Monetary Non-Neutrality in a Multi-Sector Menu Cost Model

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Abstract

We calibrate a multi-sector menu cost model using new evidence on the cross-sectional distribution of the frequency and size of price changes in the U.S. economy. The degree of monetary non-neutrality implied by this multi-sector model is triple that implied by a one-sector model calibrated to the mean frequency of price change of all firms. Our model incorporates intermediate inputs. This feature generates a substantial amount of real rigidity, which also roughly triples the degree of monetary non-neutrality in the model without affecting the size of price changes. The model with intermediate inputs also generates positive comovement of output of different sectors, unlike a model with no real rigidities. We compare our menu cost model to an extension of the Calvo model that is able to match the large size of price changes observed in the data.

Keywords: Menu Cost Models, Price Rigidity, Real Rigidity, Intermediate Inputs.

JEL Classification: E30

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1 Introduction

Menu costs are a simple way of explaining the empirical fact that prices adjust infrequently. Menu costs were first studied in a partial equilibrium setting (Barro, 1972; Sheshinski and Weiss, 1977; Mankiw, 1985; Akerlof and Yellen, 1985). General equilibrium analysis of menu cost models has long been restricted to relatively special cases (Caplin and Spulber, 1987; Caballero and Engel, 1991 and 1993; Caplin and Leahy, 1991 and 1997; Danziger, 1999; Dotsey et al., 1999). However, recently it has become feasible to solve much more general and quantitatively realistic menu cost models using numerical methods. Golosov and Lucas (2006) advanced the literature on menu cost models substantially by quantitatively analyzing a model rich enough to match micro-level evidence on both the frequency and absolute size of price changes.

It has been common practice in this literature to assume that all firms in the economy are identical.[1] Recent comprehensive studies of micro-level price setting behavior have, however, found a massive amount of heterogeneity across sectors in the frequency of price change (Bils and Klenow, 2004; Dhyne et al., 2006; Nakamura and Steinsson, 2006). Table 1 reports the monthly frequency of price change excluding sales for a decomposition of U.S. consumer prices into 11 sectors for 1998-2005 taken from Nakamura and Steinsson (2006). Figure 1 plots a finer decomposition. The frequency of price change ranges from 1% all the way to 100%. Most goods have a frequency of price change between 1% and 20%, but the distribution is highly asymmetric with a very long right tail.

The asymmetry of the distribution of the frequency of price change implies that the mean frequency of price change is much higher than the median frequency of price change. Table 2 reports the expenditure weighted mean and median frequency of price change of consumer prices excluding sales in the U.S. The mean monthly frequency is 21.1%, while the median is only 8.7%. Producer prices display a similarly large difference between the mean and median frequency of price change. Table 2 reports that the mean frequency of price change for finished producer goods is 24.7% while the median is only 10.8%.[2]

[1] Exceptions to this include Caballero and Engel (1991, 1993).

[2] Most of the difference between the mean and the median arises from heterogeneity across sectors. The mean frequencies of price change for gasoline, utilities, and used cars was 87.6%, 38.1% and 100% respectively over the 1998-2005 period. Excluding these product categories (which account for about 13% of the total expenditure weight) causes the mean frequency of non-sale price changes to fall from 21% to 13%, while the median falls only from 8.7% to 7.7%.

What implications does this heterogeneity have for the degree of monetary non-neutrality generated by a menu cost model? Does a single-sector menu cost model calibrated to match the average frequency of price change provide a good measure of the degree of monetary non-neutrality in an economy with the huge amount of heterogeneity in price rigidity we observe in the U.S. economy? In other words, how does the distribution of price changes across firms affect the degree of monetary non-neutrality in the economy? To address these questions, we develop a multi-sector menu cost model. We calibrate the model to match the distribution of price rigidity across sectors in the U.S. economy. We find that the monetary non-neutrality implied by our multi-sector model is triple that implied by a single-sector model calibrated to the mean frequency of price change.

To understand the effect that heterogeneity has on the degree of monetary non-neutrality, assume for simplicity that the pricing decisions of different firms are independent of one another. This implies that the degree of monetary non-neutrality in the economy is approximately a weighted average of the monetary non-neutrality in each sector. In this case, heterogeneity in the frequency of price change across sectors increases the overall degree of monetary non-neutrality in the economy if the degree of monetary non-neutrality in different sectors of the economy is a convex function of each sector's frequency of price change (Jensen's inequality).

Consider the response of the economy to a permanent shock to nominal aggregate demand. In the Calvo model, the effect of the shock on output at any given point in time after the shock is inversely proportional to the fraction of firms that have changed their price at least once since the shock occurred. If some firms have vastly higher frequencies of price change than others, they will change their prices several times before the other firms change their prices once. But all price changes after the first one for a particular firm do not affect output on average since the firm has already adjusted to the shock. Since a marginal price change is more likely to fall on a firm that has not already adjusted in a sector with a low frequency of price change, the degree of monetary non-neutrality in the Calvo model is convex in the frequency of price change (Carvalho, 2006).

The relationship between the frequency of price change and the degree of monetary non-neutrality is more complicated in a menu cost model. Firms are not selected at random to change their price. Rather the firms that change their prices are the firms whose prices are furthest from their desired prices (Caplin and Spulber, 1987; Golosov and Lucas, 2006). This "selection effect" greatly diminishes the degree of monetary non-neutrality in a menu cost model relative to the

Calvo model. It also affects the relationship between the frequency of price change and the degree of monetary non-neutrality. Consider two sectors of the economy that are identical except that one faces larger menu costs than the other. The sector with larger menu costs will have fewer price changes. But the average absolute size of price changes in this sector will also be larger. While a lower frequency of price change tends to raise the degree of monetary non-neutrality, the larger size of price changes tends to lower the degree of monetary non-neutrality. The net effect depends on the strength of the selection effect. In the Caplin-Spulber model, the selection effect is strong enough that it yields complete monetary neutrality regardless of the frequency of price change.

The strength of the selection effect is determined by a number of characteristics of a firm's environment, including the level of the menu cost, the level and variance of the inflation rate in the economy and the variance and kurtosis of idiosyncratic shocks to the firm's marginal costs.[3] Because of the selection effect, menu cost models can generate a wide range of relationships between the frequency of price change and the degree of monetary non-neutrality depending on what causes the variation in the frequency of price change across firms. If the selection effect is strong enough, the relationship between the frequency of price change and the degree of monetary non-neutrality may be concave or even increasing.

Despite the complications introduced by the selection effect, we find that heterogeneity amplifies the degree of monetary non-neutrality by roughly a factor of 3 for our multi-sector menu cost model calibrated to data on the U.S. economy. The features of the U.S. data that drive this result are: 1) the low average level of inflation in the U.S. economy, and 2) the fact that the average size of price changes is large and a substantial fraction of price changes are price decreases.

Bils and Klenow (2002) and Carvalho (2006) investigate the effect of heterogeneity in the frequency of price change in multi-sector Taylor and Calvo models. Bils and Klenow (2002) analyze the Taylor model and find that heterogeneity amplifies the degree of monetary non-neutrality by a modest amount. Carvalho (2006) considers both the Taylor and Calvo model as well as several time-depentent sticky information models. He incorporates strategic complementarity into his model and considers a different shock process than Bils and Klenow (2002). He finds a larger effect of heterogeneity. Our results are quantitatively similar to the results he finds when he considers the same shock process as we do.

[3]Midrigan (2005) shows how the strength of the selection effect at a given frequency of price change is affected by the kurtosis of idiosyncratic shocks marginal costs.

We incorporate intermediate inputs into our menu cost model, following Basu (1995). Intermediate inputs generate a substantial degree of strategic complementarity in the model. The degree of monetary non-neutrality generated by the model with intermediate inputs is roughly triple that of the model without intermediate inputs. Intuitively, in the model with intermediate inputs, firms that change their price soon after a shock to nominal aggregate demand choose to adjust less than they otherwise would because the price of many of their inputs have not yet responded to the shock. We find a similar affect of heterogeneity in both the model with and without intermediate inputs. The model with intermediate inputs generates positive comovement of output of different sectors, unlike a model with no real rigidities.[4]

Strategic complementarity has long been an important source of amplification of nominal rigidities (Ball and Romer, 1990; Woodford, 2003). However, recent work has cast doubt on this mechanism as a source of amplification in menu cost models with idiosyncratic shocks by showing that the introduction of certain sources of strategic complementarity implies that the models are unable to match the average size of micro-level price changes for plausible parameter values (Klenow and Willis, 2006; Golosov and Lucas, 2006). Following Ball and Romer (1990) and Kimball (1995), we divide sources of strategic complementarity into two classes—ω-type strategic complementarity and Ω-type strategic complementarity. We show that models with a large amount of ω-type strategic complementarity are unable to match the average size of price changes, while this problem does not afflict models with a large amount of Ω-type strategic complementarity. The introduction of intermediate inputs increases the amount of Ω-type strategic complementarity. It therefore does not affect the size of price changes or require unrealistic parameter values.

Finally, we compare the results of our menu cost model to a model in which price changes are largely time-dependent. The menu cost model abstracts completely from the idea that price reviews may require less resources in some periods than others. Such variation may arise due to, e.g., the introduction of new products or economies of scale in decision making. The Calvo model takes the opposite extreme position. It abstracts completely from selection by firms regarding the timing of price changes. This causes the Calvo model to have problems matching the micro-data on price setting. To capture the idea that price changes may require less resources in some periods than others but at the same time match the micro-level evidence on the frequency and absolute

[4] The lack of comovement of output across sectors in models with heterogeneity in the frequency of price change has been emphasized recently by Bils et al. (2003), Barsky et al. (2003) and Carlstrom and Fuerst (2006).

size of price changes, we develop an extension of the Calvo model in which firms face a high menu cost with probability α and a low menu cost with probability $1 - \alpha$. We refer to this model as the CalvoPlus model. The CalvoPlus model has the appealing feature that it nests both the menu cost model and the Calvo model as special cases.[5]

In the Calvo limit—when all price changes occur in the low menu-cost state—monetary non-neutrality is six times what it is in the menu cost model. However, the degree of monetary non-neutrality drops rapidly as the fraction of price change in the low menu-cost state falls below 100%. When 85% of price changes occur in the low menu cost state, the CalvoPlus model generates half as much monetary non-neutrality as in the Calvo limit. When 50% of price changes occur in the low menu cost state the degree of monetary non-neutrality in the CalvoPlus model is close to identical to the value in the menu cost model. This suggests that the relatively large amount of monetary non-neutrality generated by the Calvo model is quite sensitive to even a modest amount of selection by firms regarding the timing of price changes.

Our analysis builds on the original work on menu cost models in partial equilibrium by Barro (1972), Sheshinski and Weiss (1977), Mankiw (1985), Akerlof and Yellen, 1985 and others. The implications of menu costs in general equilibrium have been analyzed analytically in simple models by Caplin and Spulber (1987), Caballero and Engel (1991, 1993), Caplin and Leahy (1991, 1997), Danziger (1999), Dotsey et al. (1999) and Gertler and Leahy (2006). Willis (2003), Burstein (2005), Golosov and Lucas (2006) and Midrigan (2005) analyze the implications of menu cost models in general equilibrium using numerical solution methods similar to ours. Finally, we build on a long literature in monetary economics on real rigidities by Ball and Romer (1990), Basu (1995), Kimball (1995), Woodford (2003) and others.

The paper proceeds as follows. Section 2 presents a single-sector menu cost model with intermediate inputs. The section shows how intermediate inputs amplify the degree of monetary non-neutrality in the model without affecting the size of price changes. Section 3 presents the CalvoPlus model and analyzes its behavior. Section 4 introduces the multi-sector version of the menu cost model and analyzes the effects of heterogeneity. Section 5 concludes.

[5] Our CalvoPlus model is related to the random menu cost model analyzed by Dotsey et al. (1999), Klenow and Kryvtsov (2005) and Caballero and Engel (2006). The results we find regarding amplification of monetary non-neutrality in our CalvoPlus model relative to the Calvo model are consistent with the results of Caballero and Engel (2006).

2 A Single-Sector Menu Cost Model

We first present a single-sector general equilibrium model in which firms face menu costs. This model is a generalization of the model presented by Golosov and Lucas (2006).

2.1 Household Behavior

The households in the economy maximize discounted expected utility given by

$$E_t \sum_{j=0}^{\infty} \beta^j \left[\frac{1}{1-\gamma} C_{t+j}^{1-\gamma} - \frac{\omega}{\psi+1} L_{t+j}^{\psi+1} \right], \tag{1}$$

where E_t denotes the expectations operator conditional on information known at time t, C_t denotes household consumption of a composite consumption good and L_t denotes household supply of labor. Households discount future utility by a factor β per period; they have constant relative risk aversion equal to γ; the level and convexity of their disutility of labor are determined by the parameters ω and ψ, respectively.

Households consume a continuum of differentiated products indexed by z. The composite consumption good C_t is a Dixit-Stiglitz index of these differentiated goods:

$$C_t = \left[\int_0^1 c_t(z)^{\frac{\theta-1}{\theta}} dz \right]^{\frac{\theta}{\theta-1}}, \tag{2}$$

where $c_t(z)$ denotes household consumption of good z at time t and θ denotes the elasticity of substitution between the differentiated goods.

The households must decide each period how much to consume of each of the differentiated products. For any given level of spending in time t, the households choose the consumption bundle that yields the highest level of the consumption index C_t. This implies that household demand for differentiated good z is

$$c_t(z) = C_t \left(\frac{p_t(z)}{P_t} \right)^{-\theta} \tag{3}$$

where $p_t(z)$ denotes the price of good z in period t and P_t is the price level in period t given by

$$P_t = \left[\int_0^1 p_t(z)^{1-\theta} dz \right]^{\frac{1}{1-\theta}}. \tag{4}$$

The price level P_t has the property that $P_t C_t$ is the minimum cost for which the household can purchase the amount C_t of the composite consumption good.

A complete set of Arrow-Debreu contingent claims are traded in the economy. The budget constraint of the households may therefore be written as

$$P_tC_t + E_t[D_{t,t+1}B_{t+1}] \leq B_t + W_tL_t + \int_0^1 \Pi_t(z)dz, \tag{5}$$

where B_{t+1} is a random variable that denotes the state contingent payoffs of the portfolio of financial assets purchased by the households in period t and sold in period $t+1$, $D_{t,t+1}$ denotes the unique stochastic discount factor that prices these payoffs in period t, W_t denotes the wage rate in the economy at time t and $\Pi_t(z)$ denotes the profits of firm z in period t. To rule out "Ponzi schemes", we assume that household financial wealth must always be large enough that future income suffices to avert default.

The first order conditions of the household's maximization problem are

$$D_{t,T} = \beta^{T-t}\left(\frac{C_T}{C_t}\right)^{-\gamma}\frac{P_t}{P_T}, \tag{6}$$

$$\frac{W_t}{P_t} = \omega L_t^{\psi} C_t^{\gamma}, \tag{7}$$

and a transversality condition. Equation (6) describes the relationship between asset prices and the time path of consumption, while equation (7) describes labor supply.

2.2 Firm Behavior

There are a continuum of firms in the economy indexed by z. Each firm specializes in the production of a differentiated product. The production function of firm z is given by,

$$y_t(z) = A_t(z)L_t(z)^{1-s_m}M_t(z)^{s_m}, \tag{8}$$

where $y_t(z)$ denotes the output of firm z in period t, $L_t(z)$ denotes the quantity of labor firm z employs for production purposes in period t, $M_t(z)$ denotes an index of intermediate inputs used in the production of product z in period t, s_m denotes the materials share in production and $A_t(z)$ denotes the productivity of firm z at time t. The index of intermediate products is given by

$$M_t(z) = \left[\int_0^1 m_t(z,z')^{\frac{\theta-1}{\theta}}dz'\right]^{\frac{\theta}{\theta-1}},$$

where $m_t(z,z')$ denotes the quantity of the z'th intermediate input used by firm z.

