Inventories, Sticky Prices, and the Persistence of Output and Inflation

Martin Boileau and Marc-André Letendre[†*]

August 2008

Abstract

Post-war business cycle fluctuations of output and inflation are remarkably persistent. Many recent sticky-price models, however, grossly underpredict this persistence. We assess whether adding inventories to a standard sticky-price model raises the persistence of output and inflation. For this addition, we consider a shopping-cost model. In the model, consumers find shopping activities costly, and the cost of shopping depends on the stock of goods available. In this context, producers manage inventories to smooth production and to affect the cost of shopping. We find that the shopping-cost model generates a persistence for output and inflation that matches the persistence observed in the post-1985 US data.

JEL classification: E22, E30.

Keywords: Inventory investment, nominal rigidities.

Martin Boileau
Department of Economics
University of Colorado
256 UCB
Boulder, Colorado 80309
United States
Tel.: (303) 492-2108
Fax: (303) 492-8960
E-mail: martin.boileau@colorado.edu

Marc-André Letendre[†]
Department of Economics
McMaster University
1280 Main Street West
Hamilton, Ontario L8S 4M4
Canada
Tel.: (905) 525-9140 x23817
Fax: (905) 521-8232
E-mail: letendre@mcmaster.ca

[†] Corresponding Author.

[*] We are grateful to Alok Johri, Nathalie Moyen, Jack Robles, and Gregor Smith for helpful discussions. We are also grateful to seminar participants at the Canadian Economics Association meetings, HEC Montreal, the University of Colorado, the University of Oklahoma, and anonymous referees. Parts of this paper were written while Boileau was visiting the Federal Reserve Bank of Minneapolis. The paper previously circulated under the title Inventories, Sticky Prices, and the Propagation of Nominal Shocks. Letendre thanks the Social Science and Humanities Research Council of Canada and the Arts Research Board of McMaster University for financial support.

1. Introduction

Post-war US business cycle fluctuations of output and inflation are remarkably persistent. A number of recent papers argue that existing monetary business cycle models with explicit microfoundations fail to explain the persistence of output and inflation. For example, Ascari (2000) and Chari, Kehoe, and McGrattan (2000) show that monetary business cycle models with a price staggering version of the Taylor (1980) overlapping contracts fail to explain persistent output fluctuations. Nelson (1998) documents that several existing monetary business cycle models fail to explain persistent inflation changes.

Our objective is to determine whether adding inventories to a standard sticky-price monetary business cycle model raises the persistence of output and inflation.[1] To achieve our objective, we study the persistence of output and inflation in a monetary business cycle model with and without inventories. The baseline model without inventories is a standard monetary business cycle model, where prices are sticky because producers find it costly to change nominal prices. The model with inventories, the shopping-cost model, is inspired from Bils and Kahn (2000). In the model, producers carry inventories not only to smooth production, but also to manage sales. More precisely, consumers find shopping activities costly. A larger stock of inventory augments the stock of available goods, which makes it easier to shop. Then, producers can manage sales by changing the stock of inventories and the cost of shopping.

There are a number of reasons why the shopping-cost model of inventories might deliver more persistence for output and inflation. First, from a purely technical perspective, adding inventories adds a state variables that will affect the dynamics of all endogenous

[1] Several papers alter the basic monetary business cycle model to explain higher persistence. To enhance the persistence of output, some papers add staggered wage contracts (Andersen 1998, Edge 2002, Erceg 1997, and Huang and Liu 2002), change the demand structure (Bergin and Feenstra 2000), and alter the production structure (Huang and Liu 2001 and Kiley 2000). To enhance the persistence of inflation, some papers add monetary policy rules (Dittmar, Gavin, and Kydland 2005 and Ireland 2001, 2003) and introduce relative real wage concerns (Ben Aissa and Musy 2007, Fuhrer and Moore 1995). Finally, to enhance the persistence of both output and inflation, some papers introduce relative real wage concerns (Ascari and Garcia 2004) and consider habit formation and capacity utilization (Christiano, Eichenbaum, and Evans 2005).

variables. Second, from an intuitive perspective, adding inventories adds a lever that producers can use to respond to demand and supply shocks. In particular, the additional lever can be used to further smooth production when producers have a production smoothing motive (say because of increasing marginal costs of production). This directly adds persistence to output fluctuations. As shown in Das (1998), this also smooths changes in the marginal costs of production and prices, which adds persistence to inflation fluctuations. Third, adding inventories as in the shopping-cost model directly alters the behavior of aggregate prices. In this model, aggregate prices depend directly on individual prices and on the stock of available goods. The dependence of aggregate prices on this stock should further smooth fluctuations in aggregate prices and raise the persistence of inflation. Admittedly, the first two reasons apply to most models with inventories, but the third reason is unique to the shopping-cost model.

Research on inventories has been surveyed by Blinder and Maccini (1991) and Ramey and West (1999). In this literature, some studies examine the relation between inventories and the business cycle (Bils and Kahn 2000, Blinder and Fischer 1981, Fisher and Hornstein 2000, Kahn and Thomas 2007, West 1990), between inventories and sticky prices (Blinder 1982, Borenstein and Shepard 2002, Hornstein and Sarte 1998), and between inventories and costly price changes (Aguirregabiria 1999). We follow these studies and focus on the impact of inventories for several reasons. First, Ramey and West (1999) document that, although changes in inventories form on average less than one percent of gross domestic product, reductions in inventories arithmetically account for about 49 percent of the fall in gross domestic product during post-war US recessions. Second, Blinder and Fischer (1981) argue that the gradual adjustment of the stock of inventories is responsible for lasting real effects of changes in the stock of money. Finally, Blinder (1982) argues that inventories generate (real) price stickiness.

Our paper proceeds as follows. Section 2 presents the baseline sticky-price model without inventories. It consists of an artificial economy populated by an infinitely-lived representative consumer, a representative competitive retailer, monopolistically competitive producers, and a monetary authority. The consumer purchases an aggregate good from the retailer. The retailer purchases individual goods from producers and aggregates them.

As both the consumer and the retailer are price-takers, our economy is equivalent to one where the consumer purchases individual goods directly from producers. We nevertheless introduce the retailer because this modeling choice simplifies the exposition. Individual goods are produced by monopolistically competitive producers using labor and capital. Producers find it costly to adjust nominal prices. We find that both money growth shocks and total factor productivity (TFP) shocks have real effects on output and inflation. The persistence of these effects, however, is much smaller than that found in post-war US data. More precisely, the benchmark baseline model produces a first-order autocorrelation of output that is only 0.45, while it is 0.97 in the full post-war US sample and 0.93 in the post-1985 US sample. Also, the benchmark baseline model produces a first-order autocorrelation of inflation that is only 0.01, while it is 0.78 in the full post-war US sample and 0.42 in the post-1985 US sample.

Section 3 presents the shopping-cost model. It simply adds inventories to the baseline model using the assumptions of Bils and Kahn (2000). In the model, only producers hold inventories, while the retailer does not. Ramey and West (1999) document that, for 1995, about 37 percent of inventories were held in manufacturing and 52 percent were held in either retail or wholesale trade. We abstract from inventories in the retail sector for two reasons. First, we introduce the retailer only to simplify the exposition. Second, we are interested in the interaction between inventories and pricing decisions of monopolistic producers. In doing so, we follow Blinder and Fischer (1981) and Hornstein and Sarte (1998). Producers carry inventories to manage sales and to smooth production. We find that the shopping-cost model explains persistent real effects of money growth shocks and total factor productivity (TFP) shocks on output and inflation. The benchmark shopping-cost model produces a first-order autocorrelation of output that is 0.92 and a first-order autocorrelation of inflation that is 0.54. This is well in the range of autocorrelations found in the data.

We also verify whether the model replicates the main features of sales and inventories. We document that changes in inventories are less volatile than sales and procyclical in post-war US data. We also document that the behavior of sales and inventories has changed in the post-1985 period. Sales are generally less volatile than output in the post-war period,

but more volatile than output in the post-1985 period. We find that the shopping-cost model qualitatively matches the later subsample better. The model predicts that sales are slightly more volatile than output, that changes in inventories are less volatile than sales, and that changes in inventories are mildly procyclical. That said, the model does not provide a great quantitative match for either periods. In that sense, the shopping-cost model does not provide as good an explanation of the inventory facts as that provided by the (S, s) inventory policy model of Khan and Thomas (2007).

