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# Relative Price Shocks and Inflation*

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**Abstract**

Inflation is determined by interaction between real factors and monetary policy. Among the most important real factors are shocks to the supply and demand for different components of the consumption basket. We use an estimated multi-sector New Keynesian model to decompose the behavior of U.S. inflation into contributions from sectoral (or "relative price") shocks, monetary policy shocks, and aggregate real shocks. The model is estimated by maximum likelihood with U.S. data for the post-1994 period in which inflation and the monetary policy regime appeared to be stable. In addition to providing a broad decomposition of inflation behavior, we enlist the model to help us understand the inflation shortfall from 2012 to 2019, and the dramatic inflation movements during the COVID pandemic.

*JEL classification*: E31, E52, E58
*Key Words*: Monetary policy, sectoral shocks, inflation shortfall, COVID-19.

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# 1. Introduction

How do factors that drive relative price changes across consumption categories affect inflation? In theory, monetary policy can offset these factors and perfectly stabilize inflation. This does not happen in practice for two broad reasons: first, monetary policy may be unable to control inflation perfectly; second, monetary policy may choose not to control inflation perfectly, instead following a policy that results in equilibrium fluctuations in inflation. Following the latter branch, we ask what is the contribution of "relative price" shocks to the behavior of inflation. We focus on inflation determination in a stable monetary policy regime, namely the post-1994 United States. The paper makes three contributions, all based on an estimated multi-sector New Keynesian model. First, we provide summary information on the importance of relative price shocks for the behavior of inflation since 1994. Second, we examine the inflation shortfall from target that occurred between 2012 and 2019 in the U.S., decomposing that shortfall into policy and real shocks. Third, we apply the model to studying the dramatic change in inflation during the COVID pandemic, providing an out-of-sample version of that same decomposition.

The relative influence of monetary policy and real factors on inflation is one of the most important and long-studied questions in monetary economics. Any such analysis immediately confronts the issue of monetary policy regimes. At one extreme, if there is a stable underlying monetary policy regime, then the tools of rational expectations and local approximation of DSGE models may be appropriate. At another extreme, clearly identified breaks in regime can be the source of facts against which theories are evaluated, but the researcher must decide how to model information sets of private agents and the policymaker. The fundamental assumption of this paper is that from January 1995 to December 2019 the United States was in a stable, well-understood monetary policy regime and that it is appropriate to use a locally approximated DSGE model with rational expectations to study that period.

The first contribution involves basic analysis of inflation and relative price shocks. The model has 15 consumption categories, shocks to productivity whose volatility and dynamics differ across categories, and Rotemberg costs of price adjustment that are allowed to vary across categories. We estimate the model on monthly data from 1995-2019 by maximum likelihood. The observable variables are rates of price change for the 15 consumption categories, and the level of the nominal interest rate. We decompose inflation into the contribution of monetary policy shocks and shocks to productivity in each of the consumption categories. Over the sample, inflation was low and stable, but nonetheless exhibited substantial month-to-month volatility. Our estimates explain that volatility primarily with sectoral shocks, which we label relative price shocks. One way we

evaluate the model fit is through its ability to match the historical relationship between the monthly inflation rate and the distribution of relative price changes. As discussed in Hornstein, Ruge-Murcia and Wolman (2022), from 1995 to 2019 there was a tight negative relationship between the monthly inflation rate and the share of consumption expenditures exhibiting relative price inreases. The model reproduces and explains that relationship.

The second contribution is to decompose the shortfall of inflation from target in the 2012-2019 period. According to this decomposition, which uses the smoothed estimates of the model's structural shocks, the largest contributors to the cumulative shortfall of the price level from the 2% trend implied by the Fed's target were shocks to gasoline and energy goods and to health care. Note that we are intentionally describing causality; absent a model, when one analyzes inflation and category price changes, it is only possible to describe the extent to which a particular category's price change accounts for inflation. The model allows us to provide estimates of the extent to which particular shocks *caused* the inflation shortfall. While nontrivial, the monetary policy contribution is relatively small (about 17%).

A leading theoretical explanation for the inflation shortfall is that it resulted from interaction between the lower bound on nominal interest rates and the Fed's implicit policy rule. See for example Bianchi, Melosi and Rottner (2021). Our current results cannot speak directly to that view because we do not impose a lower bound on nominal interest rates. However, during much of the period when the shortfall occurred, the interest rate was at its lower bound, and we do use interest rate data in estimation. The 17% contribution from monetary policy shocks can be interpreted as a lower bound for the effects of the zero bound.

The third contribution is an out-of-sample analysis of the high inflation episode that began in March 2021 during the COVID-19 pandemic, and is ongoing as of this writing. As with the inflation shortfall, we decompose inflation into contributions of the sectoral shocks and monetary policy. Here, however, the smoothed estimates of the model's shocks use out-of-sample data, as our estimation sample ends in December 2019. In conducting local analysis around the model's (trending) steady state, we assume that the same policy rule remains in place during this high inflation episode. But has inflation in fact remained anchored? Our approach describes the contributions to inflation of policy shocks and real shocks under the assumption that inflation remains anchored. If one has outside information about the shocks, then that can be used together with our estimates to evaluate the anchoring question. Summarizing what we find: of the 2.7% inflation overshoot from March 2021 through November 2021, the largest contributor is shocks to the motor vehicle sector, at 31%. According to the model, monetary policy shocks explain 22% of the inflation overshoot.

There is a large and varied literature on relative prices and inflation. One branch focuses on the

role of oil shocks in driving short-run inflation fluctuations; see for example Kilian and Zhou (2021) and the references therein. Our paper embodies a generalization of that idea: oil shocks are the most volatile relative price shocks, but in any given period some other category might experience an unusually large shock that accounts for a sizable movement in inflation—for example, motor vehicles during the COVID period. Some other branches of the literature were concerned mainly with periods when inflation was *not* stable—in particular a set of papers from the 1970s and '80s that studied causality in the opposite direction, from inflation to the variability of relative prices. A key reference is Parks (1978). In principle, our model can have inflation (i.e., policy) affect relative price variability but in practice that channel is weak, as one would expect in a stable policy regime.

The papers closest to ours are Ball and Mankiw (1995), Balke and Wynne (2000), Reis and Watson (2010), and Smets, Tielens, and Van Hove (2019). In Ball and Mankiw (1995), menu costs mean that inflation tends to move with the price change of sectors hit by the largest shocks to their desired price; prices don't change in sectors hit by small shocks to their desired price. In our model, Rotemberg costs mean that any firm hit by a shock will adjust its price; in equilibrium, the interaction of policy and shocks delivers a relationship between inflation and the distribution of actual relative prices consistent with the data. Balke and Wynne (2000) conduct an analysis quite similar to ours, but their model has flexible prices and monetary policy is characterized by a constant money growth rule. Reis and Watson's (2010) empirical analysis using a factor model leads them to conclude that "most of the variation in standard aggregate inflation indices is associated with relative-price movements." Our estimated DSGE model leads us to the same conclusion. Like Smets, Tielens, and Van Hove (2019) we use the Kalman filter to decompose the behavior of inflation into aggregate and sectoral shocks. They study network interactions absent from our model, and estimate over a longer sample in which inflation was not stable. They do not address the inflation-shortfall or COVID episodes.

Our paper also relates to the literature that discusses how the Phillips curve can appear to flatten when policy is conducted optimally so as to stabilize inflation. McLeay and Tenreyro (2020) is a leading example. While we do not study optimal policy, in practice the Federal Reserve did stabilize inflation from 1995-2019, and that is embodied in our estimated model. We emphasize that the remaining small fluctuations in inflation were associated with variation in relative prices across categories. Borio, Disyatat, Xia, and Zakrajšek (2021) also emphasize that in a stable monetary policy regime, sector-specific factors can play a major role in driving inflation.

The paper proceeds as follows. Section 2 describes the model and its balanced growth path. Section 3 describes the empirical analysis and presents the parameter estimates. Section 4 presents

the basic analysis of inflation and relative price shocks. Sections 5 and 6 cover the inflation shortfall and COVID inflation, respectively. Section 7 concludes.

## 2. The Model

The economy consists of an infinitely-lived representative household, continua of firms in a finite number of sectors, and a monetary authority. Firms are monopolistic-competitors that each produce a differentiated good using labor as the sole input of production.

### 2.1 Households: Preferences, Constraints, and Optimality

The household maximizes

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{t-\tau} \left( \ln\left(C_t\right) + \psi \frac{\left(1-N_t\right)^{1-\eta}}{1-\eta} \right), \tag{1}$$

where $E_\tau$ denotes the conditional expectation as of time $\tau$, $\beta \in (0,1)$ is the discount factor, $C_t$ is consumption, $N_t$ is hours worked, and $\psi$ and $\eta$ are positive preference parameters. The time endowment is normalized to be one. Consumption is an aggregate of goods produced in different sectors $s = 1, 2, \ldots, S$,

$$C_t = \prod_{s=1}^{S} \left(\xi^s\right)^{-\xi^s} \left(c_{s,t}\right)^{\xi^s}, \tag{2}$$

where $\xi^s \in (0,1)$ are aggregation weights that satisfy $\sum_{s=1}^{S} \xi^s = 1$ and $c_{s,t}$ is consumption of goods produced in sector $s$. Under the Cobb-Douglas specification in (2), the elasticity of substitution between goods produced in different sectors is one.

Within each sector, there is a continuum of monopolistically-competitive firms that each produce a differentiated good. The household's preferences for these goods are represented by the CES aggregator

$$c_{s,t} = \left( \int c_{i,s,t}^{(\theta-1)/\theta} \right)^{\theta/(\theta-1)}, \tag{3}$$

where $c_{i,s,t}$ is consumption of the good produced by firm $i$ in sector $s$ and $\theta > 1$ is the elasticity of substitution between goods produced in the same sector. Since this elasticity is larger than one, goods produced in the same sector (e.g., apples and pears) are closer substitutes than goods produced in different sectors (e.g., apples and nails).

