the exchange rate. The first two elements of the vector, $\mathbf{e}_t$, are thus the structural shocks to these variables. Our basic identification scheme introduces the following restrictions on the structural model: (a) In the first two equations, the coefficients on $\Delta \log P_{Mt}$, $\Delta \log P_{Xt}$, $\Delta \log P_{Yt}$, $\Delta \log P_{Ct}$ and $\Delta \log W_t$ equal zero. (b) In the first equation, the coefficient on $\Delta \log S_t$ equals zero.

Restriction (a) is based on the view that while prices in asset markets are monitored and reported quickly, there are delays in obtaining information on prices in the goods and labor markets.[15] We assume that prices in the goods and labor markets are observed with, at least, a one-period lag, and thus the structural shocks to the interest and exchange rates are not contemporaneously correlated with these prices.[16] Restriction (b) is suggested by our estimation of the interest rate rule, which we identify with the first structural equation. Our estimates of the interest rate rule (discussed later) indicate that the coefficient of $\Delta \log S_t$ in

[14] We checked the possibility that some of the VAR variables are cointegrated because the real exchange rate, relative home prices, or the terms of trade are stationary. For all countries in our sample, however, augmented Dickey-Fuller tests do not reject the hypothesis that the following series contain a unit root: $\log(S_t P_{Ct}^* / P_{Ct})$, $\log(P_{Yt} / P_{Ct})$, $\log(P_{Mt} / P_{Ct})$, $\log(W_t / P_{Ct})$ and $\log(P_{Xt} / P_{Mt})$.

[15] The assumption that information delays do not allow monetary authorities to respond to prices and output within the period has been used to identify monetary policy shocks (see Sims and Zha (1995) and Kim and Roubini (2000)). Here we also assume similar information delays for exchange market dealers.

[16] This assumption may be more appealing for monthly data, but even for quarterly data used in this study, this assumption may not be unreasonable for most prices.

this relation is not significantly different from zero for most countries in our sample. Given restrictions (a) and (b), the dynamic response of an endogenous variable to a structural exchange rate shock is simply the orthogonalized impulse response function for the variable in response to a shock to the $\Delta \log S_t$ equation, using a recursive ordering with R_t as the first and $\Delta \log S_t$ as the second variable. Note that the ordering of the remaining variables can be shown not to matter for calculating this impulse response function.

The VAR model with four lags for both endogenous and exogenous variables was estimated for each country in our sample. Dynamic responses of the five price indexes to an exchange rate shock were then derived from this model using our basic identification scheme. Tables 1 summarizes the evidence on the short and medium term price effects of an exchange rate shock for non-U.S. G-7 countries. It shows the response of each price index in quarters 1, 4 and 10 to a one-unit exchange rate shock in quarter 1.[17] The response of the terms of trade (which can be readily derived from the responses of export and import prices) is also shown in this table.

For each variable, the average response for the non-U.S. G-7 countries is also shown in Table 1 and illustrated in Figure 1 (from quarter 1 through 10). As the figure shows, the exchange rate shock has little effect in the short run on consumer and producer prices, as well as on the wage rate. The response of these variables, especially consumer and producer prices, increases over time but remains modest. The effect of a unit exchange rate shock on consumer prices, for example, is less than 0.2 after 10 quarters. The pattern of the response of import prices to the exchange rate shock is much different. The effect of the exchange rate shock on import prices is close to one-half in the first quarter. This effect increases over the first four quarters, but then declines sharply. Indeed, the effect on import prices after ten quarters is not much different than that on consumer prices. Export prices follow a similar pattern, but their response is weaker than import prices. The terms of trade thus worsen initially in response to the exchange rate shock, but begin to improve afterwards. The terms of trade effect after ten quarters is, in fact, close to zero.

In Section IV, we evaluate the performance of different models in matching non-U.S. G-7 response functions illustrated in Figure 1. We also undertake sensitivity analysis to explore how additional variables in the VAR model or alternative recursive structures (to identify the exchange rate shock) would affect the performance of different models.

[17] An individual country's response in quarter $j\ (\geq 1)$ is calculated as $\partial \log Z_{t+j} / \partial e_{S,t+1}$, for $Z_t = P_{Ct},\ P_{Yt},\ W_t,\ P_{Mt},\ P_{Xt}$, where e_{St} is the orthogonalized shock to the equation for $\Delta \log S_t$. The effect on log levels is derived by accumulating the effect of the shock on log differences.

III. Model

This section discusses a general version of the model, which combines features highlighted by different approaches. Major variants of the LCP and PCP models are identified at the end of the section as special cases of the general model. The relative performance of these variants is evaluated in the next section.

A. Basic Setup

Assume two types of products, a nontraded final (consumer) good and a traded intermediate good and one primary factor, labor. Let both types of products and labor represents a continuum of differentiated varieties in the unit interval. In discussing the model, we focus on the relations for the home economy, which is assumed to be small. Analogous relations are assumed for the foreign economy with an asterisk denoting foreign variables (foreign nominal values are expressed in foreign currency).

The expected lifetime utility of a household, indexed by $l \in [0, 1]$, is assumed to be

$$E_t \sum_{\tau=t}^{\infty} \beta^{\tau-t} [\frac{1}{1-\rho} C_\tau(l)^{1-\rho} - \frac{1}{1+\mu} L_\tau(l)^{1+\mu}], \tag{1}$$

where $C_\tau(l)$ and $L_\tau(l)$ are the household's consumption basket and labor supply, and β is the discount rate. The consumption basket for each household is an aggregate of the consumer good varieties, indexed by $c \in [0, 1]$, and is given by

$$C_t = [\int_0^1 C_t(c)^{1-1/\varepsilon} dc]^{\varepsilon/(\varepsilon-1)}. \tag{2}$$

Each consumer good variety is produced by the following technology:

$$C_t(c) = A_C Q_t(c)^\gamma N_{Ct}(c)^{1-\gamma}, \tag{3}$$

where $Q_t(c)$ is an index of both home and foreign varieties of the intermediate good, and $N_{Ct}(c)$ is a bundle of differentiated labor services. This technology combines traded goods with nontraded labor services to produce consumption services. The technology for producing a home variety of the intermediate good, indexed by $y \in [0, 1]$, is given by

$$Y_t(y) = A_Y Z_t(y)^\alpha N_{Yt}(y)^{1-\alpha}, \tag{4}$$

where $Z_t(y)$ and $N_{Yt}(y)$ are composites of differentiated intermediate and labor inputs. This specification allows for a Leontief type input-output structure suggested by Basu (1995), where the production of each intermediate variety uses a basket of intermediates as an input.

Let $Y_{QHt}(y)$ and $Y_{ZHt}(y)$ denote the amounts of the home variety y used in the production of the consumption and intermediate goods, and let $Y_{QMt}(y^*)$ and $Y_{ZMt}(y^*)$ denote the corresponding amounts of an imported foreign variety, indexed by $y^* \in [0, 1]$. The intermediate input bundles for the consumer and intermediate goods are defined as

$$Q_t = [\nu^{1/\sigma} Q_{Mt}{}^{1-1/\sigma} + (1-\nu)^{1/\sigma} Q_{Ht}{}^{1-1/\sigma}]^{\sigma/(\sigma-1)}, \tag{5}$$

$$Z_t = [\nu^{1/\sigma} Z_{Mt}{}^{1-1/\sigma} + (1-\nu)^{1/\sigma} Z_{Ht}{}^{1-1/\sigma}]^{\sigma/(\sigma-1)}, \tag{6}$$

$$Q_{Mt} = [\int_0^1 Y_{QMt}(y^*)^{1-1/\varepsilon} dy^*]^{\varepsilon/(\varepsilon-1)}, \ Z_{Mt} = [\int_0^1 Y_{ZMt}(y^*)^{1-1/\varepsilon} dy^*]^{\varepsilon/(\varepsilon-1)}, \tag{7}$$

$$Q_{Ht} = [\int_0^1 Y_{QHt}(y)^{1-1/\varepsilon} dy]^{\varepsilon/(\varepsilon-1)}, \ Z_{Ht} = [\int_0^1 Y_{ZHt}(y)^{1-1/\varepsilon} dy]^{\varepsilon/(\varepsilon-1)}. \tag{8}$$