Following Basu (1995), we assume that all products serve both as final output and inputs into the production of other products. This "round-about" production model reflects the complex input-output structure of a modern economy.[6] When the material share s_m is set to zero, the production function reduces to the linear production structure considered by Golosov and Lucas (2006). Basu shows that the combination of round-about production and price rigidity due to menu costs implies that the pricing decisions of firms are strategic complements. In this respect, the round-about production model differs substantially from the "in-line" production model considered, for example, by Blanchard (1983). The key difference is that in the round-about model there is no "first product" in the production chain that does not purchase inputs from other firms. The fact that empirically almost all industries purchase products from a wide variety of other industries lends support to the "round-about" view of production.[7]

Firm z maximizes the value of its expected discounted profits

$$E_t \sum_{j=0}^{\infty} D_{t,t+j} \Pi_{t+j}(z), \tag{9}$$

where profits in period t are given by

$$\Pi_t(z) = p_t(z) y_t(z) - W_t L_t(z) - P_t M_t(z) - K W_t I_t(z). \tag{10}$$

Here $I_t(z)$ is an indicator variable equal to one if the firm changes its price in period t and zero otherwise. We assume that firm z must hire an additional K units of labor if it decides to change its price in period t. We refer to this fixed cost of price adjustment as a "menu cost".

Firm z must decide each period how much to purchase of each of the differentiated products it uses as inputs. Cost minimization implies that the firm z's demand for differentiated product z' is

$$m_t(z, z') = M_t(z) \left(\frac{p_t(z')}{P_t} \right)^{-\theta}. \tag{11}$$

Combining consumer demand—equation (3)—and input demand—equation (11)—yields total demand for good z:

$$y_t(z) = Y_t \left(\frac{p_t(z)}{P_t} \right)^{-\theta}, \tag{12}$$

where $Y_t = C_t + \int_0^1 M_t(z) dz$. It is important to recognize that C_t and Y_t do not have the same interpretations in our model as they do in models that abstract from intermediate inputs. The

[6] See Blanchard (1987) for an earlier discussion of a model with "horizontal" input supply relationships between firms.

[7] See Basu (1995) for a detailed discussion of this issue.

variable C_t reflects *value-added* output while Y_t reflects *gross* output. Since gross output is the sum of intermediate products and final products, it "double-counts" intermediate production and is thus larger than value-added output. GDP in the U.S. National Income and Product Accounts measures value-added output. The variable in our model that corresponds most closely to real GDP is therefore C_t.

The firm maximizes profits—equation (9)—subject to its production function—equation (8)—demand for its product—equation (12)—and the behavior of aggregate variables. We solve this problem by first writing it in recursive form and then by employing value function iteration. To do this, we must first specify the stochastic processes of all exogenous variables.

We assume that the log of firm z's productivity follows a mean-reverting process,

$$\log A_t(z) = \rho \log A_{t-1}(z) + \epsilon_t, \tag{13}$$

where ϵ_t is independent and identically distributed.

We assume that the monetary authority targets a path for nominal value-added output, $S_t = P_t C_t$. Specifically, the monetary authority acts so as to make nominal value-added output follow a random walk with drift in logs:

$$\log S_t = \mu + \log S_{t-1} + \eta_t \tag{14}$$

where η_t is independent and identically distributed. We will refer to S_t either as nominal value-added output or as nominal aggregate demand.[8]

The state space of the firm's problem is infinite dimensional since the evolution of the price level and other aggregate variables depend on the entire joint distribution of all firms' prices and productivity levels. Following Krusell and Smith (1998), we make the problem tractable by assuming that the firms perceive the evolution of the price level as being a function of a small number of moments of this distribution.[9] Specifically, we assume that firms perceive that

$$\frac{P_t}{P_{t-1}} = \Gamma\left(\frac{S_t}{P_{t-1}}\right). \tag{15}$$

[8]This type of specification for nominal aggregate demand is common in the literature. It is often justified by a model of demand in which nominal aggregate demand is proportional to the money supply and the central bank follows a money growth rule. It can also be justified in a cashless economy (Woodford, 2003). In a cashless economy, the central bank can adjust nominal interest rates in such a way to achieve the target path for nominal aggregate demand.

[9]Willis (2003) and Midrigan (2005) make similar assumptions.

Forecasting the price level based on this single variable turns out to be highly accurate. Figure 2 plots the actual log inflation rate as a function of $\log(S_t/P_t)$ over a 280 month simulation of the model using our benchmark calibration. A linear regression of log inflation on $\log(S_t/P_t)$ has an $R^2 = 0.989$. To allow for convenient aggregation, we also make use of log-linear approximations of the relationship between aggregate labor supply, aggregate intermediate product output and aggregate value-added output.

Given these assumptions, firm z's optimization problem may be written recursively in the form of the Bellman equation

$$V\left(A_t(z), \frac{p_{t-1}(z)}{P_t}, \frac{S_t}{P_t}\right) = \max_{p_t(z)} \left\{\Pi_t^R(z) + E_t\left[D_{t,t+1} V\left(A_{t+1}(z), \frac{p_t(z)}{P_{t+1}}, \frac{S_{t+1}}{P_{t+1}}\right)\right]\right\}, \tag{16}$$

where $V(\cdot)$ is firm z's value function and $\Pi_t^R(z)$ denotes firm z's profits in real terms at time t.[10]

An equilibrium in this economy is a set of stochastic processes for the endogenous price and quantity variables discussed above that are consistent with household utility maximization, firm profit maximization, market clearing and the evolution of the exogenous variables $A_t(z)$ and S_t. We use the following iterative procedure to solve for the equilibrium: 1) We specify a finite grid of points for the state variables, $A_t(z)$, $p_{t-1}(z)/P_t$ and S_t/P_t. 2) We propose a function $\Gamma(S_t/P_{t-1})$ on the grid. 3) Given the proposed Γ, we solve for the firm's policy function F by value function iteration on the grid. 4) We check whether Γ and F are consistent.[11] If so, we stop and use Γ and F to calculate other features of the equilibrium. If not, we update Γ and go back to step 3. We approximate the stochastic processes for $A_t(z)$ and S_t using the method proposed by Tauchen (1986).[12]

[10] In appendix A, we show how the firm's real profits can be written as a function of $(A_t(z), p_{t-1}(z)/P_t, S_t/P_t)$ and $p_t(z)$.

[11] We do this in the following way: First, we calculate the stationary distribution of the economy over $(A(z), p(z)/P, S/P)$ implied by Γ and F as described in appendix B. Second, we use the stationary distribution and equation (4) to calculate the price index implied by Γ—call it P_Γ—for each value of S/P. Third, we check whether $|P_\Gamma - P| < \xi$, where $|\cdot|$ denotes the sup-norm.

[12] A drawback of numerical methods of the type we employ in this paper is that it is difficult to prove uniqueness. The main feature of our model that potentially could generate non-uniqueness is the combination of strategic complementarity and menu costs (Ball and Romer, 1991). However, the large idiosyncratic shocks that we assume in our model significantly reduce the scope for multiplicity (Caballero and Engel, 1993). In particular, the type of multiplicity studied by Ball and Romer does not exist in our model since the large idiosyncratic shocks prevent sufficient synchronization across firms. In this respect our results are similar to John and Wolman (2004). It is also conceivable that our use of Krusell and Smith's approximation method could yield self-fulfilling approximate equilibria. There is, however, nothing in the economic link between agents beliefs and their pricing decision that suggests such self-fulfilling equilibria. In fact, the actual behavior of the price level in our model is quite insensitive to even relatively large changes in beliefs. The reason for this is that by far the most important factor in agent's decisions is movements in their idiosyncratic productivity levels as opposed to movements in aggregate variables. We solved our

2.3 Calibration

We focus attention on the behavior of the economy for a specific set of parameter values (see table 3). We set the monthly discount factor equal to $\beta = 0.96^{1/12}$. We assume log-utility in consumption ($\gamma = 1$). Following Hansen (1985) and Rogerson (1988), we assume linear disutility of labor ($\psi = 0$). We set ω such that in the flexible price steady state labor supply is 1/3. We set $\theta = 4$ to roughly match estimates of the elasticity of demand from the industrial organization and international trade literatures.[13] Our choices of $\mu = 0.002$ and $\sigma_\eta = 0.0037$ are based on the behavior of U.S. nominal and real GDP during the period 1998-2005. Since our model does not incorporate a secular trend in economic activity, we set μ equal to the mean growth rate of nominal GDP less the mean growth rate of real GDP. We set σ_η equal to the standard deviation of nominal GDP growth.

The parameter s_m denotes the cost share of intermediate inputs in the model. Table 4 contains information from the 2002 U.S. Input-Output Table published by the Bureau Economic Analysis. The table provides information about both the share of intermediate inputs in the gross output of each sector (column 1) and about how intensively the output of each sector is used as an intermediate input in other sectors (column 2). The revenue share of intermediate inputs varies from about 1/3 to about 2/3. It is highest in manufacturing and lowest in utilities. The use of different sectors as intermediate inputs is closely related to their weight in gross output. The main deviations are that the output of manufacturing and services are used somewhat more intensively as intermediate inputs than their weight in gross output would suggest while the output of the government sector and the construction sector are used less.

The weighted average revenue share of intermediate inputs in the U.S. private sector using CPI expenditure weights was roughly 52% in 2002. The input-output table treats health insurance as employee compensation rather than as an intermediate input. But roughly 35% of health expendi-

model with more sophisticated beliefs (additional moments) and starting our fixed point algorithm at various initial values. In all cases the resulting approximate fixed point is virtually identical.

[13] Berry et al. (1995) and Nevo (2001) find that markups vary a great deal across firms. The value of θ we choose implies a markup similar to the mean markup estimated by Berry et al. (1995) but slightly below the median markup found by Nevo (2001). Broda and Weinstein (2006) estimate elasticities of demand for a large array of disaggregated products using trade data. They report a median elasticity of demand below 3. Also, Burstein and Hellwig (2006) estimate an elasticity of demand near 5 using a menu cost model. Midrigan (2005) uses $\theta = 3$ while Golosov and Lucas (2006) use $\theta = 7$. The value of θ affects our calibration of the menu cost—a higher θ imply higher menu costs—and it affects our calibration of the intermediate input share—a higher θ implies lower values for s_m. Given the large size of price changes we observe, a high value of θ has extreme implications about quantity variation.

tures (roughly 5% of GDP) are paid by employers. For our purposes it seems appropriate to count these as intermediate inputs. This raises the share of intermediate inputs in revenue to roughly 56%. The cost share of intermediate inputs is equal to the revenue share times the markup. Our calibration of θ implies a markup of 1.33. Our estimate of the weighted average cost share of intermediate inputs is therefore roughly 75%.

This calibration depends on a number of assumptions. Alternative assumptions yield estimates of the intermediate inputs share that are either lower or higher. Above we employed CPI weights as we do elsewhere in the paper. Using gross output weights would yield a slightly lower number (68% rather than 75%) since services have a higher weight in gross output than in the CPI. However, increasing the weight of services would also lower the mean frequency of price change and increase the skewness of the frequency distribution. A higher value for the elasticity of demand would also yield a lower intermediate input share. For example, Golosov and Lucas (2006) use $\theta = 7$. This would yield and intermediate input share equal to 65% rather than 75%. On the other hand, we have assumed that intermediate inputs make up the same fraction of marginal costs as they do average variable costs. With a more general production structure, this is not necessarily the case. Materials might be disporportionately important at the margin, in which case the share of intermediate inputs in marginal costs would be higher than we estimate. Also, intermediate input use is skewed toward the more flexible sectors of the economy (manufacturing as opposed to services) while the more sticky sectors make up most of the intermediate inputs (services rather than manufacturing). This should imply that marginal costs move more sluggishly than our simple model with complete symmetry suggests. Given the uncertainty associated with these factors, we report results for $s_m = 0.65$ and $s_m = 0.85$ as well as $s_m = 0.75$.[14]

We set the menu cost K and the standard deviation of the idiosyncratic shocks σ_ϵ for each case we consider below to match moments of the distribution of the frequency and size of price changes reported in table 2. For computational reasons, we set the speed of mean reversion of the firm productivity process equal to $\rho = 0.7$. This value is close to the value we estimate for ρ in

[14]Basu (1995) argues for values of the parameter s_m between 0.8 and 0.9. Bergin and Feenstra (2000) also focus on values of s_m between 0.8 and 0.9. Other authors—e.g., Rotemberg and Woodford (1995), Chari et al. (1996) and Woodford (2003, ch. 3)—use values closer to $s_m = 0.5$. The lower values of s_m are based on much lower calibrations of the markup of prices over marginal costs than we use. These low markups are meant to match the fact that pure profits are a relatively small fraction of GDP in the U.S.. We base our calibration of the markup of prices over marginal costs on evidence from the industrial organization and international trade literature. These high markups are consistent with small pure profits if firms have fixed costs and/or if firm entry involves sunk investment costs that must be recouped with flow profits post-entry (Dixit and Pindyck, 1994; Ryan, 2006).

Nakamura and Steinsson (2006).

The assumption of round-about production implicitly assumes that prices are rigid to both consumers and producers. Direct evidence on producer prices from Carlton's (1986) work on the Stigler-Kindahl dataset as well as Blinder et al.'s (1998) survey of firm managers supports the view that price rigidity is an important phenomenon at intermediate stages of production. Nakamura and Steinsson (2006) present a more comprehensive analysis of producer prices based on the micro-data underlying the producer price index and find that the rigidity of producer prices is comparable to the rigidity of non-sale consumer prices. The median frequency of price change of finished goods and intermediate goods producer prices is 10.8% and 14.3%, respectively, while the median frequency of price change of consumer prices is 8.7% (see table 2). Moreover, table 5 shows that the frequency of non-sale consumer price changes is highly correlated across sectors with the frequency of producer price change in that same sector. We match detailed CPI categories with detailed PPI categories and compare the frequency of price change. Over the 153 matches, the correlation between the frequency of price change for producer prices and consumer prices excluding sales is 0.83.

2.4 Results

Table 6 presents results for several calibrations of our menu cost model. We present results for four different values of s_m. In rows (1) through (4), we choose the menu cost and the variance of the idiosyncratic shocks to match the mean frequency of price change of U.S. CPI prices reported in table 2, while in rows (5) through (8) we choose these parameters to match the median frequency of price change. For clarity, in all cases we calibrate the model to match the median size of price changes.

We report the menu cost as a fraction of steady state monthly revenues under flexible prices.[15] In all cases considered in table 6, the size of the menu cost is quite modest—0.3-2% of steady state monthly revenue. Since the firm only pays the menu cost every 5 to 10 months, the resources devoted to changing prices as a fraction of revenue over a typical year are about 0.2% in the model without intermediate inputs and 0.05% in the model with intermediate inputs ($s_m = 0.75$).[16]

Figure 3 plots a sample path for the model with intermediate inputs calibrated to the median

[15] That is, the menu cost we report in table 6 is $((\theta-1)/\theta)(K/Y_{ss})$, where K is the menu cost in units of labor, $(\theta-1)/\theta$ is the steady state real wage under flexible prices and Y_{ss} denotes flexible price steady state gross output.

[16] Levy at al. (1997) estimate the menu costs of a large U.S. supermarket chain to be 0.7% of revenue.

frequency of price change. The variance of the idiosyncratic shocks is many times larger than the variance of the shocks to nominal aggregate demand. This is crucial for generating price changes sufficiently large to match the data, as well as the substantial number of price decreases observed in the data, a point emphasized by Golosov and Lucas (2006).

Our primary interest is the degree of monetary non-neutrality generated by the model. We report two measures of monetary non-neutrality. Our primary measure is the cumulative impulse response (CIR) of real value-added output to a permanent shock to nominal aggregate demand. More precisely, we consider the following experiment: Starting from steady state at time 0, the economy is hit by a nominal shock $\eta_0 = \delta$.[17] We assume that no subsequent shocks occur and calculate the response of the price level and real value-added output to the shock. The response of these variables for our baseline model—the model with intermediate inputs and calibrated to the median frequency of price change—are shown in figures 4 and 5. Both the price level and real output converge monotonically to their steady state values with a half-life of between 4 and 5 months. The cumulative impulse response of real value-added output is equal to the cumulative difference between actual output and steady state output after the shock occurs (the area under the impulse response function in figure 5).[18]

While the CIR of real value-added output is convenient due to its simplicity and intuitive appeal, it is an imperfect measure of the degree of monetary non-neutrality if the relationship between inflation and real aggregate demand is non-linear in logs. This is due to the fact that the CIR measures the response of output for a shock of a particular size and it does not scale with the size of the shock unless the model is log-linear. Fortunately, the relationship between inflation and aggregate demand is close to being log-linear in our model. Figure 2 illustrates this by plotting log inflation as a function of $\log(S_t/P_{t-1})$ for a 280 period simulation of our baseline case. The function $\Gamma(S_t/P_{t-1})$ is almost identical to the regression line plotted through these points. We however also report the variance of real value-added output as a alternative measure of monetary non-neutrality. In a linear AR(1) model, the CIR of output and the variance of output are proportional.