In every period, the household faces the budget constraint

$$P_t C_t + B_t \leq P_t w_t N_t + \left(1 + R_{t-1}\right) B_{t-1} + D_t, \tag{4}$$

where $P_t$ is the aggregate price level, $B_t$ is nominal bonds, $w_t$ is the real wage, $R_t$ is the net nominal interest rate, and $D_t$ are profits from firms, which are transferred to the household in the form of dividends. The price index satisfies

$$P_t = \prod_{s=1}^{S} (P_{s,t})^{\xi_s}. \tag{5}$$

The solution to the household's maximization problem shows that the optimal labor supply satisfies

$$\frac{\psi (1 - N_t)^{-\eta}}{1/C_t} = w_t, \tag{6}$$

meaning that the marginal rate of substitution between leisure and consumption equals the real wage; the optimal consumption of good $i$ produced in sector $s$ is

$$c_{i,s,t} = \xi_s \left( \frac{P_{i,s,t}}{P_{s,t}} \right)^{-\theta} \left( \frac{P_{s,t}}{P_t} \right)^{-1} C_t, \tag{7}$$

where

$$P_{s,t} = \left( \int P_{i,s,t}^{1-\theta} dl \right)^{1/(1-\theta)} \tag{8}$$

is a sector-specific price index; and the optimal (total) consumption satisfies the intertemporal Euler equation

$$\frac{1}{P_t C_t} = \beta (1 + R_t) E_t \left( \frac{1}{P_{t+1} C_{t+1}} \right). \tag{9}$$

### 2.2 Firms: Technology, Market Structure, and Optimality

Firm $i$ in sector $s$ produces output using the technology

$$y_{i,s,t} = e^{z_t} e^{z_{s,t}} n_{i,s,t}, \tag{10}$$

where $y_{i,s,t}$ is output, $e^{z_t}$ and $e^{z_{s,t}}$ are, respectively, the aggregate and sectoral levels of productivity, and $n_{i,s,t}$ is labor input. Labor is completely mobile across firms and sectors. Sectoral productivity follows the trend-stationary process,

$$z_{s,t} = \mu_s t + a_{s,t}, \tag{11}$$

$$a_{s,t} = \rho_s a_{s,t-1} + \varepsilon_{s,t}, \tag{12}$$

where $t$ is a time index, $\mu_s$ is a constant, $a_{s,t}$ represents stochastic deviations from the time trend, $\rho_s \in (-1, 1)$ is a parameter, and $\varepsilon_{s,t}$ is an independent and identically distributed (i.i.d.) innovation drawn from a normal distribution with mean zero and constant conditional variance $\sigma_s^2$. The deviation from the time trend has different persistence and variance across sectors. The trend itself

is also different across sectors, which is important for our model to account for the trends in relative prices observed in the data. Aggregate productivity follows the process,

$$z_t = \rho z_{t-1} + \varepsilon_t, \tag{13}$$

where $\rho \in (-1, 1)$ is a parameter and $\varepsilon_t$ is an i.i.d. innovation drawn from a normal distribution with mean zero and constant conditional variance $\sigma^2$.[1]

Each firm must incur a cost when it changes its nominal price. The cost is specified in units of the aggregate consumption good, is convex in the size of the adjustment, and is proportional to the quantity produced by the firm. The per-unit cost, $\Phi_{i,s,t}$, for firm $i$ in sector $s$ in period $t$ is

$$\Phi_{i,s,t} = \Phi\left(P_{i,s,t}, P_{i,s,t-1}\right) = \frac{\zeta_{s,t}\phi_s}{2}\left(\frac{1}{e^{\alpha\pi+\alpha_s\pi_s}}\frac{P_{i,s,t}}{P_{i,s,t-1}} - 1\right)^2, \tag{14}$$

where $\phi_s \geq 0$, $\alpha \geq 0$ and $\alpha_s \geq 0$ are parameters that satisfy $0 \leq \alpha + \alpha_s \leq 1$, $\zeta_{s,t}$ is a deterministic trend, and $\pi$ and $\pi_s$ are, respectively, the steady-state inflation rate and the steady-state sectoral rate of price change. The parameter $\phi_s$ controls the degree of price rigidity and takes value zero in the special case where prices are completely flexible. Since $\phi_s$ is indexed by $s$ (but not by $i$), price rigidity differs across sectors, but is constant across firms within a sector. The deterministic trend $\zeta_{s,t}$ is specified as

$$\zeta_{s,t} = (1/e^{\mu_s})^t \left(\prod_{k=1}^{S} (e^{\mu_k})^{\xi_k}\right)^t.$$

We require that price-adjustment costs grow at the trend rate $\zeta_{s,t}$ because the labor part of costs for sector $s$ grows at rate $e^{\gamma_w}/e^{\mu_s}$; if the price-adjustment part of costs were to grow at a different rate, then one or the other components of costs would become negligible in the long run. This means that there would be no balanced growth path. We will see below that $e^{\gamma_w} = \prod_{s=1}^{S} (e^{\mu_s})^{\xi_s}$, so that the trend can be written as $\zeta_{s,t} = e^{(\gamma_w - \mu_s)t}$.

Finally, the factors in the denominator of (14) determine the degree and the form of indexation as follows. If $\alpha = \alpha_s = 0$, then there is no indexation and firms incur a cost for any nominal price adjustment. If $0 < \alpha + \alpha_s < 1$, then there is partial indexation. If $\alpha = 1$ and $\alpha_s = 0$, then there is complete indexation to the aggregate inflation rate. Thus, price increases equal to the steady-state rate of aggregate price change are costless. If $\alpha = 0$ and $\alpha_s = 1$, then there is complete indexation to the sectoral inflation rate and price increases at the steady-state rate of sectoral price change

[1] Results would be unchanged if we were also to assume a trend in aggregate productivity, for instance, equal to the growth rate of aggregate output and with sectoral trends adjusted accordingly because what matters in this model are relative productivity trends rather than absolute ones.

are costless. And, if $\alpha + \alpha_s = 1$ with $\alpha < 1$ and $\alpha_s < 1$, then there is complete indexation to an average of the aggregate and sectoral price changes.

The firm chooses output, labor input, and the price of its good to maximize profits, where costs comprise labor costs and adjustment costs. The maximization is subject to the demand function (7), the demand associated with other firms' adjustment costs,[2] and the technology (10). The solution to this problem delivers the following optimality condition for firm $i$ in sector $s$:

$$\begin{aligned}\left(\frac{\theta-1}{\theta}\right)\frac{P_{i,s,t}}{P_t} &= \frac{w_t}{e^{z_t}e^{t\mu_s}e^{a_{s,t}}} + \zeta_{s,t}\frac{\phi_s}{2}\left(\frac{P_{i,s,t}}{e^{\alpha\pi+\alpha_s\pi_s}P_{i,s,t-1}}-1\right)^2 \\ &-\zeta_{s,t}\left(\frac{\phi_s}{\theta}\right)\left(\frac{P_{i,s,t}}{e^{\alpha\pi+\alpha_s\pi_s}P_{i,s,t-1}}-1\right)\frac{P_{i,s,t}}{e^{\alpha\pi+\alpha_s\pi_s}P_{i,s,t-1}} \\ &+\zeta_{s,t+1}\left(\frac{\phi_s}{\theta}\right)\left(\frac{1}{e^{\alpha\pi+\alpha_s\pi_s}}\right)E_t\left(1+R_t\right)^{-1}\frac{P_{t+1}}{P_t}\times \\ &\left(\frac{P_{i,s,t+1}}{e^{\alpha\pi+\alpha_s\pi_s}P_{i,s,t}}-1\right)\left(\frac{P_{i,s,t+1}}{P_{i,s,t}}\right)^{1-\theta}\left(\frac{P_{s,t}}{P_{s,t+1}}\right)^{-\theta}\frac{y_{s,t+1}}{y_{s,t}}.\end{aligned} \tag{15}$$

This equation relates the optimal price selected by firm $i$ to its marginal cost, including that associated with current and future expected price adjustments.

### 2.3 Monetary Policy

The monetary authority sets the nominal interest rate following the rule,

$$1 + R_t = \delta(1 + R_{t-1}) + (1-\delta)(1/\beta)\exp(\pi + \gamma_y + \lambda_\pi(\pi_t - \pi) + \lambda_y(\ln(Y_t) - \ln(Y)) + u_t), \tag{16}$$

where $\delta \in (-1, 1)$, $\lambda_\pi$, and $\lambda_y$ are parameters representing responsiveness to the lagged interest rate, inflation, and output, respectively, $\pi_t$ is the gross inflation rate ($= P_t/P_{t-1}$), $\gamma_y$ is the growth rate of output (see below), $\pi$ is a policy parameter denoting the inflation target, $Y_t$ is aggregate output, $Y$ is output in the balanced-growth steady state, and $u_t$ is a disturbance that represents movements in the interest rate beyond the control of the central bank.[3] This disturbance follows the process

$$u_t = \kappa u_{t-1} + \varsigma_t, \tag{17}$$

where $\kappa \in (-1, 1)$ is a parameter and $\varsigma_t$ is an i.i.d. innovation drawn from a normal distribution with mean zero and constant conditional variance $\sigma^2_\varsigma$.

[2] Note that since price adjustment costs require each firm to purchase the final good, this implies that each firm demands output of all other firms in the economy.

[3] We also estimated the model under a policy rule where the monetary authority responds to average quarterly inflation. Parameter estimates are very similar to those reported here and support the same conclusions. These results are available from the authors upon request.

## 2.4 Equilibrium and Balanced Growth Path

The equilibrium of the model is symmetric within sectors but asymmetric across sectors. That is, in equilibrium, all firms within a sector are identical and make exactly the same choices (labor input, price, and output), but firms in different sectors make different choices. In particular, firms in different sectors choose different prices and, hence, rates of price change will differ across sectors. In a symmetric equilibrium we can simplify the optimality conditions by dropping the $i$ subscripts, and we impose market clearing in the different markets. Since we will approximate the model solution around a steady state with long-term growth, it is also helpful to derive some relationships between the steady state growth rates of different variables.

### 2.4.1 Sectoral Phillips Curve

The fact that firms in the same sector are identical in equilibrium means that the price charged by each firm is equal to the sectoral price index,

$$P_{i,s,t} = P_{s,t},\ i \in (0,1), s = 1, 2, \ldots, S.$$

The firm's optimality condition can then be written as the sectoral Phillips curve,

$$\left(\frac{\theta-1}{\theta}\right)\frac{P_{s,t}}{P_t} = \frac{w_t}{e^{z_t}e^{t\mu_s}e^{a_{s,t}}} + \zeta_{s,t}\phi_s\left(\frac{\pi_{s,t}}{e^{\alpha\pi+\alpha_s\pi_s}}-1\right)\left(\left(\frac{1}{2}-\frac{1}{\theta}\right)\frac{\pi_{s,t}}{e^{\alpha\pi+\alpha_s\pi_s}}-\frac{1}{2}\right)$$
$$+\zeta_{s,t+1}\left(\frac{\phi_s}{\theta}\right)\left(\frac{1}{e^{\alpha\pi+\alpha_s\pi_s}}\right)E_t\left(\left(\frac{1}{1+R_t}\right)\pi_{t+1}\pi_{s,t+1}\left(\frac{\pi_{s,t+1}}{e^{\alpha\pi+\alpha_s\pi_s}}-1\right)\frac{y_{s,t+1}}{y_{s,t}}\right),$$

where $\pi_{s,t} = P_{s,t}/P_{s,t-1}$. As in previous literature that derives sectoral Phillips curves in multi-sector economies (e.g., Imbs, Jondeau and Pelgrin, 2011, and Rubbo, 2022), the slope of the linearized Phillips curve is heterogenous across sectors, in our case as a result of heterogeneity in price rigidity.