Here, the elasticity of substitution between domestic and foreign bundles of the intermediate good, σ , is allowed to be different than the elasticity between varieties within each bundle, ε. Each variety is supplied to both final and intermediate demand at home and abroad. The output of a variety thus equals

$$Y_t(y) = Y_{QHt}(y) + Y_{ZHt}(y) + Y^*_{QMt}(y) + Y^*_{ZMt}(y). \tag{9}$$

We assume that imported varieties need to go through distribution channels before use in production of the intermediate and final goods, and the distribution process requires local labor services. Assume a Leontief technology for distribution and suppose that the distribution of one unit of the imported variety y^* requires δ units of the labor service bundle, $N_{Mt}(y^*)$, so that

$$N_{Mt}(y^*) = \delta[Y_{QMt}(y^*) + Y_{ZMt}(y^*)]. \tag{10}$$

This formulation adds trade costs based on local distribution services and provides a basis for international price discrimination as in Corsetti and Dedola (2002).[18]

The total supply of each variety of labor equals

$$L_t(l) = L_{Yt}(l) + L_{Ct}(l) + L_{Mt}(l). \tag{11}$$

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[18] We assume that a Leontief-type distribution process is needed only for moving intermediate goods across borders. For simplicity, we do not require such a process for converting intermediates into the consumption good (the distribution cost for imports is thus the same whether they are used in the production of the intermediate or the final good). Note, however, that the consumption technology (3) allows for a Cobb-Douglas distribution process for transforming (both home and foreign) intermediates into a final good.

where $L_{Ct}(l)$, $L_{Yt}(l)$ and $L_{Mt}(l)$ represent amounts of household l's labor service used in the production of the final and intermediate goods and the distribution of imports. We define the labor service bundles in the three activities as

$$N_{Ct} = [\int_0^1 L_{Ct}(l)^{1-1/\varepsilon} dl]^{\varepsilon/(\varepsilon-1)}, N_{Yt} = [\int_0^1 L_{Yt}(l)^{1-1/\varepsilon} dl]^{\varepsilon/(\varepsilon-1)}, N_{Mt} = [\int_0^1 L_{Mt}(l)^{1-1/\varepsilon} dl]^{\varepsilon/(\varepsilon-1)}. \quad (12)$$

The elasticity of substitution between varieties of labor services is also assumed, for simplicity, to equal ε.

The consumer price and wage indexes can be defined as the cost–minimization prices of C_t and N_{Jt}, for $J = C, Y, M$, and can be derived from (2) and (12), as follows:

$$P_{Ct} = [\int_0^1 P_{Ct}(c)^{1-\varepsilon}\, dc]^{1/(1-\varepsilon)}, \; W_t = [\int_0^1 W_t(l)^{1-\varepsilon}\, dl]^{1/(1-\varepsilon)}, \quad (13)$$

where $P_{Ct}(c)$ is the price of variety c and $W_t(l)$ is the wage rate for labor service l. Define the producer price index, P_{Yt}, as the price of the intermediate good variety that minimizes the unit costs of Q_{Ht} and Z_{Ht}. Also define the export price index, P_{Et}, as the cost–minimization price of Q^*_{Mt} and Z^*_{Mt}. Letting $P_{Yt}(y)$ and $P_{Et}(y)$ denote the prices of variety y for the domestic and foreign markets, and using (8) and the foreign counterpart of (7), we have

$$P_{Yt} = [\int_0^1 P_{Yt}(y)^{1-\varepsilon}\, dy]^{1/(1-\varepsilon)}, \; P_{Et} = [\int_0^1 P_{Et}(y)^{1-\varepsilon}\, dy]^{1/(1-\varepsilon)}. \quad (14)$$

The import price of a foreign variety at the border (before adding the distribution costs) is $P_{Mt}(y^*) = S_t P^*_{Et}(y^*)$, where S_t is the exchange rate. Let $\widetilde{P}_{Mt}(y^*)$ be the price of the foreign variety including the distribution cost. This price represents the cost of the imported variety to domestic users (i.e., producers of both final and intermediate goods), and in view of (10), equals

$$\widetilde{P}_{Mt}(y^*) = P_{Mt}(y^*) + \delta W_t. \quad (15)$$

The import price indexes with and without the distribution cost can be defined as

$$\widetilde{P}_{Mt} = [\int_0^1 \widetilde{P}_{Mt}(y^*)^{1-\varepsilon}\, dy^*]^{1/(1-\varepsilon)}, \; P_{Mt} = [\int_0^1 P_{Mt}(y^*)^{1-\varepsilon}\, dy^*]^{1/(1-\varepsilon)}. \quad (16)$$

Note that the index, $\widetilde{P}_{Mt}$, is the cost-minimizing price of Z_{Mt} as well as Q_{Mt} according to (7).

Finally, the marginal costs for the consumer and intermediate goods can be readily derived from (3) and (4) as

$$MC_{Ct} = P_{Qt}^{\gamma} W_t^{1-\gamma} / (A_C \gamma^{\gamma} (1-\gamma)^{1-\gamma}), \; MC_{Yt} = P_{Zt}^{\alpha} W_t^{1-\alpha} / (A_Y \alpha^{\alpha} (1-\alpha)^{1-\alpha}), \tag{17}$$

where P_{Qt} and P_{Zt} are the cost-minimizing price indexes for Q_t and Z_t, which can be obtained from (5) and (6) as

$$P_{Zt} = [\nu \widetilde{P}_{Mt}{}^{1-\sigma} + (1-\nu) P_{Yt}{}^{1-\sigma}]^{1/(1-\sigma)}, \; P_{Qt} = [\nu \widetilde{P}_{Mt}{}^{1-\sigma} + (1-\nu) P_{Yt}{}^{1-\sigma}]^{1/(1-\sigma)}. \tag{18}$$

B. Firm Behavior

Each firm sets a price for its variety and meets the demand at that price. We assume staggered price setting based on a model suggested by Calvo (1983).[19] At each point in time, the probability that a firm will change its price is constant and equal to $1-\pi$. Thus, the average interval over which a price is fixed is $1/(1-\pi)$. We first discuss the behavior of firms producing the intermediate good. These firms are able to price discriminate across home and foreign markets and can choose different prices for domestic sales and exports. The export price, moreover, can be set in either home or foreign currency. Using (8), (14), and the foreign counterparts of (7), (15), and (16), we derive the (intermediate and final) demand for a variety in the home and foreign markets as

$$Y_{Ht}^{d}(y) = (Z_{Ht} + Q_{Ht})(P_{Yt}(y)/P_{Yt})^{-\varepsilon}, \; Y_{Mt}^{d*}(y) = (Z_{Mt}^{*} + Q_{Mt}^{*})[(P_{Mt}^{*}(y) + \delta W_t^{*})/P_{Mt}^{*}]^{-\varepsilon}, \tag{19}$$

where $P_{Mt}^{*}(y) = P_{Et}(y)/S_t$. The firm sets $P_{Et}(y)$ under PCP and $P_{Mt}^{*}(y)$ under LCP.

We use the letter X to distinguish prices of varieties set at different dates. For firms that set a new price at t, let X_{Yt} represent the home price and X_{Et} the export price in home currency. The export price in foreign currency is denoted by X_{Mt}^{*} $(= X_{Et}/S_t)$. We initially consider a hybrid case where some firms use PCP while others use LCP. Assume that the proportion of firms using PCP to set a new price at each point in time is constant and equal to ϕ.