Section 4 compares the persistence of output and inflation produced by the shopping-cost model to the persistence produced by two alternative sticky-price models with inventories. We do so to verify that the unique aspect of the shopping-cost model is useful. The first alternative model shares several features with the linear-quadratic model of West (1990). In this model, producers manage an inventory stock of goods, but face costs of changing the level of production and costs of deviating from a ratio of sales to inventories. The first cost provides a production smoothing motive and the second represents stockout costs. The second alternative model embodies a feature found in the factor of production model of Kydland and Prescott (1982). In this model, producers manage an inventory stock of goods that is a direct input in production. The inventory stock is a production input because it helps economize on the cost of restocking and the cost of shifting production from one type of good to another.

We find that adding inventories as in the linear-quadratic model and the factor of production model raises the persistence of output and inflation. That said, the persistence of inflation generated by the alternative models is smaller than that generated by the shopping-cost model. In other dimensions, we find that the alternative models predict that sales are more volatile than output, that changes in inventories are less volatile than sales, and that changes in inventories are incorrectly countercyclical.

2. The Baseline Model

The baseline model does not include inventories. It depicts a stochastic economy populated by an infinitely lived representative consumer, a representative retailer, a continuum

of monopolistically competitive producers indexed by $i \in [0,1]$, and a monetary authority. The retailer aggregates individual goods, and sells the aggregate to the consumer. Production of individual goods requires both labor and capital, and producers find it costly to change nominal prices. The monetary authority supplies money according to a stochastic rule. Finally, the notation follows that of Chari, Kehoe, and McGrattan (2000). That is, in each period the economy experiences an event h_t. The history of events at time t is $h^t = (h_0, h_1, \ldots, h_t)$ and h^0 is given. The probability at period 0 of history h^t is $\pi(h^t)$ and the conditional probability of history h^{t+1} at period t is $\pi(h^{t+1}|h^t)$, where $\pi(h^{t+1}) = \pi(h^{t+1}|h^t)\pi(h^t)$ and $\pi(h^0) = 1$.

2.1 The Consumer

The representative consumer chooses consumption, hours worked, investment, and asset and money holdings to maximize expected lifetime utility

$$\sum_{t=0}^{\infty} \sum_{h^t} \beta^t \pi(h^t) U\left(C(h^t), M(h^t)/P(h^t), N(h^t)\right) \tag{1}$$

subject to the budget constraint

$$\begin{aligned} P(h^t)\left[C(h^t) + I(h^t)\right] + M(h^t) + \sum_{h_{t+1}} q(h^{t+1}|h^t) B(h^{t+1}) \leq \\ P(h^t)\left[w(h^t)N(h^t) + r^k(h^t)K(h^{t-1})\right] + M(h^{t-1}) + B(h^t) + T(h^t) + \Pi(h^t), \end{aligned} \tag{2}$$

where C denotes consumption, M is nominal money balances, P is the aggregate price level, N is hours worked, I is investment, K is the capital stock, T is nominal transfers, w is the real wage rate, r^k is the rental rate of capital, and Π is the aggregate of all profits. Also, the consumer purchases contingent one-period nominal bonds B, but faces the borrowing constraint $B \geq \bar{B}$ for some large negative number $\bar{B}$. The price $q(h^{t+1}|h^t)$ denotes the price of a bond purchased in period t that pays one dollar in period $t+1$ if state h_{t+1} is realized. The period utility is given by

$$U(C, M/P, N) = \frac{1}{1-\sigma}\left(\left[\omega C^{\frac{\chi-1}{\chi}} + (1-\omega)\left(M/P\right)^{\frac{\chi-1}{\chi}}\right]^{\frac{\chi}{\chi-1}} (1-N)^{\psi}\right)^{1-\sigma}.$$

The capital stock evolves according to

$$K(h^t) = I(h^t) + (1-\delta)K(h^{t-1}) - \frac{\nu}{2}\left(\frac{I(h^t)}{K(h^{t-1})} - \delta\right)^2 K(h^{t-1}), \tag{3}$$

where the last term of equation (3) denotes capital adjustment costs. As in Chari, Kehoe, and McGrattan (2000) and Ireland (2001), the adjustment cost is used to dampen the extreme volatility of investment produced by some of the models considered.

2.2 The Retailer

The competitive retailer chooses purchases to maximize profits

$$P(h^t)G(h^t) - \int p_i(h^t)\, s_i(h^t)\, di, \tag{4}$$

subject to the aggregation technology

$$G(h^t) = \left[\int g_i(h^t)^{\frac{\theta-1}{\theta}} di\right]^{\frac{\theta}{\theta-1}}, \tag{5}$$

where G denotes the quantity of aggregate goods sold to the consumer, p_i is the sales price for good i, and $s_i = g_i$ is the quantity purchased of good i.

The retailer's first-order conditions imply the goods demand function

$$s_i(h^t) = \left[\frac{P(h^t)}{p_i(h^t)}\right]^{\theta} G(h^t). \tag{6}$$

The demand functions for all goods and the retailer's zero-profit condition yield the aggregate price index

$$P(h^t) = \left[\int p_i(h^t)^{1-\theta} di\right]^{\frac{1}{1-\theta}}. \tag{7}$$

2.3 Producers

Monopolistic producer i chooses labor, capital, and prices to maximize expected discounted profits

$$\sum_{t=0}^{\infty}\sum_{h^t} q(h^t)\Big(p_i(h^t)s_i(h^t) - P(h^t)\left[w(h^t)n_i(h^t) + r^k(h^t)k_i(h^t)\right]\Big), \tag{8}$$

subject to the production technology

$$y_i(h^t) = z(h^t)k_i(h^t)^{\alpha}n_i(h^t)^{1-\alpha}, \tag{9}$$

the definition of net output

$$y_i^n(h^t) = y_i(h^t) - \frac{\phi_p}{2}\left(\frac{p_i(h^t)}{\bar{\mu}p_i(h^{t-1})} - 1\right)^2 y_i(h^t), \tag{10}$$

and the demand for good i depicted in equation (6), where n_i is labor, k_i is capital, y_i is gross output, y_i^n is net output, z is an aggregate TFP shock, and $\bar{\mu}$ denotes the steady-state level of inflation. The price $q(h^t) = q(h^t|h^{t-1})q(h^{t-1})$ where $q(h^0) = 1$ is constructed from the consumer's first-order conditions. Also, as shown in equation (10), price adjustments are costly and drive a gap between net and gross output. The price adjustment costs guarantees nominal price rigidity.

Finally, the TFP shock evolves as

$$\ln\left(z(h^t)\right) = (1-\rho_z)\ln(\bar{z}) + \rho_z \ln\left(z(h^{t-1})\right) + \epsilon_{zt}, \tag{11}$$

where $\bar{z}$ is the mean level of TFP and ϵ_z is a mean zero random variable with variance σ_z^2.

2.4 The Monetary Authority

The monetary authority provides nominal transfers according to

$$T(h^t) = M(h^t) - M(h^{t-1}). \tag{12}$$

The growth rate of money, $\mu(h^t) = \ln\left(M(h^t)/M(h^{t-1})\right)$, evolves as

$$\mu(h^t) = (1-\rho_\mu)\ln(\bar{\mu}) + \rho_\mu \mu(h^{t-1}) + \epsilon_{\mu t}, \tag{13}$$

where ϵ_μ is a mean zero random variable with variance σ_μ^2.

