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Investment Frictions and the Relative Price of Investment Goods in an Open Economy Model[*]

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ABSTRACT

Is the relative price of investment goods a good proxy for investment frictions? We analyze investment frictions in an open economy, flexible price, two-country model and show that when the relative price of investment goods is endogenously determined in such a model, the relative price of investment can actually rise in response to a reduction in investment frictions. The data congruent negative correlation between investment and the relative price of investment goods is obtained in economies where TFP is the sole driver of technical change. In economies where IST is the principal technology driver, such a negative correlation holds if there is a moderate home bias in investment goods sector and this hime bias is less than the consumption goods home bias. The model predictions accord well with the US data although it raises news challenges in identifying TFP and IST shocks.

JEL Classification: E22; E32; F41.

Keywords: Investment frictions, investment specific technological progress, total factor productivity, relative price of investment goods terms of trade.

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1 Introduction

The relative price of investment goods with respect to consumption goods (the ratio of PPI to CPI) has shown a remarkable decline during the 80s in the United States. At the same time, there has been a pronounced increase in the investment rate since the early 1990s (see Figure 1).[1] A number of papers interpret this decline in the relative price of investment goods as evidence of a decline in capital market frictions. Greenwood *et al* (2000) use the relative price of equipment as a driver of investment specific technological (IST) change in their calibrated model. Chari, Kehoe and McGrattan (2007) similarly interpret investment friction as simply a tax on investment which raises its price relative to consumption. Fisher (2006) derives a long run identifying restriction that a positive IST shock means a concomitant negative shock to the real price of investment. The paper then highlights the importance of IST change as a key fundamental for the observed negative correlation between real investment activity and the real price of investment in the US economy.

In this paper, we argue that this price based approach to investment friction has its merits and demerits. It is a useful measure of IST change if the prototype real business cycle model is a one sector model. In a simple closed economy RBC model, a positive shock to the investment technology raises the marginal efficiency of investment which means a decrease in the relative price of investment with respect to consumption. Given this intuition, identifying the IST shock from the data is straightforward. One can construct a series for IST using the inverse of the relative price of investment goods. Alternatively, one can use the negative correlation between the investment rate and the relative price of investment goods as restriction in a structural VAR to identify the shock to IST.

As soon as one extends the model to an open economy, this relative price can become a misleading indicator of investment frictions. To demonstrate this point, we set up a formal two-country international real business cycle model such as Heathcote and Perri (2002). In our model, each country specializes in the production of traded intermediate goods. Final consumption and investment goods can be produced with a combination of foreign and home-produced intermediate goods. As in Fisher (2006) the investment friction is modelled as an IST shock which impacts the relative price of investment goods through its effects on (i) the composition of demand for consumption and investment goods, and (ii) the resulting effect on the terms of trade.

A positive IST shock at home is initially similar to a demand shock. It raises the demand for home-produced investment goods without any immediate change in capacity. This immediately raises the price of home-produced intermediate goods which can be used either for consumption or investment goods production. What happens to the relative price of investment goods with

[1] The relative price of investment is the ratio of the equipment price deflator to the CPI of nondurable and services obtained from Bureau of Economic Anlsysis.

respect to consumption depends on the relative home bias in consumption versus investment. If there is greater home bias in consumption than in investment expenditure, diverting resources from consumption to investment goods will raise the price of consumption goods more than that of investment thus contributing to a lower relative price of investment goods with respect to consumption; the effect will be opposite if the investment goods sector has a greater home bias. Thus, no straightforward relationship can be established between IST shocks and the relative price of investment in our open economy framework. It depends on the relative degree of home bias in consumption and investment goods sectors.

A positive total factor productivity (TFP) shock to the intermediate goods sector, on the other hand, has an immediate supply side effect on the production of intermediate goods. The response of the relative price of investment goods is linked to the terms of trade via the relative degree of home bias in consumption and investment. Following a TFP shock, the terms of trade depreciate (rise). If relative home bias is such that the relative price of investment goods declines, we observe a negative correlation between the investment rate and the relative price of investment goods. If relative home bias is such that a terms of trade depreciation is associated with a rise in the relative price of investment goods, we find that the increase in the price of investment goods is sufficient to actually cause the investment rate to decline. Consequently, we also find a negative correlation between the relative price of investment goods and the investment rate.

Since the relative price of investment goods is thus endogenous in an open economy model, the observed negative relationship between the relative price of investment with respect to consumption and the level of investment can be attributed to a combination of IST and TFP shocks. Our calibrated model of the US economy where there is greater home bias in consumption than investment suggests that the IST shock cannot be disentangled from TFP. In order to get further insights about the determinants of the relative price of investment goods for the US economy, we proceed to examine the behaviour of the relative price of equipment with respect to final consumption goods in the US economy during the postwar period. The variance decompositions and impulse response of this relative price with respect to TFP and IST shocks suggests that the IST is the principal driver of the fluctuation of this relative price of investment goods.

Our paper thus makes two important contributions. First, it provides new insights about the determinants of the correlation between relative price of investment and the rate of investment in an open economy setting. Second, at a methodological level, to our best knowledge this is one of the first international real business cycle models which explicitly addresses the relationship between investment friction and the relative price of investment goods.

The remainder of this paper is organized as follows. In the following section, we describe the basic intuition behind our results. Section 3 lays out the formal model. Sections 4 and 5 report the calibration results and the impulse response analysis of the relative price of investment goods with respect to TFP and investment specific technology shocks. In section 6, analyse the second moments of our calibrated model. In section 7, we check the robustness of our findings by examining a number of alternative calibrations. Finally, section 8 puts forward some empirical support for our claims, before Section 9 concludes by summarizing our main findings.

2 Some Intuition

In this section, we outline the simple intuition behind the mechanism generating the results of our paper. We model the relationship between investment specific technological progress and the relative price of investment goods in an open economy setting. This modelling choice has important implications for the determinants of the relative price of investment goods. Cummins and Violante (2002) argue that a comparison of constant-quality investment prices with a constant-quality consumption price is an informative measure of technological change in the investment goods sector. The intuition for this inverse relationship between the relative price of investment goods and changes in IST is straight forward: An IST shock, defined as ε_t^x, which enters a dynamics stochastic general equilibrium (DSGE) model in the following way:

$$k_t = (1-\delta)k_{t-1} + \varepsilon_t^x F(x_t, x_{t-1}) \tag{1}$$

raises the amount of net capital accumulation for a given level of past and current investment. In effect the marginal efficiency of investment rises and its relative price declines to clear the investment goods market.

Different from the closed economy framework, we model the relative price of investment to consumption goods as endogenous to the model, and not necessarily linked to the investment specific technology shock in the above manner.

In terms of modelling strategy, our treatment of investment goods is similar to that of consumption goods in the sense that both are assumed to be composite goods made up of home and foreign-produced intermediate goods:

$$C = \left[v^{\frac{1}{\theta}} c_H^{\frac{\theta-1}{\theta}} + (1-v)^{\frac{1}{\theta}} c_F^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}, \tag{2}$$

$$x = \left[\varphi^{\frac{1}{\tau}} x_H^{\frac{\tau-1}{\tau}} + (1-\varphi)^{\frac{1}{\tau}} x_F^{\frac{\tau-1}{\tau}} \right]^{\frac{\tau}{\tau-1}}, \tag{3}$$

where C is the final consumption and x the final investment good. In a two-country open economy setting familiar from among many others Backus *et al* (1994), Heathcote and Perri (2002), Corsetti *et al* (2008), and Benigno and Thoenissen (2008) agents are assumed to consume a composite consumption good made up of domestically produced and imported intermediate goods. Likewise, we assume that investment goods used to augment the capital stock, x_t, are a composite good made up of home and foreign-produced intermediate goods.

The relative price of foreign to home consumption baskets, i.e. the real exchange rate, in these models fluctuates or departs from purchasing power parity due to consumption home-bias (defined as cross-country differences in the composition of home and foreign-produced intermediate goods in the home and foreign final consumption goods baskets, domestic $v >$ foreign v^*). The relative price of final investment to final consumption goods, an internal relative price, fluctuates due to differences in the share of home-produced intermediate goods in the final home consumption and final home investment goods baskets. In other words, the relative price differs from unity because of different degrees of home bias in consumption than investment ($v \neq \varphi$). If the composition of the final investment good is the same as that of the final consumption good, $v = \varphi$, then the two goods baskets are identical and their relative price is unity. However, as investment and consumption are two distinct activities, often undertaken by different agents, it is not unreasonable to assume that the relative preference for home-produced goods can differ across investment and consumption decisions, thus we get an endogenous relative price of investment goods.

The real exchange rate and the relative price of investment goods are thus linked conceptually as well as through their main determining factor: the terms of trade. The terms of trade are defined as the relative price of the foreign to the home-produced intermediate good. As we show below, the link between the relative price of investment goods and the terms of trade depends on the relative degree of home bias in consumption and investment. If home bias is greater in investment than in consumption, i.e. if $\varphi > v$, then a depreciation or rise of the terms of trade results in a decline in the relative price of investment goods. Conversely, if consumption home bias exceeds investment home bias, $v > \varphi$, a depreciation of the terms of trade will be associated with an increase in the relative price of investment goods.

In our model, the response of the relative price of investment goods to IST shocks depends on the response of the terms of trade as well on the relative degrees of home bias in consumption and investment. Furthermore, we show that depending on the underlying parameters of the model, a total factor productivity shock can have the same effect on the terms of trade and thus the relative price of investment goods as an IST shock. Therefore, an IST shocks can no longer be identified as the inverse of the relative price of investment goods, as this price can be driven by both IST and TFP shocks. Having outlined the intuition behind our result, the next section proceeds to set up our formal model.

3 The model

We propose, what is essentially an international real business cycle model with incomplete financial markets where each country produces one tradable intermediate good that forms part of the home as well as the foreign consumption and investment goods basket. Examples of this model are Heathcote and Perri (2002), Corsetti *et al* (2008), Backus *et al* (1994) and Benigno and Thoenissen (2008). We modify this simple model to incorporate some of recent modelling features put forward by Smets and Wouters (2003) and Christiano, Eichenbaum and Evans (2005), specifically, we include investment adjustment costs and external habit formation in consumption. The basic structure of our model is also similar to related work by Boileau (2002).

3.1 Consumer behavior

The world economy is populated by a continuum of agents on the interval $[0, 1]$. The population on the segment $[0, n)$ belongs to the country H (Home), while the segment $[n, 1]$ belongs to F (Foreign). Preferences for a generic Home-consumer are described by the following utility function:

$$U_t^j = \mathrm{E}_t \sum_{s=t}^{\infty} \beta^{s-t} (u(C_s^j - \gamma C_{s-1}), z(1 - h_s^j)) \tag{4}$$

where E_t denotes the expectation conditional on the information set at date t, while β is the intertemporal discount factor, with $0 < \beta < 1$. The Home consumer obtains utility from current consumption, C_s^j adjusted by the previous period's aggregate level of consumption and receives dis-utility from supplying labour, h^j.

In our model, we assume that international asset markets are incomplete.[2] The asset market structure in the model is relatively standard in the literature. We assume that home residents are able to trade two nominal risk-less bonds denominated in the domestic and foreign currency. These bonds are issued by residents in both countries in order to finance their consumption expenditure. Among these two nominal bonds, we assume that home bonds are only traded nationally. On the other hand, foreign residents can allocate their wealth only in bonds denominated in the foreign currency. This asymmetry in the financial market structure is made for simplicity. The results would not change if we allow home bonds to be traded internationally. We would, however, need to consider a further arbitrage condition. Home households face a cost (i.e. transaction cost) when they take a position in the foreign bond market. This cost depends on the net foreign asset position of the home economy as in Benigno (2001). Domestic firms are assumed to be wholly owned by

[2] We have also analysed a complete markets version, and have found that our results are not affected by the asset market structure. Smidt-Grohe and Uribe (2003) describe other ways of eliminating the unit root in bond holding problem.

domestic residents, and profits are distributed equally across households. Consumer j faces the following budget constraint in each period t:

$$P_t C_t^j + \frac{B_{H,t}^j}{(1+i_t)} + \frac{S_t B_{F,t}^j}{(1+i_t^*)\Theta\left(\frac{S_t B_{F,t}}{P_t}\right)} = B_{H,t-1}^j + S_t B_{F,t-1}^j + P_t w_t h_t^j + \Pi_t^j \tag{5}$$

where $B_{H,t}^j$ and $B_{F,t}^j$ are the individual's holdings of domestic and foreign nominal risk-less bonds denominated in the local currency. i_t is the Home country nominal interest rate and i_t^* is the Foreign country nominal interest rate. S_t is the nominal exchange rate expressed as units of domestic currency needed to buy one unit of foreign currency, P_t is the consumer price level and w_t is the real wage. Π_t^j are dividends from holding a share in the equity of domestic firms obtained by agent j. All domestic firms are wholly owned by domestic agents and equity holding within these firms is evenly divided between domestic agents.