Let superscripts P and L denote prices set under PCP and LCP. For firms using PCP, values of X_{Yt}^{P} and X_{Et}^{P} are chosen to maximize the present discounted value of profits:

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[19] The Calvo staggered pricing generates the same price dynamics as pricing based on quadratic adjustment costs. The choice of the Calvo formulation is convenient, however, since it can be readily modified to obtain staggered pricing based on Taylor (1980), which we also explore.

$$E_t \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \{ (X_{Yt}^P - MC_{Y\tau})[(Z_{H\tau} + Q_{H\tau}) P_{Y\tau}^{\varepsilon} (X_{Yt}^P)^{-\varepsilon}] \\ + (X_{Et}^P - MC_{Y\tau})[(Z_{M\tau}^* + Q_{M\tau}^*) P_{M\tau}^{*\varepsilon} (X_{Et}^P / S_\tau + \delta^* W_\tau^*)^{-\varepsilon}] \}, \tag{20}$$

where $DR_{t,\tau}$ is the stochastic discount rate based on household preferences (defined in (32) below), $\pi^{\tau-t}$ is the probability that a price set at t will be in force at τ, and the expressions in the square brackets represent the domestic and foreign demands for the home variety [based on (19)], conditional on the price set at t. The solution to this profit-maximization problem can be expressed as

$$X_{Yt}^P = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{Y\tau} MC_{Y\tau}}{(\varepsilon - 1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{Y\tau}}, \tag{21}$$

$$X_{Et}^P = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{E\tau} MC_{Y\tau} (1 + \chi_\tau^* / \varepsilon)}{(\varepsilon - 1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{E\tau}}, \tag{22}$$

where $\Omega_{Y\tau} \equiv (Z_{H\tau} + Q_{H\tau}) P_{Y\tau}^{\varepsilon}$, $\Omega_{E\tau} \equiv (Z_{M\tau}^* + Q_{M\tau}^*) S_\tau P_{M\tau}^{*\varepsilon} (X_{Et}^P / S_\tau + \delta^* W_\tau^*)^{1-\varepsilon}$, and $\chi_\tau^* \equiv \delta^* S_\tau W_\tau^* / MC_{Y\tau}$. Note that the effect of the distribution cost operates via the ratio, χ_τ^*, which increases in S_τ. Thus, in the presence of distribution costs ($\delta^* > 0$), there would be a positive exchange rate pass-through to export prices even under PCP.

For the LCP firms, it can be shown that the profit-maximizing export price (in foreign currency) set at t is

$$X_{Mt}^{*L} = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{M\tau}^* MC_{Y\tau} (1 + \chi_\tau^* / \varepsilon) / S_\tau}{(\varepsilon - 1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} \Omega_{M\tau}^*}, \tag{23}$$

where $\Omega_{Mt}^* \equiv (Z_{M\tau}^* + Q_{M\tau}^*) S_\tau P_{M\tau}^{*\varepsilon} (X_{Mt}^* + \delta^* W_\tau^*)^{1-\varepsilon}$. Note that the optimal home-market price is the same regardless of whether PCP or LCP is used, so that $X_{Yt} = X_{Yt}^P = X_{Yt}^L$.

For the consumer good, let X_{Ct} denote the price for firms that set a new price at t. The value of X_{Ct}, which would maximize the present discounted value of profits can be derived as

$$X_{Ct} = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} C_\tau P_{C\tau}^{\varepsilon} MC_{C\tau}}{(\varepsilon - 1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} C_\tau P_{C\tau}^{\varepsilon}}. \tag{24}$$

In the presence of staggered price setting, the price indexes for the final and intermediate goods in (13) and (14) can be restated as

$$P_{Ct} = [\sum_{\tau=t}^{-\infty} \pi^{t-\tau} X_{C\tau}^{1-\varepsilon}]^{1/(1-\varepsilon)}, \quad P_{Yt} = [\sum_{\tau=t}^{-\infty} \pi^{t-\tau} X_{Y\tau}^{1-\varepsilon}]^{1/(1-\varepsilon)}. \tag{25}$$

Similarly, the export and import price indexes in (14) and (16) can be expressed as

$$\begin{aligned} P_{Et} &= [\sum_{\tau=t}^{-\infty} \pi^{t-\tau} \{\phi (X_{E\tau}^{P})^{1-\varepsilon} + (1-\phi)(S_t X_{M\tau}^{*L})^{1-\varepsilon}\}]^{1/(1-\varepsilon)}, \\ P_{Mt} &= [\sum_{\tau=t}^{-\infty} \pi^{t-\tau} \{\phi^{*} (S_t X_{E\tau}^{*P})^{1-\varepsilon} + (1-\phi^{*})(X_{M\tau}^{L})^{1-\varepsilon}\}]^{1/(1-\varepsilon)}, \end{aligned} \tag{26}$$

where X_{Et}^{*} is given by the foreign counterparts of (20), (22) and (23).

C. Household Behavior, Asset Markets

Each household is a monopolistically competitive supplier of a labor service and a shareholder in profits of all home firms. The wage rate for a labor service is also set in a staggered fashion based on the Calvo model. There are two bonds: home bonds denominated in home currency and foreign bonds denominated in foreign currency. Only foreign bonds are used for international transactions. To allow a role for noise traders, we adopt the setup suggested by Devereux and Engel (2001) and assume that all international transactions by the home country are undertaken by foreign exchange dealers on behalf of households. Households cannot trade directly in foreign bonds and thus hold only domestic bonds. Profits or losses realized by the foreign exchange dealers are transferred to households.

The budget constraint of a household is

$$P_{Ct} C_t(l) + B_{H,t+1}(l) = W_t(l) L_t(l) + \Pi_t(l) + TR_t(l) + (1 + R_{t-1}) B_{Ht}(l), \tag{27}$$

where $B_{Ht}(l)$ is the household's holding of the home bond, R_{t-1} is the interest rate on a loan in period $t-1$ paid out at the beginning of period t, $TR_t(l)$ are transfers from the foreign exchange dealers and $\Pi_t(l)$ is the household's share of profits from monopolistically competitive firms producing the final and intermediate goods. The demand for a variety of labor service derived from the production and distribution activities is given by

$$L_t^d(l) = (N_{Ct} + N_{Yt} + N_{Mt})(W_t(l)/W_t)^{-\varepsilon}. \tag{28}$$

Households set the wage rate and meet the demand for their service at the predetermined wage rate. We assume that domestic markets are complete. In this case, the marginal utility of consumption is the same across households and we let $C_t^{-\rho}(l) = C_t^{-\rho}$.

Households choose the consumption path and the wage rate to maximize expected lifetime utility (1) subject to the budget constraint (27) and the demand constraint (28). The optimal consumption choice implies the Euler condition:

$$E_t \beta \frac{P_{Ct} C_t^{\rho}}{P_{C,t+1} C_{t+1}^{\rho}} = \frac{1}{1+R_t}, \tag{29}$$

Let X_{Wt} denote the wage rate for households who set a new wage rate at t. Assume that the probability that a household will change the wage rate at a point in time is also equal to $1-\pi$. We can then derive the optimal value of X_{Wt} as

$$X_{Wt} = E_t \frac{\varepsilon \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} (N_{C\tau} + N_{Y\tau} + N_{Mt}) W_\tau^{\varepsilon} L_\tau^{\mu}}{(\varepsilon-1) \sum_{\tau=t}^{\infty} DR_{t,\tau} \pi^{\tau-t} (N_{C\tau} + N_{Y\tau} + N_{Mt}) W_\tau^{\varepsilon} P_{C\tau}^{-1} C_\tau^{-\rho}}, \tag{30}$$

Given staggered wage setting, the wage index in (13) can be written as

$$W_t = [\sum_{\tau=t}^{-\infty} \pi^{t-\tau} X_{W\tau}^{1-\varepsilon}]^{1/(1-\varepsilon)}. \tag{31}$$

We can also derive the household stochastic discount rate as

$$DR_{t,\tau} = \beta^{\tau-t} \frac{P_{Ct} C_t^{\rho}}{P_{C\tau} C_\tau^{\rho}}, \tag{32}$$

We assume that this rate is used by firms and foreign exchange dealers to discount future payoffs. Foreign exchange dealers maximize the excess returns from purchasing a foreign bond. Free entry drives these returns to zero, so that

$$E_t^f [DR_{t,t+1}(1+R_t^*) S_{t+1} - S_t] = 0, \tag{33}$$

where E_t^f denotes the expectations of the foreign exchange dealers. As suggested by the noise-trader model, we assume that there is a stochastic bias in these expectations, which gives rise to shocks to the interest parity relation and can account for much of the short-term volatility of the exchange rate. The interest parity shock is referred to as the exchange rate shock. Assuming that the expected discount rate is the same for foreign exchange dealers and households (i.e., $E_t^f DR_{t,t-1} = E_t DR_{t,t+1}$), the exchange rate shock simply represents a stochastic bias in the expected value of the next period exchange rate. Since we use a log-linearized version of the interest parity relation in the quantitative application of the model, we define the shock as

$$u_t = \log(E_t^f S_{t+1} / E_t S_{t+1}), \tag{34}$$

Next, we can derive the national budget constraint by summing the household budget constraint over all households and noting that the net holding of domestic bonds is zero in equilibrium while aggregate transfers from foreign exchange dealers equal $S_t(B_{F,t+1} - (1+R^*_{t-1})B_{Ft})$, where B_{Ft} is the holding of foreign currency external bonds. The national budget constraint can be expressed as

$$P_{Ct}C_t + S_t B_{F,t+1} = W_t L_t + \Pi_t + (1+R^*_{t-1})S_t B_{Ft}. \tag{35}$$

The domestic interest rate is set by the home monetary authority according to an interest rate rule. We assume that the rule targets the inflation rate and possibly other variables such as the rate of change in the exchange rate and the level of economic activity.