The last two columns of table 6 report the CIR and variance of real value-added output. Allow-

[17]We set δ equal to the standard deviation of the change in nominal aggregate demand. We then normalize the CIR by multiplying it by $0.01/\delta$. If the model where exactly log-linear, the CIR number we report would therefore be equal to the cumulative output response to a one percent shock to nominal aggregate demand.

[18]The CIR has been used as a measure of monetary non-neutrality, e.g., by Christiano et al. (2005) and Carvalho (2006). Andrews and Chen (1994) argue that the CIR is a good measure of persistence in an AR(p) model.

ing for intermediate products ($s_m = 0.75$) raises the CIR by a factor of 2.6-3.2 depending on the frequency of price change. The variance of output is amplified by a slightly larger amount—a factor of between 2.9-4.0. This amplification of the monetary non-neutrality results from the fact that the pricing decisions of firms are strategic complements in the model with intermediate products.

The logic behind this amplification is simple to illustrate. Given our calibration of $\gamma = 1$ and $\psi = 0$, the labor supply curve is $W_t/P_t = \omega C_t$. Using $S_t = P_t C_t$, we can rewrite labor supply as $W_t = \omega S_t$. In other word, nominal wages are proportional to nominal value-added output. A firm with perfectly flexible prices would set its price equal to a constant markup over marginal costs. This "desired price" equals

$$\tilde{p}_t(z) = \frac{\kappa\theta}{\theta - 1} \frac{W_t^{1-s_m} P_t^{s_m}}{A_t(z)}. \tag{17}$$

Equation (17) implies that when $s_m = 0$ the firm's marginal costs are proportional to the nominal wage. A one percent rise in S_t therefore raises the firm's desired price by one percent if $s_m = 0$. In contrast, when the firm uses intermediate inputs, its marginal costs are proportional to a weighted average of the nominal wage and the price level with the weight on the price level being equal to s_m. Since the price level responds sluggishly to an increase in S_t when firms face menu costs, the firm's marginal costs rise by less then one-percent in response to a one-percent increase in S_t when $s_m > 0$. As a consequence, firms that change their price soon after a shock to S_t choose a lower price than they otherwise would because the price of many of their inputs have not yet responded to the shock.[19]

Recent work has cast doubt on strategic complementarity as a source of amplification in menu cost models with idiosyncratic shocks by showing that the introduction of strategic complementarity can make it difficult to match the large observed size of price changes for plausible values of the menu cost and the variance of the idiosyncratic shocks. Klenow and Willis (2006) show that a model with demand-side strategic complementarity of the type emphasized by Kimball (1995) requires massive idiosyncratic shocks and implausibly large menu costs to match the size of price changes observed in the data. Golosov and Lucas (2006) note that their model generates price changes that are much smaller than those observed in the data when they consider a production

[19] The firm's profit function in our model simply implies that a fraction $1 - s_m$ of costs are proportional to S_t while a fraction s_m are proportional to P_t. In the derivation of this equation, we assume that the "flexible" input is labor and the "sluggish" input is intermediate inputs. However, this profit function is consistent with other models in which, e.g., wages are sluggish (Burstein and Hellwig, 2006) and perhaps some other input—such as a commodity—is flexible.

function with diminishing returns to scale due to a fixed factor of production. Burstein and Hellwig (2006) use supermarket scanner data to calibrate a model with a fixed factor of production and both demand and supply shocks. They find that even with large demand shocks, a substantial amount of strategic complementarity requires large menu costs to match the micro data on the size of price changes.

Table 7 illustrates this point for a model with a fixed factor of production implying a production function $y_t(z) = A_t(z)L_t(z)^a$. The first row of the table presents results for this model with $a = 1$ as a benchmark.[20] In the second row of the table we hold the variance of the idiosyncratic shock constant but set $a = 2/3$ and vary the menu cost to match the frequency of price change. The average absolute size of price changes that results is less than half as large as in the data. In the third row, we match both the frequency and size of price changes in the data by recalibrating both the menu cost and the variance of the idiosyncratic shock. Matching the data requires extremely large shocks and menu costs.

In contrast, strategic complementarity caused by firms' use of intermediate inputs does not affect the size of price changes or require unrealistically large menu costs and idiosyncratic shocks. The reason for this difference can be illustrated using a dichotomy developed by Ball and Romer (1990) and Kimball (1995). A firm's period t profit function may be written as $\Pi(p_t/P_t, S_t/P_t, \tilde{A}_t)$, where p_t/P_t is the firm's relative price, S_t/P_t denotes real aggregate demand and $\tilde{A}_t$ denotes a vector of all other variables that enter the firms period t profit function. The firm's desired price under flexible prices is then given by $\Pi_1(p_t/P_t, S_t/P_t, \tilde{A}_t) = 0$, where the subscript on the function Π denotes a partial derivative. Notice that

$$\frac{\partial p_t}{\partial P_t} = 1 + \frac{\Pi_{12}}{\Pi_{11}}. \tag{18}$$

Pricing decisions are strategic complements if $\zeta = -\Pi_{12}/\Pi_{11} < 1$ and strategic substitutes otherwise.[21] Following Ball and Romer (1990), we can divide mechanisms for generating strategic complementarity into two classes: 1) those that raise $-\Pi_{11}$, and 2) those that lower Π_{12}. We refer to these two classes as ω-type strategic complementarity and Ω-type strategic complementarity, respectively.[22] Mechanisms that generate ω-type strategic complementarity include local

[20] In table 7 we set $\theta = 7$ for comparability with Golosov and Lucas (2006). In the fixed factor model, the degree of strategic complementarity is increasing in θ.

[21] At the equilibrium $\Pi_{11} < 0$ and $\Pi_{12} > 0$.

[22] These names are based on the notation used by Kimball (1995).

labor markets, non-isoelastic demand and fixed factors of production. Mechanisms that generate Ω-type strategic complementarity include real wage rigidity and sticky intermediate inputs. Notice that $\partial p_t / \partial \tilde{A}_t = -\Pi_{13}/\Pi_{11}$. This implies that ω-type strategic complementarity mutes the response of the firm's desired price to other variables such as idiosyncratic shocks, while Ω-type strategic complementarity does not. Models with a large amount of ω-type strategic complementarity will therefore have trouble matching the large size of price changes seen in the micro-data, while this problem will not arise in models with a large amount of Ω-type strategic complementarity.

The key difference is that strategic complementarity due to intermediate inputs only affects the firm's response to aggregate shocks while strategic complementarity due to a fixed factor or non-isoelastic demand mutes the firm's response to both aggregate shocks and idiosyncratic shocks. In the model with a fixed factor, the firm's marginal product of labor increases as its level of production falls. The firm's marginal costs therefore fall as it raises its price in response to a fall in productivity, since a higher price leads to lower demand. This endogenous feedback of the firm's price on its marginal costs counteracts the original effect that the fall in productivity had on marginal costs and leads the firms desired price to rise by less than it otherwise would. In the model with intermediate inputs, the firm's marginal cost is not affected by its own pricing decision. The strategic complementarity in the model with intermediate inputs arises because of the rigidity of other firms' prices rather than because of endogenous feedback on marginal costs from the firm's own pricing decision.

Gertler and Leahy (2006) explore an alternative menu cost model with strategic complementarity that does not affect the size of price changes. Their model has sector specific labor markets in which firms receive periodic idiosyncratic shocks. They assume that in each period firms in only a fraction of sectors receive idiosyncratic shocks. The resulting staggering of price changes across sectors generates strategic complementarity that amplifies the monetary non-neutrality in their model. The fact that the labor market is segmented at the sectoral level rather than the firm level avoids endogenous feedback on marginal costs from the firms' own pricing decisions and allows their model to match the size of price changes without resorting to large shocks or large menu costs.[23]

[23] An important driving force behind the strategic complementarity in Gertler and Leahy's model is the assumption of staggering of price changes across sectors. If an equal fraction of firms in each sector received an idiosyncratic shock and changed their price in each period their model would not generate strategic complementarity. An alternative mechanism for generating strategic complementarity in a model with segmented labor markets is to allow for

3 The CalvoPlus Model

In this section, we introduce a model in which price changes are largely time-dependent as a benchmark for comparision purposes. The model in section 2 makes the simplifying assumption that the menu cost K is constant. This assumption implies that a firm's decision about whether to change its price is based entirely on the external economic environment that the firm faces. There are however a number of factors that could generate variation in the costs of price adjustment including information acquisition by the firm that is undertaken for other reasons than to make pricing decisions, economies of scale in decision-making, product upgrades, the introduction of new products and variation in managerial workload. Blinder et al. (1998) report that managers in 60% of firms say they have "customary time intervals ... between price reviews". Zbaracki et al. (2004) discuss the existence of a "pricing season" at firms that occurs at regular intervals during the year. Recent empirical evidence has furthermore found support for some time-dependent elements in pricing. Bils and Klenow (2004) present evidence that product substitutions are frequent in many sectors of the U.S. economy. Nakamura and Steinsson (2006) find evidence of a spike in the hazard function of price change at 12 months as well as evidence of seasonality in the frequency of price change for U.S. CPI and PPI prices.[24]

The goal of this section is to develop a model that captures the idea that repricing may be less costly at some points in time than others. The most widely used model with this feature is the model of Calvo (1983).[25] In this model, price changes are free with probability $(1-\alpha)$ but have infinite cost with probability α. These extreme assumptions make the Calvo model highly tractable. However, they also cause the model to run into severe trouble in the presence of large idiosyncratic shocks or a modest amount of steady state inflation.[26] The reason is that the firm's implicit desire to change its price can be very large and it frequently prefers to shut down rather than continue producing at its pre-set price. As we discuss below, the Calvo model is also unable

heterogeneity across sectors in the frequency of price change. We simulated a 6-sector menu cost model with sector specific labor markets in which the frequency and size of price change was calibrated to match the mean of these statistics in different of the U.S. economy. We found that this multi-sector menu cost model was not able to generate a quantitatively significant degree of strategic complementarity.

[24]Baumgartner et al. (2005), Álvarez et al. (2005a), Jenker et al. (2004), Dias et al. (2005), Fougere et al. (2005), Álvarez et al. (2005b) and Dhyne et al. (2006) present analogous results for consumer prices in Europe.

[25]Examples of papers that use the Calvo model include Christiano et al. (2005) and Clarida et al. (1999). An alternative "time-dependent" price setting model was proposed by Taylor (1980). Examples of papers that have used the Taylor model include Chari et al. (2000).

[26]See Bakhshi et al. (2006) for an analysis of the latter issue.

to match the average size of price changes observed in the data for reasonable parameter values.

Rather than assuming that price changes are either free or infinitely costly, we assume that with probability $(1-\alpha)$ the firm faces a low menu cost K_l, while with probability α it faces a high menu cost K_h. These assumptions are meant to capture the idea that the timing of some price changes are largely orthogonal to the firm's desire to change its price in a more realistic way than the Calvo model does but at the same time to retain the tractability of the Calvo model. We refer to this model as the "CalvoPlus" model. The CalvoPlus model has the appealing feature that it nests both the Calvo model and the menu cost model as special cases.[27]

We can use the CalvoPlus model to illustrate the deficiencies of the Calvo model. The first two rows of table 8 present results for a calibration of the CalvoPlus model that closely approximates the Calvo model. We set $K_l = 0$, $\alpha = 1 - 0.087$ and K_h high enough that 99% of price changes occur in the low menu cost state. In the first row, we set the standard deviation of the idiosyncratic shocks σ_ϵ equal to the value we use for the menu cost model. To prevent the firm from changing prices in the high menu cost state, we must set the menu cost in the high menu cost state equal to 30% of monthly revenue. Also, the average size of price change is less than 1/3 the value observed in the data. In the second row, we quadruple the size of the idiosyncratic shocks. In this case, the menu cost in the high menu cost state must be truly huge—1.5 times monthly revenue—to prevent price changes in this state, but the average size of price changes is still considerably smaller than in the data.

Suppose instead that the menu cost in the low cost state is small but not zero. Rows 3 through 5 of table 8 present the implications of assuming that the menu cost in the low menu cost state is 0.001, 0.0025 and 0.005 of monthly revenue, respectively. In these cases, we calibrate K_h and σ_ϵ to match the frequency and size of price changes in the data. Even for these modest values of the menu cost in the low menu cost state, the behavior of the CalvoPlus model is dramatically different. The model is able to match the size of price changes in the data without resorting to implausibly high values of K_h and σ_ϵ. When the menu cost in the low menu cost state is 1/4% of monthly revenue, the CalvoPlus model matches the frequency and size of price changes in the data with a menu cost in the high state equal to 11.3% of monthly revenue and a standard deviation of idiosyncratic shocks equal to 7.25%.

[27] Caballero and Engel (2006) analyze a similar hybrid model. In their model, firms generally face a menu cost but randomly get an opportunity to change prices for free.

We use the CalvoPlus model as a benchmark against which we compare the monetary non-neutrality in the menu cost model. Table 9 shows that the incorporation of intermediate goods has a similar effect in the CalvoPlus model as it does in the menu cost model considered in section 2. In this table, we assume that $K_l = K_h/40$. This calibration of the CalvoPlus model implies that roughly 75% of price changes occur in the low menu cost state. As in table 6, we consider four values for s_m—0, 0.65, 0.75 and 0.85—and we choose K_h and σ_ϵ to match either the mean or median frequency of price change as well as the median size of price changes. We set $(1 - \alpha)$ equal to the frequency of price change, i.e., 8.7% or 21.1%. In all four cases, the CalvoPlus model calibrated in this way yields a CIR that is about twice the size of the CIR for the menu cost model in table 6. As with the menu cost model, the incorporation of intermediate inputs roughly triples the CIR for $s_m = 0.75$.

Golosov and Lucas (2006) emphasize the fact that in the menu cost model firms are not selected at random to change their prices. Rather the firms that change their prices are the firms that have the largest desire to change their price. Golosov and Lucas (2006) show that this "selection effect" reduces the degree of monetary non-neutrality generated by their menu cost model by a factor of 5 relative to the Calvo model. The CalvoPlus model provides a useful framework for analyzing the robustness of this conclusion. Is the degree of monetary non-neutrality in a model in which a modest fraction of price changes occur due to an exogenous opportunity to change prices rather than a large desire to change prices close to what it is in the Calvo model? Or is it closer to the degree of monetary non-neutrality in the menu cost model?

Figure 6 plots the CIR of real value-added output to a shock to nominal aggregate demand as the fraction of price changes in the low menu cost state varies from zero to one. In this experiment, we fix $\alpha = 1 - 0.087$ and $\sigma_\epsilon = 0.0425$ and vary K_h and K_l so that the model matches the median frequency of price changes in the data and a particular fraction of price changes in the low menu cost state. This figure shows that the degree of monetary non-neutrality drops off rapidly as the fraction of price changes in the low cost state falls below 100%. When 85% of price changes occur in the low menu cost state, the CIR is less than half of what it is when all of price changes occur in the low cost state. When 50% of price changes occur in the low menu cost state, the CIR is close to identical to the value in the constant menu cost model. Figure 6 therefore suggests that the relatively large amount of monetary non-neutrality generated by the Calvo model is quite sensitive to even a modest amount of selection by firms regarding the timing of price changes.

4 The Multi-Sector Model

How does the distribution of price changes across sectors in the economy affect the degree of monetary non-neutrality that results from price rigidity? To address this question, we analyze a multi-sector version of the model developed in section 2. The firms in different sectors of our multi-sector model differ in the size of their menu cost K and the variance of their idiosyncratic productivity shock σ_ϵ. Otherwise, the model is identical to the single-sector model in section 2. In particular, we assume that consumption index—equation (2)—and the price index—equation (4)—are the same as in the single sector model.

We calibrate the sectors based on the empirical evidence on the frequency and size of price changes excluding sales in consumer prices across sectors of the U.S. economy presented in Nakamura and Steinsson (2006).[28] We group goods with similar price change characteristics into 6 sectors, 9 sectors and 14 sector. Table 10 presents the mean frequency and mean absolute size of price changes for these sectors.[29] Both the frequency and size of price changes varies enormously across sectors. There is no simple relationship between the frequency of price change and the size of price changes. To the contrary, sectors with very similar frequencies of price change have very different average sizes and vice versa (see figure 7). The distribution of the frequency of price change is highly asymmetric. The right tail being much longer than the left tail. This is evident from the fact that the median frequency of price change in the economy is 8.7% while the mean is 21.1% (see table 2).