### 2.4.2 Goods Market Clearing

In each sector, there is a goods market clearing condition,

$$y_{s,t} = c_{s,t} + f_{s,t},$$

where $f_{s,t}$ denotes the output from sector $s$ used for adjustment costs. Note that this is different from $\Phi_{s,t}$, the adjustment costs incurred by sector $s$, and is given by

$$f_{s,t} = \xi_s\left(\frac{P_{s,t}}{P_t}\right)^{-1}F_t.$$

Aggregate adjustment costs are

$$F_t = \sum_{s=1}^{S} \left( \zeta_{s,t} \frac{\phi_s}{2} \left( \frac{\pi_{s,t}}{e^{\alpha\pi + \alpha_s \pi_j}} - 1 \right)^2 y_{s,t} \right).$$

### 2.4.3 Steady-state Growth Rates

The model has an exogenous growth rate for the overall price index in the balanced growth path. That growth rate, $\pi$, is determined by the inflation target in the policy rule. The model also has $S$ exogenous trend growth rates for sectoral productivity, $\mu_s$. Each sector's output growth rate is equal to its productivity growth rate. Productivity growth rates determine the growth rates of consumption and the real wage. Then, the inflation target, along with the productivity growth rates, determine the growth rates of sectoral prices as follows:

$$\gamma_c = \gamma_w = \sum_{s=1}^{S} \xi_s \mu_s,$$

$$\pi_s = \pi + \gamma_w - \mu_s = \pi + \sum_{k=1}^{S} \xi_k \left( \mu_k - \mu_s \right).$$

The trend growth (or decline) in sectoral *relative* prices is determined entirely by a real factor, namely sectoral relative productivity growth,

$$\pi_s - \pi = -\mu_s + \sum_{k=1}^{S} \xi_k \mu_k.$$

This point bears stressing: while sectoral relative prices can move around temporarily because of monetary policy shocks or the interaction between real shocks and the policy rule, the trend in relative prices is invariant to monetary policy and to parameters representing price stickiness. Finally, note that because we incorporate the exogenous trend $\zeta_{s,t}$ in the adjustment cost specification, output growth ($\gamma_y$) is equal to consumption growth and adjustment cost growth on the balanced growth path, both in the aggregate and by sector.

The model is solved using a first-order perturbation with the rational-expectation solution of the linearized system found using the approach in Klein (2000).

## 3. Empirical Analysis

In this section, we describe the data used for estimation and the estimation method, and we discuss the parameter estimates.

### 3.1 Data

The data used to estimate the model are monthly observations of the nominal interest rate and rates of price change for fifteen consumption expenditure categories of the U.S. economy from 1995M1 to 2020M1. The sample starts around the time that the Federal Reserve Board settled on implicitly targeting an inflation rate of 2% per year (see the transcripts of the meeting of the Federal Open Market Committee on January 31). The inflation target was officially adopted in January 2012 and applies to the personal consumption expenditures (PCE) price index.

The nominal interest rate is the effective federal funds rate and was taken from the FRED website of the Federal Reserve Bank of St. Louis (fred.stlouisfed.org). The original interest rate series quoted as a net annual rate is transformed into a monthly rate and quadratically detrended to account for its secular decline over the sample period. Since inflation has been stable over the sample, this secular decline is attributable to the persistent decrease in the natural real rate. This decrease has been widely documented and studied in previous literature (see, for example, Laubach and Williams, 2003, King and Low, 2014, and Rachel and Summers, 2019). Because our model does not contain elements that can capture the decrease in the natural real rate, we follow an econometric strategy that accounts for this decrease by means of a nonlinear time trend, and we focus instead on the cyclical component of the nominal interest rate.

The fifteen categories comprise the entirety of PCE. The sectors are motor vehicles and parts, furnishings and household durables, recreational goods, other durable goods, food consumed at home, clothing and footwear, gasoline and other energy goods, other nondurable goods, housing and utilities, health care, transportation services, recreation services, food services and accommodations, financial services and insurance, and other services. The raw data used to construct the sectoral price changes are seasonally adjusted price indices available from the website of the Bureau of Economic Analysis (www.bea.gov). To be consistent with the model solution, which describes the dynamics of the variables in deviation from their steady state values, all data series are demeaned prior to the structural estimation of the model.

### 3.2 Estimation

The model is estimated by the method of maximum likelihood (ML) using the Kalman filter to evaluate the likelihood function. The state equation of the state-space representation of the model solution is the joint process of exogenous and predetermined variables,

$$X_{t+1} = HX_t + v_{t+1},$$

where $X_t = (z_t, a_{1,t}, \ldots, a_{S,t}, u_t, R_{t-1}, P_{1,t-1}, \ldots, P_{S,t-1})'$ and $v_t = (\varepsilon_t, \varepsilon_{1,t}, \ldots, \varepsilon_{S,t}, \varsigma_t, 0, 0, \ldots, 0)'$

are $(2S+3)\times 1$ vectors, and $H$ is a $(2S+3)\times(2S+3)$ matrix whose elements are the parameters of the exogenous shock processes (in the first $S+2$ elements of $X_t$) and the coefficients of the decision rules of the predetermined variables in the last $S+1$ elements of $X_t$.

The observation equation is

$$Q_t = GX_t,$$

where $Q_t = (R_t, \pi_{1,t}, \ldots, \pi_{S,t})'$ is $(S+1)\times 1$ vector and $G$ is a $(S+1)\times(S+1)$ matrix whose elements are the coefficients of the decision rules of the interest rate and sectoral price changes in $Q_t$. The coefficients of the decision rules are nonlinear functions of the structural parameters. As it is well known, this estimation approach is equivalent to using a Bayesian estimation strategy with diffuse priors. Hansen and Sargent (2013, ch. 8) shows that the ML estimator obtained by applying the Kalman filter to the state-space representation of dynamic linear models is consistent and asymptotically efficient. Standard errors are estimated by the square root of the diagonal elements of $(T\mathcal{I})^{-1}$ where $T$ is the sample size and $\mathcal{I}$ is the information matrix, which is computed using the outer product of the scores at the maximum.

A difficulty that we face in estimating this model is that the steady state has to be computed numerically in every iteration of the algorithm that maximizes the likelihood function. Given the relatively large size of our model, this computation is time-consuming. In order to address this challenge, we first fix the parameters that determine the steady state and, with these parameters set, we estimate the parameters that determine the dynamics of the model by ML. The parameters that determine the steady state are fixed as follows. The weight of leisure in the utility function ($\psi$) is set to 1.8, such that households work 1/3 of the time in steady state. The parameter that determines the elasticity of substitution between goods from the same sector ($\theta$) is fixed to 10. This value is standard in the literature and implies a mark-up of approximately 10%. We assume complete indexation, meaning that $\alpha + \alpha_s = 1$. Provided that the latter condition is satisfied, the steady state is independent of the relative magnitude of $\alpha$ and $\alpha_s$, and we assume $\alpha = \alpha_s = 1/2$. The discount rate ($\beta$) is fixed to 0.998.

The consumption weights are computed using the consumption expenditure shares in each sector. Recall that the optimal consumption of good $i$ produced in sector $s$ is

$$c_{i,s,t} = \xi_s \left(\frac{P_{i,s,t}}{P_{s,t}}\right)^{-\theta} \left(\frac{P_{s,t}}{P_t}\right)^{-1} C_t.$$

Using the fact that the equilibrium is symmetric within sectors, which implies $P_{i,s,t} = P_{s,t}$, and solving for $\xi_s$ delivers

$$\xi_s = \frac{P_{s,t}c_{s,t}}{P_t C_t},$$

where $P_{s,t}c_{s,t}$ are expenditures in sector $s$ and $P_tC_t$ are total consumption expenditures. Estimates of $\xi_s$ for each sector are reported in Column 1 of Table 1.

Finally, the model suggests a natural strategy to estimate the trends in sectoral productivity based on the result that sectoral price changes in steady state are

$$\pi_s = \pi + \gamma_c - \mu_s, \tag{18}$$

for $s = 1, 2 \ldots, S$. Solving for $\mu_s$, so that $\mu_s = \pi + \gamma_c - \pi_s$, and using the fact that the model implies that the steady state values of aggregate inflation, aggregate consumption growth, and sectoral price changes are equal to their respective unconditional means, delivers estimates of $\mu_s$ for each sector. These estimates are reported in the Column 2 of Table 1.

### 3.3 Parameter Estimates

ML estimates of the price rigidity parameter in each sector and the parameters of all shock processes are reported in Table 2. There is substantial heterogeneity in price rigidity across sectors and the null hypothesis that rigidity is the same in all sectors is strongly rejected by the data (see the $p$-value of the Wald test reported in the last row of Table 2). Heterogeneity in price rigidity across product categories has been documented by previous literature using highly disaggregated components of the consumer price index (CPI) (see, among others, Bils and Klenow, 2004, Klenow and Kryvtsov, 2008, and Nakamura and Steinsson, 2008) and estimated multi-sector dynamic equilibrium models (see, e.g., Bouakez, Cardia, and Ruge-Murcia, 2014). In line with that literature, we find that service prices are generally the most rigid in the U.S. economy. The only exceptions in our sample are transportation services and financial services and insurance, for which the null hypothesis that prices are flexible (i.e., $\phi = 0$) cannot be rejected at the 5% level. Quantitatively, the most rigid prices are those of food services and accommodations, and housing and utilities. The prices of some categories of durables and nondurable goods are also rigid, meaning that the hypothesis $\phi = 0$ can be rejected at standard levels (e.g., food at home and motor vehicles). There are, however, other categories like furnishing and clothing for which the hypothesis cannot be rejected. In terms of the expenditure shares, 70% of consumption by U.S. household may be considered to have rigid prices.