D. Variations

To examine the role of the choice of the currency of denomination for international trade and other features in explaining the exchange rate pass-through, we now briefly consider a number of special versions of the general model. Models with only LCP or PCP are represented by the special cases, $\phi = 0$ and $\phi = 1$. If there are no trade costs based on local distribution, we can simply set $\delta = \delta^* = 0$ (which implies that χ and χ^* also equal zero). Either goods prices or wages can be flexible, in which case the staggered pricing model is replaced by straightforward conditions for determining prices in each period.[20]

We explore a number of variants, which are suggested by the literature or represent an interesting combination of features. Table 2 lists these variants and summarizes their features. Models 1-3 assume LCP. Model 1 follows Chari, Kehoe, and McGrattan (2000) and others in combining LCP with staggered goods prices and flexible wage rates. Distribution costs are absent in this model. Model 2 assumes that both goods prices and wages are determined in a staggered fashion as in Kollmann (2001). Although distribution costs have been incorporated only in the PCP models, Model 3 adds these costs to LCP (with sticky wages and prices) to facilitate comparison with the PCP based models. Models 4-6 are suggested by the literature assuming PCP. Model 4 represents the basic version similar to Obstfeld and Rogoff (2000a), which assumes sticky wages, flexible goods prices and no distribution costs. Model 5 follows Corsetti and Dedola (2002) in adding distribution costs to a flexible-price model. Model 6 also incorporates PCP based sticky goods prices. Note that although models 4 and 5 are associated with the PCP approach, the currency of price setting for these flexible-price models does not really matter under our informational assumption

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[20] In the case of flexible goods prices, $P_{Ct} = \frac{\varepsilon}{\varepsilon-1}MC_{Ct}$, $P_{Yt} = \frac{\varepsilon}{\varepsilon-1}MC_{Yt}$, and $P_{Et} = \frac{\varepsilon}{\varepsilon-1}MC_{Yt}(1+\chi^*_t/\varepsilon)$. Alternatively, $W_t = \frac{\varepsilon}{\varepsilon-1}P_{Ct}C_t^{\rho}L_t^{\mu}$ in the case of flexible wages.

that the exchange rate is known before the price is determined. Finally, Models 7 and 8 represent hybrid models that allow both LCP and PCP (i.e., $0 \leq \phi \leq 1$). Only goods prices are sticky in Model 7, while both wages and prices are sticky in Model 8. Distribution costs are included in both models.

IV. Performance of Different Models

In this section, we examine the relative performance of different models (listed in Table 2) in explaining the evidence on the pass-through of exchange rate shocks to different prices. For each model, we obtain an approximate solution based on relations linearized around a deterministic steady state with zero net foreign assets. Some parameters of the model can be readily estimated from the data, but there are a number of parameters for which no clear-cut empirical measures are available. For such parameters, we chose values similar to those used by other quantitative models if there is a not much disagreement in the literature. In cases where there is no consensus, we start with a reasonable common value for all models but later search for values that would provide the best fit for each model (according to a criterion discussed below). A number of stochastic shocks can be added to linearized relations in our model. However, since we are concerned mainly with the impulse response analysis for the exchange rate shock, we focus only on this shock.

A. Parameter Values

Parameters in the linearized versions of different models can be expressed as functions of a basic set of parameters. This set can be divided into three groups: (1) structural parameters appearing in the specification of preferences, technology and the wage-price adjustment mechanism, (2) policy-determined parameters in the interest rate rule, and (3) steady-state values of certain variables. Values chosen for parameters in each group are shown in Table 3. Only initial values are shown for parameters whose values were later varied across models. Values of foreign parameters (when needed) were set equal to the values of the corresponding home parameters.

The values for the structural parameters are chosen as follows. The discount rate (β) is set equal to its typically assumed quarterly value of 0.99 (which implies that the real rate of interest in the steady state equals 0.04 at an annualized rate). For the coefficient of relative risk aversion (ρ), we chose a value of 4.0, which is not too different from the values used in a number of recent quantitative models. There appears to be no consensus on the appropriate value for the elasticity of labor supply ($1/\mu$). We initially choose a value of 2.0 for this elasticity ($\mu = 0.5$) for all models, but later allow the elasticity to vary between zero and infinity. We set both the elasticity of substitution between varieties of different bundles (ε) and the elasticity of substitution between home and foreign bundles of goods (σ) equal to 5.0. This value is within the range of estimates suggested by recent studies (see Obstfeld and Rogoff (2000b) for a review). However, we later allow σ to differ from ε and consider a wide range from 1.5 to 12.5 for this parameter. Finally, we assume that the probability of changing prices in the Calvo model ($1-\pi$) equals 0.25, so that the average fixed-price interval is 4 quarters.

We estimated an interest rate rule for non-US G-7 countries. Our basic version of the rule ignores the possible influence of economic activity and assumes the following form:

$$R_t = \varphi_0 + \varphi_1 R_{t-1} + \varphi_2 E_t \Delta \log P_{Ct} + \varphi_3 \Delta \log S_t + v_t, \tag{36}$$

where v_t is a monetary policy shock. Policymakers target the expected inflation rate under our assumption that they do not observe current consumer prices. Instrumental variables were used to estimate the effect of the expected inflation rate in the policy rule.[21] We also used the SUR method to allow for the possibility of contemporaneous correlation between policy shocks across countries. Estimates of φ_1 and φ_2 were positive and significant for all non-U.S. G-7 countries. Estimates of φ_3, however were close to zero for all countries and insignificant in most cases. We set the value of this parameter equal to zero. The values of φ_1 and φ_2 were set equal to the simple averages of their estimates for the non-U.S. G-7 countries.

To solve different models, we also need steady state values of the following variables and their foreign counterparts: the shares of intermediate inputs in total revenue for the traded and non-traded goods sectors, θ_{ZY} and θ_{QC}, and the share of imports in total costs of intermediates, $\tilde{\theta}_M$. The available data report the share of imports valued at international rather than domestic (distribution-cost inclusive) prices. However, letting θ_M denote the import share at international prices, we can solve for $\tilde{\theta}_M$ as a function of θ_M and χ (the ratio of home distribution cost to foreign marginal cost). Also note that the technology parameters, α and γ, represent shares of intermediates in total costs, which can be calculated using estimates of the revenue shares (θ_{ZY} and θ_{QC}) and the markup implied by the elasticity, ε. We used the available input-output data for our non-U.S. G-7 sample to estimate steady state values of θ_{ZY}, θ_{QC} and θ_M.[22] We do not have a good estimate of χ. The evidence on distribution costs suggests an upper bound of about 1.0 for this parameter.[23]

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[21] After replacing $E_t \Delta \log P_{Ct}$ by $\Delta \log P_{Ct}$ in (36), this equation was estimated using 4 lagged values of $\Delta \log P_{Ct}$, $\Delta \log P_{Yt}$, $\Delta \log P_{Mt}$, $\Delta \log P_{Et}$, $\Delta \log W_t$ and $\Delta \log S_t$ as instruments for $\Delta \log P_{Ct}$.

[22] The data for each country were first averaged over the years for which they were available in the sample period to obtain country measures. Simple averages of these measures were then used to estimate the parameters.