2.5 Market Clearing and Aggregation

Clearing of the bond, capital, and labor markets requires

$$B(h^t) = 0, \tag{14.1}$$

$$K(h^{t-1}) = \int k_i(h^t)\, di. \tag{14.2}$$

$$N(h^t) = \int n_i(h^t)\, di. \tag{14.3}$$

Note that, as individual producers face identical problems, they will charge identical prices. Our symmetric equilibrium thus imposes that $P(h^t) = p_i(h^t)$ and $s_i(h^t) = g_i(h^t)$. This implies that $K(h^{t-1}) = k_i(h^t)$, $N(h^t) = n_i(h^t)$, $Y(h^t) = \int y_i(h^t)\, di = y_i(h^t)$, $Y^n(h^t) = \int y_i^n(h^t)\, di = y_i^n(h^t)$, and $S(h^t) = \int s_i(h^t)\, di = s_i(h^t)$. Then, the goods market clearing conditions simplify to

$$C(h^t) + I(h^t) = G(h^t). \tag{14.4}$$

$$Y^n(h^t) = Y(h^t) - \frac{\phi_p}{2}\left(\frac{P(h^t)}{\bar{\mu}P(h^{t-1})} - 1\right)^2 Y(h^t), \tag{14.5}$$

$$G(h^t) = S(h^t), \tag{14.6}$$

$$S(h^t) = Y^n(h^t). \tag{14.7}$$

2.6 Simulation Method and Benchmark Parameter Values

The baseline model does not have an analytical solution for general values of the underlying parameters. Instead, we find an approximate solution using the method described in King, Plosser, and Rebelo (2002). This method requires that values be assigned to all parameters.

Table 1 reports parameter values for the different models. For the baseline model, we set several parameters to the values used in Chari, Kehoe, and McGrattan (2000): $\chi = 0.39$, $\omega = 0.94$, $\delta = 0.025$ $\alpha = 0.36$, $\theta = 10$, $\bar{z} = 1$, and $\bar{\mu} = 1$. Also, we follow their guidelines and set $\psi = 1.7119$ to ensure that hours worked are 30 percent of the time endowment. The source of nominal rigidity in our baseline model differs from that used in Chari, Kehoe, and McGrattan (2000). This influences the values of both β and ϕ_p. We follow Kydland and Prescott (1982) and set $\beta = 0.99$. Ireland (2001) provides estimates for the value of ϕ_p that are between $\phi_p = 72.01$ for the pre-1979 period and $\phi_p = 77.10$ for the post-1979 period. Unfortunately, those values impose large costs to adjusting prices and may imply a large persistence of inflation. To limit this exogenous persistence, we set $\phi_p = 25$, roughly a third of the estimated value. This value is rather on the low side of

plausible values derived in Keen and Wang (2007). For this reason, we verify the sensitivity of our results to $\phi_p = 75$.

For the TFP shocks, we follow King and Rebelo (1999) and set $\rho_z = 0.979$ and $\sigma_z = 0.0072$. For the money growth shocks, we use quarterly data on $M2$ from 1959:1 to 2000:1 to estimate $\rho_\mu = 0.69$ and $\sigma_\mu = 0.006$.

Finally, the values of both σ and ν remain to be set. Prescott (1986) argues for a value of σ between 1 and 2, and Chari, Kehoe, and McGrattan (2000) set ν so that the model implies a relative volatility of investment that matches that observed in the data. Several combinations of σ and ν satisfy these criteria and deliver similar empirical results. As a benchmark, we set $\nu = 0$ and $\sigma = 1.325$ to ensure that the standard deviation of investment is 2.9 times the standard deviation of output, as in our post-war US sample. In the alternative models presented below, we keep $\sigma = 1.325$ and vary ν to match the relative volatility of investment.

2.7 Simulation Results

The last two columns of Table 2 show the first autocorrelation of output and inflation, while Figure 1 displays the autocorrelations of output and inflation for up to 10 lags. The autocorrelations in the post-war US data are computed as the sample autocorrelations of output and inflation over the full 1959:1 to 2000:1 period. In addition, the tables report the first autocorrelation of output and inflation for a subsample of 1985:1 to 2000:1 (see Appendix A for a description of the data). Output corresponds to the detrended logarithm of per capita gross domestic product and inflation to the detrended first difference of the logarithm of the consumer price index. Following Chari, Kehoe, and McGrattan (2000), we detrend all variables by removing a linear-quadratic trend. In the data, output displays an obvious upward trend, but inflation does not. That said, Boileau and Letendre (2003) and Levin and Piger (2004) document low frequency fluctuations in inflation. For example, post-war US inflation is on average much higher during the 1970s and early 1980s than during the 1960s and 1990s. This feature alone would make inflation fluctuations extremely persistent. It is doubtful, however, that it reflects a business cycle fluctuation of inflation. Our detrending method may not completely eliminate the influence of this period, but it

is a step in the right direction.

The first sample autocorrelations for the full post-war US sample are 0.97 for output and 0.78 for inflation. At higher lags, the sample autocorrelations of output and inflation decline slowly, and are positive for all 10 lags. Although the subsample truncation will be mostly useful for the inventory models, note that output and inflation appear less persistent for the more recent subsample. The subsample first autocorrelations decline to 0.93 for output and 0.42 for inflation.

The autocorrelations predicted by the baseline model are computed as the average autocorrelations over 1000 simulations of 164 quarters (the number of quarters of the full post-war US sample) using variables detrended as in the post-war US sample. Table 2 and Figure 1 show that the baseline model underpredicts the persistence of output and inflation. The first-order autocorrelations of output and inflation predicted by the benchmark baseline model are only 0.45 and 0.01, and much smaller than those computed with either the full sample or the subsample. Figure 1 shows that the autocorrelations of output and inflation predicted by the benchmark baseline model also decline much more rapidly than those computed from the full US sample. In particular, the predicted autocorrelations of output and inflation are smaller than the observed autocorrelations for all 10 lags.

Figure 2 displays the dynamic responses of output and inflation to a one standard deviation innovation to the money growth shock and a one standard deviation innovation to the TFP shock. It shows the responses in percent deviations from their steady-state levels. The responses document a number of interesting feature. First, the responses indicate that the benchmark baseline model is dominated by money shocks. The responses of output and inflation are much larger at impact and much less persistent for the money growth shock. This explains the low first-order autocorrelations presented in Table 2.

Second, the baseline model generates real effects from the money growth shock. The higher money growth generates a larger transfer from the monetary authority to the consumer. As long as prices are sticky, the larger transfer raises the consumer's real balances. The increase in real balances stimulates demand for goods because it raises his wealth and because real balances and consumption are complements.

In reaction to the increase in the demand for its good, a monopolistic producer can change its price and output levels. The larger the change in price, the smaller the change in output required to meet the new demand. The relative sizes of the price and output changes depend on the cost of changing nominal prices and the marginal cost of production. The cost of changing nominal prices depends on ϕ_p: the larger ϕ_p, the more costly it is to raise prices. The marginal cost of production is $[1/\alpha]^{\alpha}[1/(1-\alpha)]^{1-\alpha}[1/z(h^t)]w(h^t)^{\alpha}r^k(h^t)^{1-\alpha}$. In equilibrium, the marginal cost is increasing in output. That is, raising output requires an increase in the demand for inputs, which pushes wages and rental rates up and raises the marginal cost.

Finally, the responses also document that the baseline model generates a rise in output and a reduction of inflation in response to a TFP shock. As is standard, the TFP shock reduces the marginal cost of production, which lowers prices and inflation.

The baseline model contains two features that could slow down the adjustment of output and inflation in responses to shocks. These features are the adjustment costs to prices and capital. To verify the effects of these costs, Table 2 reports the results of two experiments. The first experiment sets $\phi_p = 75$, a tripling of its benchmark value (see High Price Cost in Table 2). The higher cost of adjusting nominal prices marginally raises the persistence of inflation, but reduces the persistence of output. This occurs because it further magnifies the dominance of money growth shocks over TFP shocks. The second experiment sets $\nu = 10$ (see High Investment Cost in Table 2). The higher cost of adjusting capital raises the persistence of both output and inflation. This occurs because it lowers the dominance of money growth shocks and dampens the responses of the marginal cost. An unfortunate side effect is that the relative volatility of investment drops to an unreasonable 1.84.