Sectoral productivity shocks are persistent with autoregressive coefficients ranging from 0.455 to 0.998. The hypothesis that the coefficients are statistically the same in all sectors can be rejected at standard levels and the $p$-value of the Wald test is less than 0.001. The former estimate (0.455) corresponds to food services and accommodations and all other estimates are concentrated in the interval between 0.962 and 0.998. We explore the possibility that the above rejection is driven by food services and accommodations by performing the Wald test excluding this sector. Since

the $p$-value of this test is also less than 0.001, we conclude that the finding that the persistence of productivity shocks is heterogenous across sectors is not only due to the moderate estimate for food services and accommodations.

There is large heterogeneity in the standard deviation of productivity innovations, and the hypothesis that they are the same in all sectors is strongly rejected by the data. The largest standard deviation is that of gasoline and energy goods, followed by food services and accommodations, which are one order of magnitude larger than that of other sectors. The finding that the standard deviation of productivity shocks to gasoline and energy goods is large helps explain why even though their price rigidity parameter is of moderate magnitude and statistically significant, the observed frequency of price adjustments for these goods is high. For instance, Bils and Klenow (2004, Table A1 in p. 983) report that the estimated average monthly frequency of price changes for gasoline over 1995–1997 ranges between 0.762 and 0.789 depending on its grade.

The estimate of the standard deviation of the aggregate productivity innovation is small and not statistically significant. This has two implications. First, the estimate of the autoregressive coefficient of the productivity shock is poorly identified (see the large standard error in Table 2). Second, as we will see below, aggregate productivity plays a limited role in explaining the aggregate and sectoral inflation dynamics. For this reason, the conclusions in this paper are robust to considering a restricted version of the model without an aggregate productivity shock.

Table 3 reports the ML estimates of the monetary policy rule under the heading "Benchmark." The smoothing parameter is large (0.733) and in line with values reported elsewhere in the literature. The coefficients of inflation and output are positive, as expected, but imprecisely estimated. It is interesting to compare these estimates, based on the full model, with reduced-form estimates obtained under minimal assumptions and also reported in Table 3 under the heading "Unrestricted." The latter are estimates of the first-order linearization of (16) computed by ML but without imposing the restrictions of the model. Estimates are quantitatively similar suggesting that the restrictions of the model do not limit its ability to correctly represent the dynamics of the monetary policy rule. (The last two columns of Table 3 will be discussed later).

### 3.4 Predicted Moments

Table 4 reports the standard deviations and autocorrelations of the nominal interest rate, aggregate inflation, and sectoral price changes predicted by the model and compares them with U.S. data. In contrast to method of moments estimators (e.g., GMM or SMM), our ML estimation procedure does not explicitly target these moments. The table shows that the model quantitatively captures the high persistence of the interest rate, the low autocorrelation of month-to-month inflation and

sectoral price changes, and the volatility of all series, notably the large standard deviation of price changes in gasoline and other energy goods. The correlation between the two sets of moments is high: 0.994. We, therefore, conclude that our model does a good job reproducing the key moments of the data.

# 4. Relative Price Shocks and Inflation over the Entire Sample

With parameter estimates in hand, we can now turn to the model's implications regarding the role of relative price shocks in driving inflation dynamics. We begin with impulse response analysis and variance decompositions. Then we focus on a summary statistic for the distribution of relative price changes that has not—to our knowledge—previously been examined in the literature. We conclude this section with a discussion of the (non)importance of sticky prices for some of our qualitative findings.

## 4.1 Impulse Responses

Figure 1 reports the responses of relative prices ($P_{s,t}/P_t$) to a negative productivity shock in each sector. For example, panel A reports the response of the relative price of motor vehicles (thick line) and other relative prices (thin lines) to a negative productivity shock in the motor vehicles sector. The size of the shock is one standard deviation of the productivity innovation, $\sigma_s$ (see (11)). In all panels, the productivity shock leads to a large increase in the relative price of the good produced in that sector. This increase is one or two orders of magnitude larger than the muted decrease in the relative price of goods produced by the other 14 sectors.[4] These 14 impulse responses are quantitatively similar, and for this reason they sometimes appear as a single black line in Figure 1. The result that a sectoral productivity shock yields a large response in the relative price of its own good and a mild response in other relative prices motivates our interpretation of sectoral productivity shocks as relative price shocks.

Figure 2 reports the response of inflation to aggregate and sectoral shocks. The horizontal axis is months, and the vertical axis is the inflation deviation from in steady state value, expressed in percentage points at an annual rate. Panel A reports the inflation response to a monetary policy shock that reduces the nominal interest by $\sigma_\varsigma$ (see eq. (17)). The other panels report the inflation response to a negative relative price shock with size equal to one standard deviation of the productivity innovation, $\sigma_s$.[5] Note that to allow comparisons across panels, the scale of the vertical

[4] Recall that the aggregate price index, $P_t$, is a geometric average of sectoral prices (see eq. (5)) and hence the sum of the weighted responses of relative prices must add up to zero.

[5] We abstract from reporting the response to the aggregate productivity shock because its small standard deviation (see Table 2) implies that the inflation response to a productivity shock of a plausible magnitude is basically zero.

axis is the same in all panels except for panels A, H, and O, which respectively report the responses to the monetary policy shock and the shocks to gasoline and finance and insurance. This figure shows that different shock sizes across sectors and, to some extent, different price stickiness across sectors, imply heterogeneity in the effects of relative price shocks on inflation. Quantitatively, the largest effects are due to relative price shocks to gasoline (panel H), finance and insurance (panel O), housing and utilities (panel J), other services (panel P), and food at home (panel F).

### 4.2 Accounting for the Variance of Inflation

This section reports the variance decomposition for the inflation rate at different horizons. (Recall that this is the proportion of the mean squared error of the forecast of inflation at different horizons that is accounted for by each of the shocks.) Panel A in Figure 3 shows that the aggregate productivity shock accounts for a negligible proportion—less than 0.001%—of the variance of the inflation forecast error at all horizons. Instead, monetary policy and relative price shocks account for basically all the variance of the inflation forecast error. Panels B and C show that they respectively account for 23.7% and 76.3% of the variance of the inflation forecast error one-month ahead and 24.7% and 75.3% of the unconditional variance of inflation. The finding that relative price shocks account for a large proportion of the inflation forecasts error at all horizons is consistent with results in Reis and Watson (2010, p. 146) who report that 76% of the movements in aggregate inflation are accounted for by a relative-price index.[6] A similar result is reported by Smets, Tielens, and Van Hove (2019) who find that sectoral shocks, by ways of pipeline pressures, are an important contributor to the variance and persistence of headline inflation.

The remaining panels in Figure 3 (D through R) report the contribution of relative price shocks in each sector to the variance decomposition of inflation. Panel J shows that relative price shocks to gasoline account for around 43% of the variance of the inflation forecast error one-month ahead and for 42% of the unconditional variance of inflation. Panels H, L, M, P, and Q show that relative price shocks to food at home, housing and utilities, health, food services, and financial services substantially contribute to the variance of the inflation forecast error one-month ahead (3%, 4.7%, 4.4%, 2.8%, and 8.2%, respectively) and to its unconditional variance (2.9%, 4.6%, 4.3%, 3.1%, and 7.8%, respectively). Research based on dynamic factor models (e.g., see Boivin, Giannoni, and Mihov, 2009) typically finds that aggregate factors are the main driver of aggregate inflation.[7]

[6] Note, however, that the structural interpretation of their index, which is based on a model of price setting under imperfect information, is different from our relative-price shocks because their index includes, for instance, the unanticipated component of the rate of money growth, which is an aggregate variable.

[7] Boivin, Giannoni and Mihov (2009) also emphasize differential responses of sectoral prices to aggregate and sectoral shocks. Carvalho, Lee and Park (2021) show how adding input-output linkages and labor market segmentation can help a multi-sector New Keynesian model match these patterns.

Using a structural model with input-output interactions, Onatski and Ruge-Murcia (2013) show that macroeconomics shocks can indeed be considered factors in that they nontrivially affect most variables in the model. However, principal components analysis has a hard time replicating the macroeconomic factor space because sectoral shocks can act as aggregate shocks.

Table 5 reports the contribution of the "own" relative price shock (Column 1) and of the monetary policy shock (Column 2) to the unconditional variance of each sectoral price change under the benchmark model. (Columns 3 and 4 will be discussed below.) The table shows that the "own" relative price shock accounts for most of the variance of all sectoral price changes. The contribution of the monetary policy shock is also substantial. In contrast, the contribution of the aggregate productivity shock and relative price shock in other sectors is negligible.[8] The finding that the sector-specific shocks account for most of the variance of sectoral price changes is consistent with results reported in Boivin et al. (2009) and Mackowiak, Moench, and Wiederholt (2009) based on estimated dynamic factor models. Boivin et al. (p. 356) report that 85% percent of the monthly disaggregated inflation fluctuations are attributable to sector-specific shocks, while Mackowiak et al. (p. 82) report that the proportion of the variance in sectoral price changes due to sector-specific shocks in their median sector is 90% with a 90% confidence interval ranging from 79% to 95%. In our sample, sector-specific shocks account for 80% of the variance of sectoral price changes in the median sector, and 87% of our estimates (that is, 13 out of 15 sectors) fall in the interval from 62.4% to 94.8%.

It is interesting to note that there is basically no relationship between price rigidity and the proportion of the variance that is accounted for by the monetary policy shock. The correlation between the price rigidity parameters in Table 2 and the proportions in Column 2 is $-0.287$ and not statistically significant. In contrast, the correlation between the standard deviation of sectoral productivity shocks in Table 2 and the proportions in Column 1 is 0.584 and statistically significant at the 5% level.

### 4.3 Inflation and the Distribution of Relative Price Changes

Panel A in Figure 4 displays the monthly PCE inflation rate rate on the vertical axis against the share of relative price increases—or equivalently, the share of price increases greater than the inflation rate—from 1995 through 2019. A striking feature of this plot is the close empirical relationship between the two variables.[9] Panel B in the same figure plots the same relationship but

[8] These figures are not reported to save space, but their sum can be computed by substracting the contributions in Table 5 from 100% for each sector.

[9] This empirical relationship is discussed in Wolman (2022) in relation to the high inflation observed since in March 2021, and it is examined in more detail by Hornstein, Ruge-Murcia, and Wolman (2022).

based on artificial data simulated from our estimated model. Comparing both panels shows that the model can account for this feature of the U.S. data. This result is due to the fact that our estimated specification matches well the behavior of category price changes and, importantly, that it does so by assigning a large role to sectoral, versus aggregate, shocks.