The cost function $\Theta(.)$ drives a wedge between the return on foreign-currency denominated bonds received by domestic and by foreign residents. We follow Benigno, P. (2001) in rationalizing this cost by assuming the existence of foreign-owned intermediaries in the foreign asset market who apply a spread over the risk-free rate of interest when borrowing or lending to home agents in foreign currency. This spread depends on the net foreign asset position of the home economy. We assume that profits from this activity in the foreign asset market are distributed equally among foreign residents (see Benigno (2001)).[3]

As in Benigno (2001), we assume that all individuals belonging to the same country have the same level of initial wealth. This assumption, along with the fact that all individuals face the same labour demand and own an equal share of all firms, implies that within the same country all individuals face the same budget constraint. Thus they will choose identical paths for consumption. As a result, we can drop the j superscript and focus on a representative individual for each country.

The maximization problem of the Home individual consists of maximizing (4) subject to (5) in determining the optimal profile of consumption and bond holdings and the labour supply schedule.

The Lagrange multiplier corresponding to agent j's maximisation problem is:

$$L = \mathrm{E}_t \sum_{s=t}^{\infty} \beta^{s-t} \left\{ \begin{array}{c} (u(C_s^j - \gamma C_{s-1}) + z(1-h_s^j)) + \\ \mu_s \left[\frac{B_{H,s-1}^j}{P_s} + \frac{S_s B_{F,s-1}^j}{P_s} + w_s h_s^j + \frac{\Pi_s^j}{P_s} - C_s^j - \frac{B_{H,s}^j}{P_s(1+i_s)} - \frac{S_s B_{F,s}^j}{P_s(1+i_s^*)\Theta\left(\frac{S_s B_{F,s}}{P_s}\right)} \right] \end{array} \right\}$$

[3]Here we follow Benigno (2001) in assuming that the cost function $\Theta(.)$ assumes the value of 1 only when the net foreign asset position is at its steady state level, ie $B_{F,t} = \overline{B}$, and is a differentiable decreasing function in the neighbourhood of $\overline{B}$. This cost function is convenient because it allows us to log-linearise our economy properly since in steady state the desired amount of net foreign assets is always a constant $\overline{B}$. The expression for profits from financial intermediation is given by $K = \frac{B_{F,t}}{P_t^*(1+i_t^*)}\left[\frac{RS_t}{\Theta\left(\frac{S_t B_{F,t}}{P_t}\right)} - 1\right]$.

The domestic households' first order conditions are described by the following equations:

$$\frac{\partial L_t}{\partial C_t^j} : u_{C_s^j}(C_s^j - \gamma C_{s-1}) - \mu_t = 0 \tag{6}$$

$$\frac{\partial L}{\partial h_t^j} : \frac{z_{h_s^j}(1 - h_s^j))}{u_{C_s^j}(C_s^j - \gamma C_{s-1})} = w_t \tag{7}$$

$$\frac{\partial L_t}{\partial B_{H,t}^j} : -\mu_t \frac{1}{P_t(1+i_t)} + \beta \mathrm{E}_t \mu_{t+1} \frac{1}{P_{t+1}} = 0 \tag{8}$$

$$\frac{\partial L_t}{\partial B_{F,t}^j} : -\mu_t \frac{S_t}{P_t(1+i_t^*)\Theta\left(\frac{S_t B_{F,t}}{P_t}\right)} + \beta \mathrm{E}_t \mu_{t+1} S_{t+1} \frac{1}{P_{t+1}} = 0 \tag{9}$$

where (8) is the optimality condition for the Home country's holding of home-currency denominated bonds. (9) is the optimality condition for the Home country's holdings of foreign-currency denominated bonds.

3.2 Final consumption goods sector

Home and foreign agents consume a final consumption good. Here we describe the home final goods producing sector. Home final consumption goods (C) are produced with the aid of home and foreign-produced intermediate goods (c_H and c_F) in the following manner:

$$C = \left[v^{\frac{1}{\theta}} c_H^{\frac{\theta-1}{\theta}} + (1-v)^{\frac{1}{\theta}} c_F^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \tag{10}$$

where θ is the elasticity of intratemporal substitution between home and foreign-produced intermediate goods. Final goods producers maximize (11) subject to (10).

$$\max_{c_H, c_F} PC - P_H c_H - P_F c_F \tag{11}$$

This maximization yields the following input demand functions for the home economy (similar conditions hold for Foreign producers)

$$c_H = v \left(\frac{P_H}{P} \right)^{-\theta} C \ , \quad c_F = (1-v) \left(\frac{P_F}{P} \right)^{-\theta} C \tag{12}$$

The price index that corresponds to the previous demand function is defined as:

$$P^{1-\theta} = [v P_H^{1-\theta} + (1-v) P_F^{1-\theta}] \tag{13}$$

The foreign final goods producing sector is symmetric, with the exception that v^* the share of home-produced intermediate goods in the foreign final consumption good is less than v. This assumption captures consumption home bias.

3.3 Investment goods sector

Similar to final consumption goods, investment goods (x) are produced with the aid of home and foreign-produced intermediate goods (x_H and x_F) in the following manner:

$$x = \left[\varphi^{\frac{1}{\tau}} x_H^{\frac{\tau-1}{\tau}} + (1-\varphi)^{\frac{1}{\tau}} x_F^{\frac{\tau-1}{\tau}} \right]^{\frac{\tau}{\tau-1}} \tag{14}$$

Investment goods producers maximize (15) subject to (14).

$$\max_{x_H, x_F} P_x x - P_H x_H - P_F x_F \tag{15}$$

The investment goods producer's maximization yields the following investment demand functions and price index:

$$x_H = \varphi \left(\frac{P_H}{P_x} \right)^{-\tau} x \ , \quad x_F = (1-\varphi) \left(\frac{P_F}{P_x} \right)^{-\tau} x \tag{16}$$

$$P_{x,t}^{1-\tau} = \left[\varphi P_{H,t}^{1-\tau} + (1-\varphi) P_{F,t}^{1-\tau} \right] \tag{17}$$

The investment goods price index is a function of the price of home and foreign-produced intermediate goods prices. It differs from the consumption goods price index due to different substitution elasticities and different degrees of consumption and investment home biases. Specifically, φ, the share of home-produced intermediate goods in the home final investment good can differ from v, the share of home-produced intermediate goods in the final consumption good. Unlike in Greenwood, *et al* (2000), $\frac{P_{x,t}}{P_t}$, the relative price of investment goods in terms of the consumption goods basket is an endogenous relative price, that responds to exogenous shocks such as changes in total factor productivity (TFP) or investment specific technology shocks, ε_t^x.

3.4 Intermediate goods sectors

Firms in the intermediate goods sector produce output, y_t, that is used in the production of the final consumption and investment goods at home and abroad using capital and labour services employing the following constant returns to scale production function:

$$y_t = A_t f(k_{t-1}, h_t) \tag{18}$$

where A_t is total factor productivity. The cash flow of this typical firm in the intermediate goods producing sector is:

$$\Pi_t = P_{H_t} A_t f(k_{t-1}, h_t) - P_t w_t h_t - P_{x,t} x_t \tag{19}$$

where w is the real wage, P_{H_t} is the price of home-produced intermediate goods and P_t and $P_{x,t}$ are the consumption and investment goods deflators, respectively. The firm faces the following capital accumulation constraint:

$$k_t = (1-\delta)k_{t-1} + \varepsilon_t^x F(x_t, x_{t-1}) \tag{20}$$

where δ is the rate of depreciation of the capital stock and $F(x_t, x_{t-1})$ captures investment adjustment costs as proposed by Christiano *et al* (2005), i.e. it summarizes the technology which transforms current and past investment into installed capital for use in the following period. Specifically, we assume that $F(x_t, x_{t-1}) = (1 - s(\frac{x_t}{x_{t-1}}))x_t$ and that the function s has the following properties: $s(1) = s'(1) = 0$ and $s''(1) > 0$. Finally, ε_t^x is a multiplicative shock to $F(x_t, x_{t-1})$ that increases (or decreases) the amount of installed capital available next period for any given value of current or past investment.

The firm maximizes shareholder's value using the household's intertemporal marginal rate of substitution as the stochastic discount factor. The Lagrangian corresponding to the maximization problem of the representative domestic intermediate goods firm is thus:

$$J = E_t \sum_{s=t}^{\infty} \beta^{s-t} \mu_s \left\{ \frac{\Pi_s}{P_s} \right\} + E_t \sum_{s=t}^{\infty} \beta^{s-t} \lambda_s \left[(1-\delta)k_{s-1} + \varepsilon_s^x (1 - s(\frac{x_s}{x_{s-1}}))x_s - k_s \right] \tag{21}$$

The first-order conditions for the choice of labour input, investment and capital stock in period t are:

$$\frac{\partial J_t}{\partial h_t} : \frac{P_{H,t}}{P_t} A_t F_h(k_{t-1}, h_t) - w = 0 \tag{22}$$

$$\frac{\partial J_t}{\partial x_t} : q_t(1 - s(\frac{x_t}{x_{t-1}}))\varepsilon_t^x = q_t s'(\frac{x_t}{x_{t-1}})\frac{x_t}{x_{t-1}} - \beta \mathrm{E}_t q_{t+1} \frac{\mu_{t+1}}{\mu_t} s'(\frac{x_{t+1}}{x_t}) \frac{x_{t+1}}{x_t} \frac{x_{t+1}}{x_t} + \frac{P_{x,t}}{P_t} \tag{23}$$

$$\frac{\partial J_t}{\partial k_t} : \beta \mathrm{E}_t \frac{\mu_{t+1}}{\mu_t} \left(\frac{P_{H,t+1}}{P_{t+1}} A_t F_{k_t}(k_t, h_{t+1}) + q_{t+1}(1-\delta) \right) = q_t \tag{24}$$

where we define Tobin's q as: $q_t \equiv \frac{\lambda_t}{\mu_t}$.

3.5 The relative price of investment goods

In this two-country model, the price of investment goods, relative to the price of consumption goods, $\frac{P_{x,t}}{P_t}$, is a function of the terms of trade. We can illustrate this by taking a log-linear approximation of the price index

$$\frac{P_{x,t}}{P_t} = \frac{P_{x,t}}{P_{H,t}} \frac{P_{H,t}}{P_t} \tag{25}$$

around its steady state value making use of the investment and consumption goods price indices.[4]

$$\begin{aligned}
\widehat{\frac{P_{x,t}}{P_t}} &= \widehat{\frac{P_{x,t}}{P_{H,t}}} + \widehat{\frac{P_{H,t}}{P_t}} \\
&= (1-\varphi)\widehat{\frac{P_{F,t}}{P_{H,t}}} + (v-1)\widehat{\frac{P_{F,t}}{P_{H,t}}} \\
&= (1-\varphi)\hat{T}_t + (v-1)\hat{T}_t \\
&= (v-\varphi)\hat{T}_t
\end{aligned} \tag{26}$$

This shows that the log-deviation, denoted by a "^", of the price of investment goods from its steady state value is a linear function of the log-deviation of the terms of trade from its steady state value. If home-bias for investment goods is stronger (weaker) than for consumption goods $v < \varphi$ $(v > \varphi)$ then the price of investment goods is negatively (positively) related to the terms of trade. Assume the terms of trade depreciate (rise), say due to a fall in the price of home-produced intermediate goods. If $v < \varphi$, if there is more home bias in consumption than investment, then the consumption goods basket will fall by more than the investment goods basket, such that the relative price investment to consumption goods increases. If, on the other hand, the share of home-produced intermediate goods is smaller in the final investment good than in the final consumption good, $v > \varphi$, then the price index of final investment goods will fall by more than the price index of final consumption goods. In other words, the relative price of final investment goods will decline as the terms of trade increase.

This clearly shows that the value of $(v - \varphi)$ is crucial for our results. However, the value of $(v-\varphi)$ does not just determine the correlation between $\frac{P_{x,t}}{P_t}$ and T in the way suggested by equation (26), it also determines the response of the terms of trade to productivity and IST shocks. We explore the implications of various parameter combinations in some detail in our sensitivity analysis below.