We parameterize the multi-sector model by minimizing the difference between the frequency and absolute size of price changes predicted by the model and the empirical statistics. Table 11 presents the parameterization of the menu cost and the variance of the idiosyncratic shocks at the sectoral level. As in the single sector model, the menu costs required to generate the observed size and frequency of price change are less than half as large when we allow for intermediate goods. Both versions of the model are able to match the observed size and frequency of price change in all

[28] We have also used the distribution of the frequency of price change including sales. We find that both of these distributions yield a similar results regarding amplification of monetary non-neutrality due to heterogeneity.

[29] To be able to aggregate the sectors easily, we calibrate the multi-sector models to the mean frequency and mean absolute size of price change at the sectoral level. The difference between the mean and median are small at this level of aggregation. See Table 1 for a comparison of means and medians at the sector level.

sectors exactly. As in the single-sector model, we assume that the firms perceive inflation as being a function of only S_t/P_{t-1}. Figure 8 plots the actual log inflation rate as a function of $\log(S_t/P_t)$ over a 280 month simulation of the 6 sector model using our benchmark calibration. A linear regression of log inflation on $\log(S_t/P_t)$ has an $R^2 = 0.979$.

Table 12 presents our two measures of monetary non-neutrality for the multi-sector model with and without idiosyncratic shocks. Panel A of table 12 presents the CIR of real value-added output to a shock to nominal aggregate demand, while panel B presents the variance of real value-added output. Both measures of monetary non-neutrality are increasing in the degree of heterogeneity. The 14-sector model with intermediate goods yields a CIR of 4.2%. This is slightly less than three times the CIR of the one sector model calibrated to the mean frequency of price change across all firms and roughly equal to the CIR of the one sector model calibrated to the median frequency of price change across all firms. For the model without strategic complementarity, the 14 sector model yields a CIR of 1.6%, also approximately triple the CIR of the one sector model calibrated to the mean. The degree of amplification due to heterogeneity is similar when it is measured using the variance real value-added output.

How important a role in economic fluctuations does our menu cost model suggest for monetary non-neutrality? The standard deviation of HP-filtered U.S. real GDP for 1960-2006 is 1.5%. The standard deviation of real output in a simulation of our multi-sector model with intermediate inputs is 0.5%. Our model therefore generates monetary non-neutrality that amounts to roughly 1/3 of the business cycle. In contrast, the standard devation of real output in a simulation of our single sector model without intermediate inputs is only 0.13%—less than 10% of the business cycle. Golosov and Lucas (2006) analyze a model that is virtually identical to this latter model and conclude that monetary non-neutrality "small and transient".[30]

We also consider multi-sector versions of the CalvoPlus model. In the multi-sector CalvoPlus model, we allow the probability of a low menu cost $1 - \alpha$ to vary across sectors as well as the magnitude of the menu costs and the idiosyncratic shock. We set the probability of a low menu

[30] Evidence from structural VARs suggests that output responds with a lag to monetary distrubances and that the response of output is hump-shaped. While our model generates a substantial amount of monetary non-neutrality, it does not generate these features. A large recent literature has combined nominal price rigidities with a number of other frictions such as decision lags, nominal wage rigidity, habit formation and capital adjustment costs in order to match the response of the economy to monetary shocks (Rotemberg and Woodford, 1997; Christiano et al., 2005; Smets and Wouters, 2003). Introducing these types of frictions into a menu cost model of the type we study is a promising area for future research.

cost equal to the frequency of price change in each sector. We again set $K_l = K_h/40$. We then calibrate K_h and σ_ϵ to match the mean frequency and mean absolute size of price changes in each sector. The parameter values are presented in table 11. As in the multi-sector menu cost models, the multi-sector CalvoPlus models are able to exactly match these empirical moments.

Table 12 presents the results on monetary non-neutrality in the multi-sector CalvoPlus model. As in the menu cost model, we find that heterogeneity amplifies the degree of monetary non-neutrality by roughly a factor of three relative to the single sector model calibrated to the mean frequency of price change of all firms. The degree of amplification due to heterogeneity is somewhat larger in the CalvoPlus model with intermediate inputs than it is in the CalvoPlus model without intermediate inputs. This interaction between strategic complementarity and heterogeneity is consistent with the findings of Carvalho (2006). This interaction does not, however, exist in the pure menu cost model.

4.1 Understanding the Effect of Heterogeneity

To understand the effect of heterogeneity on the degree of monetary non-neutrality, it is useful to analyze the relationship between the frequency of price change and the CIR in the single-sector menu cost model. Figure 9 plots the CIR of the single-sector model as a function of the frequency of price change holding the average log absolute size of price changes constant at 8.5%. The CIR is highly convex as function of the frequency of price change.

With two simplifying assumptions, we can illustrate what drives the convexity of the CIR in figure 9. First, assume that the frequency of price change f_t in the menu cost model is constant at f. Panel A of figure 10 is a scatter plot of the frequency of price change as a function of $\log(S_t/P_{t-1})$ for a 800 period simulation of our menu cost model. The large variance of the idiosyncratic shocks in our model imply that the frequency of price change in fact does not vary greatly relative to its overall level. Second, assume that the average log size of price changes is linear in $\log(S_t/P_{t-1})$, i.e., $s_t = \nu \log(S_t/P_{t-1})$.[31] Panel B of figure 10 is a scatter plot of the average log size of price change as a function of real value-added output for a 800 period simulation of our menu cost model. The average log size of price changes is in fact approximately linear in $\log(S_t/P_{t-1})$ in our model.

Given these assumptions, it is simple to calculate the CIR of real value-added output to a

[31] Notice, that here we are making an assumption about the average size of price changes, not the average absolute size.

permanent increase in nominal aggregate demand that occurs in period 0 of size δ. For simplicity, we normalize $\log P_{-1} = 0$ and $\log C_{-1} = 0$. In period 0, $\log(S_0/P_{-1}) = \delta$. This implies that $\log P_0 = s_0 f = \nu\delta f$ and $\log C_0 = \delta - \log P_0 = (1-\nu f)\delta$. In period 1, $\log(S_1/P_0) = (1-\nu f)\delta$. This implies that $\log P_1 = s_1 f = (1-\nu f)\delta f$ and $\log C_1 = \delta - \log P_1 = \delta - (1-\nu f)\delta f = (1-\nu f)^2\delta$. Iterating this procedure yields

$$\log C_j = (1-\nu f)^{j+1}\delta.$$

This implies that

$$\text{CIR} = \sum_{j=0}^{\infty} \log C_j = \frac{1-\nu f}{\nu f}\delta$$

which is highly convex in the frequency of price change. Using the property of renewal processes that $E(d) = 1/f$, where $E(d)$ denotes the expected duration of price spells,[32] it furthermore follows that

$$\text{CIR} = \frac{\delta}{\nu}E(d) - \delta. \tag{19}$$

Equation (19) shows that the CIR is linear in the expected duration of price changes given our two simplifying assumptions. Figure 11 plots the CIR for our single-sector menu cost model as a function the expected duration of price spells, holding constant the average absolute size of price changes. It shows that the CIR is indeed approximately linear in the expected duration of price spells.

Carvalho (2006) proves that a similar property holds up to a linear approximation in the Calvo model. A key difference between the Calvo model and the menu cost model is that $\nu = 1$ in the Calvo model whereas ν is substantially larger than one in the menu cost model. In the Calvo model, the firms that change their price are chosen randomly. This implies that the average size of price changes is equal to the average amount by which prices differ from their desired level. In other words, $\nu = 1$ in the Calvo model. In the menu cost model, however, the firms that change their prices in response to a positive shock to a nominal aggregate demand are disproportionately those that have the lowest real prices before the shock. This selection effect implies that the average size of price changes is larger than the average difference between the current prices and their desired levels, i.e., $\nu > 1$.

[32]This property does not rely on the assumption of a constant hazard. Theorem 1 in Chapter 5 of Lancaster (1990) states that for any renewal processes with constant expected duration and finite variance of durations, the frequency of price change converges to the reciprocal of the expected duration in a large sample.

In general, menu cost models need not generate a convex relationship between the frequency of price change and the degree of monetary non-neutrality. This relationship can be linear or concave if the selection effect is strong enough. One way to increase the strength of the selection effect is to raise the average inflation rate and lower the variance of the idiosyncratic shocks. Intuitively, this moves the model closer to the assumptions in Caplin and Spulber (1987). Figure 12 plots the variance of value added output as a function of the frequency of price change for a high inflation/small idiosyncratic shocks case—specifically, $\mu = 0.01$ and $\sigma_\epsilon = 0.01$—as well as for our benchmark calibration—$\mu = 0.002$ and $\sigma_\epsilon = 0.0425$. In the high inflation/small idiosyncratic shocks case, the degree of monetary non-neutrality is smaller than in the benchmark calibration for each frequency of price change. Furthermore, the degree of monetary non-neutrality is much less convex in the frequency of price change than it is in our benchmark calibration.

4.2 Heterogeneity and Sectoral Output

The relatively modest response of aggregate value-added output to aggregate demand shocks in the model without intermediate inputs masks much larger responses of output in individual sectors. Figure 13 plots the response of aggregate output and sectoral output to an expansionary demand shock in our 14 sector model without intermediate inputs. The sectoral responses vary greatly. Output in the sectors with most price rigidity rises by several times as much as aggregate output, while output in the sectors with most price flexibility falls sharply.

In the model without intermediate inputs, the desired price of all firms rises approximately one-for-one in percentage terms with nominal aggregate demand and is approximately independent of the prices charged by other firms—equation (17) with $s_m = 0$. As a consequence, the sectoral price index in sectors with a high frequency of price change—such as gasoline—quickly rises proportionally to the shock, while the sectoral price index in sectors with more rigid prices adjusts more slowly. This causes the prices in the sectors with most flexible prices to rise sharply relative to the prices in the sectors with more rigid prices. This change in relative prices leads consumers to shift expenditures toward the sectors in which prices are more rigid. In the model without intermediate inputs, this expenditure switching effect is strong enough that output in the sectors with most flexible prices falls after the demand shock. We simulate the model for 600 periods and find that the heterogeneity in price flexibility implies that the correlation of output in different sectors with aggregate output ranges from -0.99 to 0.95, with output in the sticky price sectors being highly positively correlated with aggregate output while output in the flexible price sectors is highly negatively correlated with aggregate output.[33]

In contrast, in the model with intermediate goods, a firm's desired price is heavily dependent on the prices of other firms—equation (17) with $s_m = 0.75$. Since the prices of other firms make up a large component of the marginal costs of all firms, the higher are other firms' prices, the higher is any particular firm's desired price. This leads to a strikingly different response of sectoral output to aggregate demand shocks.

Figure 14 plots the response of aggregate output and sectoral output to an expansionary demand shock in our 14 sector model with intermediate inputs. Since each firm's desired price is heavily dependent on other firms' prices, even sectors with highly flexible prices do not raise their prices immediately by the full amount of the increase in nominal aggregate demand. Instead, they adjust their prices more gradually. This leads to far smaller differences in relative prices across sectors and far greater comovement in output across sectors. Figure 14 shows that output in all sectors rises sharply in response to an expansionary demand shock. As a consequence, in a 600 period simulation of the 14 sector model with intermediate inputs, the correlation of output in different sectors with aggregate output is positive for all sectors, ranging from 0.05 to 0.99.

A key characteristic of business cycles is that virtually all sectors of the economy comove strongly (Lucas, 1977; Stock and Watson, 1999). The lack of comovement across sectors in the multi-sector model without intermediate inputs is therefore grossly at odds with the data.[34] This lack of comovement across sectors in models with heterogeneity in the degree of price flexibility has been noted and analyzed by several recent papers including Bils et al. (2003), Barsky et al. (2003) and Carlstrom and Fuerst (2006). The discussion above shows that allowing for intermediate goods substantially increases the comovement between different sectors of the economy.[35] Barsky et al. (2003) present a number of alternative mechanisms for ameliorating this "comovement problem".

[33] The magnitude of the expenditure switching effect depends on the elasticity of substitution across sectors, which we assume is equal to 4. The effect would be smaller for a smaller assumed elasticity across sectors. Barsky et al. (2003) show that the expenditure switching effect can be large in the presence of durable goods even if the elasticity of substitution between sectors is small.

[34] It is easy to show that aggregate productivity shocks lead to similar lack of comovement across sectors.

[35] Hornstein and Praschnik (1997), Dupor (1999) and Horvath (2000) discuss the effects of input-output linkages for comovement in a real business cycle framework.

4.3 Product Introduction

The menu cost model we have been analyzing up until now in this paper implicitly assumes that products are infinitely lived. In fact, however, product turnover is quite rapid in certain sectors of the economy. When a firm introduces a new product, it must necessarily set a new price for this product. Rapid product turnover can therefore affect the degree of price flexibility in the economy. Furthermore, since firms can often anticipate future product turnover—e.g., fall-spring turnover in apparel—they may decide not to incur the fixed cost needed to change the price of an existing product.

Table 10 reports the frequency of product substitution for the sectors in our multi-sector models. [36] Table 10 reveals that product substitution is a frequent occurrence in several categories of durable goods—Apparel, Transportation Goods (Cars), Household Furnishing and Recreation Goods—but less frequent for other products. A number of these categories—especially Apparel—have a very low frequency of price change. Since our results regarding amplification due to heterogeneity rely heavily outlying sectors such as Apparel, it is important to understand how accounting for product flexibility affects our results.

Many factors influence a firm's decision about the introduction of a new product. These include seasonality, development cycles, innovation and random shifts in consumer tastes. Figure 15 plots the frequency of product substitution across different months of the year for the four categories for which product substitution is most frequent. In Apparel, seasonal variation in tastes seems to be a dominant factor in the timing of product introduction. In the automobile industry, product introduction seems to be heavily influenced by a yearly development cycle with new models being introduced in the fall of each year.

This evidence suggests that product turnover may be largely orthogonal to a firm's desire to change its price and to macroeconomic conditions. A computationally tractable way of modelling this type of event is to consider a model in which new products arrive according to an exogenous Poisson process. This model is equivalent to the CalvoPlus model where $K_l = 0$ and $1 - \alpha$ in each

[36] Ideally we would have a measure of the rate of product introduction since pricing decisions are made when new products are introduced. However, the BLS does not tract the introduction of new products. When a product that the BLS has been tracking becomes permanently unavailable, the BLS agent is instructed to substitute to the most similar existing product. In most cases this product will have existed for some time. If the hazard of product exit is upward sloping, the frequency of product substitution is therefore an upward biased measure of the frequency of product introduction.

sector is equal to the frequency of product substitution. The menu cost in the high cost state is calibrated so that the frequency of high cost price changes in the model matches the frequency of price change in the data for each sector.

Table 13 shows that product turnover associated with factors unrelated to the firms' pricing decisions have little effect on the monetary non-neutrality implied by the model. This is because the "selection effect" applies only to the regular price changes. While new fashions are priced to keep up with inflation, they are not (in this model) introduced *because* the old fashions were mispriced. For comparison purposes, table 13 also presents results for a calibration of the menu cost model where we treat product introductions as if they were in the same as regular price changes. In this case, the shorter durations of prices associated with "product flexibility" would have a much larger effect on monetary non-neutrality. In either case, the inclusion of product substitutions in the model has little effect on the amplification effect associated with heterogeneity.

5 Conclusion

This paper analyzes the responsiveness of real output to monetary shocks in a multi-sector menu cost model that allows for intermediate goods. We calibrate the model to new evidence on the frequency of non-sale price changes from Nakamura and Steinsson (2006). We find that heterogeneity across sectors approximately triples the monetary non-neutrality in the model relative to a one-sector model calibrated to the mean frequency of price change across all goods. Intuitively, the magnification arises because the degree of monetary non-neutrality in a one-sector model is a convex function of the frequency of price change, implying that greater heterogeneity increases the average degree of monetary non-neutrality. The degree of monetary non-neutrality in the multi-sector model with intermediate goods is comparable to the degree of monetary non-neutrality of a single-sector model calibrated to match the median frequency of price change.

Allowing for intermediate goods generates strategic complementarity in the menu cost model. The menu cost model with intermediate inputs generates three times as much monetary non-neutrality as a corresponding model without intermediate inputs. Incorporating strategic complementarities into menu cost models designed to fit the size and frequency of micro-level price changes has proven challenging. Standard sources of strategic complementarity—such as fixed factors of production and non-isoelastic demand curves—yield price changes that are much too small on average for reasonable parameter values. This is not the case for intermediate inputs. Allowing for intermediate goods generates strategic complementarities without requiring unrealistically large variation in marginal costs or menu costs.