We now provide some intuition for Figure 4 from the perspective of the model. To begin, note that there is a simple relationship between (i) the shares of relative price increases and decreases and (ii) the average sizes of relative price increases and decreases. Because the average relative price change is zero, the ratio of the share of relative price increases to the share of relative price decreases is identical to the ratio of the average relative price decrease to the average relative price increase,

$$\omega \left(\Delta r^{+}\right) - (1-\omega) \left(\Delta r^{-}\right) = 0,$$

which implies

$$\omega/(1-\omega) = (\Delta r^{-})/(\Delta r^{+}),$$

where $\omega$ is the share of relative price increases, and $\Delta r^{+}$ and $\Delta r^{-}$ are the average relative price increase and decrease, respectively. Note that the way we have written these equations, the average relative price decrease is a positive number.

Consider now a point on the far right of panel A; because the share of relative price increases is close to one, the ratio of the share of relative price increases to the share of relative price decreases is very high, and therefore the average relative price *increase* is very *small* compared to the average relative price decrease. In principle, this can happen in many ways—we'll consider two. One possibility is that inflation is much higher than target. This does not occur in the data or in the model, but it's instructive to work through what it would involve. A large share of relative price increases and inflation far above target would mean that the relative price increases correspond to *nominal* price increases that are much higher than target. This could happen from a combination of a large inflationary aggregate shock and a small share of sectors experiencing a large increase in productivity, so that they choose to reduce their relative price by a large amount. But according to our estimates, large aggregate shocks are unlikely. Or, it could happen without an aggregate shock, if most sectors experienced negative sectoral productivity shocks. But this is also unlikely, because the sectoral shocks are uncorrelated.

A second possibility when there is a large share of relative price increases is that inflation is much lower than target, which is the typical outcome in the figure. A large share of relative price increases and inflation far below target means that the relative price decreases—few in number, correspond to *nominal* price decreases that are much lower than target. This could happen from a combination of a large deflationary aggregate shock and a small share of sectors experiencing a

large (possibly additional) increase in productivity, so that they choose to reduce their relative price by a large amount. But again, large aggregate shocks are unlikely. Or, it could happen without an aggregate shock, if a small share of sectors experienced large positive productivity shocks, and in response chose large nominal price decreases. While this scenario is *unconditionally* unlikely, conditional on a high share of relative price increases, and conditional on the model estimates, it is in fact likely.

The discussion thus far has not touched on the systematic behavior of monetary policy, but that behavior is of course central to the relationship in Figure 4. The key point here is that monetary policy responds—in the model and generally in the data—to economywide aggregates, as opposed to sectoral price changes. When a relative price shock hits a particular sector, the desired relative price change is accomplished mainly by a nominal price change of the same sign for that sector, so that inflation moves in the same direction (Figure 2). It's theoretically possible for monetary policy to perfectly stabilize inflation (a flat line in Figure 4), or even to generate an upward sloping relationship between the share of relative price increases and the inflation rate. But either of these cases would require that in the face of a large relative price shock for just one sector, monetary policy generates large nominal price changes for all other sectors in the opposite direction. This seems implausible, and is not what we see in the data.[10]

We summarize as follows: most of the time, the share of relative price increases is close to one half, and inflation is close to target. When the share of relative price increases is large, it is associated with a small share of sectors experiencing large positive productivity shocks, and choosing large *nominal* price decreases, which results in low inflation. When the share of relative price increases is small, it is associated with a small share of sectors experiencing large negative productivity shocks, and choosing large *nominal* price increases, which results in high inflation. The systematic behavior of monetary policy delivers these relationships as equilibrium outcomes: it is optimal for sectors experiencing changes in their desired relative price to move their nominal price in the same direction, and for other sectors to respond very little.

### 4.4 A Flexible-Price Version of the Model

As discussed above and reported in Table 2, there is substantial heterogeneity in our estimates of price stickiness across sectors. The price-stickiness parameter $\phi_s$ is statistically significant for more than half of sectors that account for 70% of the expenditures by U.S. households. Most notably, the

[10] Additionally, in New Keynesian models such as the one we employ, it is generally not optimal to stabilize the price level in response to large relative price shocks, unless those shocks hit sectors in which nominal rigidities are especially large. Goodfriend and King (1997) first made this general point; Aoki (2001) provided analytical results in a two-sector model; and Eusepi, Hobijn and Tambalotti (2011) conducted quantitative analysis in a model similar to ours.

joint hypothesis that the $\phi_s$ are all equal is rejected by the data. It may be tempting to conclude then that the relationship between relative price changes and inflation displayed in Figure 4 is also closely related to price stickiness. We find this *not* to be the case.

We estimate a flexible-price version of the model, meaning a version of the model in section 2 subject to the constraint that the price rigidity parameters are zero in all sectors. ML estimates of the parameters are reported in Table 6 and the last two columns of Table 3. Note in Table 6 that the estimates of the autoregressive coefficients of sectoral productivity shocks are extremely high. The reason is simply that without price rigidity, the persistence of sectoral price changes can only be accounted for by a high autocorrelation of the sectoral shocks. Estimates of the standard deviation of productivity innovations and Taylor rule parameters obtained under this model are roughly consistent with those obtained under the benchmark model with sticky prices. Note that this model is strongly rejected by the data: the likelihood ratio statistic of the test of the restriction $\phi_s = 0$ for all $s$ (that is, that all prices are flexible) is $2 \times (25612.7 - 25540.8) = 143.8$ which is larger than the 5% critical value of 25. The point that we want to make here, however, is that price rigidity is not essential for our result that the dynamics of aggregate inflation and sectoral price changes are driven by relative price shocks. To see this, consider the following. First, regarding aggregate inflation, monetary policy and relative price shocks respectively account for 33.7% and 66.3% of the unconditional variance of inflation under the flexible-price model, compared to the values of 23.7% and 76.3% reported above for the benchmark model.

Second, the last two columns in Table 5 report the contribution of the "own" relative price shock (Column 3) and of the monetary policy shock (Column 4) to the unconditional variance of each sectoral price change under the flexible-price model. These estimates are quantitatively similar to those in columns 1 and 2 obtained under the benchmark model and lead to the same conclusions. Finally, panel C in Figure 4 shows that strong negative relationship between the monthly inflation rate on the vertical axis and the share of relative price increases predicted by our model is robust to assuming that all prices are completely flexible.

These results relate to work by Balke and Wynne (2000). Compared with Ball and Mankiw (1995), whose explanation for the relationship between relative price changes and inflation relies on price stickiness, Balke and Wynne consider a flexible-price model. There are three central elements to their analysis. First, they point out that in a flexible price model, properties of the distribution of sectoral productivity growth would be reflected in the distribution of relative price changes. Second, they provide evidence that the distribution of productivity changes in fact had much in common with the distribution of sectoral price changes. These two elements are also present in our model in a more general setup where the data are allowed to determine the extent of price rigidity in each

sector (see Figure 1). Finally, they show that in a calibrated multi-sector model with flexible prices, basic properties of the empirical relationship between the inflation and the distribution of relative price changes are replicated when the model is driven by an estimated sectoral productivity process. In contrast to their work, we focus on the heterogeneity in the variance of sectoral productivity innovations and the limited role of aggregate shocks in accounting for the empirical relationship between relative price changes and inflation.

## 5. Inflation Shortfall 2012-2019

We estimated the model over post-1994 U.S. data. Over that period, inflation averaged around 2% and was quite stable by historical standards. Since 2012, the Federal Reserve has had a formal 2% target for PCE inflation, but from 2012 to 2019, PCE inflation averaged only 1.4%. We focus here on the post-2012 period and use the model to decompose the inflation shortfall into contributions from the various estimated shocks.

Because mean inflation is 2%, if the model state variables were at their steady states and there were no shocks, then inflation would be constant at 2%. The model explains an episode of deviations from 2% inflation by a combination of initial state variables being away from steady state and subsequent shocks. Figure 5 plots annual inflation during the undershoot period, along with the contributions to the cumulative price level undershoot from the gasoline shock, the health care shock and the monetary policy shock. The cumulative undershoot is measured starting from January 2012. The contributions are based on the smoothed inferences of each shock from the Kalman filter with our estimated parameters. The early part of the undershoot was driven mainly by health care shocks, and then somewhat later by gasoline shocks, whereas monetary policy became more important starting in late 2016. Note however that the period where monetary policy began to account for more of the undershoot coincided with the Fed's increase in interest rates. With the caveat that our estimation procedure does not impose the zero bound, the narrative that seems most consistent with Figure 5 is that health care and gasoline shocks drove inflation below target initially, with policy at the lower bound, then inflation stayed below target in part because of the Fed's raising the Funds rate starting late in 2015. While that rate increase was gradual by historical standards, according to our estimated model, it represented contractionary policy shocks.

## 6. COVID Inflation

We now use our estimated model to interpret the behavior of U.S. inflation in the period immediately after our estimation sample; that period corresponds to the COVID-19 pandemic, when inflation

was at first volatile and then consistently far above the Fed's 2% target.[11] Because it interprets the data through the lens of the estimated model, this analysis assumes that the U.S. economy has remained in a rational expectations equilibrium involving local fluctuations around a steady state with 2% inflation. One might respond sceptically that we are assuming the answer to the most important question: has the U.S. economy remained in that equilbrium, or has the Fed's behavior deviated from its previous rule to such an extent that private agents no longer perceive that rule to be in place? We do not dispute the importance of that question, and in fact see our work as contributing to an answer: under the assumption that inflation has remained anchored, we provide estimates of the contributions to observed inflation from monetary policy and sectoral shocks. An evaluation of those estimates based on independent information can then help in assessing whether inflation has in fact remained anchored.

As above, we decompose observed inflation into the contributions of the various shocks. The data is now outside our estimation sample, but the procedure is otherwise identical. Note that this procedure also yields a counterfactual policy analysis: in the absence of monetary policy shocks, how would inflation have behaved? Figure 6 presents selected elements of the COVID inflation decomposition. In this case, we plot the price level instead of inflation, along with the 2% trend line and the price level paths implied by the shocks to gasoline, motor vehicles, food at home, and monetary policy. The figure uses data only though November 2021, so it misses some of the high inflation months. (The figure will be updated in the next revision of the paper). According to our estimated model, expansionary monetary policy and (to a lesser extent) food at home were significant contributors to inflation in this period. However, their positive contributions came early, when the Fed lowered its interest rate target, and they were compensated by a large drop in the price of gasoline and energy goods. A few shocks (especially motor vehicles) were the main culprits in the subsequent increase in inflation (along with dissipation of other shocks).