3.6 Tobin's q and the Relative Price of Capital

In this section, we analyze the link between Tobin's q and the relative price of investment goods. Taking a log-linear approximation of the first-order condition of the intermediate goods firm (23) yields the following relationship between deviations in Tobin's q and the relative price of investment

[4] We make use of the consumption and investment goods price indices and normalise the price of home-produced traded goods such that in the steady state $P_H = P_F$. Because the law of one price holds, we can define the terms of trade as $T = P_F/P_H$

goods:

$$\hat{q}_t = \left[(1+\beta)s''()\hat{x}_t - s''()\hat{x}_{t-1} - s''()\beta\hat{x}_{t+1} - \hat{\varepsilon}_t^x + \widehat{\frac{P_{x,t}}{P_t}}\right] \tag{27}$$

alternatively, if we abstract from adjustment costs, i.e. if $s''() = 0$

$$\hat{q}_t = -\hat{\varepsilon}_t^x + \widehat{\frac{P_{x,t}}{P_t}} = -\hat{\varepsilon}_t^x + (v-\varphi)\hat{T}_t. \tag{28}$$

From equation (28), it is easy to see that if we do not allow for a separate investment goods sector, or if the share of home produced intermediate goods is the same in investment than in consumption then the relative price of capital is unity and therefore, the Tobin's q is just the reciprocal of the investment shock $\hat{\varepsilon}_t^x$. In the present context, the investment shock $\hat{\varepsilon}_t^x$ drives a wedge between Tobin's q and the relative price of capital. Therefore we can refer to our investment shock as an investment friction. Even in the absence of any adjustment cost, Tobin's q may not necessarily be the inverse of the investment shock $\hat{\varepsilon}_t^x$, depending on the covariance between $\hat{\varepsilon}_t^x$ and $(v-\varphi)\hat{T}_t$

Two special cases deserve attention: (i) One sector closed economy case**:** Here $v = \varphi = 1$. In this case using (13) and (17) one can immediately verify that $P = P_x$. In other words, the relative price of investment goods is unity. In this case, Tobin's q varies inversely with the investment friction shock $\hat{\varepsilon}_t^x$.(ii) Same home-bias in consumption as in investment case**.** This case is very common in the literature, see for instance Heathcote and Perri (2002), Backus *et al* (1994), or Corsetti *et al's* alternative calibration. When $v = \varphi$ the relative price of investment goods, as defined in our model is constant. In this case, Tobin's q varies inversely with the investment friction shock. Chari *et al.* (2005), Greenwood *et al.* (2000) and Fisher (2006) basically refer to the first special case of our model. In an open economy context, the Tobin's q is not just the reciprocal of the investment friction shock. It is a function of the terms of trade which depend not only on the investment shock ε_t^x but also on the TFP shock A_t.

3.7 Monetary policy

Since we are characterizing a nominal model we need to specify a monetary policy rule. In what follows we simply assume that the monetary authorities in both countries follow a strategy of setting producer price inflation equal to zero.

3.8 Market Equilibrium

The solution to our model satisfies the following market equilibrium conditions must hold for the home and foreign country:

1. Home-produced intermediate goods market clears:

$$y_t = c_{H_t} + c^*_{H_t} + x_{H_t} + x^*_{H_t}$$

2. Foreign-produced intermediate goods market clears:

$$y^*_t = c_{F_t} + c^*_{F_t} + x_{F_t} + x^*_{F_t}$$

3. Bond Market clears:

$$\frac{S_t B_{F,t}}{P_t(1+i^*_t)\Theta\left(\frac{S_t B_{F,t}}{P_t}\right)} - \frac{S_t B_{F,t-1}}{P_t} = \frac{P_{H_t}}{P_t}\left(c^*_{H,t} + x^*_{H,t}\right) - \frac{P_{F,t}}{P_t}\left(c_{F,t} + x_{F,t}\right)$$

3.9 Solution technique

Before solving our model, we log-linearize around the steady state to obtain a set of equations describing the equilibrium fluctuations of the model. The log-linearization yields a system of linear difference equations which can be expressed as a singular dynamic system of the following form:

$$\mathbf{A}\mathrm{E}_t\mathbf{y}(t+1 \mid t) = \mathbf{B}\mathbf{y}(t) + \mathbf{C}\mathbf{x}(t)$$

where $\mathbf{y}(t)$ is ordered so that the non-predetermined variables appear first and the predetermined variables appear last, and $\mathbf{x}(t)$ is a martingale difference sequence. There are four shocks in $\mathbf{C}$: shocks to the home intermediate goods sectors' productivity, shocks to the foreign intermediate goods sectors' productivity, and shocks to home and foreign investment frictions. The variance-covariance as well as the autocorrelation matrices associated with these shocks are described in table 1. Given the parameters of the model, which we describe in the next section, we solve this system using the King and Watson (1998) solution algorithm. The linearized equations of the model are listed in the appendix.

4 Calibration

In this Section, we outline our baseline calibration. Our calibration assumes that countries Home and Foreign are of the same size, and that both countries are symmetric in terms of their deep structural parameters. For our calibration, we specify the following functional form for the utility function:

$$U_t = E_t \sum_{s=t}^{\infty} \beta^{s-t} \left[\frac{(C_s^j - \gamma C_{s-1})^{1-\rho}}{1-\rho} + \chi \frac{(1-h_s^j)^{1-\eta}}{1-\eta} \right]$$

where β is the subjective discount factor, ρ and η are the constant relative risk aversion parameters (inverse of the intertemporal elasticity of substitution) associated with consumption and leisure, respectively. We follow Christiano *et al* (2005) who suggest a value of γ, the parameter determining the degree of habits in consumption of around 0.6 for the US economy. For our baseline calibration, we assume a moderate amount of consumption home-bias, $v = (1-v^*) = 0.85$, which corresponds to a 15% share of imports in US final consumption and is similar to the value assumed by Enders and Mueller (2008). Initially, we assume complete specialization in the production of the final investment good, $\varphi = (1-\varphi^*) = 1$. The rather extreme assumption that $\varphi = 1$ is nevertheless also made in the baseline calibrations in Corsetti *et al* (2008) and Benigno and Thoenissen (2008). In our sensitivity analysis below, we allow φ to vary from 0.5 to 1. Following Benigno and Thoenissen (2008), the intratemporal elasticity of substitution between home and foreign-produced intermediate goods in consumption, θ, is set to 2, whereas τ, the intertemporal elasticity of substitution between home and foreign intermediate goods in investment goods is initially set to 1. In our sensitivity analysis, we experiment with different values of this parameter. As is common in the literature, we set the share of labour in production to 0.64 and assume a 2.5% depreciation rate of capital per quarter. Following Benigno (2001), we introduce a bond holding cost to eliminate the otherwise arising unit root in foreign bond holdings. This cost can be very small, and thus we choose a 10 basis point spread of the domestic interest rate on foreign assets over the foreign rate, such that $\varepsilon \equiv -\Theta'(\bar{b})\bar{C} = 0.001$. The curvature of the investment adjustment cost function $s''(.)$ is set so as to allow the calibrated model, driven by both TFP and IST shocks to match the volatility of investment relative to GDP.

The stochastic processes for total factor productivity and investment specific technological change are taken from Boileau (2002), whose model structure is similar to ours. Specifically, the stochastic process for TFP is taken from the seminal work of Backus *et al* (1994) on international real business cycles. The investment specific productivity shock calculated by Boileau (2002) is price based and calculated using G7 data on the relative price of a new unit of equipment relative to final goods output. The home country in this calibration is assumed to be the United States. Matrix $V[\mu]$ in table 1 above shows the variance-covariance matrix of our shock processes, and matrix Ω their first-order autocorrelation coefficients. The upper left hand quadrant of matrices $V[\mu]$ and Ω contain the TFP shocks, while the lower right hand quadrant contain the investment specific technology shocks.

Table 1: Baseline calibration

Preferences	$\beta = 1/1.01, \rho = 1, \eta = 0.25, \bar{h} = 1/3,\ \gamma = 0.6$
Final goods tech	$v = (1 - v^*) = 0.85,\ \theta = 2,\ \tau = 1,\ \varphi = (1 - \varphi^*) = 1$
Intermediate goods tech	$\alpha = 0.64,\ \delta = 0.025,\ s''(.) = 1.15$
Financial markets	$\varepsilon = 0.001$
Shocks	$\Omega = \begin{bmatrix} 0.906 & 0.088 & 0 & 0 \\ 0.088 & 0.906 & 0 & 0 \\ 0 & 0 & 0.553 & 0.027 \\ 0 & 0 & 0.027 & 0.553 \end{bmatrix}$
	$V[\mu] = 10^{-4} \begin{bmatrix} 0.726 & 0.187 & 0 & 0 \\ 0.187 & 0.726 & 0 & 0 \\ 0 & 0 & 1.687 & 0.582 \\ 0 & 0 & 0.582 & 1.687 \end{bmatrix}$

5 Impulse Response Analysis

Having described the model and its calibration, we now proceed to use impulse response analysis to examine the effect of investment specific technology (IST) shocks and total factor productivity (TFP) shocks on investment, its relative price, the terms of trade and Tobin's q, using our baseline calibration.

Figure 2 shows the response of the model economy to a unit IST shock.[5] For this shock, we observe that the investment rate and the relative price of investment goods are positively correlated. An investment specific shock is initially similar to a demand shock. Such a shock increases demand for investment goods without, initially at least, increasing the output capacity of the economy. In order for the market for home-produced investment goods to clear following a domestic investment shock, resources must be diverted from domestic and foreign consumers to domestic producers of investment goods. To achieve this reallocation of resources, the relative price of investment goods must rise. In our baseline calibration, the share of home-produced investment goods in final investment goods spending exceeds the share of home-produced consumption goods in final consumption goods spending, i.e. $v < \varphi$. Therefore, the relative price of investment goods is a negative function of the terms of trade (P_F/P_H). A rise in the price of investment goods is thus associated with a decline, or appreciation, of the terms of trade. An appreciation of the terms of trade transfers purchasing power from the foreign to the home consumer. This reduces the

[5]For our impulse response analysis, we ignore the cross-country spillovers present in the shock processess.

demand for home-produced intermediate goods coming from foreign consumers. Within the home economy, an appreciation of the terms of trade also shifts demand away from home to foreign-produced goods. Both of these re-allocations of resources allow the producers of investment goods to meet the increased demand from the home intermediate goods sector. This makes the correlation between the investment rate (x/y) and the relative price of investment goods (P_x/P) positive.

A unit TFP shock, as shown in Figure 3, raises output of home intermediate goods and induces a negative correlation between the investment rate, and the relative price of investment goods. In order for the market for home-produced intermediate goods to clear their international relative price must fall which causes the terms of trade (P_F/P_H) to depreciate (rise). This depreciation leads to a positive wealth effect abroad, raising foreign demand for home-produced intermediate goods. Since, for this calibration $\varphi > v$, the relative price falls (see equation (26)). Put differently, the final investment good is more biased towards home-produced intermediate goods than is the final consumption good, the relative price of investment goods to CPI must fall as the price of home produced intermediate goods declines.

[Figures 2 and 3 here]

So far, we have made the perhaps somewhat unrealistic assumption that all investment goods are home produced. Next, we assume that producers of final investment goods have no home-bias at all. This assumption is not unreasonable, as the factors that determine consumption home bias may not apply in equal measure to investment goods. Based on equation (26), when $v > \varphi$ the relationship between the relative price of investment goods and the terms of trade changes sign relative to our baseline calibration. A terms of trade depreciation is now associated with a rise in the relative price of investment goods. Assume there is a decline in the relative price of home produced intermediate goods causing the terms of trade to depreciate (rise). If, in this case, final investment goods are less intensive in home-produced intermediate goods than consumption goods, their price index will fall by less than the price index of final consumption, causing the relative price of investment goods to increase.

In Figure 4, we analyze an IST shock when $\varphi = 0.5$. As in Figure 2, the investment rate rises and Tobin's Q falls, however, the response of the terms of trade and hence the relative price of investment goods is different. Whereas the terms of trade appreciate in the $\varphi = 1$ case, here the terms of trade depreciate. Causing the correlation between the relative price of investment goods and the investment rate to be positive. The terms of trade depreciation can be explained as follows: The positive IST shock raises the demand for both home and foreign-produced intermediate goods. But since final investment goods are more intensive in foreign-produced intermediate goods than are consumption goods, the terms of trade has to depreciate, causing home and foreign producers of final goods to substitute home for foreign-produced inputs.

When the economy is subjected to TFP shocks, the response of the terms of trade remains the same as in the case where $\varphi = 1$. However, since the relative price of investment goods is now positively correlated with the terms of trade, a depreciation raises the relative price of investment goods, thus lowering the investment response. In Figure 5, the rise in the relative price of investment goods is so large that the output response of the home economy is actually greater than the initial investment response, causing the investment rate to decline. The result is a negative correlation between the investment rate and the relative price of investment goods.