3. The Shopping-Cost Model

The shopping-cost model adds inventories to the baseline model by adopting some elements of Bils and Kahn (2000). In particular, producers face a demand that depends on the available stock of goods. That is, consumers, via retailers, find it costly to engage in

shopping activities. A larger stock of available goods helps economize on the resources expanded while shopping. Our shopping-cost model, however, differs from that of Bils and Kahn. Our demand for goods is derived from the consumer's problem, while their demand is a reduced form. Finally, our demand shocks come money growth shocks, while their real demand shocks are of unspecified nature. In our model, money growth shocks have real effects because of the nominal price stickiness created by the price adjustment costs. Without price stickiness, inflation dynamics would be closely related to that of money growth while output dynamics would be unrelated to that of money growth. Price stickiness would not be required for demand shocks to have real effects if we assumed, for example, that demand shocks are real government expenditure shocks. As noted before, we study money growth shocks rather than other types of demand shocks since our work is part of a literature on monetary business cycle models.

Our version of the shopping model uses the consumer and the monetary authority of the baseline model, but it modifies the retailer and producers.

3.1 The Retailer

The competitive retailer chooses purchases to maximize profits given in equation (4) subject to the aggregation technology displayed in equation (5). In this case, however, the retailer finds it costly to purchase goods. The cost of purchasing $s_i(h^t)$ units of good i is $[1 - \gamma a_i(h^t)^\xi]s_i(h^t)$, such that

$$g_i(h^t) = \gamma a_i(h^t)^\xi s_i(h^t), \tag{15}$$

where $a_i(h^t) = y_i^n(h^t) + x_i(h^{t-1})$ is the stock of available good i at time t and $x_i(h^{t-1})$ is the stock of inventories. Thus, the greater the stock of available good, the lower the purchasing or shopping cost. Comparing the demand for the shopping-cost model displayed in equation (16) with the demand for the baseline model displayed in equation (6) is instructive. In the shopping-cost model, producers face demand functions that depend directly on the stock of available goods. Thus, a producer can manage its sales by altering the stock of available goods.

The retailer's first-order conditions imply the goods demand function

$$s_i(h^t) = \left[\frac{P(h^t)}{p_i(h^t)}\right]^{\theta} G(h^t)\left[\gamma a_i(h^t)^{\xi}\right]^{\theta-1}. \tag{16}$$

Finally, the demand for all goods combined with the zero-profit condition of the retailer yields the price index

$$P(h^t) = \left(\int p_i(h^t)^{1-\theta}\left[\gamma a_i(h^t)^{\xi}\right]^{\theta-1} di\right)^{\frac{1}{1-\theta}}. \tag{17}$$

Comparing the aggregate price index for the shopping-cost model in equation (17) with the index for the baseline model in equation (7) is also instructive. The evolution of aggregate prices in the shopping-cost model depends directly on the evolution of the stock of available goods. Thus, shocks might have more persistent effects on prices via their effects on the stock of available goods.

3.2 Producers

Producer i chooses labor, capital, inventories, and prices to maximize expected discounted profits given in equation (8) subject to the production technology in equation (9), the definition of net output in equation (10), the demand for goods in equation (16), and the evolution of the stock of inventories:

$$x_i(h^t) = x_i(h^{t-1}) + y_i^n(h^t) - s_i(h^t). \tag{18}$$

3.3 Market Clearing and Aggregation

In our symmetric equilibrium, the bond, capital, and labor markets clear as in equations (14.1), (14.2), and (14.3). Clearing of the goods market requires equations (14.4) and (14.5), as well as

$$X(h^t) = X(h^{t-1}) - S(h^t) + Y^n(h^t). \tag{19.1}$$

and

$$G(h^t) = S(h^t)\gamma A(h^t)^{\xi}. \tag{19.2}$$

Aggregate quantities are as in the baseline model, with the addition of $X(h^t) = \int x_i(h^t)di = x_i(h^t)$ and $A(h^t) = \int a_i(h^t)di = a_i(h^t)$.

3.4 Benchmark Parameter Values

Table 1 reports the benchmark parameter values. The shopping-cost model has two new parameters: γ and ξ. Although the models differ, the parameter estimates of Bils and Kahn (2000) offer a good benchmark. They provide estimates for $\xi(\theta - 1)$ (See Bils and Kahn Table 6). The constrained estimates range from 0.023 to 0.486. We set $\xi = 0.0168$ so that steady-state sales are 60 percent of available goods (output plus inventories) as in the full post-war US sample. Given our value of $\theta = 10$, the implied value of $\xi(\theta - 1)$ is 0.151, which is well within Bils and Kahn's range of estimates. We also set $\gamma = 0.9906$ to remove steady-state transaction costs. In what follows, we study the robustness of our results to different settings for these two parameters.

3.5 Simulation Results

The results appear in Table 2 and Figure 1. The autocorrelations of output and inflation predicted by the benchmark shopping-cost model are much larger than those predicted by the baseline model. The predicted first-order autocorrelations of output and inflation are 0.92 and 0.54. At higher lags, the predicted autocorrelations of output decline slowly, as in the full post-war US sample. The predicted autocorrelations of inflation decline too rapidly, but are much closer to the data than those produced by the benchmark baseline model.

Figure 3 displays the dynamic responses of output, sales, and inflation to a positive one standard deviation innovation to money growth and to a positive one standard deviation innovation to TFP. The responses to the money growth shock show that producers raise output and prices, and deplete inventories to meet the new demand. The stock of inventories gets depleted because sales go up by more than production. The responses of output and inflation to the money growth shock are much more persistent than those generated by the benchmark baseline model. The responses to the TFP shock show that producers raises output more than sales, such that the stock of inventories rises. The

higher TFP lowers marginal costs which reduces inflation. The responses of inflation is also much more persistent than that produced by the benchmark baseline model.

The dynamic responses of the shopping-cost model differ importantly from those generated by the baseline model. This is especially true for the response to the money growth shock. In the baseline model, a producer meets a larger demand by increasing output and price. In making his decisions, he accounts for the cost of adjusting prices and for the (increasing) marginal cost of production. In the shopping-cost model, a producer meets a larger demand by increasing price, increasing output, and depleting inventories. In making his decisions, he accounts for the cost of adjusting prices, for the (increasing) marginal cost of production, and for the impact of his output and inventory decisions on sales (via the cost of shopping). The extra levers allow the producer to further smooth production, which raises the persistence of output fluctuations. It also dampens movements in the marginal cost of production, which raises the persistence of inflation. Finally, the resulting smooth adjustment of the stock of available goods further raises the persistence of inflation.

Table 2 reports a number of experiments to verify the robustness of the above results. As for the baseline model, the first two experiments verify the robustness of our results to the costs of adjusting prices and the capital stock. The first experiment sets $\phi_p = 75$ (see High Price Cost in Table 2). The higher cost of adjusting nominal prices raises the persistence of inflation, but has little effects on the persistence of output. The second experiment sets $\nu = 3$ (see Low Investment Cost in Table 2). This change does not affect the persistence of output and inflation, but it raises the relative volatility of investment to an unreasonable 6.22.

The next three experiments verify the robustness of our results to the values of the additional parameters γ and ξ. The third experiment sets $\gamma = 0.9415$, so that five percent of goods are lost during shopping in the steady state (see High Shopping Cost in Table 2). The fourth experiment sets $\xi = 0.0123$ so that the steady state level of the ratio of sales to all available goods is 0.82 (see Low Convenience in Table 2). This value for the ratio of sales to available goods is similar to that in Bils and Kahn (2000). Note that a large steady-state level of this ratio is associated with a low convenience yield of having inventories and a low steady-state level of inventories. The last experiment sets $\xi = 0.054$

so that the resulting value of $\xi(\theta - 1)$ is 0.486 (see High Convenience in Table 2). This value for $\xi(\theta - 1)$ is the upper bound of the range of estimates in Bils and Kahn (2000). The simulation results for these experiments show that these changes have no significant effects on the persistence of output and inflation.