[23] Burstein, Neves, and Rebelo (2001) suggest that distribution costs are large and account for roughly 40 percent of the consumer price in the United States. The ratio of distribution to marginal costs implied by this estimate would depend on the markup, and this ratio would be slightly above one under our assumed markup of 0.25 (implied by $\varepsilon = 5.0$). Their estimates

We initially assume that χ equals 0.5 in the steady state, but later allow it to vary between zero and one. Estimates of θ_{ZY}, θ_{QC}, θ_{MZ}, χ and ε were then used to derive the values of α, γ and $\widetilde{\theta}_{MZ}$.

Finally, we assume the following stochastic process for the exchange rate shock:

$$u_t = \psi u_{t-1} + \xi_t, \tag{37}$$

where ξ_t is white noise. We scale the shock ξ_t and choose the value of ψ to make the short-term and medium-term response of the exchange rate (expressed as log deviations from the steady-state value) predicted by each model close to the response generated by VAR analysis.[24] Note that the values of ξ and ψ chosen by this criterion differ across models.

B. Basic Results

We first examine the performance of each model for parameter values given in Table 3. We use a loss function to measure the overall fit of a model to the VAR data. The loss function sums the squared deviations of the model responses of the five variables over 10 quarters from the VAR responses. For models 1-8, Table 4 shows the total loss as well as components of the loss associated with each of the five variables. Figures 2 and 3 show how well different models track VAR responses of the five basic variables and the terms of trade. The relative performance of LCP based models is illustrated in Figure 2. The basic LCP versions assume no distribution costs and are represented by Models 1 and 2. Both models run into problems matching the VAR data. Predictions of Model 1 with flexible wages for consumer and producer prices deviate considerably from VAR estimates, especially after 5 quarters. The model fares even worse in predicting the responses of wages and international prices. Model 2 with sticky wages brings about only a marginal improvement, principally in predicting the behavior of the wage rate.

Distribution costs have not received much attention in the LCP models, but it is interesting to see how the introduction of such costs would affect their performance. Model 3 that incorporates distribution costs does, in fact, significantly improve the fit. The overall loss for Model 3 decreases by over 20 percent compared to Model 2. The improvement, however, results largely from better tracking of wages and domestic prices. Indeed, Model 3's

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include distribution costs for both domestic and imported goods and would represent an upper limit on distribution costs specific to imports.

[24] Specifically, the ξ shock is scaled to have the predicted effect on the exchange rate equal to 1.0 at quarter 1 (as in the impulse response analysis) and then the value of ψ is chosen to make the effect approximately equal to 0.63 at quarter 10 (which represents the average quarter 10 response for non-U.S. G-7 countries).

predictions for import and export prices (and the terms of trade), are not much different from those of Models 1 and 2. As this result illustrates, distribution costs have little influence on the exchange rate pass through to international prices.[25] Interestingly, these costs do exert a significant effect on wages and domestic prices. The essential reason for this effect is that imports and labor used in distribution are complements under the assumption of Leontief technology for distribution. The decrease in demand for imports induced by an increase in the exchange rate also decreases the demand for distribution labor and reduces the pressure on wage rates. The distribution cost thus lead to a lower exchange rate pass-through to wages as well as to producer and consumer prices.

Figure 3 illustrates the performance of Models 4-6, which are associated with the PCP approach. Model 4 represents the basic version with sticky wages, flexible prices, and no distribution costs. This model performs poorly in matching data on all prices. The addition of distribution costs in Model 5, however, brings about a considerable improvement in the fit. The loss for this model is, in fact, close to that of Model 2. The flexible-price model with distribution costs thus competes well with sticky-price LCP model. Model 6 adds sticky prices with PCP, but these features lead to only a small improvement. Comparison of Model 6 with Model 3 shows that in the presence of distribution costs and sticky prices, the LCP assumption provides a better overall fit than the PCP assumption.

We next examine the performance of sticky-price hybrid models that allow both LCP and PCP. For these models, ϕ can vary between zero (pure LCP) and one (pure PCP). We search over this range to choose the best-fitting (loss-minimizing) value. Figure 4 illustrates the performances of two hybrid models: Model 7 with flexible and Model 8 with sticky wages. Distribution costs are included in both models. These models provide a significantly better fit than the pure LCP and PCP cases. The combination of LCP and PCP is helpful in improving the tracking of international prices. Interestingly, the optimal value of ϕ is equal to 0.45 for Model 7 and 0.46 for Model 8. This result suggests an almost equal weight for LCP and PCP firms. Also, the sticky-wage version performs somewhat better than the flexible-wage version. Thus the basic analysis indicates that the best-fitting model includes all features highlighted by different approaches in the literature: sticky prices, sticky wages, distribution costs, and a combination of LCP and PCP.

C. Sensitivity Analysis

We next examine the sensitivity of our results to a number of variations. First, we explore whether changes in the procedure used to estimate the response functions would affect the relative performance of different models. We considered alternative recursive

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[25] This effect is especially weak under staggered prices because only a fraction of firms set a new price in each period, and the new price depends on expected future changes as well as current changes in the exchange rate.

procedures to identify the exchange rate shock.[26] We also used a larger VAR model that included domestic output as an additional variable. The use of response functions based on these variations, however, did not alter our key results. Model 3 continued to be the best performer among Models 1 through 6. However, hybrid Models 7 and 8 further improved the fit, as before.

As discussed above, there is considerable disagreement about the values of μ and σ. We also do not have a good estimate of χ. We thus also explore variations in the values of these parameters. We assume that $\mu \in [0, \infty]$, $\sigma \in [1.5, 12.5]$ and $\chi \in [0, 1.0]$. For each model, we search over these intervals to find values of μ, σ and χ, which minimize the loss. For the hybrid models, we also determine the optimal value of ϕ. Table 5 shows the losses for Models 1-8 for the case where values of μ, σ, and χ are chosen optimally. Comparison of Tables 4 and 5 shows that the overall fit improves considerably for all models except Model 6. One reason for the improvement is that the optimal value of μ is close to zero for these models. The low value dampens the response of wages (by making labor supply very elastic) and thus enables the models to match the low pass-through to wages and aggregate prices better. The models, however, are not as successful in improving the fit of the data for international prices. (See, for example Figure 5, which illustrates the performance of Models 7 and 8 with optimal values of the three parameters).

The distribution costs now do not make much difference to the LCP models. Models 1 and 2 without distribution costs perform as well as Model 3 with these costs. Model 5 with flexible prices and distribution costs now outperforms the LCP models. The hybrid Models 7 and 8 continue to dominate pure Models 1-6. Interestingly, the optimal value of ϕ remains close to one half, suggesting an equally important role for LCP and PCP. Also note that the losses for both hybrid models are the same. Thus, under the low value of μ, it does not matter whether wages are sticky or not.

V. Conclusions

New open economy macroeconomic models provide an appealing framework for examining the exchange rate pass-through to different prices. There has been little work, however, in assessing the ability of different models to explain the dynamic responses of key price indexes to an exchange rate shock. To explore this question, this paper considers a number of models that are suggested by different approaches or represent an interesting combination of features highlighted in the literature. The performance of each model is evaluated by comparing responses predicted by each model with the evidence for non-U.S. G-7 countries, based on impulse response analysis of a VAR model.

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[26] We estimated orthogonalized impulse response functions using alternative recursive ordering with the exchange rate as either the first or the fifth variable (after the interest rate, consumer prices, producer prices and the wage rate, but before import and export prices).

Models based on LCP are able to predict the responses of domestic (consumer and producer) prices and wages well provided that these models are extended to include distribution costs for imports. A LCP model with distribution costs, in fact, provides a better overall fit to the VAR data than a comparable PCP model. Both LCP and PCP models, however, have problems matching the responses of import and export prices. Interestingly, a hybrid model that gives roughly equal weights to LCP and PCP firms provides a significantly improved tracking of international price responses. Sticky-wage versions perform marginally better than flexible-wage versions. Thus the best-fitting model not only assumes sticky goods prices with a mixture of LCP and PCP, but also incorporates sticky wages and distribution costs for imports.