[Figures 4 and 5 here]

Our impulse response analysis suggests that in our model, where we have explicitly modelled the relative price of investment goods, a shock that exogenously increases the amount of installed capital available next period for any given value of current and past investment, will raise investment along with its relative price. This finding holds for both complete home bias in final investment goods production, as well as for the polar opposite case of no home bias in the production of final investment goods. The correlation between the relative price of investment goods and the investment rate following an IST shock is positive contrary to the standard intuition based on the closed economy literature. A key determinant of this correlation is the response of the terms of trade, which appreciates in the $\varphi = 1$ case and depreciated in the $\varphi = 0.5$ scenario. In the case of TFP shocks, our model also suggests a correlation between the relative price of investment and the investment rate that is somewhat different from the literature. The correlation is negative, due to a rise in the investment rate and a fall in the relative price of investment when $\varphi = 1$ and due to rise in the relative price and a fall in the investment rate when $\varphi = 0.5$.

Below we summarize the impact effects of positive IST and TFP shocks on the investment rate, the terms of trade and the relative price of investment goods for the $\varphi = 1$ and $\varphi = 0.5$ calibration:

Table 2: Summary of Impulse Responses

	ε_t^x	A_t
$\varphi = 1$	$x/y \uparrow$, $T \downarrow$, $P_x/P \uparrow$	$x/y \uparrow$, $T \uparrow$, $P_x/P \downarrow$
$\varphi = 0.5$	$x/y \uparrow$, $T \uparrow$, $P_x/P \uparrow$	$x/y \downarrow$, $T \uparrow$, $P_x/P \uparrow$

In the next section, we analyze a selection of second moments generated by our model when driven by both IST and TFP as well as by either shock individually. We carry out this analysis for both the $\varphi = 1$ and the $\varphi = 0.5$ case.

6 Second Moments

Following our impulse response analysis, we now analyze a selection of second moments generated by our calibrated model. The purpose of this section is to analyze if IST shocks can help our international real business cycle model match some of the salient features of the international business cycle. Our selected second moments presented in Table 3 are constructed using actual data, as well as artificial model economy data. Both data are of quarterly frequency, logged and Hodrick-Presocott filtered with a smoothing parameter set to 1600. The sample period for the data is 1960:1 - 2006:4. We refer the reader to the appendix for details of data sources.

Table 3: Second moments: baseline model

	Data	*Model both shocks*		*Model IST shocks*		*Model TFP shocks*	
Correlations		$\varphi = 1$	$\varphi = 0.5$	$\varphi = 1$	$\varphi = 0.5$	$\varphi = 1$	$\varphi = 0.5$
$\text{Corr}(\frac{P_x}{P}, \frac{x}{y})$	-0.22	0.06	-0.10	0.44	0.23	-0.02	-0.16
$\text{Corr}(c, y)$	0.86	0.57	0.61	-0.72	-0.56	0.73	0.72
$\text{Corr}(x, y)$	0.89	0.85	0.76	0.89	0.64	0.90	0.84
$\text{Corr}(h, y)$	0.88	0.95	0.94	0.93	0.89	0.96	0.95
$\text{Corr}(w, y)$	0.26	0.68	0.71	-0.46	-0.30	0.74	0.75
$\text{Corr}(t, y)$	0.14	0.37	0.45	-0.37	0.37	0.41	0.45
$\text{Corr}(\frac{ca}{c}, y)$	-0.42	0.12	-0.02	0.04	-0.02	0.13	-0.04
$\text{Corr}(c, c^*)$	0.51	0.39	0.22	0.65	0.93	0.31	0.07
$\text{Corr}(y, y^*)$	0.66	0.48	0.56	0.40	0.67	0.48	0.56
Standard deviations							
σ_y	1.57	1.95	1.88	0.30	0.27	1.92	1.86
σ_c/σ_y	0.78	0.65	0.72	2.07	2.09	0.57	0.66
σ_x/σ_y	3.18	3.18	3.18	9.34	11.15	2.86	2.77
σ_t/σ_y	1.60	0.42	0.50	0.80	0.47	0.41	0.50
σ_{rs}/σ_y	3.04	0.30	0.35	0.56	0.33	0.29	0.35
σ_{ca}/σ_y	0.22	0.09	0.35	0.14	2.26	0.09	0.13

Notation: $\frac{P_x}{P}$=relative price of investment goods, x=investment, c=consumption, y=GDP, h=hours worked, w=real wage, t=terms of trade, ca=current account, rs=real exchange rate

The key finding of our impulse response analysis is reflected in the second moments generated by our model, as reported in Table 3. Investment specific technology shocks (columns 5 and 6) induce a positive correlation between the relative price of investment and the investment output ratio. TFP shocks (columns 7 and 8), on the other hand, induce a negative correlation between the investment ratio and the relative price of investment goods. When our model is driven by both types of shocks (columns 3 and 4), the correlation is small but positive in the $\varphi = 1$ case and small but negative in the $\varphi = 0.5$ case.

Columns 3 and 4 show our selection of second moments generated by our model when driven by both IST and TFP shocks. This model generates a standard deviation of GDP, σ_y, somewhat in excess of the data, but matches the relative volatility of investment to GDP, σ_x/σ_y, (by choice of adjustment cost parameter). In common with most of the literature, this type of model fails to match the standard deviation of the terms of trade and the real exchange rate relative to GDP (σ_t/σ_y and σ_{rs}/σ_y). As is common with this type of international business cycle model, our model driven by both shocks generates a pro-cyclical current account. Unlike the standard international real business cycle model, our model generates a series for consumption that is less highly correlated across countries than is GDP. This result arises from our introduction of external habit persistence, which lowers the cross-country correlation of consumption.

When we solve the model for the case where IST shocks are the only source of variation (columns 5 and 6), we find GDP in our model is about 1/6 as volatile as the data, somewhat less than in Greenwood *et al* (2000), whereas investment is more than three times as volatile as in the data. The relative volatility of the terms of trade is still below the value suggested in the data, but almost twice as volatile than in the model driven only by TFP shocks (for the $\varphi = 1$ case). This version of the model departs from the data in terms of the cross-correlations between consumption and GDP and the real wage and GDP. In both cases, the model predicts negative correlations. Counter-cyclical consumption following IST shocks is also noted in Boileau (2002) in a two-country model and Ejarque (1999), who for a closed economy suggests that this feature could be overcome by introducing variable capital utilization. A data congruent counter-cyclical current account is generated in our model whenever we assume that $\varphi = 0.5$, which also raises the volatility of the current account relative to GDP, a finding also noted in Boileau (2002).

7 Sensitivity Analysis

In the previous section, we focussed on the two extreme cases of either complete home bias in final investment goods production ($\varphi = 1$) or no home bias in final investment goods production ($\varphi = 0.5$). In this section, we analyze the how sensitive our results are to changes in our baseline calibration. We start off analyzing the correlation between the relative price of investment goods and the investment rate for values of φ between 0.5 and 1 for a given value of υ. Figure 6 plots the cross correlation generated by our model driven by only TFP and only IST shocks. Interestingly, for IST shocks (solid line), the correlation is not universally positive. Indeed, given the calibration of the other deep parameters, positive values of the correlation are only found for values of φ below about 0.58 and above the value for υ, which is 0.85 in our baseline calibration. Outside this range, the correlation between the relative price of investment goods and the investment rate is negative when the model is driven by IST shocks. This is so because for φ above 0.58, the terms of trade appreciate (fall) following a rise in IST. When the model is driven only by TFP shocks, the correlation remains negative for most of the parameter range, save values just around $\varphi = \upsilon$.

In Figure 7, we analyse the response of the terms of trade to TFP and IST shocks when we let φ vary between 0.5 and 1. Following a positive TFP shock, GDP unambiguously rises. We therefore analyse the correlation between GDP and the terms of trade to gauge the response of the terms of trade to a TFP shock. The dotted line line in Figure 7 suggests a pro-cyclical terms of trade throughout the parameter range. To gauge the response of the terms of trade to IST shocks, we analyse the correlation between the investment rate and the terms of trade, as IST shocks are always positively correlated with the investment rate.[6] The solid line in Figure 7 shows that the correlation between the terms of trade and the investment rate is positive for values of φ below about 0.58 and negative thereafter. This result helps us to understand why the investment rate is positively correlated with the relative price of investment goods when φ is below 0.58.

One parameter whose importance we have not yet discussed is the elasticity of substitution between different home and foreign-produced intermediate goods in the final investment good, τ. Figure 8 is a three dimensional version of Figure 6 (for IST shocks) where we vary both φ and τ. The effect of varying τ on the cross correlation between the relative price of investment goods and the investment rate is minimal, the same is true for the model driven only by TFP shocks (graph not shown).

In Thoenissen (2008), the importance of θ, the elasticity of substitution between home and foreign-produced intermediate goods in consumption is highlighted. The value of θ, in an incomplete financial market IRBC model is shown to be crucial for the dynamics of the terms of trade. Does the value of θ affect our main result concerning the correlation between the relative price of investment goods and the investment rate? When the model is driven by IST shocks, varying θ from 0.5 to 2.5 while also letting φ go from 0.5 to 1, shows very little variation and we therefore do not report the figure. The same is true to a lesser extent for the model when driven by TFP shocks. We report these correlations in Figure 9. The analysis shows that following TFP shocks, the correlation between the relative price of investment goods and the investment rate is predominantly negative, for most commonly assumed values of θ and φ.

In summary, we have examined the sensitivity of our results to changes in the baseline calibration, focussing on the share of home-produced intermediate goods in final investment goods, φ and the elasticities of substitution between home and foreign produced intermediate goods in final investment and consumption goods, τ and θ, respectively. Our analysis suggests that our finding that TFP shocks can cause a negative correlation between the investment rate and the relative

[6] Since consumption is counter cyclical under IST shocks, we choose the the correlation between the terms of trade and the investment rate as opposed to GDP to gain an insight into the response of the terms of trade following IST shocks.

price of investment goods is robust across a wide range of the deep parameters of our model. For IST shocks, on the other hand, there is a significant range of values of φ that allows our model to generate negative values of the correlation in question; this occurs for 'moderate' degrees of home bias in final investment goods production, as long as there is more home bias in final consumption good production.

8 Empirical connections

The central purpose of this paper is to understand the determinants of the correlation between the relative price of investment goods and the rate of investment. We show that in our model and for a wide range of calibrated parameters, total factor productivity shocks cause the relative price of investment goods and the investment rate to negatively covary, whereas IST shocks can, depending on the relative home bias in consumption with respect to investment, result in positive as well as negative correlations between the relative price of investment goods and the investment rate. This finding makes proxying for IST shocks potentially more difficult, as our results cast some doubt on the link between IST and TFP shocks on the one hand and the relative price of investment goods on the other.

To see whether our model predictions overall accord well with the data, we ask two questions: (i) What is the relative home bias in consumption with respect to investment in the US? (ii) Is the observed correlation between the relative price of investment and the rate of investment consistent with the observed relative home bias?

The consumption home bias is proxied by one minus the share of imports in total consumption. This uniquely identifies the consumption home bias parameter ν in the steady state in (12). Using the same principle one can estimate the investment home bias parameter φ by one minus the share of imports in total investment. The data for important share in consumption came from US International Transaction Accounts data (Table 2b) published by the Bureau of Economic analysis. based on the annual data over the same period 1978-2007, the average share of imports in total consumption excluding food is about 7.1% and including food it is about 9.3%. Based on these results, the estimate of ν ranges from 0.91 to 0.93.

The home bias in investment goods is proxied by one minus the share of imported capital goods in nonresidential investment based on (16). Imported capital goods data came from the International Transactions Accounts data, Table 2a and the nonresidential investment data came from BEA GDP accounts Table 1.1.5. Based on the same sample period the average share of imports in nonresidential investment turns out to be 20%. Based on this measure, value of the investment home bias parameter φ is estimated to be 0.8.

The estimates of the these two parameters clearly suggest that the home bias in consumption is significantly higher than the home bias in investment in the US. Based on the computations reported in Table 6, our model thus predicts that both TFP and IST will contribute to the negative correlation between the relative price of investment goods and the rate of investment for empirically plausible ranges of ν and φ. In order to check the model's performance against the data, we proceed as follows. We first quantify the TFP and IST shocks using the data. The TFP shock is estimated by the conventional Solow residual of a Cobb-Douglas production function involving nonfarm output, capital stock and nonfarm employment. The appendix outlines the details of this estimation. The IST shock is estimated based on a simple linear depreciation rule (ignoring adjustment cost, see(20)) as follows:

$$\varepsilon_t^x = \frac{k_t - (1-\delta)k_{t-1}}{x_t} \tag{29}$$

Using quarterly data for capital stock and investment and assuming a 2.5% quarterly rate of depreciation of the capital stock, we generate a series for this IST shock, ε_t^x over the sample period 1960:1-2006:4. Figures 10 and 11 plot the log of both series. Our measure of IST shows significant volatility as opposed to TFP. While TFP shock shows a secular trend, the IST series shows a steep decline in the mid 70s following the oil shock. It shows remarkable growth starting from the early 1990s which approximately coincides with the information technology revolution phase.