Finally, we verify whether the shopping-cost model provides an adequate characterization of the fluctuations of sales and inventories. For this, Table 2 also reports a number of relevant statistics. The relative volatility of sales is the ratio of the standard deviation of the logarithm of per capita sales to the standard deviation of the logarithm of per capita gross domestic product. The relative volatility of inventories is the ratio of the standard deviation of changes in inventories to the standard deviation of the logarithm of output. Changes in inventories correspond to the ratio of changes in private per capita inventories to per capita gross domestic product. As before, all variables are detrended with a linear-quadratic trend. The moments are presented for the full post-war US sample and a the post-1985 subsample.

The volatility of sales and inventory investment and the correlation between inventory investment and output computed from the full post-war US sample are different from those computed in the later subsample. For the full sample, sales are less volatile than output, changes in inventories are less volatile than sales and are highly procyclical. For the later subsample, however, sales are more volatile than output and changes in inventories are almost twice as volatile as in the full sample. In addition, changes in inventories are much less procyclical: the correlation is less than half that of the full sample. These changes in the behavior of sales and inventories are discussed in Kahn, McConnell, and Perez-Quiros (2001) and McConnell and Perez-Quiros (2000).

The benchmark shopping-cost model generates moments that match better the later subsample. It predicts that sales are more volatile than output, that inventories are less volatile than output, and that changes in inventories are slightly procyclical. More precisely, the benchmark shopping-cost model produces the following moments: the relative volatility of sales is 1.27, the relative volatility of changes in inventories is 0.85, and the correlation between changes in inventories and output is 0.08. These moments are robust to the alternative parametrization of the shopping-cost model. A quick glance suggests that

the high convenience experiment provides the better match: the relative volatility of sales drops to 1.15, the relative volatility of changes in inventories is 0.86, and the correlation between changes in inventories and output raises to 0.26.

The dynamic responses displayed in Figure 3 explains these simulation results. The responses show that producers respond to higher demand from a positive money growth shock by raising sales above production so that the stock of inventories falls. This promotes a larger variance for sales than for output, and as a consequence countercyclical changes in inventories. The responses also show that producers respond to lower costs of production from a positive TFP shock by raising output above sales so that the stock of inventories rises. This promotes a smaller variance for sales than for output, and as a consequence procyclical changes in inventories. The unconditional moments recorded in Table 3 suggests that, in contrast to the benchmark baseline model, money growth shocks do not dominate TFP shocks. The unconditional moments then show influences of both money growth and TFP shocks.

Overall, the shopping-cost model predicts persistent fluctuations for output and inflation. It also predicts that sales are more volatile than output, that changes in inventories are less volatile than sales, and that changes in inventories are mildly procyclical. These results match the post-1985 behavior for these variables qualitatively, but not quantitatively. In particular, both inventories and sales are too volatile relative to output, and inventories are not procyclical enough.

4. A Comparison of Models with Inventories

We wish to compare the persistence of output and inflation produced by the shopping-cost model to that produced by two popular models with inventories. We do so to verify that the persistence produced by the shopping-cost model results from the shopping-cost framework, and not simply from adding inventories.

The popular alternative models are the linear-quadratic model and the factor of production model.

4.1 The Linear-Quadratic Model

The linear-quadratic model uses the consumer, the retailer, and the monetary authority of the baseline model. It introduces inventories as in West (1990). In particular, producers face quadratic costs of changing the level of production and of deviating from a target ratio of sales to inventories. Our version of the linear-quadratic model, however, differs from that of West. Our producers are monopolistic competitors that produce goods with both labor and capital, while his producer is a monopolist that produces goods with labor only. Also, our demand shocks are money growth shocks, while his are taste shocks.

Producer i chooses labor, capital, inventories, and prices to maximize expected discounted profits

$$\sum_{t=0}^{\infty}\sum_{h^t} q(h^t)\Big(p_i(h^t)s_i^d(h^t) - P(h^t)\left[w(h^t)l_i(h^t) + r^k(h^t)k_i(h^t)\right]\Big), \tag{20}$$

subject to the production technology in equation (9), the definition of net output in equation (10), the demand for good i depicted in equation (6), and the definition of labor usage l_i. Following West (1990), labor usage is

$$l_i(h^t) = n_i(h^t) + \frac{\zeta_1}{2}\left[\Delta y_i(h^t)\right]^2 + \frac{\zeta_2}{2}\left[x_i(h^{t-1}) - \eta s_i(h^t)\right]^2, \tag{21}$$

where x_i is the stock of inventories and Δ is the difference operator: $\Delta y_i(h^t) = y_i(h^t) - y_i(h^{t-1})$. Labor is used in three activities. The first term on the right side of equation (21) represents the time allocated to production. The second term reflects the labor used to change the level of production. Finally, the last term is a labor cost due to deviations of inventories from a fraction of sales. This term represents the labor cost associated with stockouts and is often called the convenience yield. Finally, inventories evolve as in equation (18).

In our symmetric equilibrium, clearing of the bond, capital, and labor capital markets are described by equations (14.1), (14.2), and

$$N(h^t) = n(h^t) + \frac{\zeta_1}{2}\left[\Delta Y(h^t)\right]^2 + \frac{\zeta_2}{2}\left[X(h^{t-1}) - \eta S(h^t)\right]^2, \tag{22}$$

where aggregate quantities are as before, except for $n(h^t) = \int n_i(h^t)di = n_i(h^t)$ and $X(h^t) = \int x_i(h^t)di = x_i(h^t)$. Clearing of the goods market requires equation (14.4), (14.5), (14.6), and (19.1).

Table 3 reports the benchmark parameter values for the linear-quadratic model. The values are set similarly to those of the baseline model. The linear-quadratic model has three additional parameters: ζ_1, ζ_2, and η. West (1990) estimates a cost function similar to that in equation (22). Although the exact specification differs, West's estimates offer a good benchmark (see West Table III). He provides estimates for $\zeta_1/2$, $\zeta_2/2$, and η. Estimates for $\zeta_1/2$ range from 0.344 to 0.366 and estimates for $\zeta_2/2$ range from 0.111 to 0.145. Accordingly, we set $\zeta_1 = 0.7$ and $\zeta_2 = 0.25$. West also provides estimates for η that range between -0.040 and -0.057, but argues that a value between 0.4 and 0.7 reflects the general consensus. We set $\eta = 0.68$ so that steady-state sales are 60 percent of available goods (output plus inventories) as in the full post-war US sample. The sensitivity of our results to these new parameters can be obtained from the authors.

4.2 The Factor of Production Model

The factor of production model also retains the consumer, the retailer, and the monetary authority of the baseline model. It adds inventories to the baseline model by following Kydland and Prescott (1982) and Christiano (1988). In particular, inventories are an input in production, because they reduce down time and help economize on labor. Our version of the factor of production model is different from that of Kydland and Prescott. Importantly, our producers are monopolistic competitors, while theirs are perfect competitors. Also, we consider both technology and monetary growth shocks, while they consider only technology shocks.

Producer i chooses labor, capital, inventories, and prices to maximize expected discounted profits given by equation (8) subject to the production technology in equation (9), the definition of net output in equation (10), the demand for good i in equation (6), and the evolution of inventories in equation (18). In this case, however, gross output of good i is produced using

$$y_i(h^t) = z(h^t)\Big(\big[(1-\ell)k_i(h^t)^{-\varepsilon} + \ell\, x_i(h^{t-1})^{-\varepsilon}\big]^{-1/\varepsilon}\Big)^{\alpha} n_i(h^t)^{1-\alpha}, \tag{23}$$

where $1/(1+\varepsilon)$ is the elasticity of substitution between capital and inventories.

In our symmetric equilibrium, the bond, capital, labor, and goods markets clear as in equations (14.1), (14.2), (14.3), (14.4), (14.5), (14.6), and (19.1). Aggregate quantities are

as in the linear-quadratic model, except for employment which is defined as in the baseline model.

Table 3 also reports the benchmark parameter values for the factor of production model. The values are similar to those of the previous models. The factor of production model has two new parameters: ε and ℓ. Kydland and Prescott (1982) set $\varepsilon = 4$ and $\ell = 0.28 \times 10^{-5}$ to ensure that the elasticity of substitution between capital and inventories is low and that inventories represent about one-fourth of output. Following these guidelines, we set $\varepsilon = 4$ and $\ell = 6 \times 10^{-7}$ so that the elasticity is low and that steady-state sales are 60 percent of available goods. The sensitivity of our results to these new parameters can be obtained from the authors.