We also develop an extension of the Calvo model designed to fit the microeconomic evidence on the size and frequency of price change, while still maintaining the idea that the timing of some price changes is random rather than occurring in response to changes in costs. We refer to this model as the CalvoPlus model. The effects of heterogeneity and intermediate goods on monetary non-neutrality in the CalvoPlus model are similar to the effects in the benchmark menu cost model. We show that the relatively large amount of monetary non-neutrality generated by the Calvo model is quite sensitive to even a modest amount of selection by firms regarding the timing of price changes. When 75% of price changes occur in the low menu cost state, the CalvoPlus model generates about double the amount of monetary non-neutrality generated by the menu cost model—about 1/3 of the monetary non-neutrality generated in the Calvo limit.

A Profit Function

Cost minimization by firm z implies that labor demand and demand for the composite intermediate input be governed by

$$\frac{W_t}{P_t} = (1 - s_m) A_t L_t(z)^{-s_m} M_t(z)^{s_m} \Omega_t(z),$$

$$1 = s_m A_t L_t(z)^{1-s_m} M_t(z)^{s_m - 1} \Omega_t(z),$$

where $\Omega_t(z)$ denotes the marginal costs of firm z at time t. Combining these two equations yields

$$\frac{W_t}{P_t} = \frac{1 - s_m}{s_m} \frac{M_t(z)}{L_t(z)}. \tag{20}$$

Using this equation we can rewrite the profits of firm z in period t as

$$\begin{aligned} \Pi_t^R(z) &= \left(\frac{p_t(z)}{P_t}\right) y_t(z) - \left(\frac{W_t}{P_t}\right) L_t(z) - M_t(z) - K \left(\frac{W_t}{P_t}\right) I_t(z) \\ &= \left(\frac{p_t(z)}{P_t}\right) y_t(z) - \frac{1}{1 - s_m} \left(\frac{W_t}{P_t}\right) L_t(z) - K \left(\frac{W_t}{P_t}\right) I_t(z). \end{aligned}$$

Combining the production function—equation (8)—and equation (20) yields

$$L_t(z) = \left(\frac{y_t(z)}{A_t(z)}\right) \left(\frac{s_m}{1 - s_m}\right)^{-s_m} \left(\frac{W_t}{P_t}\right)^{-s_m}.$$

Using this equation, we can rewrite profits as

$$\Pi_t^R(z) = \left(\frac{p_t(z)}{P_t}\right) y_t(z) - (1 - s_m)^{s_m - 1} s_m^{-s_m} \left(\frac{W_t}{P_t}\right)^{1 - s_m} \left(\frac{y_t(z)}{A_t(z)}\right) - K \left(\frac{W_t}{P_t}\right) I_t(z). \tag{21}$$

Using the firm's demand curve—equation (12)—and the labor supply curve—equation (7)—we can rewrite profits as

$$\begin{aligned} \Pi_t^R(z) = Y_t \left(\frac{p_t(z)}{P_t}\right)^{1-\theta} &- (1 - s_m)^{s_m - 1} s_m^{-s_m} \omega^{1 - s_m} L_t^{\psi(1 - s_m)} C_t^{\gamma(1 - s_m)} \left(\frac{1}{A_t(z)}\right) Y_t \left(\frac{p_t(z)}{P_t}\right)^{-\theta} \\ &- K \omega L_t^{\psi} C_t^{\gamma} I_t(z). \end{aligned}$$

Finally, log-linear approximations of $Y_t = C_t + \int_0^1 M_t(z) dz$, the production function and labor supply around the steady state with flexible prices yield $\hat{Y}_t = a_1 \hat{C}_t$ and $\hat{L}_t = a_2 \hat{C}_t$. Here $\hat{Y}_t = \log(Y_t / Y)$ and Y denotes the steady state of Y_t with flexible prices. $\hat{C}_t$ and $\hat{L}_t$ are defined analogously. Using these log-linear approximations and the fact that $C_t = S_t / P_t$, we can rewrite profits as a function of $(A_t(z), p_{t-1}(z)/P_t, S_t/P_t)$ and $p_t(z)$.

B Stationary Distribution

We solve for the stationary distribution over the state space of the firm's problem using the following algorithm:

0. Start with an initial distribution $Q(A(z), p_{-1}(z)/P, S/P)$. We use a uniform distribution as our initial distribution.
1. Map $Q(A(z), p_{-1}(z)/P, S/P)$ into $Q(A(z), p(z)/P, S/P)$ using the policy function F.
2. Map $Q(A(z), p(z)/P, S/P)$ into $Q(A_{+1}(z), p(z)/P, S/P)$ using the transition probability matrix for the technology process.
3. Map $Q(A_{+1}(z), p(z)/P, S/P)$ into $Q(A_{+1}(z), p(z)/P, S_{+1}/P)$ using the probability transition matrix for the nominal aggregate demand process.
4. Map $Q(A_{+1}(z), p(z)/P, S_{+1}/P)$ into $Q(A_{+1}(z), p(z)/P_{+1}, S_{+1}/P_{+1})$ using the function Γ.
5. Check whether $|Q(A_{+1}(z), p(z)/P_{+1}, S_{+1}/P_{+1}) - Q(A(z), p_{-1}(z)/P, S/P)| < \xi$ where $|\cdot|$ denotes a sup-norm. If so, stop. If not, go back to step one.

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Table 1: Sector-level Frequency of Price Change

Figure 1: Histogram of the frequency of price change

Table 2: Frequency of Price Change of CPI and PPI prices

Figure 2: Inflation as a function of Real Aggregate Demand

Table 3: Baseline Parameters

Table 4: Statistics on the Use of Intermediate Inputs

Table 5: Frequency of Price Change: CPI vs. PPI

Table 6: Menu Cost Model With and Without Intermediate Inputs

Figure 3: A Sample Path for the Single-Sector Model

Figure 4: Price Level Response to Nominal Aggregate Demand Shock

Figure 5: Output Response to Nominal Aggregate Demand Shock

Table 7: Alternative Models of Strategic Complementarity

Table 8: Calvo vs. Calvo Plus

Figure 6: Calvo vs. Calvo Plus

Table 9: CalvoPlus with and without Intermediate Goods

Table 10: Empirical Sector Statistics

Figure 7: Frequency and Size Across Sectors

Figure 8: Inflation as a function of Real Aggregate Demand in the 6 Sector Model

Table 11: Parameter Values for Multi-Sector Model

Table 12: Multi Sector CIR

Figure 9: Frequency vs. CIR

Figure 10: Freq and Size vs. Output

Figure 11: Duration vs. CIR

Figure 12: St.Dev vs. Frequency

Figure 13: Sectoral Output Responses without Intermediate Inputs

Figure 14: Sectoral Output Responses with Intermediate Inputs

Figure 15: Seasonality of Product Substitution

Table 13: Products Flexibility

Table 1: Frequency of Price Change Excluding Sales by CPI Major Group 1998-2005

Major Group	Weight	Median Freq.	Mean Freq.	Frac. Up	Median Abs. Size
	(%)	(%)	(%)	(%)	(%)
Processed Food	8.2	10.5	10.6	65.4	13.2
Unprocessed Food	5.9	25.0	25.4	61.2	14.2
Household Furnishing	5.0	6.0	6.5	62.9	8.7
Apparel	6.5	3.6	3.6	57.1	11.5
Transportation Goods	8.3	31.3	21.3	45.9	6.1
Recreation Goods	3.6	6.0	6.1	62.0	10.1
Other Goods	5.4	15.0	13.9	73.7	7.3
Utilities	5.3	38.1	49.4	53.1	6.3
Vehicle Fuel	5.1	87.6	87.4	53.5	6.4
Travel	5.5	41.7	43.7	52.8	21.6
Services (excl. Travel)	38.5	6.1	8.8	79.0	7.1
All Goods	100.0	8.7	21.1	64.8	8.5

This table presents the weighted mean and median frequencies of non-sale price change within Major Groups for the U.S. consumer price index (CPI). These statistics are from Nakamura and Steinsson (2006), and are based on the individual price quotes underlying the US CPI. The weighted mean and median are calculated across "entry level items" in the CPI using CPI expenditure weights. The "weight" is the CPI expenditure weight. "Frac. Up" is the fraction of non-sale price changes that are price increases. "Median Abs. Size" is the median absolute size of log price changes. See Nakamura and Steinsson (2006) for more detail on how these statistics are constructed.

Table 2: Frequency and Size of Price Changes 1998-2005

	CPI	PPI	
		Finished Goods	Intermed. Goods
	(%)	(%)	(%)
Median Freq. Price Change	8.7	10.8	14.3
Mean Freq. Price Change	21.1	24.7	26.7
Median Frac. Increases	64.8	65.7	57.1
Median Abs. Size Price Changes	8.5	7.7	7.5

This table presents statistics on micro-level price changes for US consumer and producer prices over the 1998-2005 period. These statistics are from Nakamura and Steinsson (2006), and are based on the individual price quotes underlying the US consumer price index (CPI) and producer price index (PPI). The weighted mean and median frequency of price change are calculated using CPI expenditure weights for consumer prices and PPI Finished Goods and Intermetiate Goods value weights for producer prices. The third and fourth rows of the table present the median fraction price changes that are price increases, and the median absolute size of log price changes. The CPI statistics refer to non-sale price changes. See Nakamura and Steinsson (2006) for more details on how these statistics are constructed.

Table 3: Benchmark Parameters

Discount factor	$\beta = 0.96^{1/12}$
Coefficient of relative risk aversion	$\gamma = 1$
Inverse of Frisch elasticity of labor supply	$\psi = 0$
Elasticity of demand	$\theta = 4$
Steady state labor supply	$L = 1/3$
Intermediate inputs share in production	$s_m = 0.75$
Speed of mean reversion of idiosyncratic productivity	$\rho = 0.7$
Mean growth rate of nominal aggregate demand	$\mu = 0.002$
St. deviation of the growth rate of nominal aggregate demand	$\sigma_\eta = 0.0037$

Table 4: Intermediate Inputs in the U.S. Economy in 2002

	% Int. Inputs	% Used	% Gross Y	% GDP	% CPI
Agriculture and Mining	55.1	5.5	2.4	1.9	0.0
Utilities	36.8	2.6	1.7	2.0	5.3
Construction	46.8	1.5	4.8	4.6	0.0
Manufacturing	64.9	28.8	20.5	12.9	51.2
Trade	31.7	6.2	10.4	12.8	0.0
Services	39.3	53.0	48.7	53.0	43.5
Government	37.9	0.9	11.5	12.8	0.0

These data (except the last column) are from the 2002 "Use" table of the U.S. Annual Input-Output Accounts published by the Bureau of Economic Analysis. The last column is taken from Nakamura and Steinsson (2006). "% Int. Inputs" denotes the fraction of intermediate inputs in each sectors gross output. "% Used" denotes the fraction of all intermediate inputs in the economy that come from each sector. "% Gross Y" denotes each sector's weight in gross output. "% GDP" denotes each sector's weight in GDP. "% CPI" denotes each sector's weight in the CPI.

Table 5: Frequency of Price Change: Comparison of CPI and PPI

Category	Num. of Matches	Frequency of Price Change CPI	PPI
Processed Food	32	10.5	7.2
Unprocessed Food	24	25.9	67.9
Household Furnishings	27	6.5	5.6
Apparel	32	3.6	2.7
Recreation Goods	16	6.8	6.1
Other Goods	13	23.2	17.1

This table presents a comparison between the frequency of price change for consumer prices excluding sales and producer prices over the 1998-2005 period. These statistics are from Nakamura and Steinsson (2006), and are based on the individual price quotes underlying the US consumer price index (CPI) and producer price index (PPI). These statistics are constructed by matching Entry Level Items (ELI's) in the CPI to 4, 6 or 8-digit commodity codes within the PPI. "Num. of Matches" denotes the number of such matches that were possible within the Major Group. "Frequency of price change" denotes the median frequency across categories among the matches found. See Nakamura and Steinsson (2006) for more details on how these statistics are constructed.

Table 6: The Single-Sector Menu Cost Model

	Intermed. Share	Menu Cost	σ_ε	Freq.	Abs. Size	CIR	Var(C)
				(%)	(%)	(%)	(10^{-4})
(1)	0.00	0.0090	0.0465	21.1	8.5	0.5	0.018
(2)	0.65	0.0027	0.0465	21.1	8.5	1.3	0.068
(3)	0.75	0.0030	0.0465	21.1	8.5	1.6	0.078
(4)	0.85	0.0048	0.0465	21.1	8.5	2.1	0.111
(5)	0.00	0.0203	0.0425	8.7	8.5	1.6	0.090
(6)	0.65	0.0048	0.0425	8.7	8.5	3.3	0.194
(7)	0.75	0.0067	0.0425	8.7	8.5	4.2	0.260
(8)	0.85	0.0103	0.0425	8.7	8.5	5.7	0.348

This table presents estimated parameter values, the cumulative impulse response (CIR) and the variance or real value-added output for the benchmark specification of the CalvoPlus model for several values of the intermediate inputs share (s_m). (See Section 2.4 for a discussion of the CIR). Specifications (1)-(4) are parameterized to match the weighted mean frequency of price change of 21.1%, while specifications (5)-(8) are parameterized to match the weighted median frequency of price change of 8.7%. The menu cost is presented as a fraction of steady state revenue: $(\theta-1)/\theta\ K/Y_{SS}$ where Y_{SS} is steady state output under flexible prices. σ_ε is the variance of shocks to the log of the idiosyncratic productivity shocks.

Table 7: The Single-Sector Menu Cost Model With Diminishing Returns to Scale

	θ	α	Menu Cost	σ_ε	Freq.	Frac.	Abs. Size	CIR
					(%)	(%)	(%)	(%)
(1)	7	1	0.0386	0.0415	8.7	66.6	8.5	1.5
(2)	7	2/3	0.0257	0.0415	8.7	85.4	3.2	3.5
(3)	7	2/3	0.1774	0.1250	8.7	67.4	8.5	3.4

This table presents the parameter values and cumulative impulse reponse (CIR) for the menu cost model both with and without diminishing returns to labor. (See Section 2.4 for a discussion of the CIR). All the specifications are parameterized to match the weighted median frequency of price change 8.7%. The parameter α is the coefficient on labor in the production function. Specification (1) presents the model without diminishing returns to labor where α=1. Specifications (2) and (3) present model with diminishing returns to labor where α=2/3. Specification (2) maintains the same variance of the idiosyncratic shock as specification (1), while specification (3) adjusts the variance of the idiosyncratic shock to match the weighted median size of price changes, 8.5%. The menu cost is presented as a fraction of steady state revenue: $(\theta-1)/\theta\ K/Y_{SS}$ where Y_{SS} is steady state output under flexible prices. σ_ε is the variance of shocks to the log of the firms' idiosyncratic productivity levels.

Table 8: Matching the Facts With the CalvoPlus Model

	Menu Cost High	Menu Cost Low	σ_ε	Frac. Low Cost	Freq.	Abs. Size	CIR	Var(C)
				(%)	(%)	(%)	(%)	(10^{-4})
(1)	0.30	0	0.0425	99	8.7	2.8	9.9	0.659
(2)	1.50	0	0.1700	99	8.7	7.2	10.2	0.699
(3)	0.340	0.0010	0.1100	89	8.7	8.5	5.1	0.312
(4)	0.113	0.0025	0.0725	74	8.7	8.5	3.4	0.210
(5)	0.049	0.0050	0.0545	54	8.7	8.5	2.4	0.135

This table presents estimated parameter values, the cumulative impulse response (CIR) and the variance or real value-added output (Var(C)) for the benchmark specification of the CalvoPlus model for several values of the intermediate inputs share (sm). The first two columns present the menu cost in the "high" and "low" menu cost states respectively. The fraction of time spent in the "low menu cost" state is set at 1-α = 0.087 in all cases. The third column gives the variance of shocks to the log of the idiosyncratic productivity shocks σ_ε. The fourth column gives the fraction of price changes that occur in the low menu cost state. The fifth and six columns give the frequency and average absolute size of log price changes implied by the model. In all cases, the parameters are set to match the weighted median frequency of price change 8.7%. The share of intermediate inputs in the production function is set to $s_m = 0$ in all cases. The first two specifications imply that all price changes occur in the low menu cost state, while specifications (3)-(5) imply that some price changes occur in both the high and low menu cost states.