It will be interesting to see how this decomposition looks with more recent data, as Wolman (2022) shows that at the end of 2021 and the beginning of 2022, the share of relative price increases has been consistent with relatively low inflation, according to the historical relationship in Figure 4. The fact that inflation has in fact been quite high suggests that expansionary policy is playing a large role.

[11] Recent work that studies the macroeconomic implications of COVID-19 include Baqaee and Farhi (2022), Guerrieri, Lorenzoni, Straub, and Werning (2022), and Woodford (2022). However, contrary to our analysis, which focuses on inflation, their work is concerned with the transmission of an asymmetric (COVID) shock in economies with complementarity in production (Baqaee and Farhi, and Guerrieri et al.) or a network payments structure (Woodford).

## 7. Conclusions

We set out to evaluate the contribution of sectoral shocks—relative price shocks — to the behavior of inflation, and we found their contribution to be very large indeed. For instance, we find that the early part of the inflation undershooting after 2012 was driven mainly by shocks to health care and to gasoline and other energy goods. We find that expansionary monetary policy has been a significant contributor to the high inflation outcomes following the COVID pandemic, but sectoral shocks (especially motor vehicles) were the main culprits in the burst of inflation from May through November 2021. To be clear, we are not claiming that inflation is always and everywhere a relative-price-shock phenomenon. Rather, the lesson is simply that if monetary policy has crediblility and behaves in a way that delivers stable inflation, then the inflation fluctuations that remain seem to be driven by sectoral shocks. Our model-based analysis assumes credibility and stability of the policy regime, and the data we use to estimate the model comes from a period when inflation was stable, so the assumption is plausible.

In future work, we plan to address some of the caveats in the analysis reported in this paper. First, we focus primarily on nominal variables but any subsquent research that also goes after the real-nominal relationship and seeks to explain inflation should also be consistent with the fact that there is a systematic relationship between the distribution of relative price changes and inflation. Second, in order to simplify the analysis as much as possible, we have considered only sectoral supply shocks. A natural and perhaps necessary extension is to add sectoral demand shocks. We expect that the qualitative results would be unchanged, but there would be an additional factor driving relative price changes.

**Table 1. Sectoral Consumption Weights and Productivity Trends**

| Sector | Consumption Weight | Productivity Trend $\times 10^2$ |
|---|---|---|
| | (1) | (2) |
| Motor vehicles and parts | 0.0488 | 0.2605 |
| Furnishings and household durables | 0.0296 | 0.3936 |
| Recreational goods | 0.0311 | 0.7428 |
| Other durable goods | 0.0166 | 0.3076 |
| Food at home | 0.0878 | 0.1710 |
| Clothing and footwear | 0.0414 | 0.3487 |
| Gasoline and other energy goods | 0.0308 | 0.1343 |
| Other nondurable goods | 0.0801 | 0.1564 |
| Housing and utilities | 0.1877 | 0.0891 |
| Health care | 0.1509 | 0.0464 |
| Transportation services | 0.0343 | 0.1586 |
| Recreation services | 0.0371 | 0.0983 |
| Food services and accommodations | 0.0661 | 0.1003 |
| Financial services and insurance | 0.0738 | 0.0978 |
| Other services | 0.0840 | 0.1041 |

**Table 2. Estimates of Sectoral Parameters and Aggregate Productivity Process**

| | Price Rigidity | | Autoregressive Coefficient | | Standard Deviation | |
|---|---|---|---|---|---|---|
| Sector | Estimate | s.e. | Estimate | s.e. | Estimate $\times 10^2$ | s.e. $\times 10^2$ |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Motor vehicles and parts | 7.316* | 2.362 | 0.990* | 0.012 | 0.460* | 0.041 |
| Furnishings and household durables | 0.186 | 0.625 | 0.991* | 0.011 | 0.386* | 0.028 |
| Recreational goods | 0.676 | 0.660 | 0.998* | 0.002 | 0.376* | 0.028 |
| Other durable goods | $< 0.001$ | 0.023 | 0.995* | 0.009 | 0.584* | 0.026 |
| Food at home | 4.229* | 1.572 | 0.997* | 0.002 | 0.324* | 0.029 |
| Clothing and footwear | 0.516 | 0.584 | 0.995* | 0.006 | 0.547* | 0.039 |
| Gasoline and other energy goods | 3.673* | 1.159 | 0.962* | 0.015 | 6.144* | 0.301 |
| Other nondurable goods | 0.030 | 0.345 | 0.990* | 0.012 | 0.315* | 0.015 |
| Housing and utilities | 8.485* | 1.752 | 0.997* | 0.002 | 0.192* | 0.016 |
| Health care | 4.090* | 1.591 | 0.997* | 0.002 | 0.184* | 0.018 |
| Transportation services | 0.255 | 0.527 | 0.975* | 0.021 | 0.530* | 0.039 |
| Recreation services | 2.094* | 0.994 | 0.997* | 0.004 | 0.243* | 0.039 |
| Food services and accommodations | 111.121* | 24.342 | 0.455* | 0.062 | 1.989* | 0.456 |
| Financial services and insurance | $< 0.001$ | 0.348 | 0.991* | 0.007 | 0.710* | 0.040 |
| Other services | 12.883* | 3.966 | 0.998* | 0.002 | 0.272* | 0.031 |
| Aggregate productivity | | | $-0.819$ | 216.745 | $< 0.001$ | 0.386 |
| Wald test ($p$-value) | $< 0.001$ | | $< 0.001$ | | $< 0.001$ | |

*Note*: s.e. stands for standard error. The superscripts $*$ and † denote statistical significance at the five and ten percent levels, respectively. The value of the log likelihood function at the optimum (excluding the constant term) is 25540.8.

**Table 3. Estimates of Taylor Rule**

| | Benchmark | | Unrestricted | | Flexible-Price | |
|---|---|---|---|---|---|---|
| Parameter | Estimate | s.e. | Estimate | s.e. | Estimate | s.e. |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Smoothing parameter | 0.733* | 0.146 | 0.989* | 0.261 | 0.721* | 0.095 |
| Inflation coefficient $\times 10^2$ | 4.312 | 2.725 | 1.007* | 0.249 | 5.122* | 2.481 |
| Output coefficient $\times 10^2$ | 0.310 | 0.227 | 0.146† | 0.079 | 0.037 | 0.111 |
| AR coefficient | 0.673* | 0.176 | 0.456* | 0.038 | 0.621* | 0.130 |
| Standard deviation $\times 10^2$ | 0.049† | 0.027 | 0.011* | $< 0.001$ | 0.052* | 0.018 |

*Note*: see notes to Table 2.

**Table 4. Empirical and Theoretical Second Moments**

| Variable | Standard Deviation | | Autocorrelation | |
|---|---|---|---|---|
| | Data | Model | Data | Model |
| | (1) | (2) | (3) | (4) |
| Nominal interest rate | 0.110 | 0.043 | 0.992 | 0.939 |
| Aggregate inflation | 0.187 | 0.252 | 0.387 | 0.139 |
| **Sectoral price changes:** | | | | |
| Motor vehicles and parts | 0.315 | 0.348 | 0.307 | 0.325 |
| Furnishings and household durables | 0.377 | 0.432 | −0.019 | 0.000 |
| Recreational goods | 0.355 | 0.415 | 0.026 | 0.047 |
| Other durable goods | 0.597 | 0.628 | −0.170 | −0.013 |
| Food at home | 0.263 | 0.307 | 0.266 | 0.228 |
| Clothing and footwear | 0.517 | 0.566 | 0.016 | 0.039 |
| Gasoline and other energy goods | 4.986 | 4.828 | 0.349 | 0.211 |
| Other nondurable goods | 0.303 | 0.382 | −0.140 | −0.024 |
| Housing and utilities | 0.140 | 0.197 | 0.338 | 0.324 |
| Health care | 0.148 | 0.224 | 0.116 | 0.207 |
| Transportation services | 0.511 | 0.558 | −0.045 | 0.005 |
| Recreation services | 0.208 | 0.273 | 0.097 | 0.127 |
| Food services and accommodations | 0.169 | 0.211 | −0.056 | 0.288 |
| Financial services and insurance | 0.722 | 0.762 | −0.236 | −0.012 |
| Other services | 0.171 | 0.221 | 0.356 | 0.410 |

*Note*: The predicted moments are the sample average of the moments computed using 1000 simulations with number of observations equal to the sample size $T = 301$.

**Table 5. Variance Decomposition**

| Variable | Benchmark | | Flexible-Price | |
|---|---|---|---|---|
| | Own Shock | Monetary Policy | Own Shock | Monetary Policy |
| | (1) | (2) | (3) | (4) |
| **Sectoral price changes:** | | | | |
| Motor vehicles and parts | 86.481 | 9.988 | 81.676 | 15.474 |
| Furnishings and household durables | 78.458 | 15.438 | 86.024 | 11.865 |
| Recreational goods | 79.421 | 14.980 | 83.966 | 13.429 |
| Other durable goods | 89.216 | 7.711 | 93.401 | 5.537 |
| Food at home | 77.909 | 16.674 | 73.178 | 22.582 |
| Clothing and footwear | 88.414 | 8.372 | 91.765 | 6.908 |
| Gasoline and other energy goods | 99.904 | 0.072 | 99.900 | 0.084 |
| Other nondurable goods | 71.308 | 20.537 | 79.135 | 17.451 |
| Housing and utilities | 62.428 | 28.985 | 52.783 | 41.515 |
| Health care | 58.413 | 31.883 | 53.192 | 40.677 |
| Transportation services | 87.256 | 9.139 | 91.800 | 6.961 |
| Recreation services | 62.771 | 27.274 | 64.388 | 29.905 |
| Food services and accommodations | 94.805 | 3.060 | 55.789 | 36.976 |
| Financial services and insurance | 92.735 | 5.240 | 95.489 | 3.782 |
| Other services | 77.021 | 17.813 | 57.717 | 35.958 |

**Table 6. Estimates of Sectoral Parameters and Aggregate Productivity Process under Flexible-Price Model**

| | Autoregressive Coefficient | | Standard Deviation | |
|---|---|---|---|---|
| Sector | Estimate | s.e. $\times 10^3$ | Estimate $\times 10^2$ | s.e. $\times 10^2$ |
| | (1) | (2) | (3) | (4) |
| Motor vehicles and parts | 0.999* | 0.010 | 0.316* | 0.012 |
| Furnishings and household durables | 0.999* | 0.006 | 0.369* | 0.015 |
| Recreational goods | 0.999* | 0.021 | 0.354* | 0.013 |
| Other durable goods | 0.999* | 0.012 | 0.583* | 0.025 |
| Food at home | 0.999* | 0.017 | 0.247* | 0.009 |
| Clothing and footwear | 0.999* | 0.025 | 0.517* | 0.017 |
| Gasoline and other energy goods | 0.982* | 0.135 | 4.948* | 0.115 |
| Other nondurable goods | 0.983* | 0.152 | 0.305* | 0.007 |
| Housing and utilities | 0.999* | 0.008 | 0.128* | 0.005 |
| Health care | 0.999* | 0.008 | 0.134* | 0.006 |
| Transportation services | 0.999* | 0.010 | 0.504* | 0.018 |
| Recreation services | 0.999* | 0.010 | 0.202* | 0.009 |
| Food services and accommodations | 0.967* | 0.180 | 0.175* | 0.007 |
| Financial services and insurance | 0.997* | 0.064 | 0.716* | 0.010 |
| Other services | 0.999* | 0.008 | 0.162* | 0.007 |
| Aggregate productivity | 0.903 | 979.108 | $< 0.001$ | 0.034 |
| Wald test ($p$-value) | $< 0.001$ | | $< 0.001$ | |

*Note*: see notes to Table 2. The value of the log likelihood function at the optimum (excluding the constant term) is 25612.7.