4.3 Simulation Results

The results appear in Table 4 and Figure 4. The moments are computed as in Table 2 and Figure 2. The results suggest that adding inventories to the baseline model as in the linear-quadratic model or as in the factor of production model raises the persistence of output and inflation. The results also suggest that the benchmark shopping-cost model yields the largest persistence for inflation, followed by the benchmark factor of production model and the benchmark linear-quadratic model.[2]

The first autocorrelation of output predicted by all three models with inventories are similar, in the 0.92 to 0.95 range. The first autocorrelation of inflation predicted by the benchmark shopping-cost model is 0.54, while that predicted by the benchmark linear-quadratic model is 0.35 and by the benchmark factor of production model is 0.48. At higher lags, the predicted autocorrelations of output for all three models decline slowly. The predicted autocorrelations of inflation decline the most slowly for the benchmark shopping-cost model and the most rapidly for the benchmark linear-quadratic model.

We also verify that the linear-quadratic model and the factor of production model provide adequate characterizations of the fluctuations of sales and inventory investment. As for the shopping-cost model, the linear-quadratic model and the factor of production

[2] See Bivin (2005) for recent econometric tests of the linear-quadratic and flexible-accelerator models.

model predict that sales are more volatile than output and that changes in inventories are less volatile than sales. In contrast to the shopping-cost model, the benchmark alternative models predict that changes in inventories are incorrectly countercyclical.

We have performed a number of experiments to verify the robustness of these results. These experiments document that the linear-quadratic model and the factor of production model struggle to simultaneously produce high first-order autocorrelations for output and inflation and procyclical inventories. These results can be obtained from the authors.

Overall, all three models with inventories produce much more persistence for output and inflation than the benchmark baseline model. That said, the shopping-cost model better matches the data because it produces a larger persistence of inflation and mildly procyclical changes in inventories.

5. Conclusion

Postwar US business cycle fluctuations of output and inflation are remarkably persistent. Standard sticky-price monetary business cycle models with explicit microfoundations, however, fail to explain this persistence. Our objective is to determine whether adding inventories to a standard sticky-price monetary business cycle model raises the predicted persistence of output and inflation.

To fulfill this objective, we compare the persistence of output and inflation computed from a baseline sticky-price model without inventories to the persistence produced by a sticky-price model with inventories. In the model with inventories, producers carry inventories to manages sales and to smooth production. We find that adding inventories significantly raises the persistence of output and inflation.

To a certain extent, the model with inventories can also match the behavior of sales and inventories along the business cycle. In the full US data sample, the standard deviation of sales is smaller than the standard deviation of output while the correlation between changes in inventories and output is positive and large. In the post-1985 US data sample, the standard deviation of sales is larger than the standard deviation of output while the correlation between changes in inventories and output is positive, but smaller. Our inven-

tory model provides a better qualitative explanation for the later sample. Quantitatively, the model produces inventories and sales that are too volatile, and inventories that are not procyclical enough.

Appendix A — Data Appendix

Our quarterly post-war US sample covers the 1959:1 to 2000:1 period. It comprises the following: *Gross Domestic Product:* Bureau of Economic Analysis, NIPA Table 1.2; *Change in Private Inventories:* Bureau of Economic Analysis, NIPA Tables 1.2, 5.11A, 5.11B; *Private Inventories:* Bureau of Economic Analysis, NIPA Tables 5.13A, 5.13B; *Final Sales of Domestic Business:* Bureau of Economic Analysis, NIPA Tables 5.13A, 5.13B; *Consumer Price Index:* Bureau of Economic Analysis, NIPA Table 7.1; *Investment:* fixed investment, Citibase, mnemonic GIFQF; *Population:* Citibase, mnemonic P16; and *M2 Money Stock:* FRED.

We construct per capita output Y_t and per capita inventories X_t by dividing Gross Domestic Product and Private Inventories by Population. Our measure of the price index P_t is the Consumer Price Index. Finally, we construct quarterly per capita M2 data by averaging the monthly data and dividing by Population.

References

Aguirregabiria, V. (1999) The dynamics of markups and inventories in retailing firms, *Review of Economic Studies* **66**, 275–308.

Andersen, T.M. (1998) Persistency in sticky price models, *European Economic Review* **42**, 593–603.

Ascari, G. (2000) Optimising agents, staggered wages and persistence in the real effects of money shocks, *Economic Journal* **110**, 664–686.

Ascari, G. and J.A. Garcia (2004) Relative wage concern: The missing piece in the contract multiplier, *Research in Economics* **58**, 343–369.

Ball, L. and D. Romer (1990) Real rigidities and the non-neutrality of money, *Review of Economic Studies* **57**, 183-203.

Ben Aissa, M.S. and O. Musy (2007) Persistence with staggered price setting in nominal and real terms, *Applied Economics Letters* **14**, 233–237.

Bergin, P.R. and R.C. Feenstra (2000) Staggered price setting, translog preferences, and endogenous persistence, *Journal of Monetary Economics* **45**, 657–680.

Bils, M. and J.A. Kahn (2000) What inventory behavior tells us about business cycles, *American Economic Review* **90**, 458–481.

Bivin, D.G. (2005) Gauging the performance of the linear-quadratic inventory model, *Applied Economics* **37**, 1215–1231.

Blinder, A.S. (1982) Inventories and sticky prices: More on the microfoundations of macroeconomics, *American Economic Review* **72**, 334–348.

Blinder, A.S. and S. Fischer (1981) Inventories, rational expectations, and the business cycle, *Journal of Monetary Economics* **8**, 277-304.

Blinder, A.S. and L.J. Maccini (1991) Taking stock: A critical assessment of recent research on inventories, *Journal of Economic Perspectives* **5**, 73–96.

Boileau, M. and M.-A. Letendre (2003) How much persistence should sticky-price models generate to match US data? *Economics Letters* **78**, 335–342.

Borenstein, S. and A. Shepard (2002) Sticky prices, inventories, and market power in wholesale gasoline markets, *RAND Journal of Economics* **33**, 156–172.

Chari, V.V., P.J. Kehoe, and E.R. McGrattan (2000) Sticky price models of the business cycle: Can the contract multiplier solve the persistence problem? *Econometrica* **68**, 1151-1179.

Christiano, L.J. (1988), Why does inventory investment fluctuate so much? *Journal of Monetary Economics* **21**, 247–280.

Christiano, L.J., M. Eichenbaum, and C. Evans (2005) Nominal rigidities and the dynamic effects of a shock to monetary policy, *Journal of Political Economy* **113**, 1–45.

Das, B.J. (1998) Price smoothing and inventory adjustments, *Applied Economics Letters* **5**, 117–119.

Dittmar, R., W.T. Gavin, and F.E. Kydland (2005) Inflation persistence and flexible prices, *International Economic Review* **46**, 245–261.

Edge, R.M. (2002) The equivalence of wage and price staggering in monetary business cycle models, *Review of Economic Dynamics* **5**, 559–585.

Erceg, C. (1997) Nominal wage rigidities and the propagation of monetary disturbances, Board of Governor of the Federal Reserve System, International Finance Discussion Paper Number 590.

Fuhrer, J. and G. Moore (1995) Inflation persistence, *Quarterly Journal of Economics* **110**, 127–159.

Fisher, J.D.M. and A. Hornstein (2000) (S, s) inventory policies in general equilibrium, *Review of Economic Studies* **67**, 117–145.

Hornstein, A. and P.D. Sarte (1998) Staggered prices and inventories: Production smoothing reconsidered, Federal Reserve Bank of Richmond Working Paper No. 98-8.

Huang, K.X.D. and Z. Liu (2002) Staggered wage-setting, staggered price-setting, and business cycle persistence, *Journal of Monetary Economics* **49**, 405–433.

Huang, K.X.D. and Z. Liu (2001) Production chains and general equilibrium dynamics, *Journal of Monetary Economics* **48**, 437–462.