Table 1. The Response of Different Prices to an Exchange Rate Shock: Non-U.S. G-7 Countries

	Canada	France	Germany	Italy	Japan	U.K.	Average
Response at Quarter:							
Consumer Prices (CPI)							
1	-0.02	0.00	0.15	0.02	-0.01	0.02	0.02
4	0.08	0.10	0.20	0.14	0.04	0.10	0.11
10	0.20	0.09	0.36	0.26	0.09	0.11	0.19
Producer Prices (PPI)							
1	0.03	-0.09	0.02	0.10	0.02	0.01	0.01
4	0.22	-0.14	0.17	0.34	0.13	0.06	0.13
10	0.28	-0.07	0.16	0.33	0.12	0.05	0.15
Wage rate (W)							
1	0.00	0.14	0.12	-0.02	0.00	-0.03	0.04
4	0.01	0.10	-0.14	0.07	0.03	-0.01	0.01
10	0.08	0.19	-0.01	0.27	-0.02	-0.02	0.08
Import prices (PM)							
1	0.34	0.32	0.39	0.50	0.80	0.37	0.45
4	0.51	0.68	0.77	0.70	1.34	0.40	0.73
10	-0.18	0.18	0.27	0.13	0.79	0.16	0.22
Export prices (PX)							
1	0.23	0.30	0.03	0.29	0.50	0.17	0.25
4	0.30	0.39	0.16	0.59	0.50	0.23	0.36
10	0.19	0.24	0.06	0.25	0.44	0.07	0.21
Terms of trade (TOT)							
1	-0.11	-0.03	-0.36	-0.21	-0.30	-0.20	-0.20
4	-0.21	-0.28	-0.61	-0.11	-0.84	-0.17	-0.37
10	0.37	0.06	-0.21	0.12	-0.35	-0.09	-0.02

Table 2. Comparison of Different Models

Model	Pricing Practice	Goods Prices	Wage Rate	Distribution Costs?	Related Models
Model 1	LCP	Sticky	Flexible	No	Chari, Kehoe and McGrattan (2000)
Model 2	LCP	Sticky	Sticky	No	Kollmann (2001)
Model 3	LCP	Sticky	Sticky	Yes	
Model 4	n.a.	Flexible	Sticky	No	Obstfeld and Rogoff (2000a)
Model 5	n.a.	Flexible	Sticky	Yes	Corsetti and Dedola (2002)
Model 6	PCP	Sticky	Sticky	Yes	
Model 7	mixed	Sticky	Flexible	Yes	
Model 8	mixed	Sticky	Sticky	Yes	

Notes: Under flexible prices, the currency of price setting does not matter.

Table 3. Parameter Values

Parameter	
1. Structural Parameters	
Discount Rate (β)	0.99
Coefficient of Relative Risk Aversion (ρ)	4.00
Elasticity of Labor Supply ($1/\mu$)	2.00
Substitution Elasticity Between Varieties (ε)	5.00
Substitution Elasticity Between Home and Foreign Goods (σ)	5.00
Probability of Changing Prices ($1-\pi$)	0.25
2. Interest Rate Rule	
Coefficient of Lagged Interest Rate (φ_1)	0.85
Coefficient of the Expected Inflation Rate (φ_2)	0.17
Coefficient of the Exchange Rate Change (φ_3)	0.00
3. Steady State Values	
Revenue Share of Intermediates, Traded Goods (θ_{ZY})	0.64
Revenue Share of Intermediates, Non-Traded Goods (θ_{QC})	0.35
Import Share at International Prices (θ_M)	0.13
Distribution to Marginal Cost Ratio (χ)	0.50

Table 4. Relative Performance of Different Models: Fixed Parameter Values

	Components of the Loss Due to:					Total Loss
	CPI	PPI	W	PM	PX	
Model 1	0.04	0.08	0.25	0.59	0.48	1.43
Model 2	0.03	0.06	0.19	0.59	0.46	1.32
Model 3	0.00	0.01	0.03	0.55	0.44	1.03
Model 4	0.37	0.67	0.42	1.06	0.12	2.63
Model 5	0.09	0.26	0.11	0.88	0.04	1.37
Model 6	0.00	0.02	0.07	0.94	0.23	1.26
Model 7	0.01	0.03	0.11	0.42	0.07	0.64
Model 8	0.00	0.03	0.08	0.42	0.07	0.60

Notes: For definitions of the models see Table 2. Models 1 through 6 are based on values of μ, σ and χ as indicated in Table 3. In Models 7 and 8 the optimal values of ϕ are 0.45 and 0.46, respectively.

Table 5. Relative Performance of Different Models: Optimal Parameter Values

	Optimal			Components of Loss Due to:					Total Loss
	μ	σ	χ	CPI	PPI	W	PM	PX	
Model 1	0.3	1.5	0.0	0.007	0.009	0.010	0.578	0.403	1.007
Model 2	0.0	10.0	0.0	0.025	0.007	0.003	0.573	0.398	1.005
Model 3	0.0	1.5	0.5	0.014	0.007	0.006	0.542	0.426	0.995
Model 4	0.0	4.0	0.0	0.049	0.232	0.021	1.137	0.040	1.478
Model 5	0.0	1.5	1.0	0.016	0.086	0.017	0.691	0.034	0.845
Model 6	1.0	1.5	1.0	0.006	0.006	0.013	0.819	0.232	1.076
Model 7	0.5	3.0	1.0	0.013	0.005	0.006	0.355	0.057	0.436
Model 8	0.3	2.0	1.0	0.013	0.006	0.007	0.354	0.058	0.437

Notes: For definitions of the models see Table 2. Models 7 and 8 have optimal ϕ =0.49.

Figure 1. Response of Different Prices to an Exchange Rate Shock: Average Non-U.S. G-7 Countries