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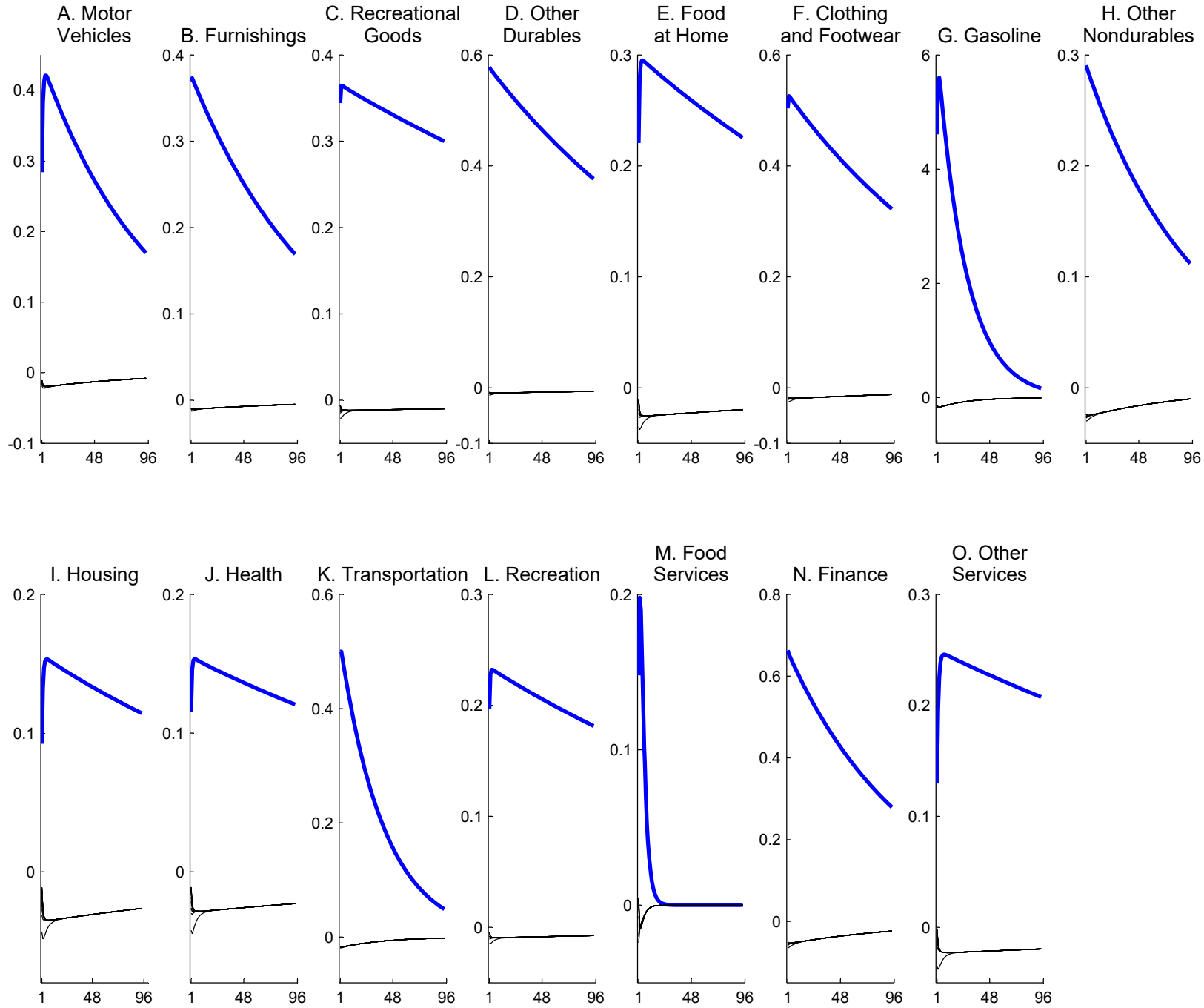
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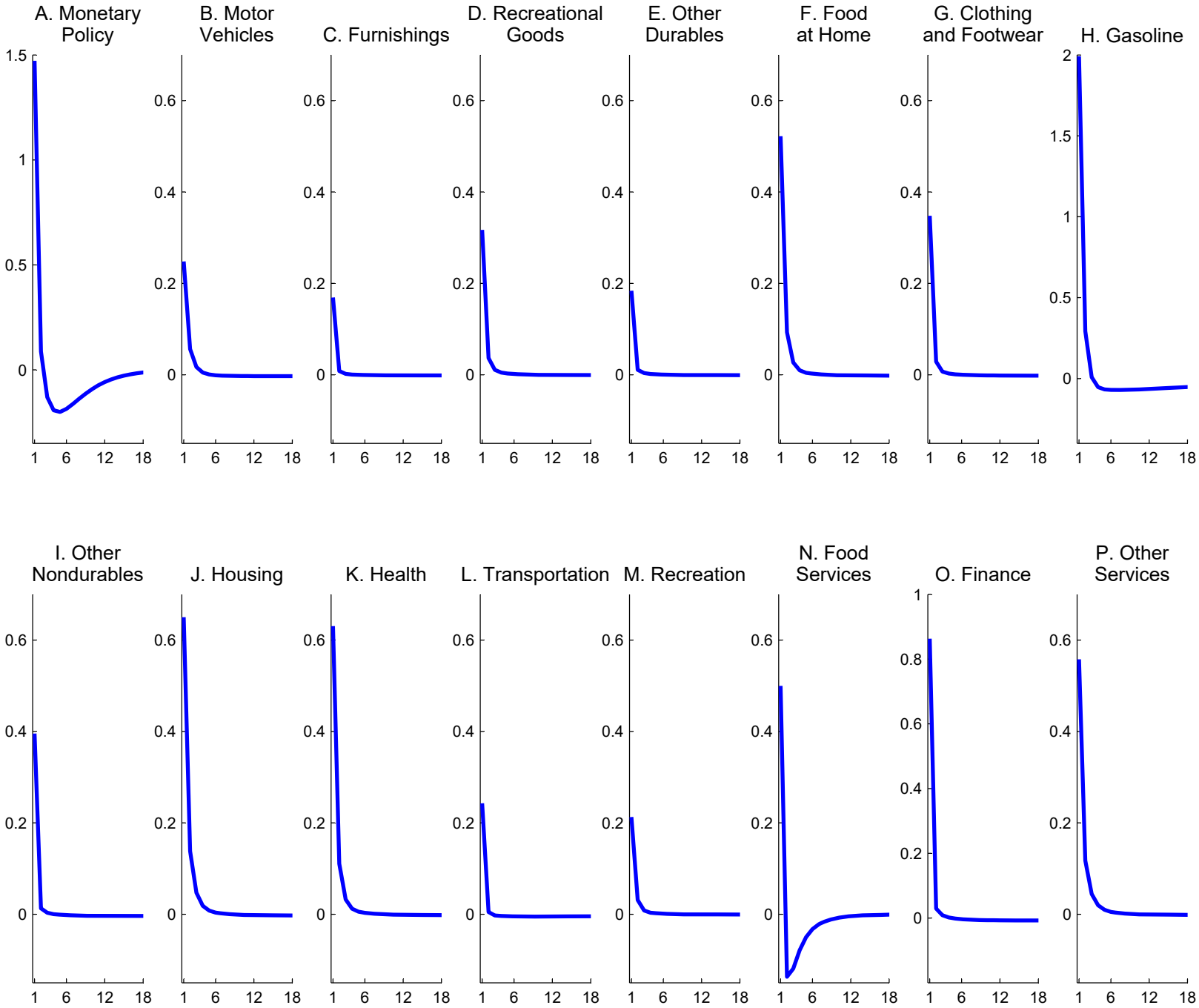
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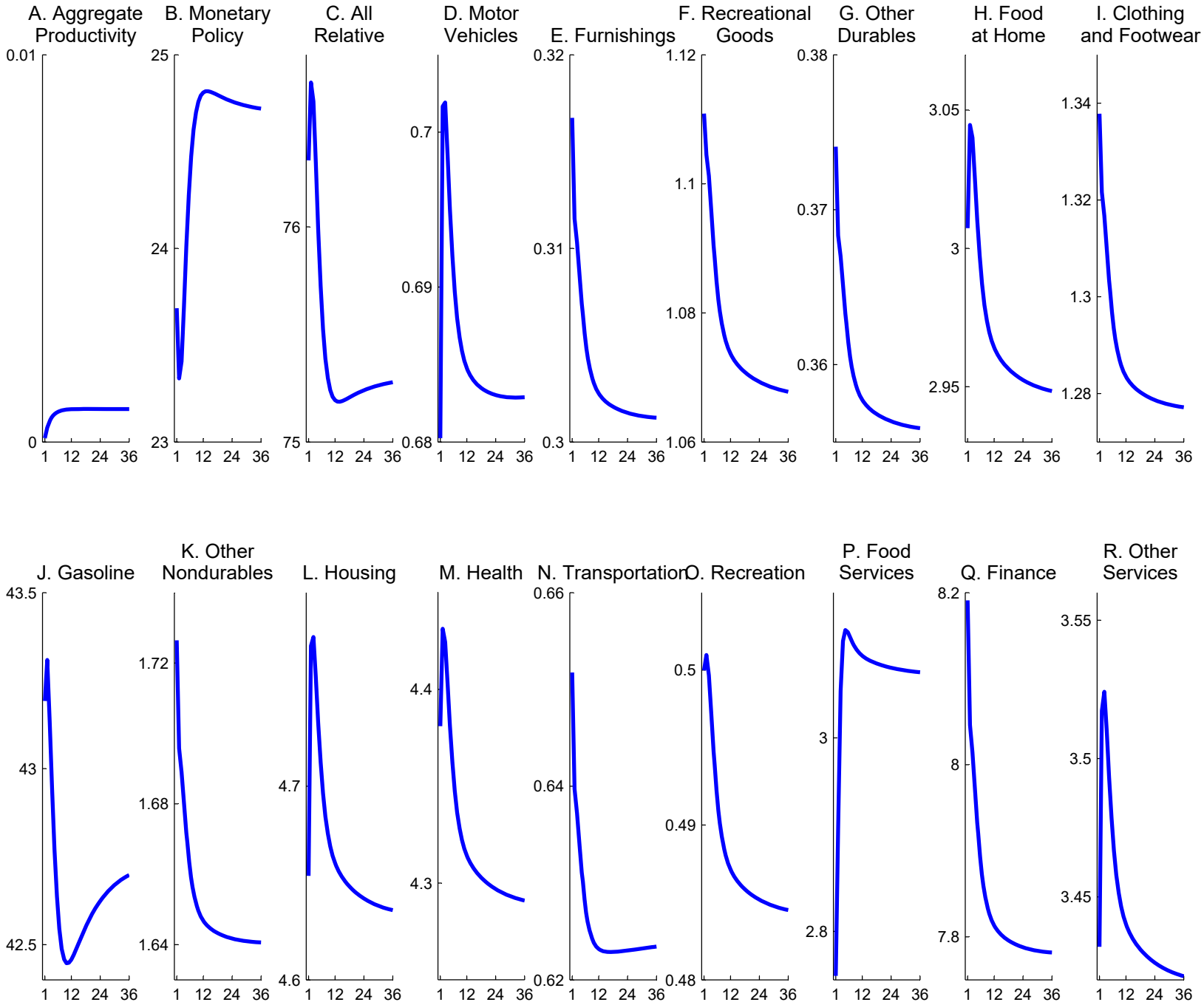
# Figure 1: Responses of Relative Prices to Negative Productive Shock in Own Sector