[Figures 10 and 11 here]

Table 4 presents the correlation matrices for the raw data for TFP (A_t), IST (ε_t^x), investment/GDP ratio (x/y) and the relative price of investment goods (P_x/P) over the sample period 1960:2-2006:4. The correlation between investment rate and the relative price of investment is -.67. The correlation between TFP and the relative price is -.98 and the correlation between IST shock and the relative price is -.72. The correlation between the investment rate, x/y and the TFP and IST shocks are .68 and .24 respectively. These correlations are overall consistent with the model prediction that both TFP and IST could contribute to a negative correlation between P_x/P and x/y given that the home bias in consumption is greater than the home bias in investment.

Table 4: Empirical correlations: 1990:1 to 2006:4

	ε_t^x	A_t	(P_x/P)	(x/y)
ε_t^x	1.00	0.6944	-0.7119	0.24
A_t		1.00	-0.98	0.68
(P_x/P)			1.00	-0.67
(x/y)				1.00

Although these correlation results accord well with the model predictions, they bring new challenges in identifying IST and TFP shocks from the observed movement of relative price of investment. All one can conclude from these correlations is that a combination of TFP and IST shocks could explain the negative correlation between investment rate and the relative price of investment goods. The question still remains which of these two shocks contribute to greater variation of these two macroeconomics variables, namely relative price of investment goods and the investment rate. To this end, we performed a variance decomposition analysis of these two variables. A vector autoregression of lag 4 was estimated involving four variables namely, $\varepsilon_t^x \quad A_t \quad (P_x/P) \quad (x/y)$. A Choleski ordering was imposed as follows, A_t, $\varepsilon_t^x, (x/y), (P_x/P)$. The underlying assumption in this ordering is that the TFP shock is the primitive shock and it impacts IST and then the investment/GDP ratio and the finally the relative price of investment goods.[7] The variance decompositions of the relative price of investment and the investment rates are reported in the following tables. It is noteworthy that, IST explains about 35% of the variation of the relative price of investment goods even after giving TFP a lead in the Choleski decomposition.

The variance decomposition of the investment rate suggests that it is explained substantially by itself although TFP explains up to 18% of its variation. The apparent exogeneity of the investment rate may suggest that investment is determined by several unobservables besides TFP and IST. It is conceivable that policy variables such as taxes could explain some variation of investment about which we do not have much to say in this paper. [8]

These variance decompositions actually deepen the puzzle: what accounts for the observed correlation between investment and the relative price of investment goods? While the relative price of investment goods is substantially explained by IST, the investment/GDP ratio is not. Although TFP appears to be the main driver of technical change (based on the Granger causality tests as described in footnote 6), the variance decomposition analysis suggests that a combination of TFP and IST could explain the observed comovement between the investment rate and the relative price of investment goods. The fact that a substantial part of the variation of the relative price of investment is explained by IST suggests that the use of this relative price as a rough proxy for investment friction in the extant literature may not be too far out of the line as long as the investigator is cautious about the identification issue that we highlight here.

[7] A Granger causality test involving TFP and ISTP with at least four lags was performed. The null hypothesis that TFP does not Granger cause ISTP is rejected while the reverse null hypothesis cannot be rejected at a 5% level of significance. On the basis of this causality test we treat TFP as the primitive shock to the system. The results about variance decompositions do not change much even if we reverse the Choleski ordering of TFP and ISTP shocks.

[8] We have tried a number of specifications and found that the variance decomposition results are remarkably robust to ordering of variables as well as lag lengths. A vector error correction model was also estimated taking into account the cointegration between these four variables. the variance decomposition numbers do not significantly change.

Table 5: Variance decomposition

	Variance Decomposition of PPI/CPI				
Period	S.E.	TFP	IST	I/Y	PPI/CPI
1	0.007773	0.859758	35.25373	0.785215	63.10129
2	0.015738	1.603075	36.07748	1.238451	61.08099
3	0.022883	2.663736	33.34407	0.901351	63.09084
4	0.029185	4.563016	31.71352	1.001232	62.72223
5	0.034652	6.174268	30.12834	1.218445	62.47895
6	0.039331	7.289515	28.89102	1.367167	62.4523
7	0.043365	7.992417	27.87781	1.525066	62.60471
8	0.046975	8.378571	27.03266	1.663543	62.92523
9	0.05031	8.539542	26.29703	1.807095	63.35633
10	0.053491	8.56343	25.6312	1.958141	63.84723

Table 6: Variance decomposition

	Variance Decomposition of IY				
Period	S.E.	TFP	IST	I/Y	PPI/CPI
1	0.001368	0.632327	2.144614	97.22306	0
2	0.001982	4.241176	1.189157	93.72677	0.842896
3	0.002671	7.012565	0.683855	91.5866	0.71698
4	0.003313	10.22986	0.783201	87.94385	1.04309
5	0.003865	12.56095	1.044247	85.23594	1.158868
6	0.004342	14.38571	1.202963	83.30814	1.10319
7	0.004742	15.77876	1.351978	81.89072	0.978544
8	0.005073	16.70367	1.45573	80.98106	0.859537
9	0.005343	17.31734	1.545766	80.35976	0.777132
10	0.005567	17.69658	1.627448	79.94132	0.734652

9 Conclusion

A pervasive empirical finding for the US economy is that the relative price of investment goods negatively correlates with the rate of investment in the economy. Based on this finding, a number of papers use the relative price of investment goods as a measure of investment friction. The central message of this paper is that in an open economy context, the relative price of investment goods may be a misleading proxy for investment friction. We set up a standard open economy model and demonstrate that the observed negative correlation between investment and the relative price of investment goods is driven by two fundamentals, namely the TFP and the IST shocks. Our calibrated model suggests that these two shocks may have differential impacts on investment and the relative price of investment goods depending on the relative home bias in consumption with respect to investment. Under a scenario where the home bias in investment is higher than the home bias in consumption, the correlation between investment and the relative price of investment could be positive if IST is the main driver of technical change. The TFP, on the other hand, predominantly gives rise to a negative correlation between these two variables. The stylized facts suggest that for the US economy the home bias in consumption is indeed higher than the home bias in investment. This gives rise to a puzzle: Is the observed negative relation between investment and the relative price of investment goods driven by TFP or IST? Our variance decomposition deepens this puzzle.

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A Log-linearized model

Home and foreign marginal utilities of consumption

$$-\rho\frac{1}{1-\gamma}\hat{C}_t + \rho\frac{\gamma}{1-\gamma}\hat{C}_{t-1} = \hat{\mu}_t \tag{A1}$$

$$-\rho\frac{1}{1-\gamma}\hat{C}^*_t + \rho\frac{\gamma}{1-\gamma}\hat{C}^*_{t-1} = \hat{\mu}^*_t \tag{A2}$$

Euler equations for home and foreign bonds

$$\hat{\mu}_t = \hat{\mu}_{t+1} + \hat{\imath}_t - \mathrm{E}_t\pi_{t+1} \tag{A3}$$

$$\hat{\mu}^*_t = \hat{\mu}^*_{t+1} + \hat{\imath}^*_t - \mathrm{E}_t\pi^*_{t+1} \tag{A4}$$

Euler equations for home and foreign labour supply

$$\hat{l}_t\frac{l}{(1-l)}\eta = \hat{\mu}_t + \hat{w}_t \tag{A5}$$

$$\hat{l}^*_t\frac{l^*}{(1-l^*)}\eta = \hat{\mu}^*_t + \hat{w}^*_t \tag{A6}$$

UIP condition

$$\mathrm{E}_t\Delta s_{t+1} = \hat{\imath}_t - \hat{\imath}^*_t + \varsigma\hat{b}_t \tag{A7}$$

Current account equation

$$\beta\hat{b}_t - \hat{b}_{t-1} = (1-v)\left((\theta-1)\,\hat{T}_t + \theta\widehat{RS}_t - \hat{C}_t + \hat{C}^*_t\right) \tag{A8}$$

Home and Foreign q equations

$$\hat{q}_t = \hat{q}_{t+1}\beta(1-\delta) + \hat{\mu}_{t+1} - \hat{\mu}_t + (v-1)\hat{T}_{t+1}\left(1-\beta(1-\delta)\right) + \hat{\rho}_{t+1}\left(1-\beta(1-\delta)\right) \tag{A9}$$

$$\hat{q}^*_t = \hat{q}^*_{t+1}\beta(1-\delta) + \hat{\mu}^*_{t+1} - \hat{\mu}^*_t + \left[v\hat{T}_{t+1} - \widehat{RS}_{t+1}\right]\left(1-\beta(1-\delta)\right) + \hat{\rho}^*_{t+1}\left(1-\beta(1-\delta)\right) \tag{A10}$$

Home and Foreign MPK equations

$$\hat{\rho}_t = \hat{A}_t - \alpha\hat{k}_{t-1} + \alpha\hat{l}_t \tag{A11}$$

$$\hat{\rho}^*_t = \hat{A}^*_t - \alpha\hat{k}^*_{t-1} + \alpha\hat{l}^*_t \tag{A12}$$

Optimal capital accumulation equations

$$\frac{\hat{q}_t}{(1+\beta)s''()} + \frac{\hat{\varepsilon}_t^i}{(1+\beta)s''()} + \frac{1}{(1+\beta)}\hat{x}_{t-1} + \frac{\beta}{(1+\beta)}\hat{x}_{t+1} - (v-\varphi)\hat{T}_t \frac{1}{(1+\beta)s''()} = \hat{x}_t \tag{A13}$$

$$\frac{\hat{q}_t^*}{(1+\beta)s''()} + \frac{\hat{\varepsilon}_t^{*i}}{(1+\beta)s''()} + \frac{1}{(1+\beta)}\hat{x}_{t-1}^* + \frac{\beta}{(1+\beta)}\hat{x}_{t+1}^* - (v^*-\varphi^*)\hat{T}_t \frac{1}{(1+\beta)s''()} = \hat{x}_t^* \tag{A14}$$

Home and Foreign MPL equations

$$(v-1)\hat{T}_t + \hat{A}_t + (\alpha-1)\hat{l}_t + (1-\alpha)\hat{k}_{t-1} = \hat{w}_t \tag{A15}$$

$$v\hat{T}_t - \widehat{RS}_t + \hat{A}_t^* + (\alpha-1)\hat{l}_t^* + (1-\alpha)\hat{k}_{t-1}^* = \hat{w}_t^* \tag{A16}$$

Home and Foreign capital accumulation constraints

$$\hat{k}_t = \hat{k}_{t-1}(1-\delta) + \delta\hat{x}_t + \delta\hat{\varepsilon}_t^i \tag{A17}$$

$$\hat{k}_t^* = \hat{k}_{t-1}^*(1-\delta) + \delta\hat{x}_t^* + \delta\hat{\varepsilon}_t^{*i} \tag{A18}$$

Home and Foreign production functions

$$\hat{y}_{H,t} = \hat{A}_t + (1-\alpha)\hat{k}_{t-1} + \alpha\hat{l}_t \tag{A19}$$

$$\hat{y}_{F^*,t} = \hat{A}_t^* + (1-\alpha)\hat{k}_{t-1}^* + \alpha\hat{l}_t^* \tag{A20}$$

Home and Foreign economy-wide constraints

$$\hat{y}_{H,t} = \frac{c_H}{y_H}\hat{c}_H + \frac{c_H^*}{y_H}\hat{c}_H^* + \frac{x_H}{y_H}\hat{x}_H + \frac{x_H^*}{y_H}\hat{x}_H^* \tag{A21}$$

$$\hat{y}_{F^*,t} = \frac{c_F}{y_{F^*}}\hat{c}_F + \frac{c_F^*}{y_{F^*}}\hat{c}_F^* + \frac{x_F^*}{y_{F^*}}\hat{x}_F^* + \frac{x_F}{y_{F^*}}\hat{x}_F \tag{A22}$$