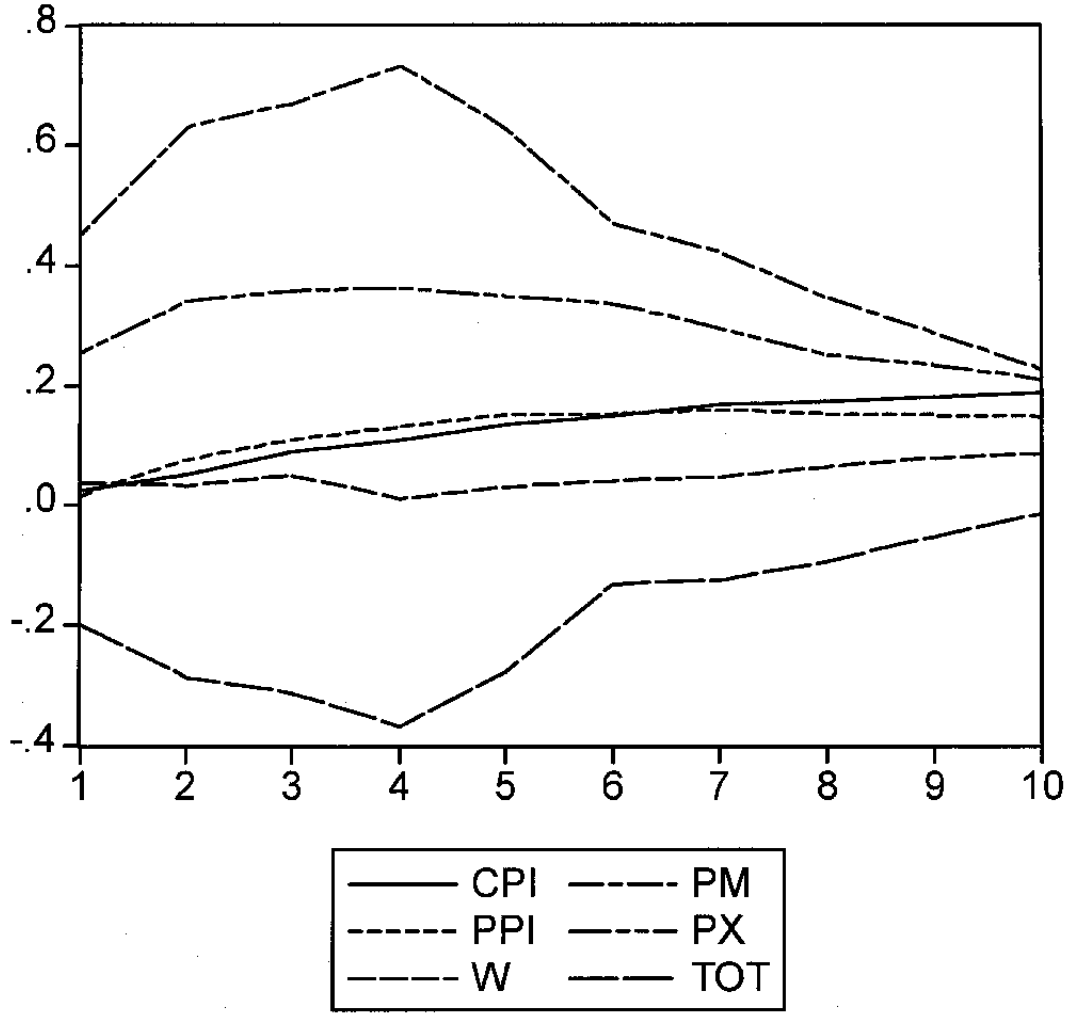


Figure 2. Performance of Models 1, 2, and 3: Fixed Parameter Values

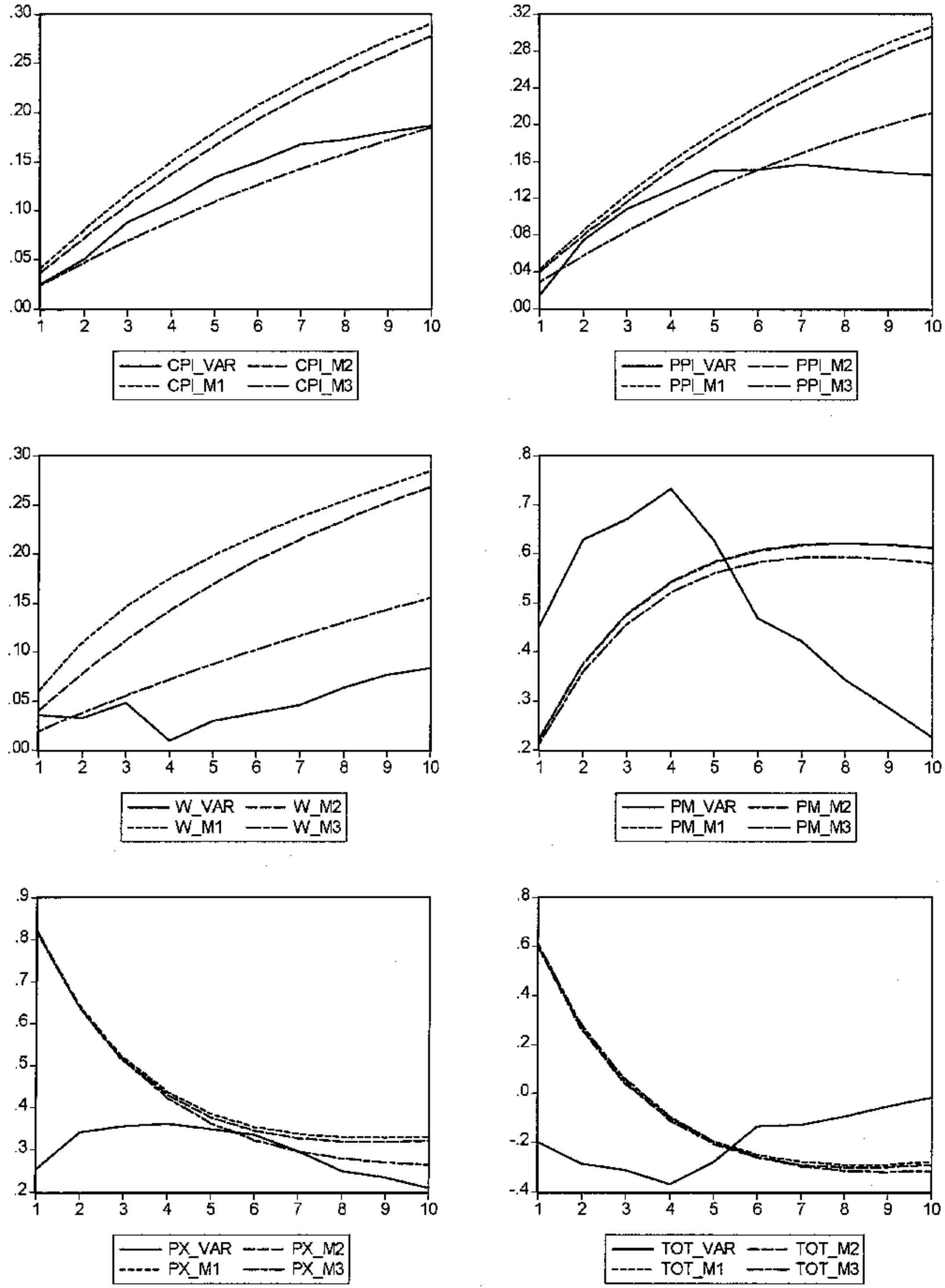


Figure 3. Performance of Models 4, 5, and 6: Fixed Parameter Values

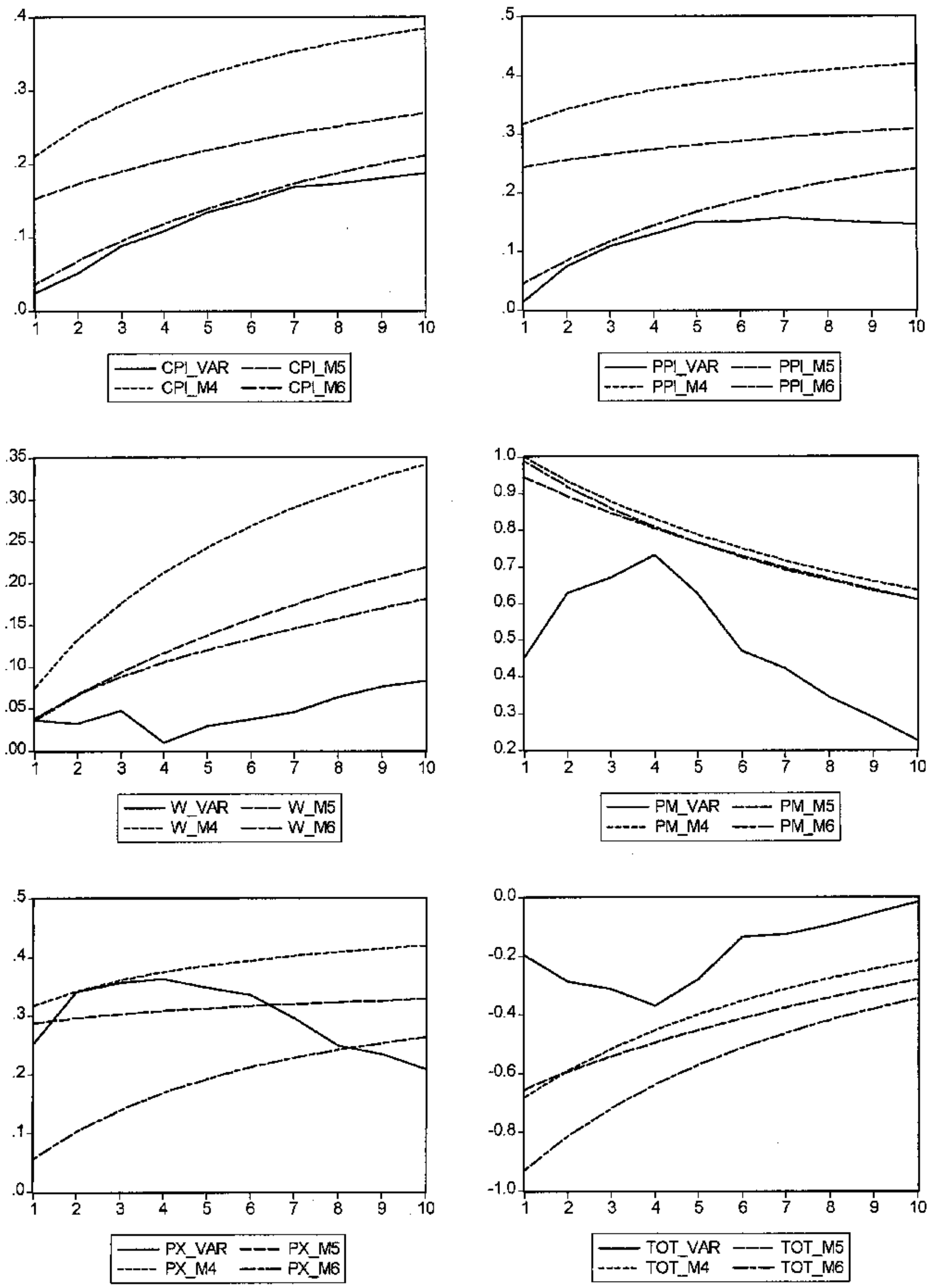