Table 9: The CalvoPlus Model With and Without Intermediate Goods

	Intermediate Inputs Share	Menu Cost High	Menu Cost Low	σ_ε	Frac. Low Cost	Freq.	Abs. Size	CIR	Var(C)
					(%)	(%)	(%)	(%)	(10^{-4})
(1)	0	0.0525	0.0013	0.0665	77	21.1	8.5	1.2	0.058
(2)	0.65	0.0128	0.0003	0.0665	77	21.1	8.5	2.5	0.144
(3)	0.75	0.1730	0.0043	0.0665	77	21.1	8.5	3.1	0.185
(4)	0.85	0.0278	0.0007	0.0665	77	21.1	8.5	4.3	0.260
(5)	0	0.1095	0.0027	0.0725	73	8.7	8.5	3.3	0.195
(6)	0.65	0.0255	0.0006	0.0725	73	8.7	8.5	6.4	0.409
(7)	0.75	0.0356	0.0009	0.0725	73	8.7	8.5	7.9	0.496
(8)	0.85	0.0563	0.0014	0.0725	73	8.7	8.5	11.4	0.834

This table presents estimated parameter values, the cumulative impulse response (CIR) and the variance or real value-added output for the benchmark specification of the CalvoPlus model for several values of the intermediate inputs share (s_m). (See Section 2.4 for a discussion of the CIR). The first two columns present the menu cost in the "high" and "low" menu cost states respectively. The "low" menu cost K_L is set at 1/40 of the high menu cost K_H in all cases. Specifications (1)-(4) are parameterized to match the weighted mean frequency of price change of 21.1%, while specifications (5)-(8) are parameterized to match the weighted median frequency of price change of 8.7%. The fraction of time spent in the "low menu cost" state is set at $1-\alpha$ = freq. in all cases. The third column gives the variance of shocks to the log of the idiosyncratic productivity shocks σ_ε. The fifth column gives the fraction of price changes that occur in the low menu cost state. The sixth and seventh columns give the frequency of price changes and the average absolute size of price changes implied by the model.

Table 10: Sector Characteristics for Multi-Sector Models

Name	Weight (%)	Freq. (%)	Abs. Size (%)	Subs (%)
Panel A: 6 Sector Model				
Vehicle Fuel, Used Cars	7.7	91.6	4.9	8.9
Transportation Goods, Utilities, Travel	19.1	35.5	10.9	4.5
Unprocessed Food	5.9	25.4	15.9	1.3
Processed Food, Other Goods	13.7	11.9	11.4	2.0
Services (excl. Travel)	38.5	8.8	8.3	2.0
Household Furnishings, Apparel, Recreation Goods	15.1	5.2	11.1	7.9
Panel B: 9 Sector Model				
Vehicle Fuel, Used Cars	7.7	91.6	4.9	8.9
Transportation Goods, Utilities, Travel	19.1	35.5	10.9	4.5
Unprocessed Food	5.9	25.4	15.9	1.3
Services(1)	9.2	19.7	4.6	2.1
Processed Food, Other Goods	13.7	11.9	11.4	2.0
Services(2)	9.6	7.6	7.2	3.7
Services(3)	10.0	5.5	8.1	1.3
Household Furnishings, Apparel, Recreation Goods	15.1	5.2	11.1	7.9
Services(4)	9.7	3.2	12.8	0.9
Panel C: 14 Sector Model				
Vehicle Fuel, Used Cars	7.7	91.6	4.9	8.9
Utilities	5.3	49.4	6.4	0.6
Travel	5.5	43.7	18.4	1.8
Unprocessed Food	5.9	25.4	15.9	1.3
Transportation Goods	8.3	21.3	8.9	8.8
Services (1)	7.7	21.7	4.0	2.2
Processed Food, Other Goods	13.7	11.9	11.4	2.0
Services (2)	7.5	8.4	6.7	4.4
Household Furnishing	5.0	6.5	10.1	5.0
Services (3)	7.8	6.2	8.8	1.7
Recreation Goods	3.6	6.1	10.2	5.9
Services (4)	7.6	4.9	8.1	0.9
Apparel	6.5	3.6	12.4	11.3
Services (5)	7.9	2.9	13.5	1.0

This table presents the weighted mean frequency and log absolute size of price changes as well as the frequency of product substitution for US consumer prices over the period 1998-2005 for divisions into 6, 9, and 14 sectors. These statistics are calculated using the methodology described in Nakamura and Steinsson (2006), based on the individual price quotes underlying the US consumer price index (CPI). The weighted means are calculated using CPI expenditure weights for entry level items (ELI's). "Weight" gives the total expenditure weight for the category, "Freq." gives the weighted mean frequency of price change for the category, "Abs. Size" gives the weighted mean absolute size of log price changes for the category. "Subs" gives the weighted mean frequency of product substitution. See Nakamura and Steinsson (2006) for more details on how these statistics are constructed. In the 9 and 14 sector models, the Service sector is divided equally into 4 and 5 groups respectively, where the ELI's are sorted into different groups according to the frequency of price change in the ELI.

Table 11 : Parameter Values for Multi-Sector Models

	Menu Cost Model				CalvoPlus Model			
	$s_m = 0.75$		$s_m = 0$		$s_m = 0.75$		$s_m = 0$	
	K	σ_ε	K	σ_ε	K_h	σ_ε	K_h	σ_ε
	$x10^{-2}$	$x10^{-2}$	$x10^{-2}$	$x10^{-2}$	$x10^{-2}$	$x10^{-2}$	$x10^{-2}$	$x10^{-2}$
Panel A: 6 Sector Model								
Vehicle Fuel, Used Cars	0.003	5.10	0.006	5.00	0.03	5.00	0.12	5.99
Transp. Goods, Utilities, Travel	0.40	6.80	1.16	6.90	2.19	8.39	7.00	8.63
Unprocessed Food	1.18	9.00	3.45	9.10	6.38	12.41	21.40	12.40
Processed Food, Other Goods	1.22	5.80	3.60	5.70	5.73	8.69	20.40	9.20
Services (excl. Travel)	0.85	4.10	2.30	3.90	4.98	7.10	12.75	6.75
Hh. Furn., Apparel, Rec. Goods	1.32	4.00	6.47	5.46	9.01	9.00	35.70	9.85
Panel B: 9 Sector Model								
Vehicle Fuel, Used Cars	0.003	5.94	0.005	5.30	0.04	5.00	0.13	5.20
Transp. Goods, Utilities, Travel	0.35	6.45	1.15	6.90	2.33	8.70	6.91	8.63
Unprocessed Food	1.14	8.88	3.30	9.00	6.11	11.60	21.79	12.30
Services(1)	0.16	2.80	0.37	2.40	0.69	3.40	2.45	3.76
Processed Food, Other Goods	1.36	6.02	3.60	5.80	6.05	8.80	20.96	9.41
Services(2)	0.57	3.15	3.50	4.00	4.73	6.50	13.00	6.10
Services(3)	1.32	4.09	3.15	3.58	6.62	7.20	15.20	6.75
Hh. Furn., Apparel, Rec. Goods	1.94	5.09	6.35	5.55	10.21	9.50	34.00	9.77
Services(4)	3.91	6.39	11.50	6.19	17.01	11.60	53.00	11.31
Panel C: 14 Sector Model								
Vehicle Fuel, Used Cars	0.003	5.20	0.007	5.20	0.04	5.30	0.13	5.39
Utilities	0.10	4.80	0.28	4.65	0.52	5.30	1.55	5.28
Travel	0.78	12.00	1.95	11.10	5.04	14.00	14.00	14.00
Unprocessed Food	1.18	9.00	3.70	9.40	6.93	12.20	21.20	12.40
Transportation Goods	0.42	4.71	1.50	5.20	2.46	6.80	7.47	6.80
Services (1)	0.16	2.97	0.41	2.70	0.54	3.20	1.45	3.00
Processed Food, Other Goods	1.22	5.75	3.40	5.60	6.24	8.90	19.50	9.00
Services (2)	0.59	3.30	1.70	3.20	3.15	5.69	10.00	5.70
Household Furnishing	1.39	4.69	4.30	4.80	8.32	8.70	25.00	8.80
Services (3)	1.10	4.10	3.30	4.10	6.43	7.60	18.50	7.40
Recreation Goods	1.54	4.80	4.50	4.80	8.95	8.90	26.00	8.80
Services (4)	1.26	4.00	3.40	3.80	7.31	7.20	22.50	7.60
Apparel	3.23	5.99	9.52	6.05	15.44	10.54	40.00	10.50
Services (5)	4.96	6.82	15.58	7.01	21.11	12.00	60.00	11.50

This table presents the parameter values for the multi-sector menu cost model both with and without intermediate goods. The menu cost K is presented as a fraction of steady state revenue: $(\theta\text{-}1)/\theta\ K/Y_{SS}$ where Y_{SS} is steady state output under flexible prices. σ_ε is the variance of shocks to the log of the idiosyncratic productivity shocks. The first panel presents the parameters for the menu cost model both with and without intermediate goods; while the second panel presents the parameters for the CalvoPlus model with and without intermediate goods. s_m is the fraction of marginal costs accounted for by intermediate goods. In the CalvoPlus model, the fraction of time spent in the "low menu cost" state is set at $1\text{-}\alpha$ = freq. for each sector in all cases.

Table 12: Monetary Non-Neutrality in the Multi-Sector Models

	Menu Cost		CalvoPlus	
	$s_m = 0.75$	$s_m = 0$	$s_m = 0.75$	$s_m = 0$
Panel A: CIR				
1 Sector Model (Mean)	1.6	0.5	3.1	1.2
6 Sector Model	3.5	1.3	8.3	2.9
9 Sector Model	4.2	1.6	9.6	3.0
14 Sector Model	4.2	1.6	9.6	3.0
1 Sector Model (Median)	4.2	1.6	7.9	3.3
Panel B: Var(C_t)				
1 Sector Model (Mean)	0.080	0.018	0.185	0.058
6 Sector Model	0.200	0.050	0.527	0.130
9 Sector Model	0.237	0.058	0.610	0.129
14 Sector Model	0.244	0.058	0.613	0.133
1 Sector Model (Median)	0.260	0.090	0.496	0.195

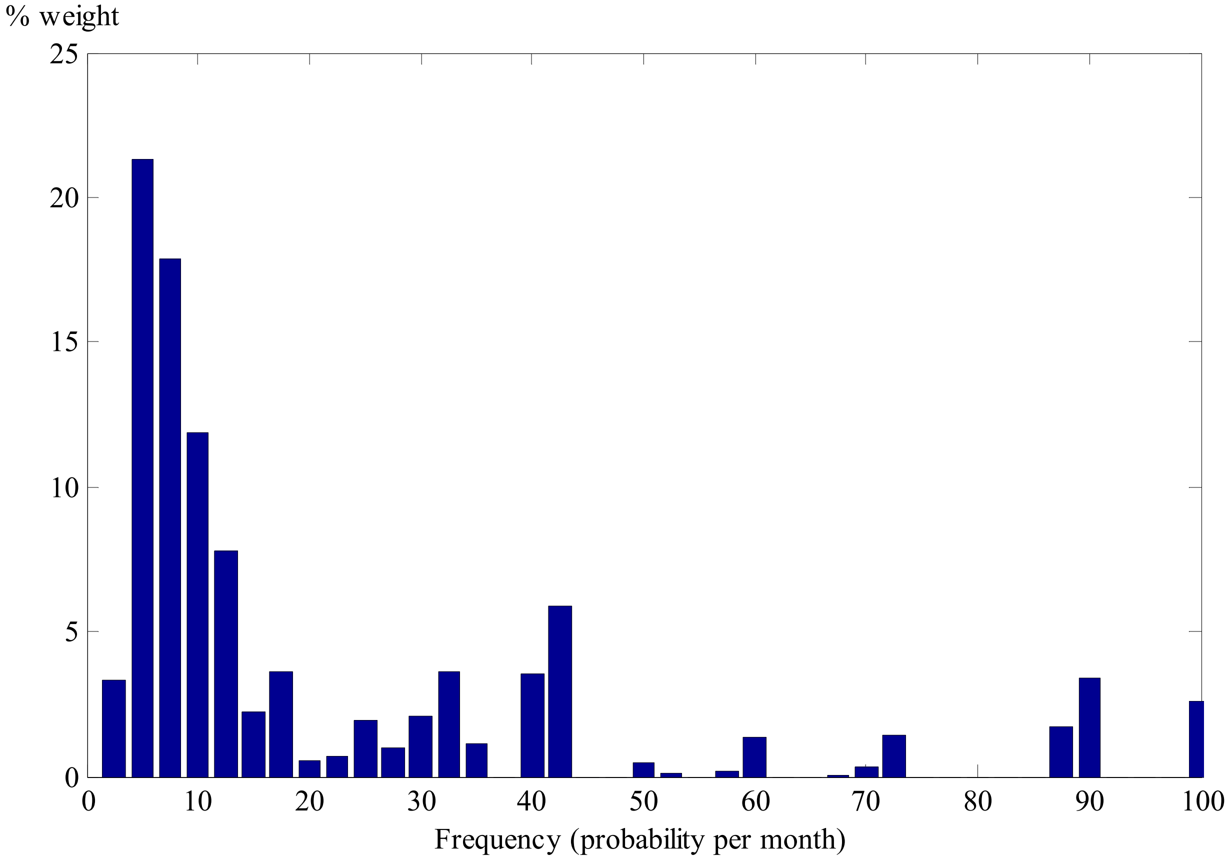
This table presents estimates of the cumulative impulse response (CIR) and the variance or real value-added output for the multi-sector menu ocst model and the benchmark specification of the multi-sector CalvoPlus model for two values of the intermediate inputs share (s_m). The CIR is measured in percent. The variance of real value added output is multiplied by 10^4. The first two columns present results for the menu cost model. The third and fourth columns present results for the CalvoPlus model. See Table 11 for the menu cost and variance of idiosyncratic shocks assumed in these models. These statistics are presented for versions of the menu cost model with 1, 6, 9 and 14 sectors. In the CalvoPlus model, the fraction of time spent in the "low menu cost" state is set at $1-\alpha$ = freq. for each sector in all cases. See Table 10 for the sectoral frequency and size of price changes used to parameterize these models.

Table 13: Multi-Sector Models with Product Flexibility

	Menu Cost		CalvoPlusSubs		Menu Cost Subs	
	$s_m = 0.75$	$s_m = 0$	$s_m = 0.75$	$s_m = 0$	$s_m = 0.75$	$s_m = 0$
Panel A: CIR						
1 Sector Model (Mean)	1.6	0.5	1.5	0.5	1.5	0.4
6 Sector Model	3.5	1.3	2.9	1.2	2.2	0.9
9 Sector Model	4.2	1.6	3.9	1.6	2.8	1.0
14 Sector Model	4.0	1.6	3.9	1.6	2.8	1.1
Panel B: Var(C_t)						
1 Sector Model (Mean)	0.080	0.018	0.072	0.015	0.063	0.012
6 Sector Model	0.200	0.050	0.168	0.044	0.125	0.030
9 Sector Model	0.237	0.058	0.219	0.053	0.151	0.033
14 Sector Model	0.244	0.056	0.221	0.054	0.152	0.035

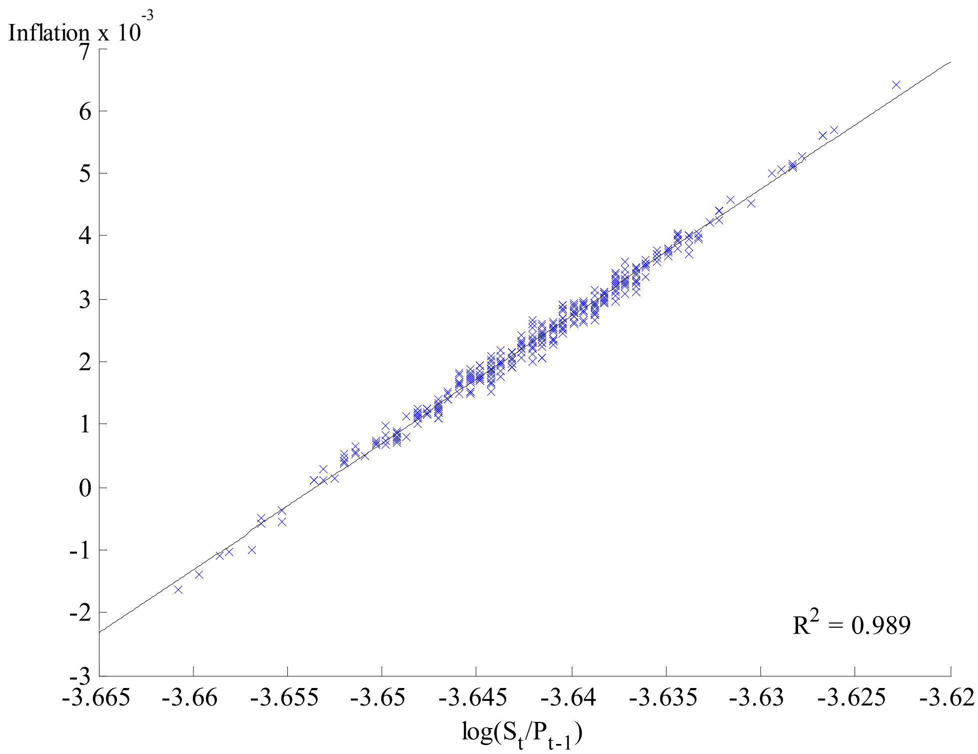
This table presents estimates of the cumulative impulse response (CIR) and the variance or real value-added output for three calibrations of our multi-sector models and two values of the intermediate inputs share (sm). The CIR is measured in percent. The variance of real value added output is multiplied by 104. The first two columns present results for the menu cost model calibrated to match the frequency of price change across sectors. The third and fourth columns present results for the CalvoPlus model with $K_l = 0$, $1 - \alpha$ = freq. of substitutions and K_h calibrated so that that frequency of price change in the high cost state equals the frequency of price change in the data. The fifth and sixth columns present results for the menu cost model calibrated to match the frequency of price change plus the frequency of substitutions across sectors.