Terms of trade based on zero PPI inflation monetary policy

$$\hat{T}_t = \hat{T}_{t-1} + \Delta s_t \tag{A23}$$

Real exchange rate

$$\widehat{RS}_t = (v-v^*)\hat{T}_t \tag{A24}$$

Home and Foreign input demand functions

$$\hat{c}_H = -\theta(v-1)\hat{T}_t + \hat{C}_t \tag{A25}$$

$$\hat{c}^*_H = -\theta(v-1)\hat{T}_t + \theta\widehat{RS}_t + \hat{C}^*_t \tag{A26}$$

$$\hat{c}_F = -\theta v\hat{T}_t + \hat{C}_t \tag{A27}$$

$$\hat{c}^*_F = -\theta v\hat{T}_t + \theta\widehat{RS}_t + \hat{C}^*_t \tag{A28}$$

$$\hat{x}_{H,t} = -\tau(\varphi-1)\hat{T}_t + \hat{x}_t \tag{A29}$$

$$\hat{x}_{F,t} = -\tau\varphi\hat{T}_t + \hat{x}_t \tag{A30}$$

$$\hat{x}_{H^*,t} = -\tau(\varphi^*-1)\hat{T}_t + \hat{x}^*_t \tag{A31}$$

$$\hat{x}_{F^*,t} = -\tau\varphi^*\hat{T}_t + \hat{x}^*_t \tag{A32}$$

Relative price of investment based on CES price indexes

$$\widehat{\frac{Px_t}{P_t}} = (v-\varphi)\hat{T}_t \tag{A33}$$

$$\widehat{\frac{Px^*_t}{P^*_t}} = (v^*-\varphi^*)\hat{T}_t \tag{A34}$$

A.1 Steady-state ratios

$$\frac{x_H}{y_H} = \frac{x}{k}\frac{k}{y} = \delta\left(\frac{i+\delta}{(1-\alpha)}\right)^{-1} \tag{B1}$$

$$\frac{x_H}{y_H} = \varphi\frac{x}{y_H} \tag{B2}$$

$$\frac{x_{H^*}}{y_H} = \varphi^*\frac{x}{y_H} \tag{B3}$$

$$\frac{y_H}{c_H} = \frac{1}{v}(1-\frac{x_H}{y_H})^{-1} \tag{B4}$$

$$\frac{c_H^*}{y_H} = 1 - \frac{c_H}{y_H} - \frac{x_H}{y_H} - \frac{x_{H^*}}{y_H} \tag{B5}$$

$$\frac{x_F}{y_{F^*}} = \delta \left(\frac{i + \delta}{(1 - \alpha)} \right)^{-1} \tag{B6}$$

$$\frac{x_F^*}{y^*} = (1 - \varphi^*) \frac{x_F}{y_{F^*}} \tag{B7}$$

$$\frac{x_F}{y^*} = (1 - \varphi) \frac{x_F}{y_{F^*}} \tag{B8}$$

$$\frac{y_F}{c_{F^*}} = \frac{1}{(1 - v^*)} \left(1 - \frac{x_t^*}{y^*} \right)^{-1} \tag{B9}$$

$$\frac{c_F}{y^*} = 1 - \frac{c_{F^*}}{y^*} - \frac{x_F^*}{y^*} - \frac{x_F}{y^*} \tag{B10}$$

B The data

Our data are of quarterly frequency and come from two main sources: the *US Department of Commerce: Bureau of Economic Analysis* (BEA) and *US Department of Labor: Bureau of Labor Statistics* (BLS) and span the sample period 1960:1 to 2006:4.

1. GDP refered to in tables 2, 3 and 8 is real GDP per capita from BEA's NIPA table 7.1. 'Selected Per Capita Product and Income Series in Current and Chained Dollars', seasonally adjusted. The series was logged and H-P filtered.

2. Consumption referred to in tables 2, 3 and 8 is total consumption expenditures deflated by the relevant GDP deflator, both from BEA's NIPA tables 2.3.5 and 1.1.9.

3. Investment referred to in tables 2, 3 and 8 is real fixed investment per capita from BEA's NIPA table 5.3.3. Real Private Fixed Investment by Type. Population is from NIPA table 7.1.

4. Hours referred to in tables 2, 3 and 8 is per capita hours worked in non-farm businesses, from BLS, series code PRS85006033. Population is from NIPA table 7.1.

5. Real wage referred to in tables 2, 3 and 8 is real hourly compensation from BLS, series code PRS85006153.

6. The Solow residual used in the emprical analysis of section 9 is constructed as follows:

$$A_t = ynfb_t - s_k \log(K_t) - (1 - s_k) \log(N_t)$$

   where $ynfb$ is the log of real GDP in the non-farm business sector, series PRS85006043 from BLS. N_t is aggregate hours worked, as above, but not deflated by the population. K is real non-residential fixed assets, constructed following Stock and Watson (1999)

7. Exchange rate, terms of trade and current account data are taken from OECD.

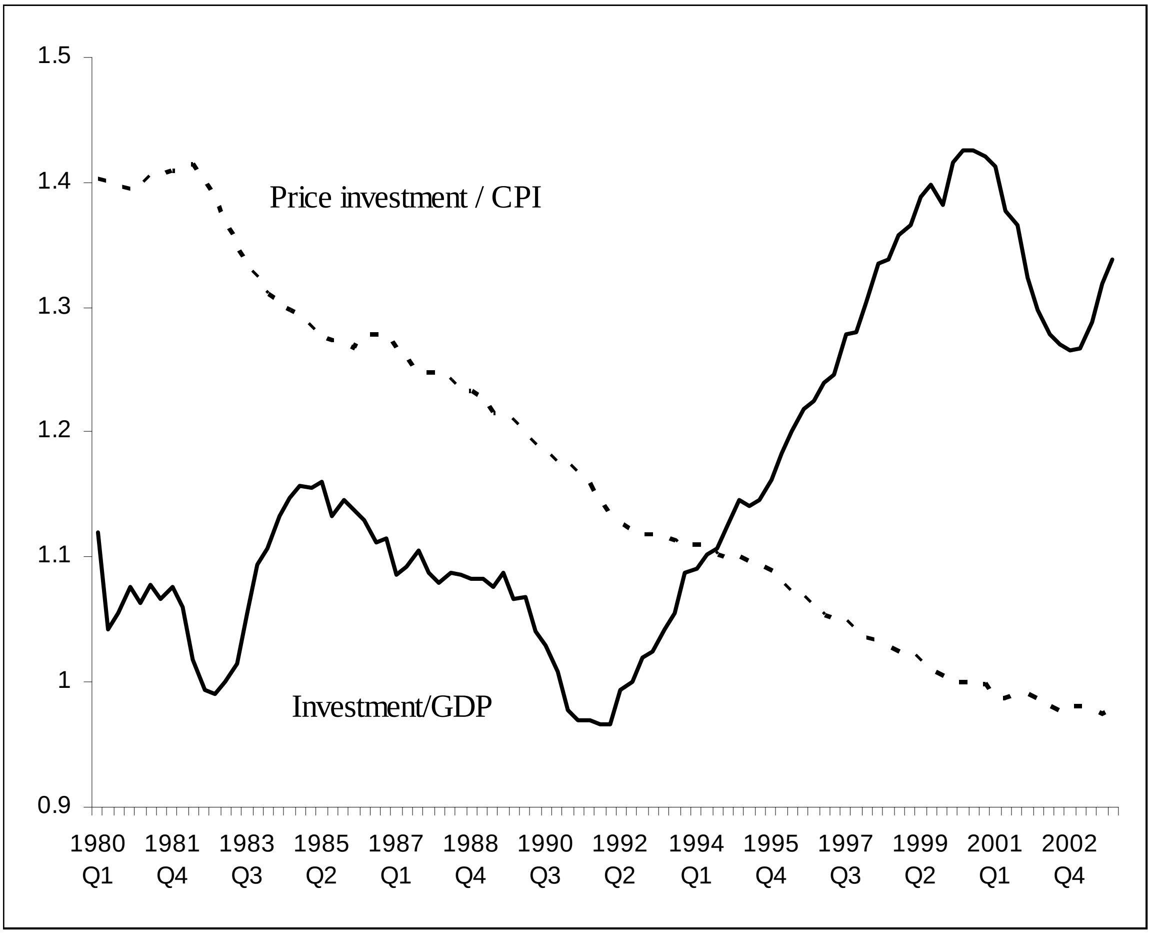

Figure 1: The relative price of investment goods and the investment to GDP ratio.

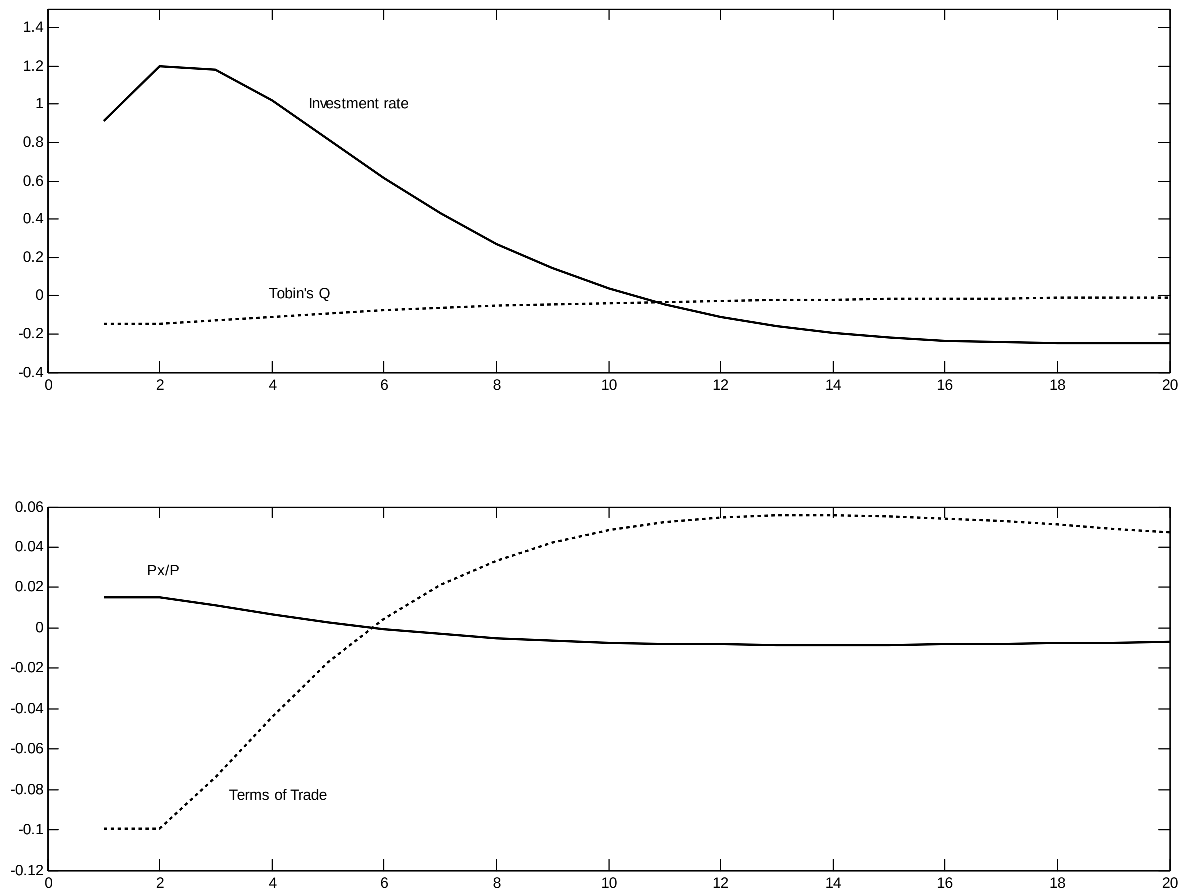

Figure 2: Investment rate, Tobin's Q, the relative price of investment goods and the terms of trade following a unit IST shock, when $\varphi = 1$.