Figure 4. Performance of Models 7 and 8: Fixed Parameter Values

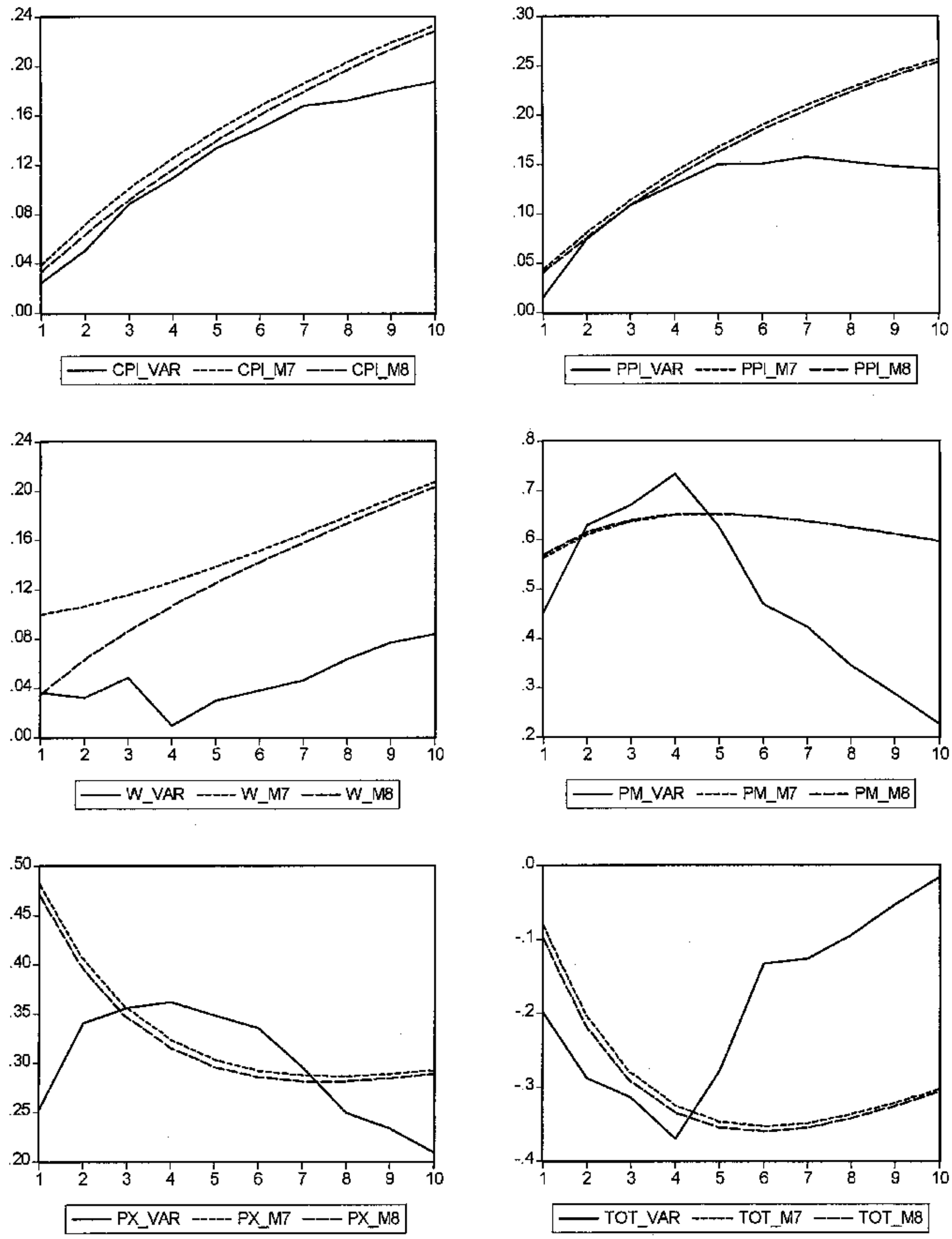
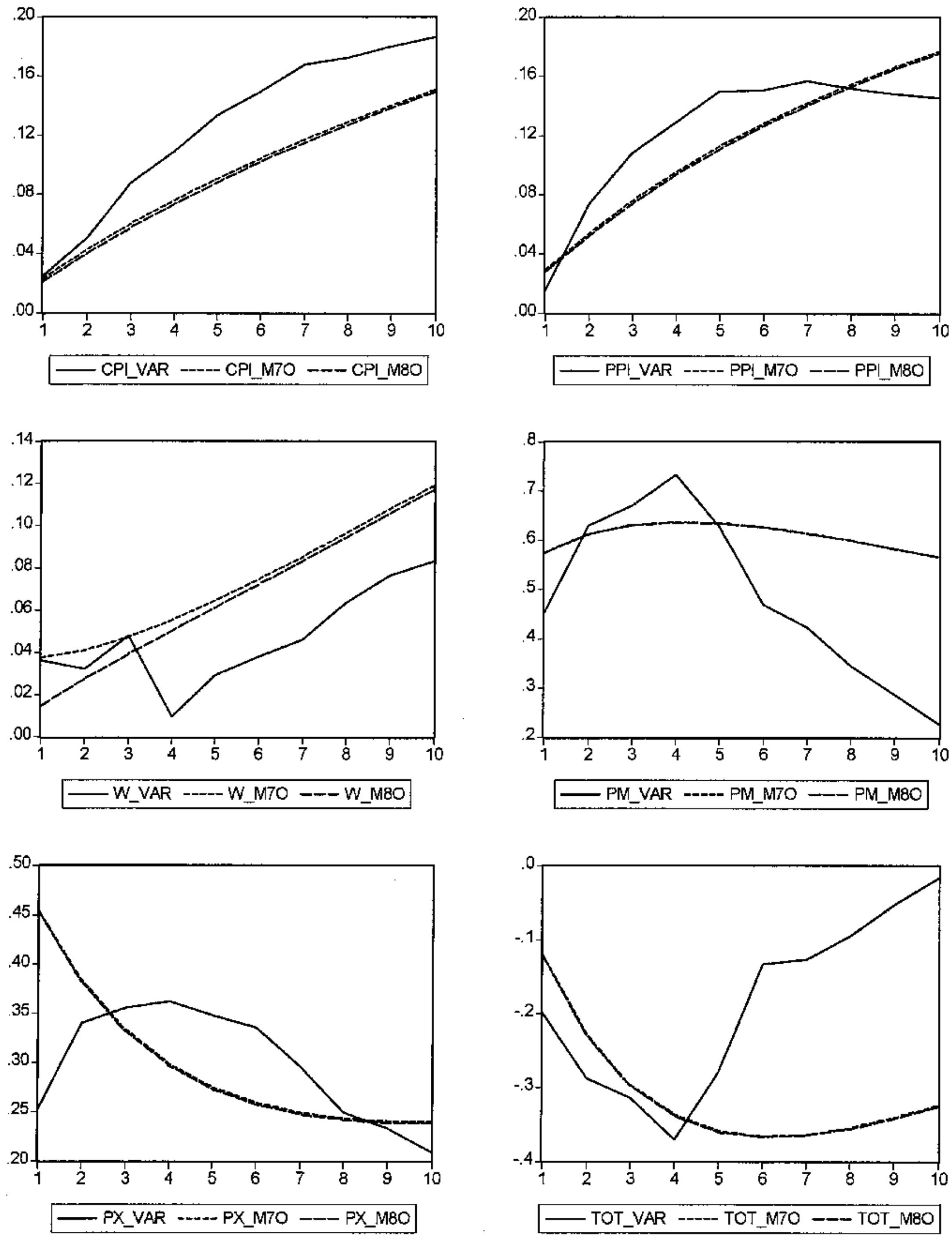


Figure 5. Performance of Models 7 and 8: Optimal Parameter Values



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