Figure 1: The Distribution of the Frequency of Price Change for U.S. Consumer Prices



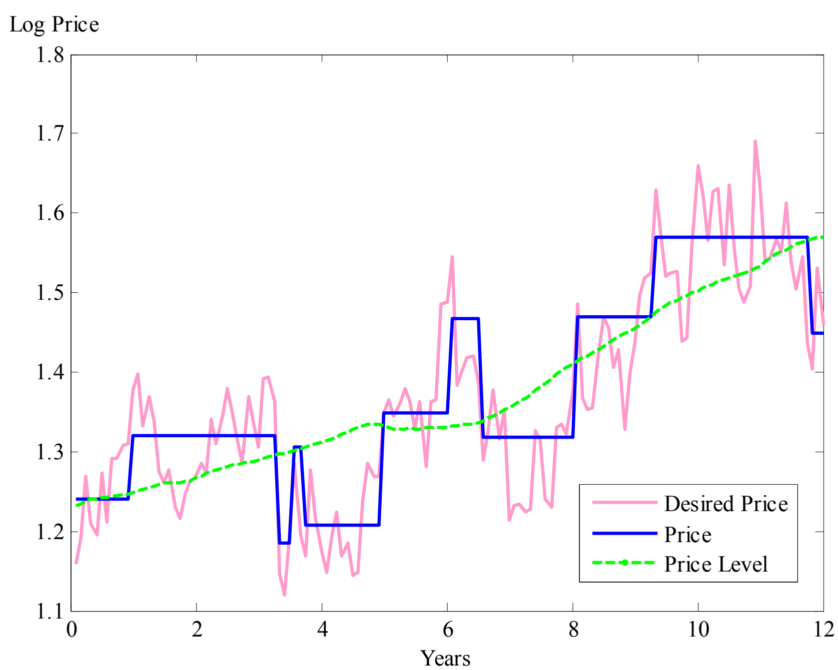
This figure presents a histogram of the cross-sectional distribution of the frequency of non-sale price changes in U.S. consumer prices for the period 1998-2005 (percent per month). The figure is based on the statistics in Nakamura and Steinsson (2006). It is based on the individual price quotes underlying the US CPI. The figure shows the expenditure weighted distribution of the frequency of price changes across entry level items (ELI's) in the CPI.

Figure 2: Log Inflation as a Function of $\log(S_t/P_{t-1})$ for the Single-Sector Menu Cost Model



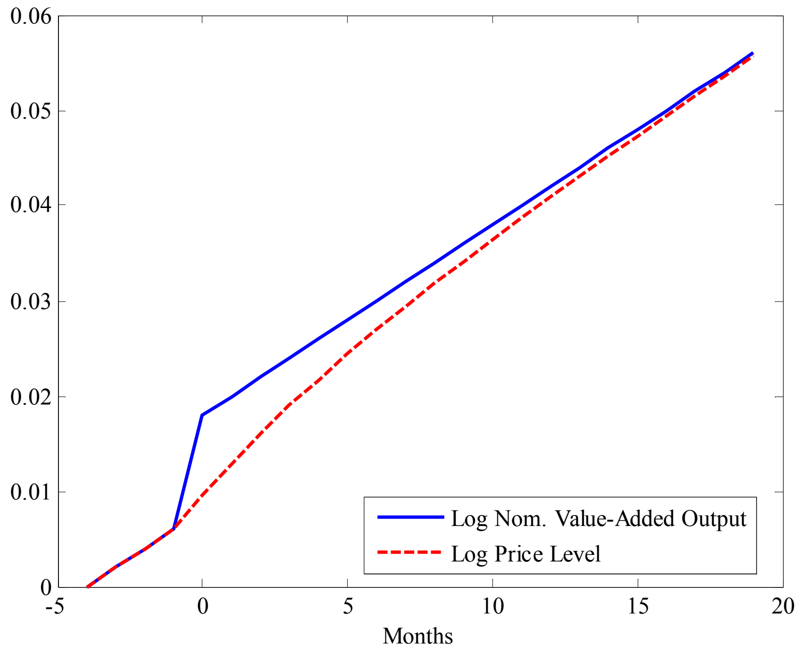
This figure presents simulated log inflation as a function of $\log(S_t/P_{t-1})$ for the single-sector menu cost model with intermediate inputs. The figure is based on 280 simulated periods of data.

Figure 3: A Sample Path from the Single-Sector Model



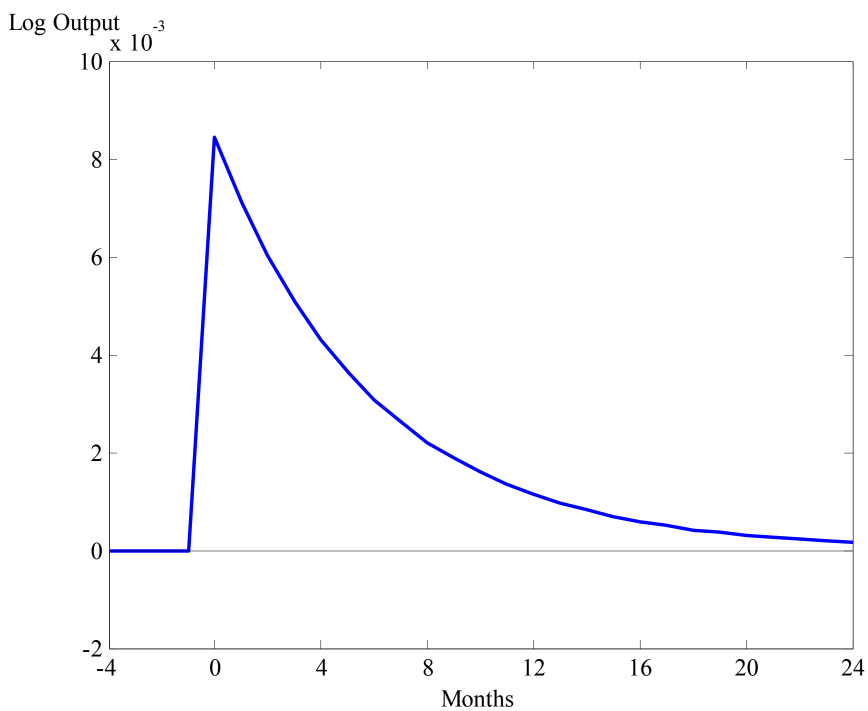
This figure plots a sample path of the price for a single firm in the single-sector model with intermediate inputs calibrated to match the median frequency and size of price changes over a 12 year period. It also plots the price level and the desired price—given by equation (17) for this simulation.

Figure 4: Price Level Response to a Permanent Shock to Nominal Aggregate Demand



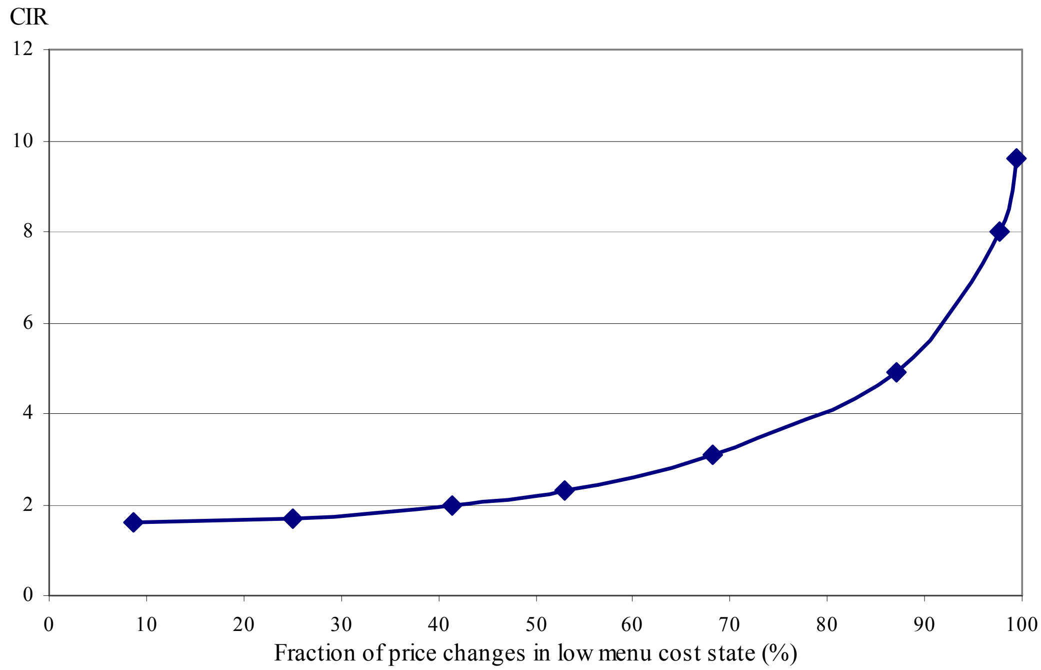
This figure presents the impulse response of the price level in response to a 1% shock to nominal aggregate demand for the single-sector model with intermediate inputs calibrated to the weighted median frequency of non-sale price changes.

Figure 5: Output Response to a Permanent Shock to Nominal Aggregate Demand



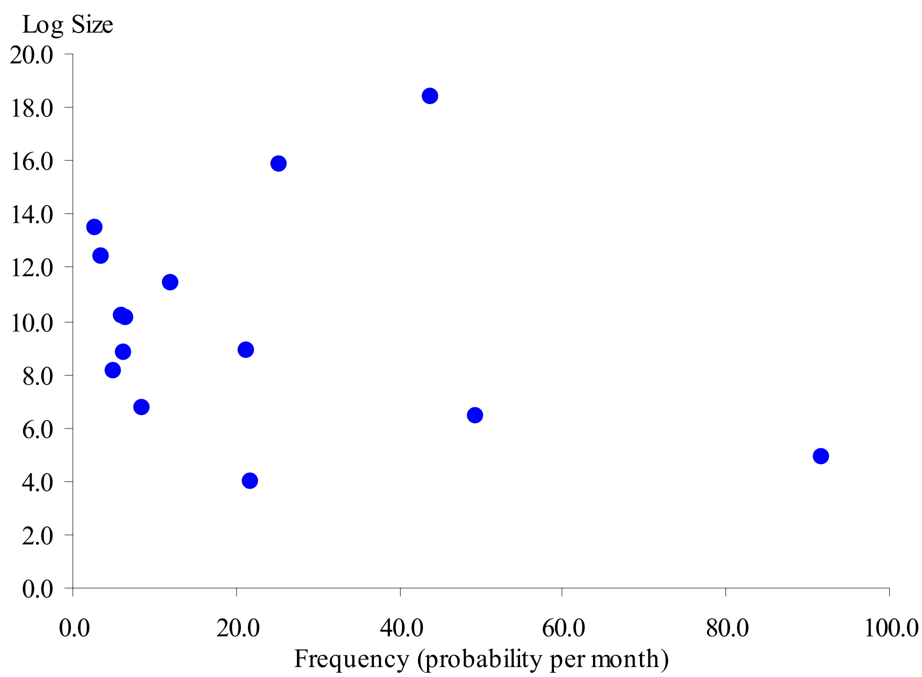
This figure presents the response of real value-added output in response to a 1% shock to nominal aggregate demand for the single-sector model with intermediate inputs calibrated to the weighted median frequency of non-sale price changes.

Figure 6: Monetary Non-Neutrality in the CalvoPlus Model



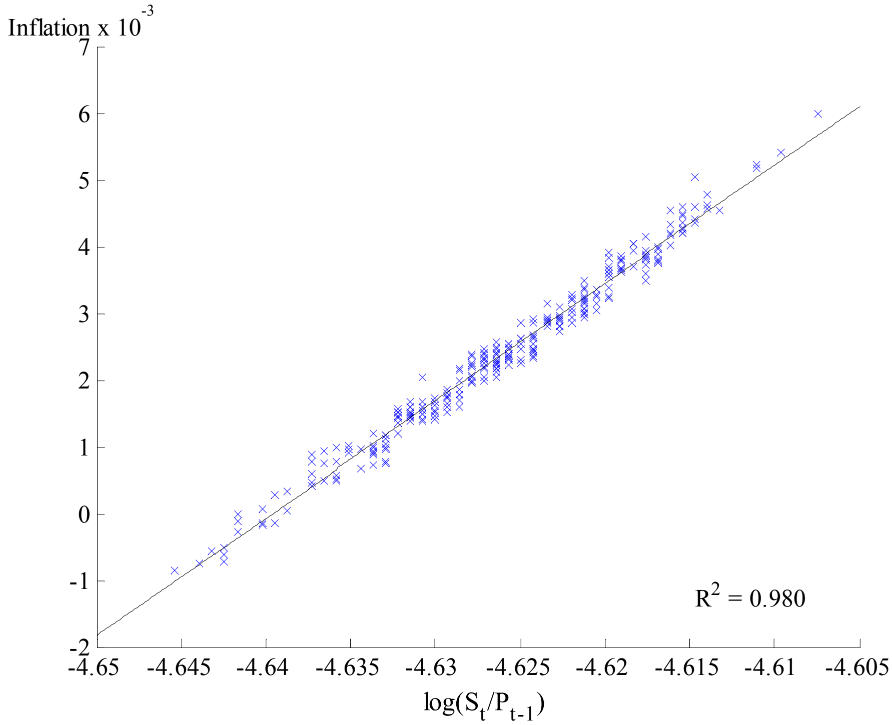
This figure presents the cumulative impulse response (CIR) of value-added output in the single-sector CalvoPlus model without intermediate inputs as a function of the fraction of price changes in the low menu cost state. The variance of the idiosyncratic shocks is fixed at σ_ε =0.0425 (the same value as in the single-sector menu cost model without intermediate goods). The menu costs in the high and low menu cost states are calibrated to match the weighted median frequency of price change 8.7% and the fraction of price changes in the low menu cost state. The fraction of time spent in the low cost state 1-α=8.7%.