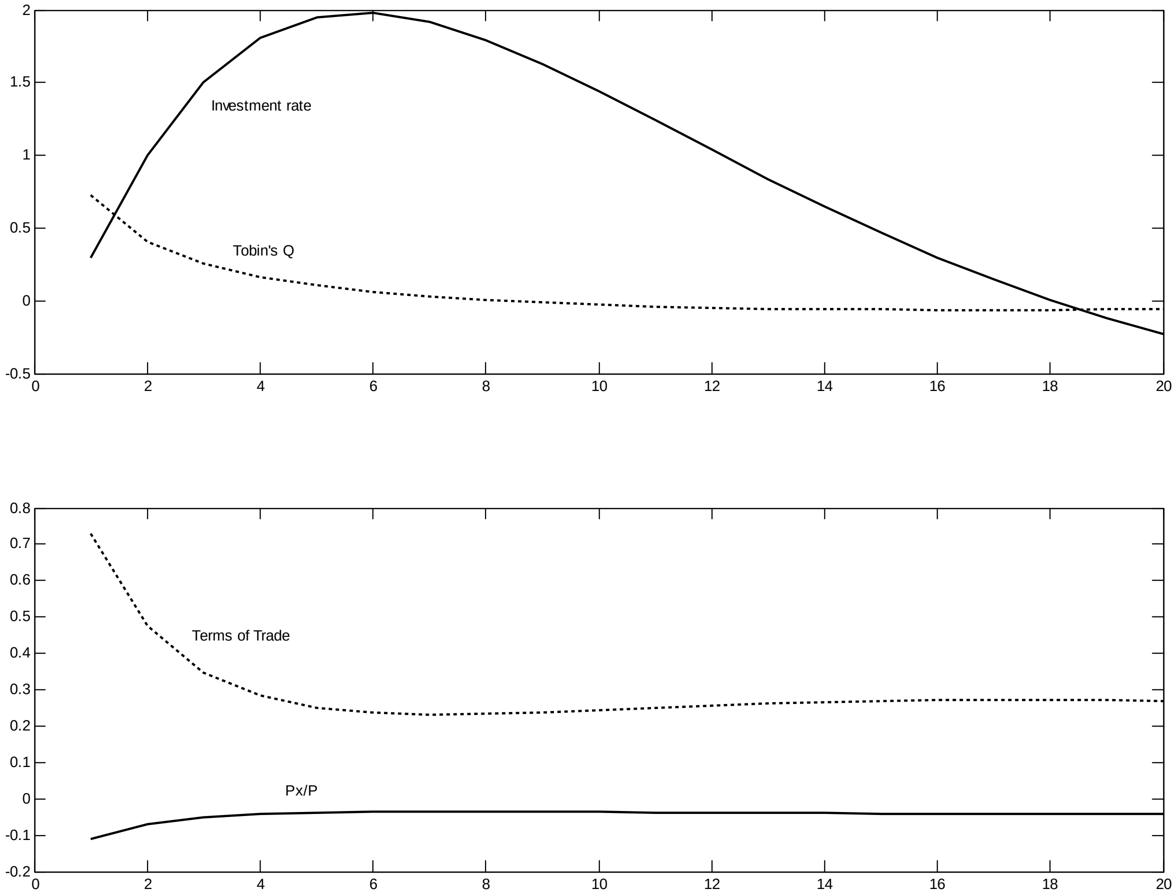

Figure 3: Investment rate, Tobin's Q, the relative price of investment goods and the terms of trade following a unit TFP shock, when $\varphi = 1$.

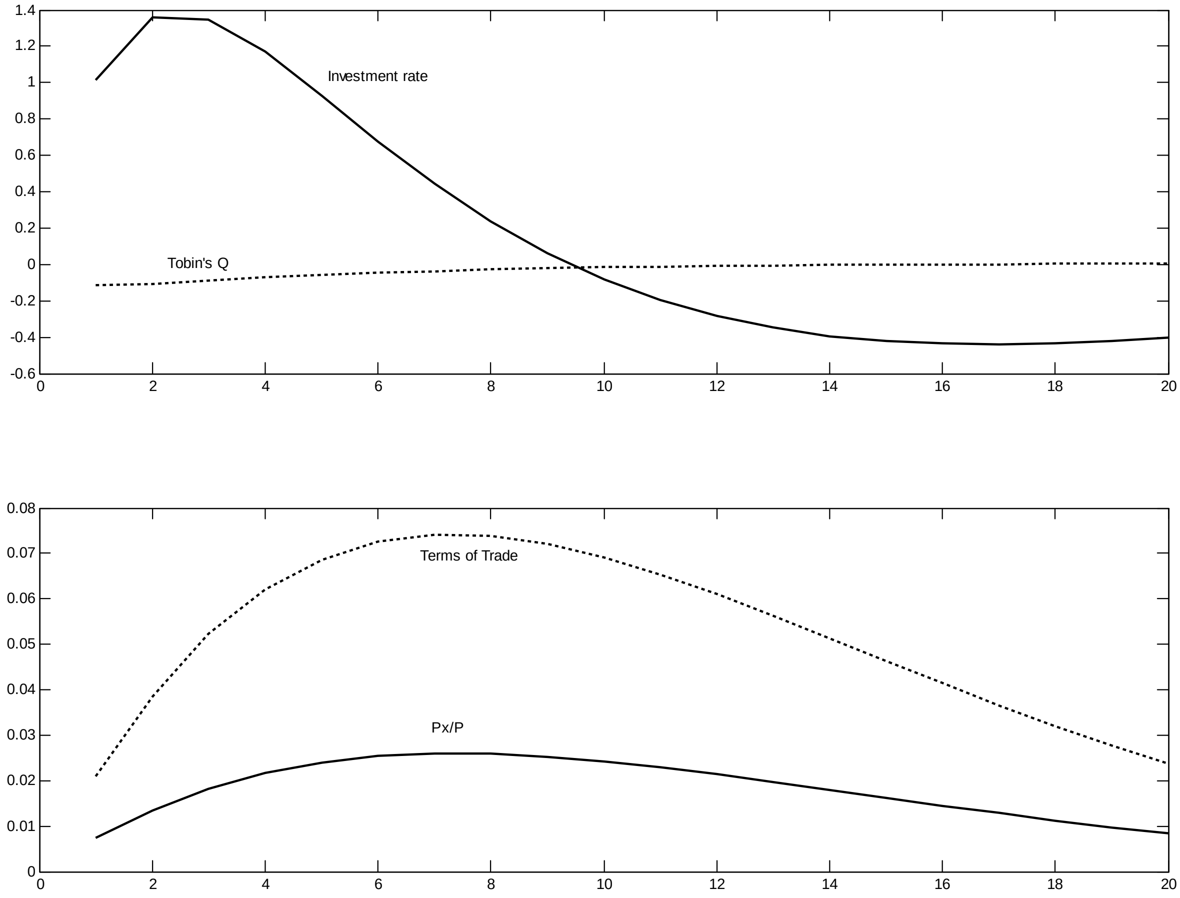

Figure 4: Investment rate, Tobin's Q, the relative price of investment goods and the terms of trade following a unit IST shock, when $\varphi = 0.5$.

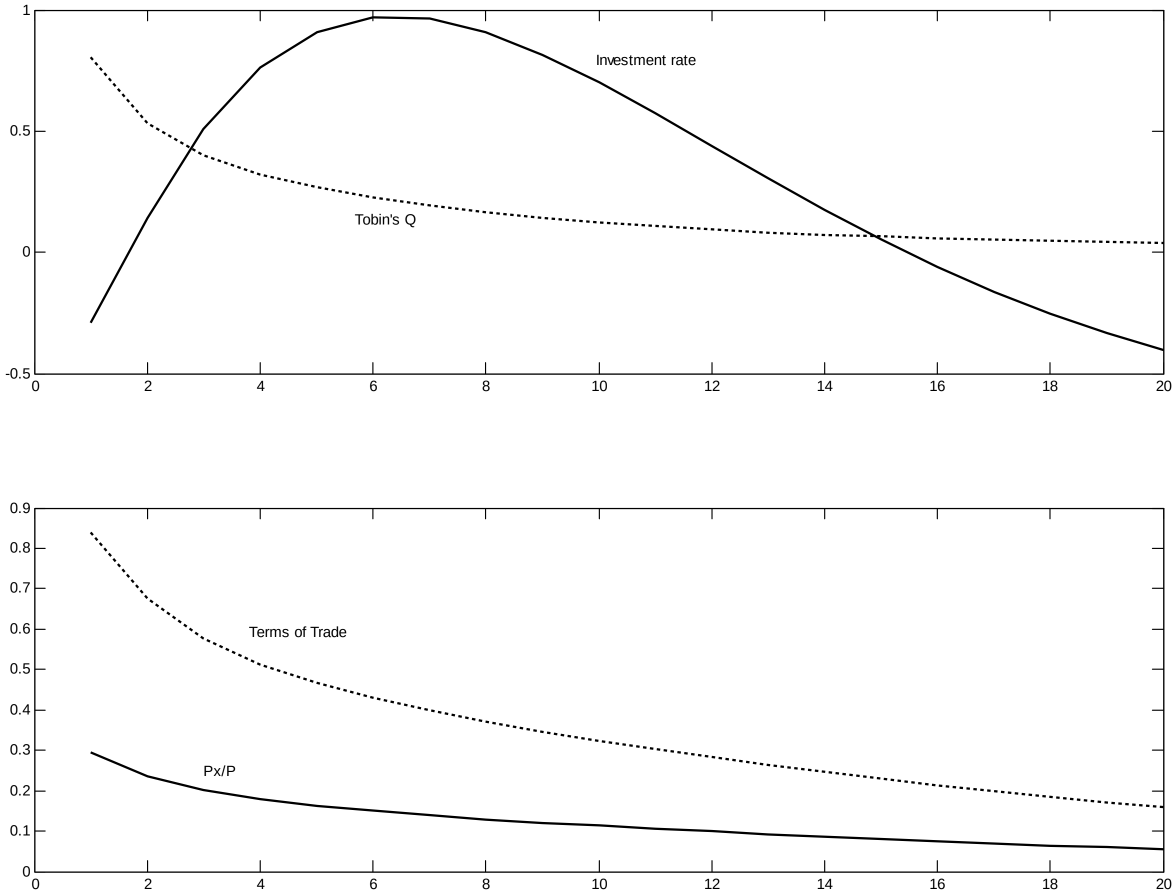

Figure 5: Investment rate, Tobin's Q, the relative price of investment goods and the terms of trade following a unit TFP shock, when $\varphi = 0.5$.

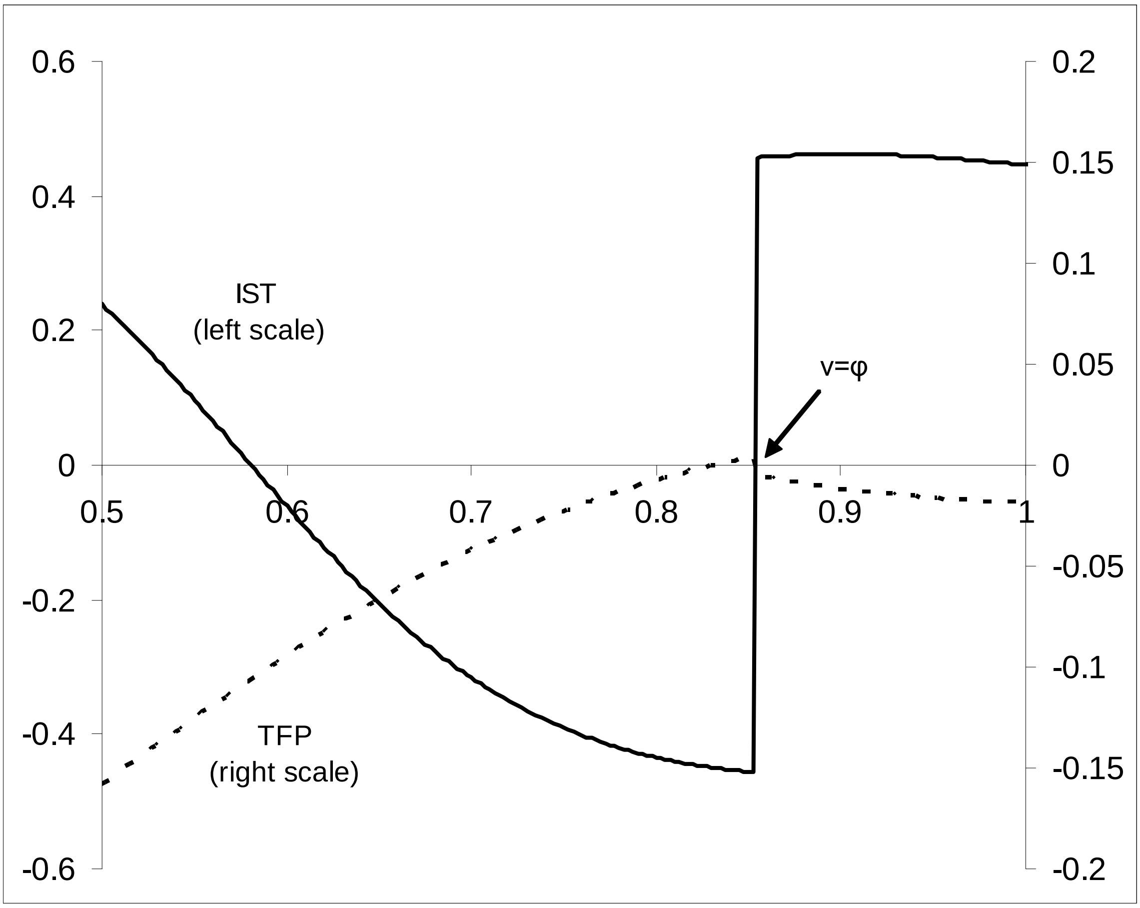

Figure 6: The correlation between the relative price of investment goods and the investment rate for various values of φ, when model is driven by IST and TFP shocks.