Ireland, P.N. (2003) Endogenous money or sticky prices? *Journal of Monetary Economics* **50**, 1623–1648.

Ireland, P.N. (2001) Sticky-price models of the business cycle: Specification and stability, *Journal of Monetary Economics* **47**, 3–18.

Kahn, A. and J.K. Thomas (2007) Inventories and the business cyle: An equilibrium analysis of (S, s) policies, *American Economic Review* **97**, 1165–1188.

Kahn, J., M.M. McConnell, and G. Perez-Quiros (2001) Inventories and the information revolution: Implications for output volatility, mimeo Federal Reserve Bank of New York.

Keen, B. and Y. Wang (2007) What is a realistic value for price adjustment costs in New Keynesian models? *Applied Economics Letters* **14**, 789–793.

Kiley, M.T. (2000) Endogenous price stickiness and business cycle persistence, *Journal of Money, Credit and Banking* **32**, 28–53.

King, R.G., Plosser, C.I., and S.T. Rebelo (2002) Production, growth and business cycles: Technical appendix, *Computational Economics* **20**, 87–116.

King, R.G., Rebelo, S.T (1999) Resuscitating real business cycles. In: Taylor, J.B., Woodford, M. (eds.), *Handbook of Macroeconomics: Vol I*, Elsevier Science, 927–1007.

Kydland, F. and E.C. Prescott (1982) Time to build and aggregate fluctuations, *Econometrica* **50**, 1345–1370.

Levin, A.T. and J.M. Piger (2004) Is inflation persistence intrinsic in industrial economies? European Central Bank Working Paper Series No. 334.

McConnell, M.M. and G. Perez-Quiros (2000) Output fluctuations in the U.S.: What has changed since the early 1980's? *American Economic Reviews* **90**, 1464–1476.

Nelson, E. (1998) Sluggish inflation and optimizing models of the business cycle, *Journal of Monetary Economics* **42**, 303–322.

Prescott, E.C. (1986) Theory ahead of business cycle measurement, *Federal Reserve Bank of Minneapolis Quarterly Review* **10**, 9–22.

Ramey, V.A. and K.D. West (1999) Inventories, in J.B Taylor and M. Woodford (eds.) *Handbook of Macroeconomics: Vol I*, Elsevier Science, 863–923.

Taylor, J. (1980) Aggregate dynamics and staggered contracts, *Journal of Political Economy* **88**, 1–23.

West, K.D. (1990) The sources of fluctuations in aggregate inventories and GNP, *Quarterly Journal of Economics* **105**, 939–971.

Table 1: Benchmark Parameter Values

The Baseline Model	
Consumers	$\beta = 0.99$, $\sigma = 1.325$, $\omega = 0.94$, $\chi = 0.39$, $\psi = 1.7119$, $\delta = 0.025$, $\nu = 0$
Producers	$\alpha = 0.36$, $\phi_p = 25$, $\bar{z} = 1$, $\rho_z = 0.979$, $\sigma_z = 0.0072$
Retailers	$\theta = 10$
Monetary Authority	$\bar{\mu} = 1$, $\rho_\mu = 0.69$, $\sigma_\mu = 0.006$
The Shopping-Cost Model	
Consumers	$\beta = 0.99$, $\sigma = 1.325$, $\omega = 0.94$, $\chi = 0.39$, $\psi = 1.7345$, $\delta = 0.025$, $\nu = 9.08$
Producers	$\alpha = 0.36$, $\phi_p = 25$, $\bar{z} = 1$, $\rho_z = 0.979$, $\sigma_z = 0.0072$
Retailers	$\theta = 10$, $\gamma = 0.9906$, $\xi = 0.0168$
Monetary Authority	$\bar{\mu} = 1$, $\rho_\mu = 0.69$, $\sigma_\mu = 0.006$

Note: Several parameters are set endogenously. The values for ψ and ν ensure that hours worked are 30 percent of the time endowment in the steady state and that the ratio of the standard deviations of the logarithm of investment and the logarithm of output is 2.9. The values for ξ and γ are set to ensure that sales are 60 percent of all available goods (output plus inventories) and that the cost of shopping vanishes in the steady state.

Table 2. Unconditional Moments

	Volatility Relative to Output		*Correlation with Output*	*First-Order Autocorrelation*	
	Sales	Inventories	Inventories	Output	Inflation
Post-war US Data					
1959:1–2000:1	0.94	0.13	0.50	0.97	0.78
1985:1–2000:1	1.07	0.23	0.22	0.93	0.42
The Baseline Model					
Benchmark	1.00	—	—	0.45	0.01
High Price Cost	1.00	—	—	0.13	0.03
High Investment Cost	1.00	—	—	0.80	0.30
The Shopping-Cost Model					
Benchmark	1.27	0.85	0.08	0.92	0.54
High Price Cost	1.57	1.28	0.08	0.92	0.69
Low Investment Cost	1.89	1.62	0.03	0.93	0.54
High Shopping Cost	1.27	0.85	0.08	0.92	0.54
Low Convenience	1.29	0.84	0.04	0.92	0.53
High Convenience	1.15	0.86	0.26	0.92	0.54

Note: Entries under volatility relative to output show the ratio of the standard deviation of a variable to the standard deviation of output (in percentages). Entries under correlation with output show the contemporaneous correlation with output. Entries under first-order autocorrelation show the first-order sample autocorrelation of the variable. All variables are detrended by removing a linear-quadratic trend. The simulated moments are computed as the average over 1000 replications of 164 periods. The benchmark parameter values appear in Table 1. The alternative parameter values retain the benchmark values with the following changes. For the Baseline Model: High Price Cost (ϕ_p=75); High Investment Cost (ν=10). For the Shopping Cost Model: High Price Cost (ϕ_p=75); Low Investment Cost (ν=3); High Shopping Costs (γ=0.9415); Low Convenience (ξ=0.0123); High Convenience (ξ=0.054).

Table 3: A Comparison of Model with Inventories: Benchmark Parameter Values

The Linear-Quadratic Model	
Consumers	$\beta = 0.99$, $\sigma = 1.325$, $\omega = 0.94$, $\chi = 0.39$, $\psi = 1.6968$,
	$\delta = 0.025$, $\nu = 4.78$
Producers	$\alpha = 0.36$, $\phi_p = 25$, $\zeta_1 = 0.7$, $\zeta_2 = 0.25$, $\eta = 0.68$,
	$\bar{z} = 1$, $\rho_z = 0.979$, $\sigma_z = 0.0072$
Retailers	$\theta = 10$
Monetary Authority	$\bar{\mu} = 1$, $\rho_\mu = 0.69$, $\sigma_\mu = 0.006$
The Factor of Production Model	
Consumers	$\beta = 0.99$, $\sigma = 1.325$, $\omega = 0.94$, $\chi = 0.39$, $\psi = 1.7022$,
	$\delta = 0.025$, $\nu = 6.95$
Producers	$\alpha = 0.36$, $\phi_p = 25$, $\ell = 6 \times 10^{-7}$, $\varepsilon = 4$
	$\bar{z} = 1$, $\rho_z = 0.979$, $\sigma_z = 0.0072$
Retailers	$\theta = 10$
Monetary Authority	$\bar{\mu} = 1$, $\rho_\mu = 0.69$, $\sigma_\mu = 0.006$

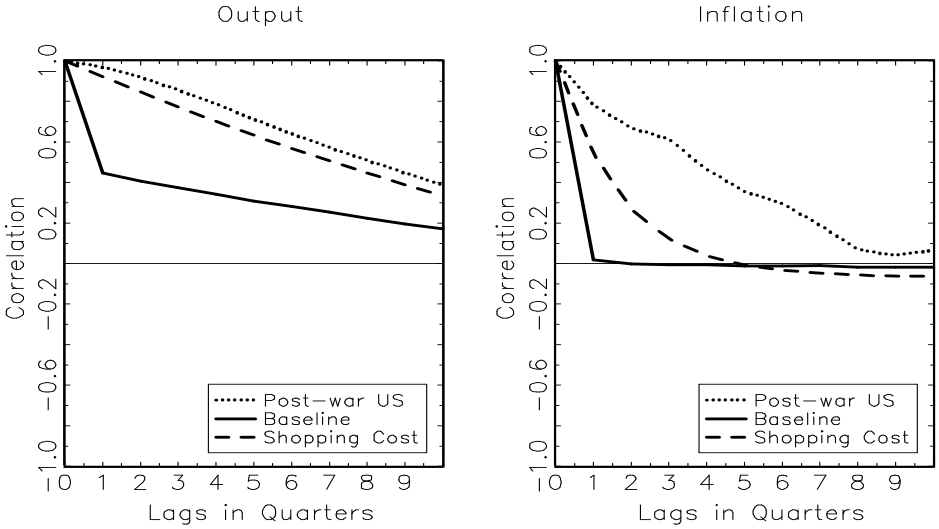
Note: Several parameters are set endogenously. The values for ψ and ν ensure that hours worked are 30 percent of the time endowment in the steady state and that the ratio of the standard deviations of the logarithm of investment and the logarithm of output is 2.9. The values for η and ℓ are set to ensure that sales are 60 percent of all available goods (output plus inventories) in the steady state.