Figure 7: The Frequency and Size of Price Changes across Different Sectors



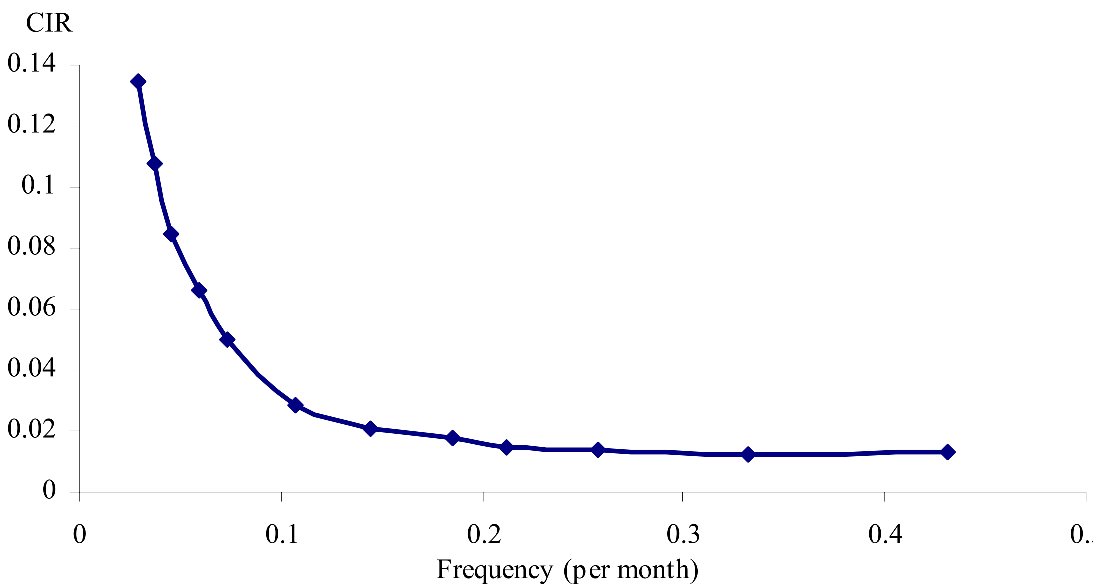
The figure plots the average frequency and size of price changes for each sector in our 14 sector model. See table 10 for the underlying data.

Figure 8: Log Inflation as a Function of $\log(S_t/P_{t-1})$ for the 6 Sector Menu Cost Model



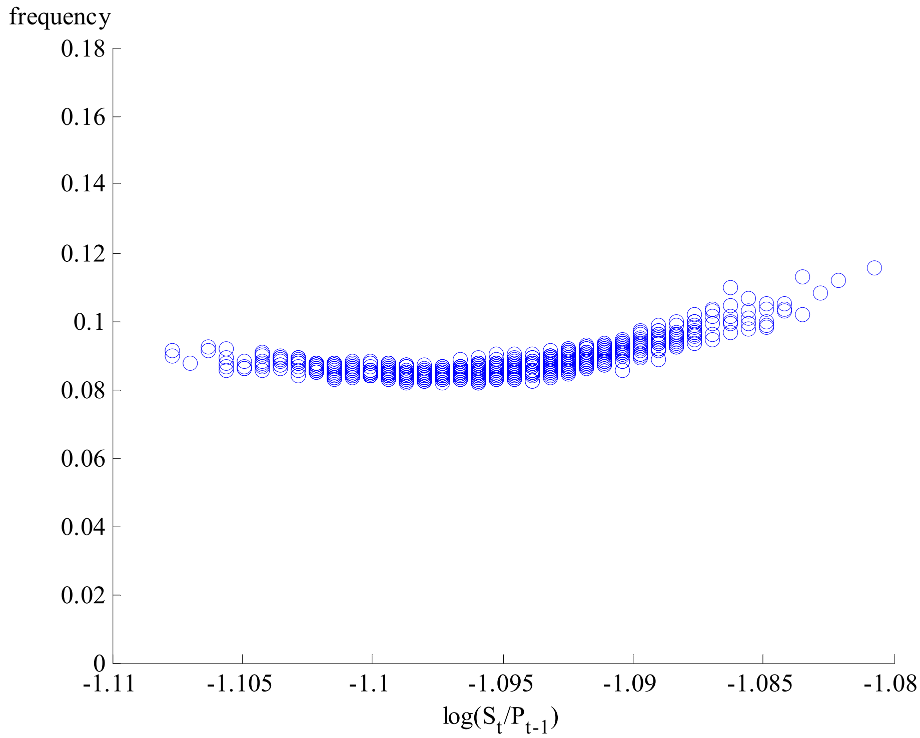
This figure presents simulated log inflation as a function of $\log(S_t/P_{t-1})$ for the multi-sector menu cost model with intermediate inputs. The figure is based on 280 simulated periods of data.

Figure 9: CIR as a Function of the Frequency of Price Change

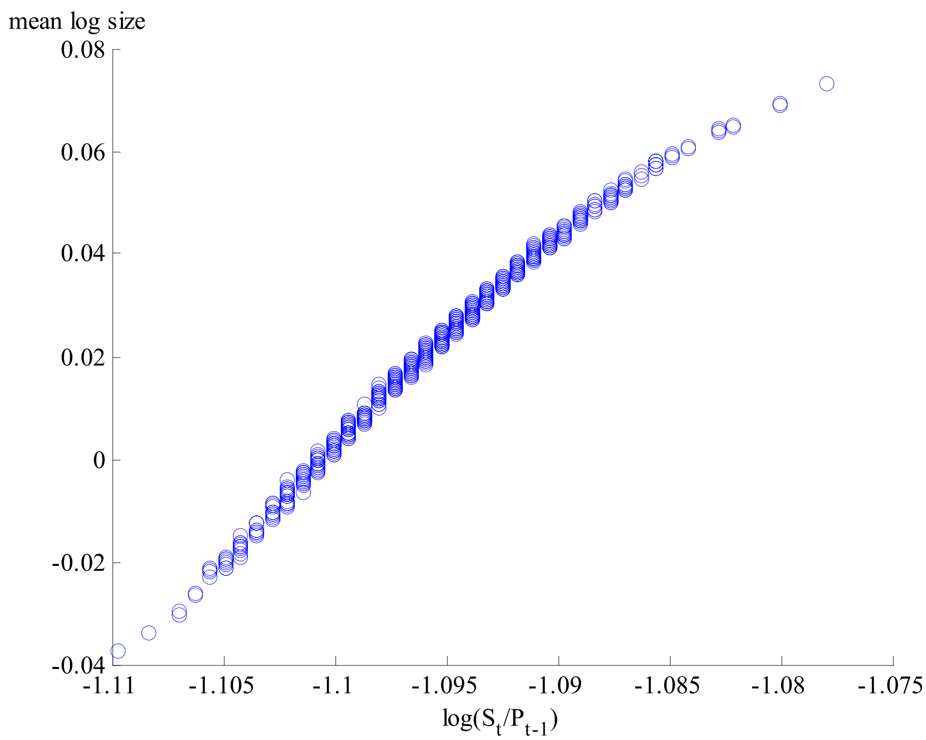


This figure presents the cumulative impulse response (CIR) of real value-added output as a function of the frequency of price change in the single-sector menu cost model with intermediate inputs. The variance of the idiosyncratic shock is set equal to 0.0425 and the menu cost parameter is varied.

Figure 10: Frequency and Average Log Size of Price Changes as a Function of $\log(S_t/P_{t-1})$



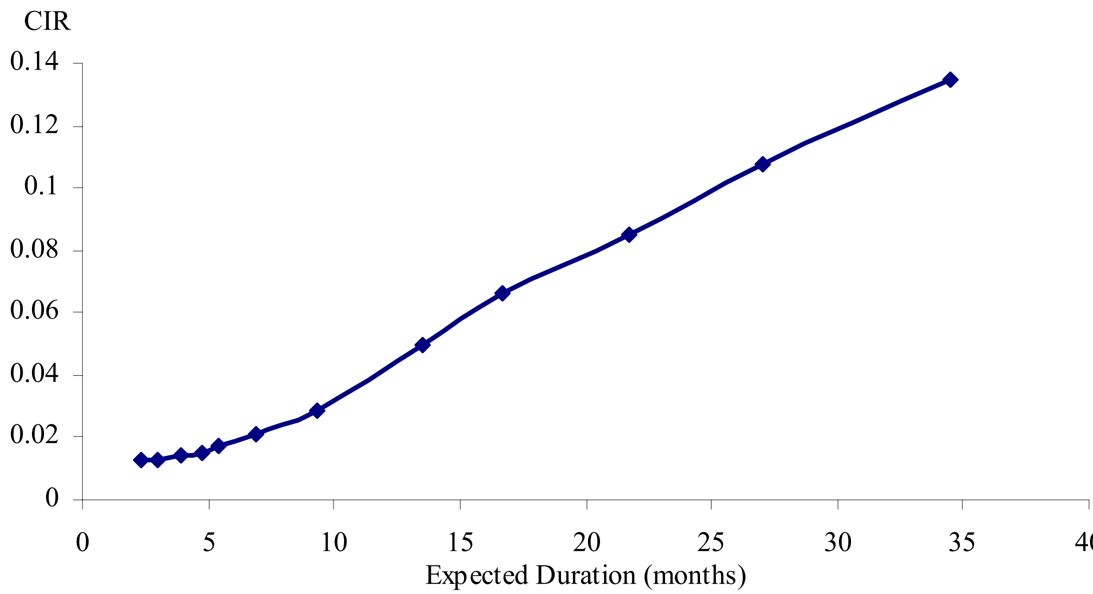
Panel A



Panel B

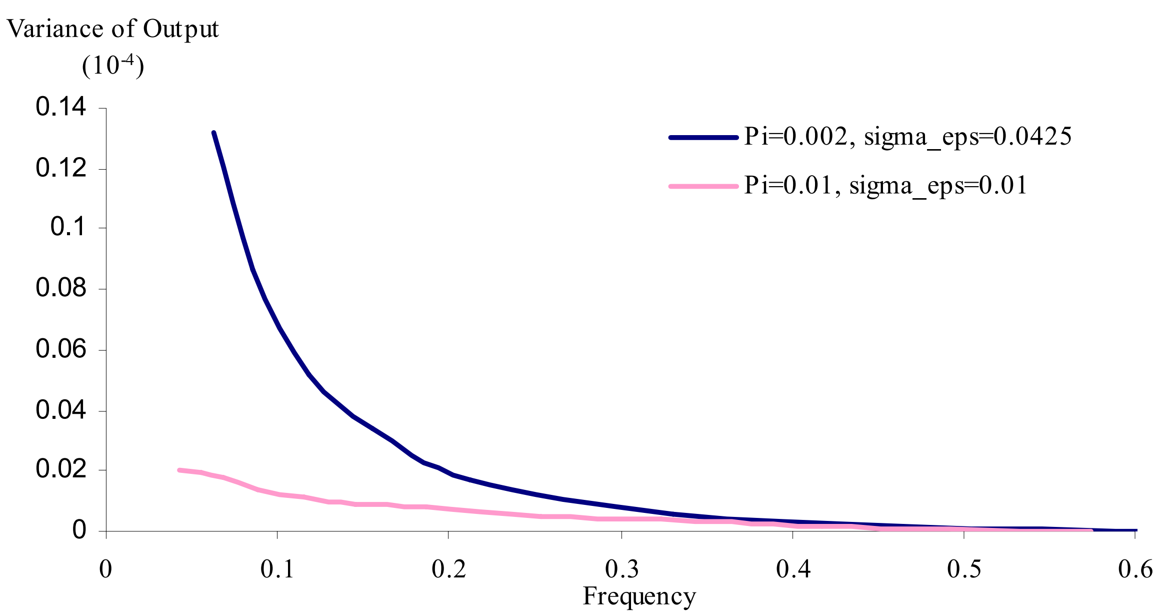
This figure plots the frequency (Panel A) and log average size (Panel B) of price changes as a function of real value-added output for an 800 period simulation of our single-sector menu cost model without intermediate inputs calibrated to match the median frequency of price change

Figure 11: CIR as a Function of the Expected Duration of Price Spells



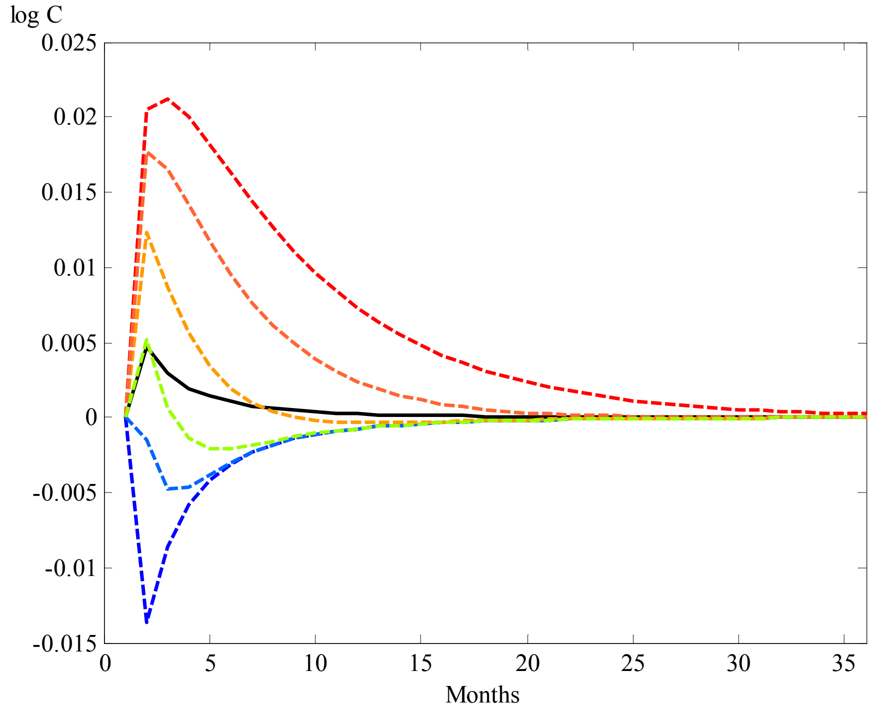
This figure presents the cumulative impulse response (CIR) of value-added output as a function of the expected duration of price spells in the single-sector menu cost model with intermediate inputs. The variance of the idiosyncratic shock is set equal to 0.0425 and the menu cost parameter is varied.

Figure 12: Variance of Output as a Function of the Frequency of Price Change



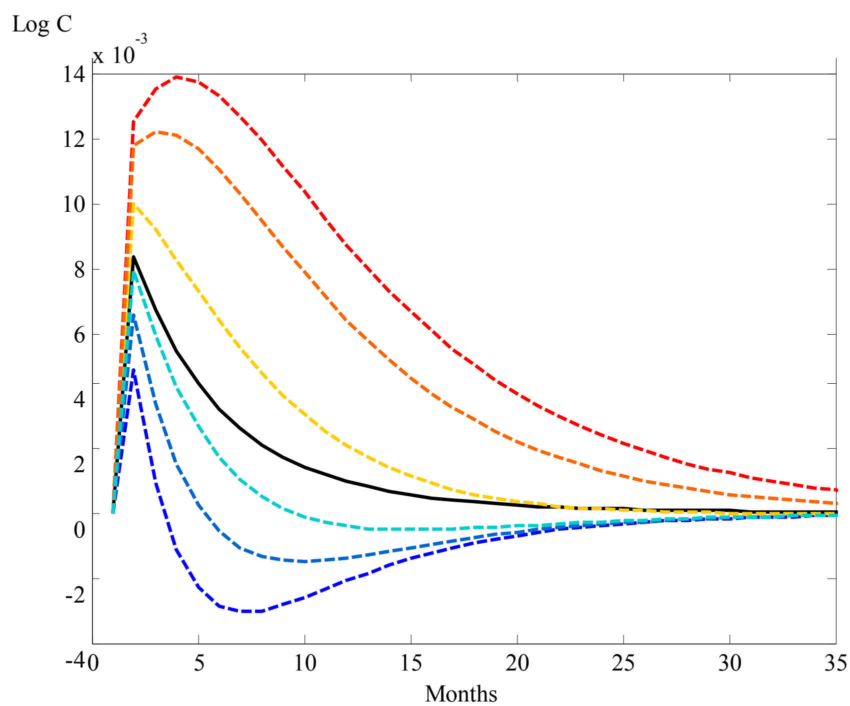
This figure plots the variance of value-added output as a function of the frequency of price change for two calibrations of our single sector model without intermediate inputs. First, we present our benchmark calibration of μ=0.002, σ_η=0.0037 and σ_ε=0.0425. Second, we present a calibration in which μ=0.01, σ_η=0.0037 and σ_ε=0.01.

Figure 13: Response of Aggregate Output and Sectoral Output without Intermediate Inputs



This figure plots the response of aggregate real value-added output (solid line) and sectoral output for several sectors of the 14 sector model without intermediate inputs to a 1% permanent increase in nominal aggregate demand. From top to bottom the sectors that are plotted are: Services(5), Apparel, Services(3), Transportation Goods, Utilities and Vehicle Fuel and Used Cars.

Figure 14: Response of Aggregate Output and Sectoral Output with Intermediate Inputs



This figure plots the response of aggregate real value-added output (solid line) and sectoral output for several sectors of the 14 sector model with intermediate inputs to a 1% permanent increase in nominal aggregate demand. From top to bottom the sectors that are plotted are: Services(5), Apparel, Services(3), Transportation Goods, Utilities and Vehicle Fuel and Used Cars.

Figure 15: Seasonality in Product Substitution