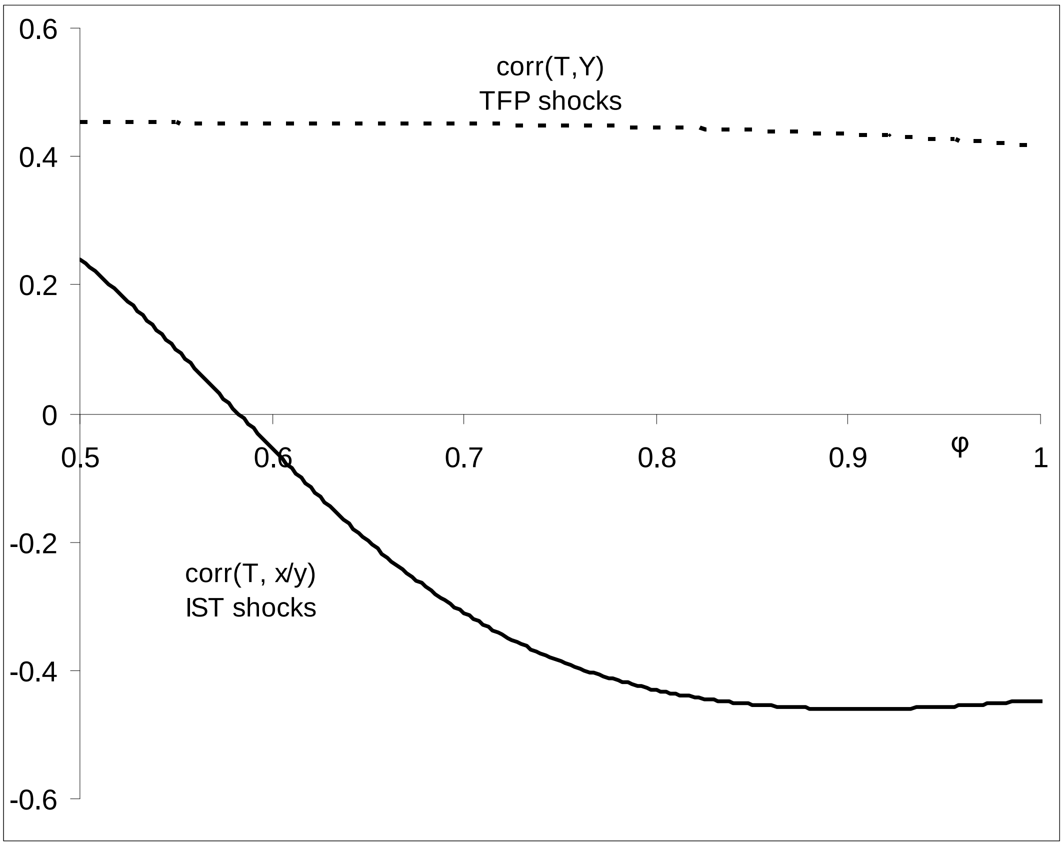

Figure 7: The correlation between the term of trade and GDP following TFP shocks and the correlation between the terms of trade and the investment rate following IST shocks, for various values of φ.

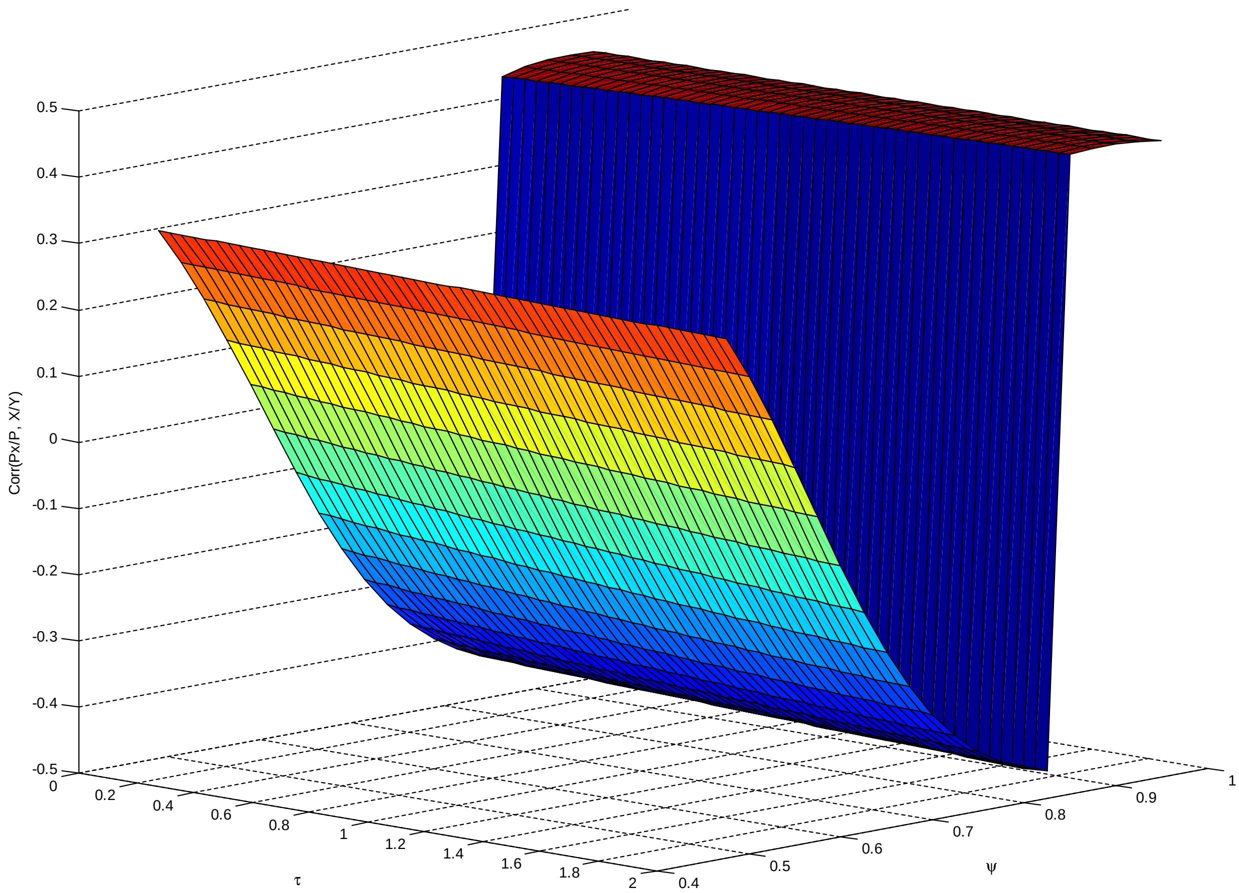

Figure 8: Correlation between the relative price of investment goods and the investment rate for various values of φ and τ when model is driven by IST shocks. H-P filtered model data.

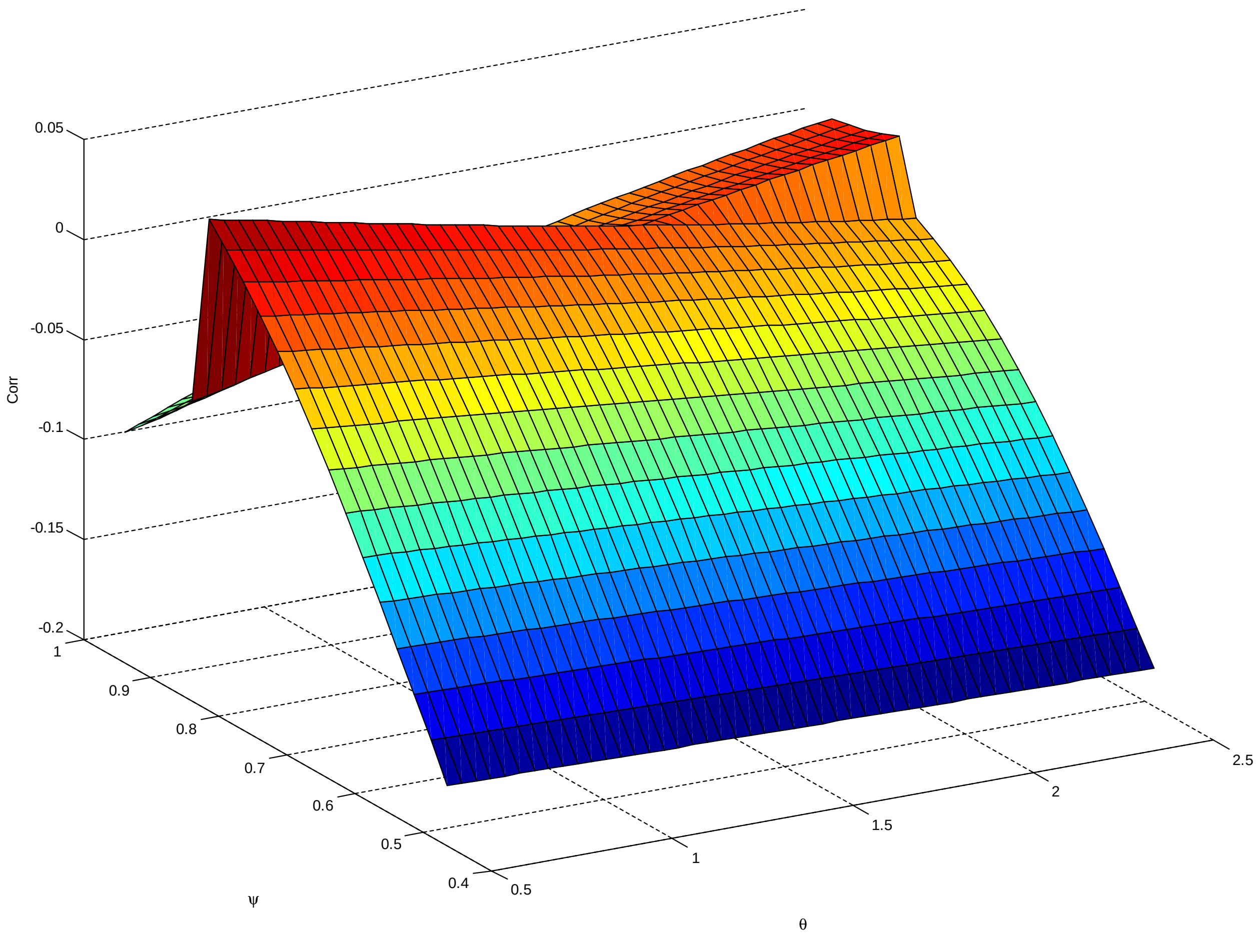

Figure 9: Correlation between the relative price of investment goods and the investment rate for various values of φ and θ when model is driven by TFP shocks. H-P filtered model data.

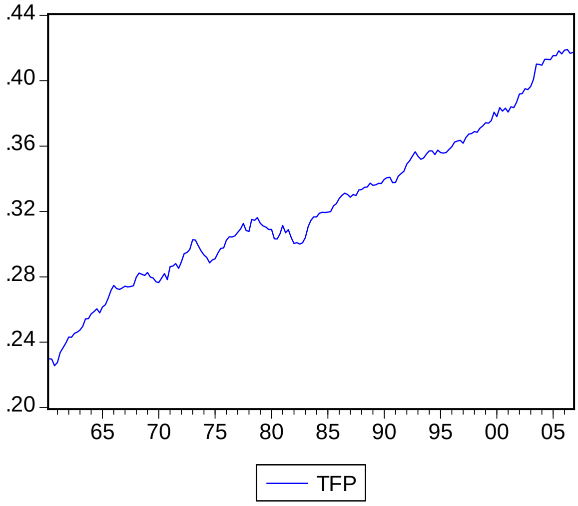

Figure 10: Total factor productivity defined as the Solow residual.

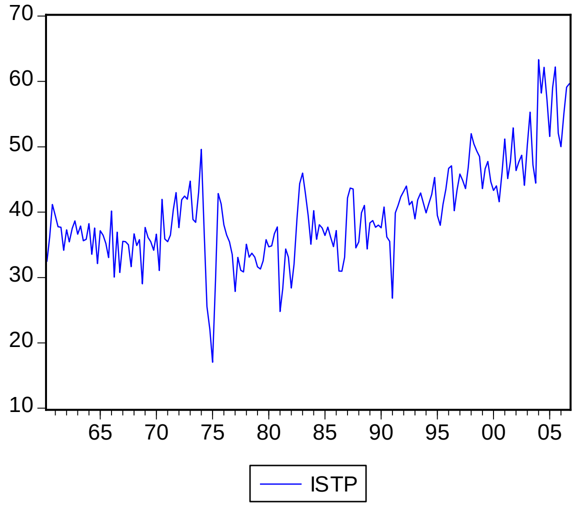

Figure 11: Constructed ISTP shock defined as $\varepsilon_t^x = \frac{k_t-(1-\delta)k_{t-1}}{x_t}$

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