Table 4. A Comparison of Model with Inventories: Unconditional Moments

	Volatility Relative to Output		*Correlation with Output*	*First-Order Autocorrelation*	
	Sales	Inventories	Inventories	Output	Inflation
The Shopping-Cost Model					
Benchmark	1.27	0.85	0.08	0.92	0.54
The Linear-Quadratic Model					
Benchmark	1.18	0.57	-0.05	0.95	0.35
The Factor of Production Model					
Benchmark	1.23	0.63	-0.08	0.92	0.48

Note: Entries under volatility relative to output show the ratio of the standard deviation of a variable to the standard deviation of output (in percentages). Entries under correlation with output show the contemporaneous correlation with output. Entries under first-order autocorrelation show the first-order sample autocorrelation of the variable. All variables are detrended by removing a linear-quadratic trend. The simulated moments are computed as the average over 1000 replications of 164 periods. The benchmark parameter values appear in Table 1 for the Shopping-Cost Model and in Table 3 for the Linear-Quadratic Model and the Factor of Production Model.

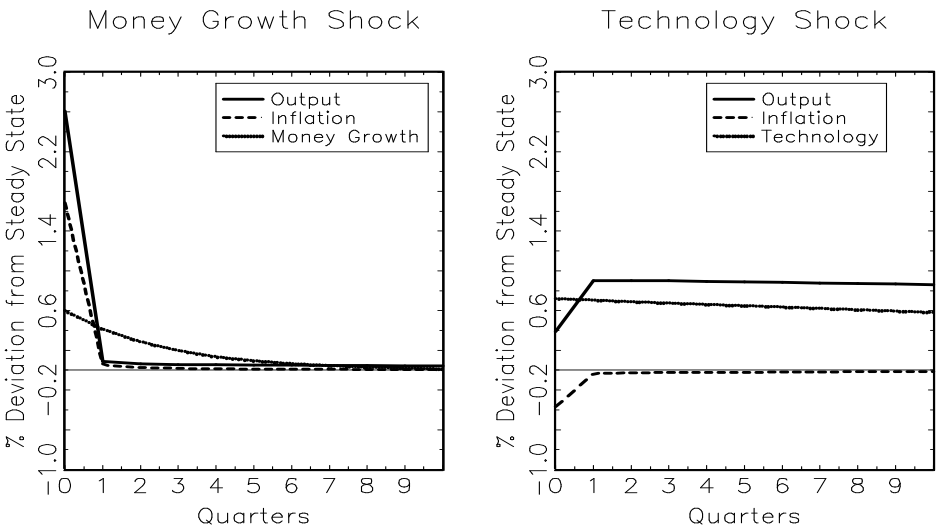
Figure 1. Autocorrelation Functions



Note: The figure shows the autocorrelation function for output and inflation. The moments are computed from the full post-war US data and from the benchmark parameter values for the baseline model and of the shopping-cost model (see Table 1 and Data Appendix).

Figure 2. Impulse Responses:

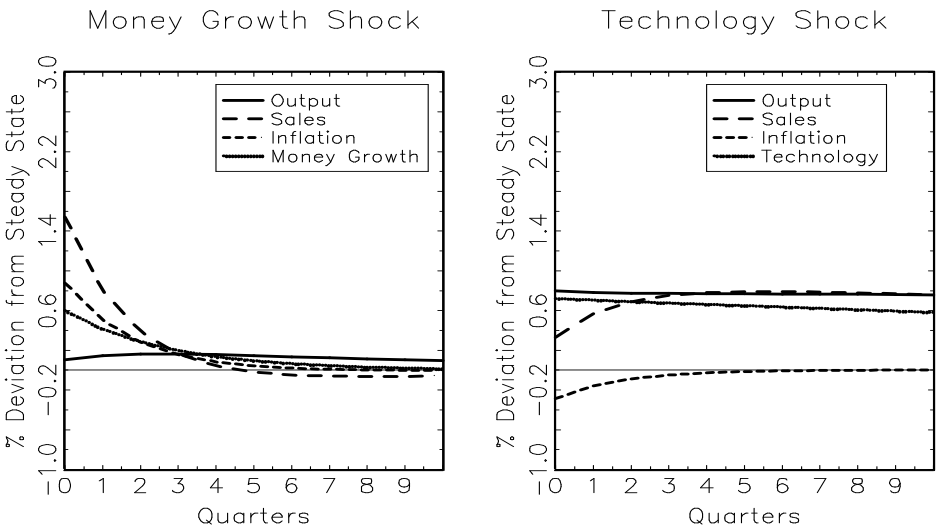
The Baseline Model



Note: The figure shows the responses to a one standard deviation shock to money growth and to technology. The responses are computed from the benchmark parameter values of the baseline model (see Table 1).

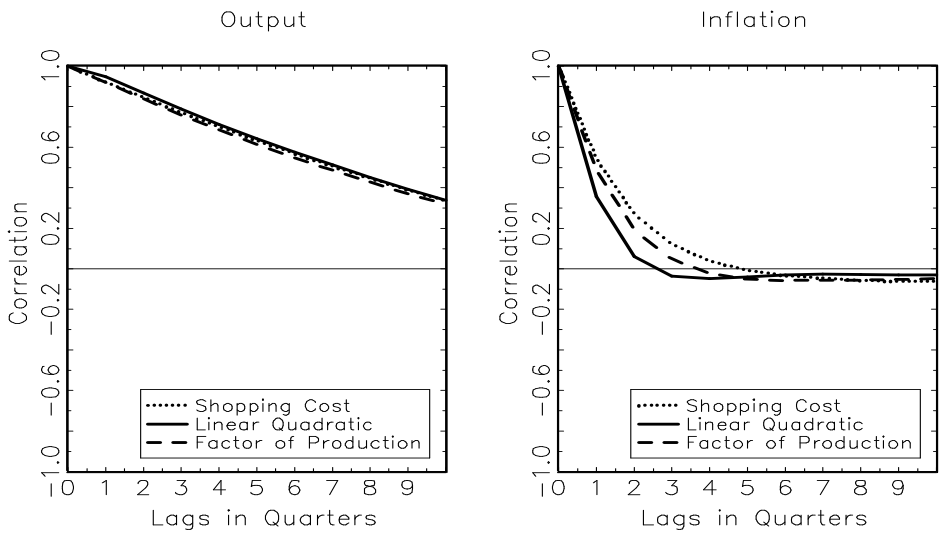
Figure 3. Impulse Responses:

The Shopping-Cost Model



Note: The figure shows the responses to a one standard deviation shock to money growth and to technology. The responses are computed from the benchmark parameter values of the shopping-cost model (see Table 1).

Figure 4. A Comparison of Model with Inventories: Autocorrelation Functions



Note: The figure shows the autocorrelation function for output and inflation. The moments are computed from the benchmark parameter values of the shopping-cost model (see Table 1) as well as of the linear-quadratic model and of the factor of production model (see Table 3).