# Figure 2: Inflation Responses



# Figure 3: Variance Decomposition of the Inflation Rate



# Figure 4: Inflation and the Share of Price Changes Larger than Inflation

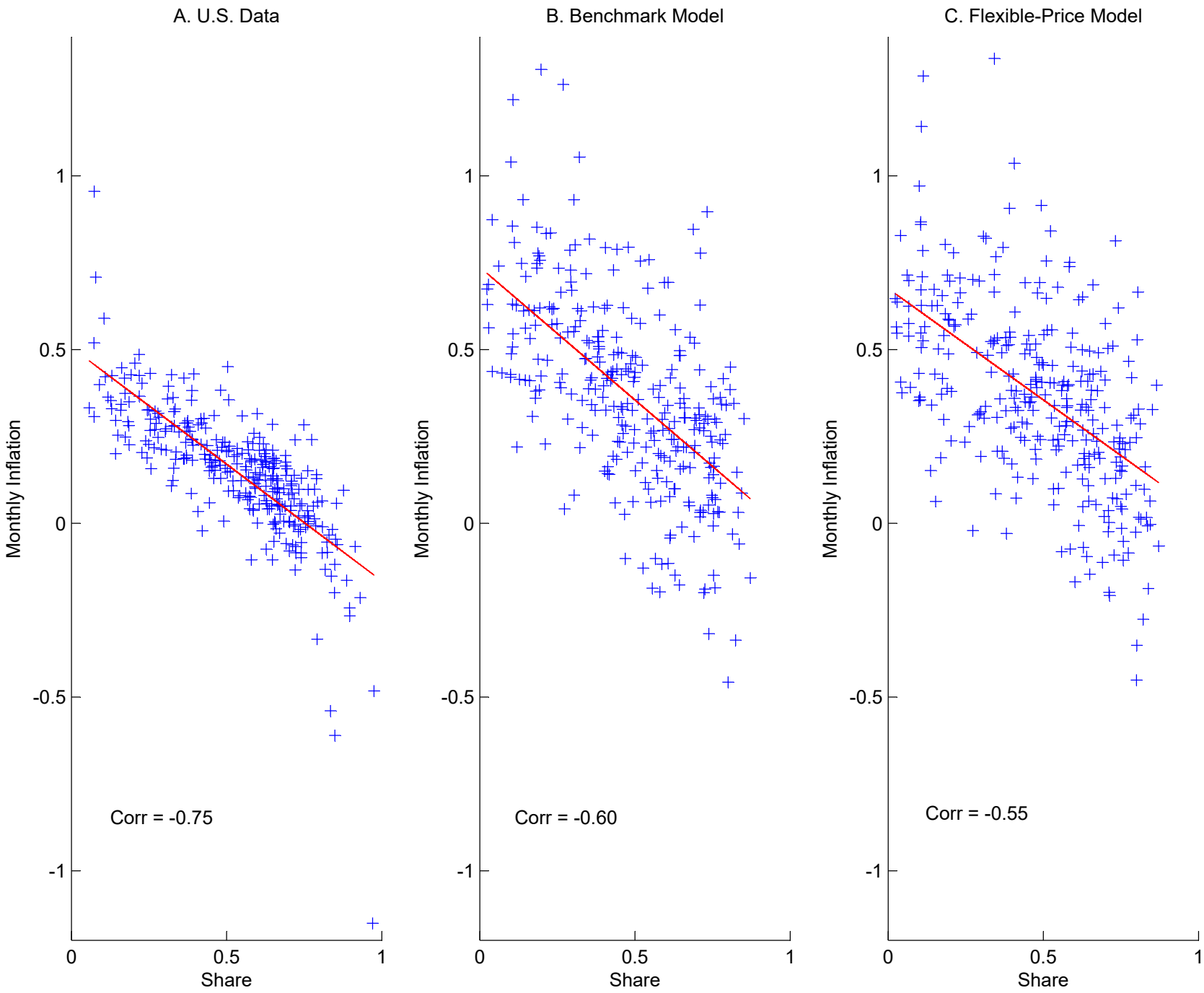


Figure 5: Undershooting: Inflation and Contributions from Gasoline, Health Care, and Monetary Policy

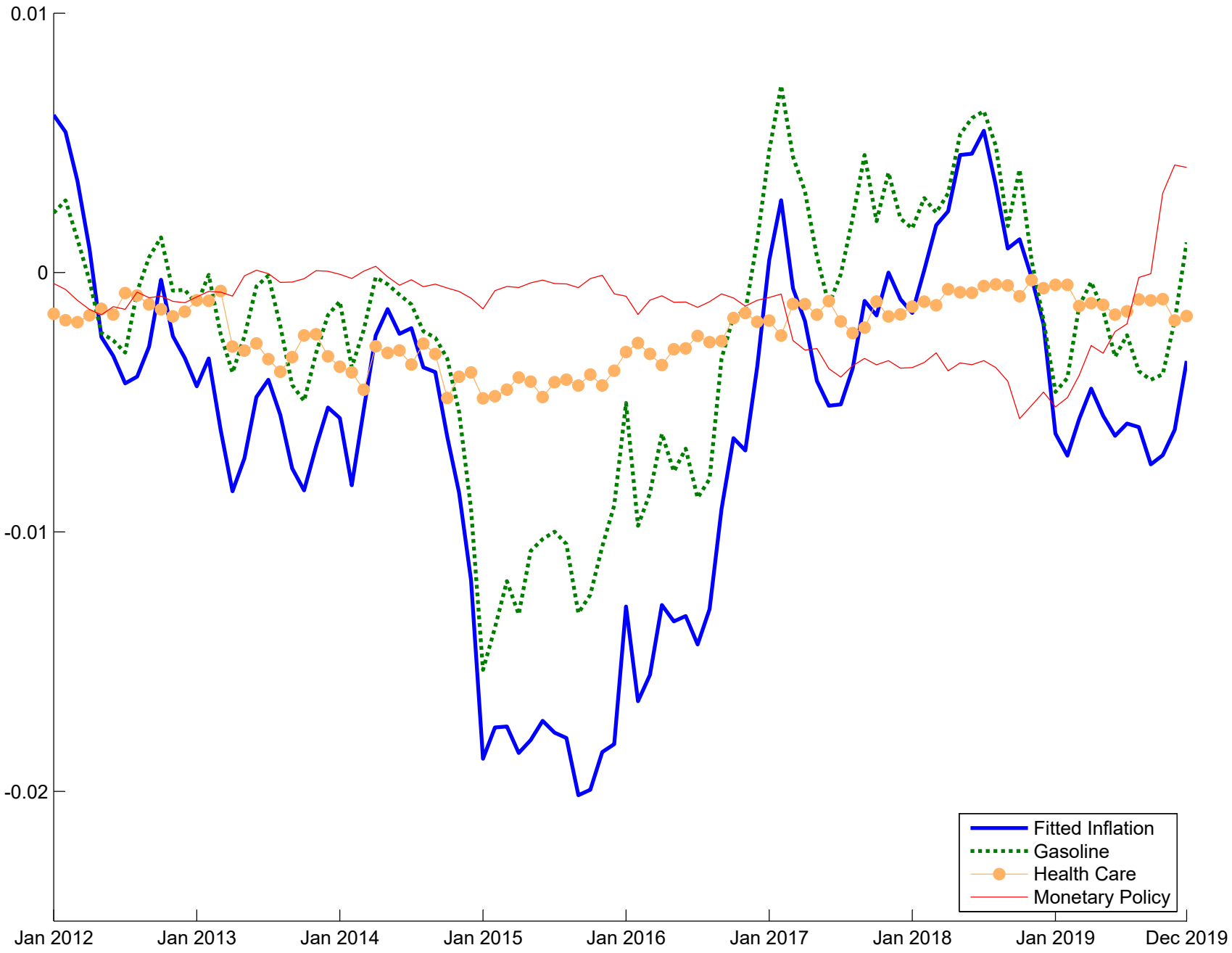


Figure 6: COVID Period: Price Level and Contribution from Selected Shocks

