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Output-Inflation Trade-offs and the Optimal Inflation Rate

Takushi Kurozumi and Willem Van Zandweghe

In staggered price models, a non-CES aggregator of differentiated goods generates empirically plausible short- and long-run trade-offs between output and inflation: lower trend inflation flattens the Phillips curve and decreases steady-state output by increasing markups. We show that the aggregator reduces both the steady-state welfare cost of higher trend inflation and the inflation-related weight in a model-based welfare function for higher trend inflation. Consequently, optimal trend inflation is moderately positive even without considering the zero lower bound on nominal interest rates. Moreover, the welfare difference between 2 percent and 4 percent inflation targets is much smaller than in the CES aggregator case.

Keywords: non-CES aggregator, output-inflation trade-off, optimal trend inflation.

JEL Classification: E52, E58.

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1 Introduction

What is the optimal inflation rate? This long-standing question in monetary economics has gained renewed attention from academics and central bank practitioners since short-term nominal interest rates encountered the zero lower bound (henceforth ZLB) during and after the Great Recession.¹ A large literature has so far established the view that the optimal rate of (trend or long-run) inflation is zero when price rigidity is the main source of monetary non-neutrality, particularly in the absence of the ZLB on nominal interest rates, downward rigidity of nominal wages, or biases in measured inflation that are rationales for the positive inflation targets set by central banks around the world.² In examining this view, much of the existing literature has employed a constant elasticity of substitution (henceforth CES) aggregator of individual differentiated goods in staggered price models.

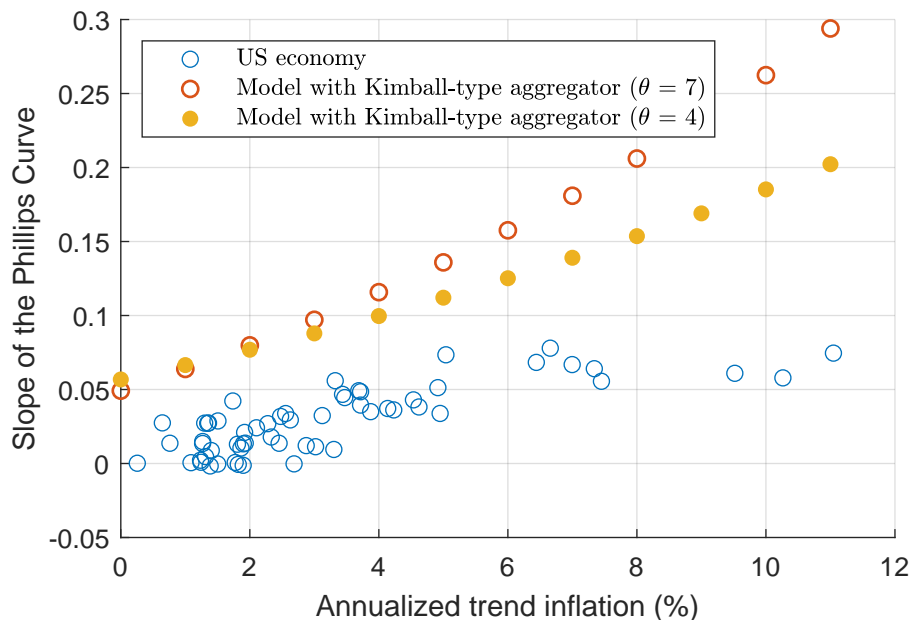
However, previous studies have pointed to several drawbacks of staggered price models with CES aggregators. [Ascari \(2004\)](#) and [Levin and Yun \(2007\)](#), for instance, indicate that such models lead *higher* trend inflation to generate a *larger* loss in steady-state output (even relative to its natural rate), that is, a *larger* long-run trade-off between output and inflation. This is because higher trend inflation increases average markup and relative price distortion in their models. They also point out that, in the models, *higher* trend inflation gives rise to a larger short-run trade-off between output and inflation, that is, a *flatter* slope of Phillips curves derived from the models. This inverse relationship between trend inflation and the slope of Phillips curves is at odds with the empirical evidence. [Benati \(2007\)](#), [Ball and Mazumder \(2011\)](#), the [International Monetary Fund \(2013\)](#), and [Matheson and Stavrev \(2013\)](#), for example, empirically show that US Phillips curves flattened after the Volcker disinflation. Indeed, in [Figure 1](#) the thin (blue) circles illustrate the positive relationship between the annual average inflation rate and the annual average estimated slope in the

¹[Blanchard et al. \(2010\)](#) observed that “it is clear that the zero nominal interest rate bound has proven costly. Higher average inflation—and thus higher nominal interest rates to start with—would have made it possible to cut interest rates more, thereby reducing the drop in output and the deterioration of fiscal positions” (p. 205).

²For a review of the literature, see, e.g., [Schmitt-Grohé and Uribe \(2010\)](#). Even in the absence of the three sources of positive inflation targets, a few recent studies have demonstrated a positive rate of optimal trend inflation. See, e.g., [Adam and Weber \(2019\)](#), who introduce heterogeneous firms and firm-level productivity trends as a new source, [Bilbiie et al. \(2014\)](#), who incorporate firm entry and product variety, and [Carlsson and Westermark \(2016\)](#), who study the interaction of nominal wage rigidity and labor market search frictions.

Phillips curve model of [Ball and Mazumder \(2011\)](#) for the period from 1961 to 2019.

Figure 1: Relationship between average or trend inflation and Phillips curve slope.



Notes: The thin (blue) circles plot annual averages of the estimated slope coefficients in the Phillips curve model of [Ball and Mazumder \(2011\)](#) (their eq. 3) against the annual average inflation rate of the personal consumption expenditures (PCE) price index. The time-varying slope coefficients are estimated with the Kalman smoother, using the quarterly inflation rate of the core PCE price index (i.e., the one excluding food and energy) and the Congressional Budget Office’s output-gap measure from 1959:Q2 to 2019:Q4. The thick (red) circles and the filled (orange) circles show predictions of our model with the Kimball-type non-CES aggregator, respectively, for two values of the parameter θ that governs the elasticity of substitution between goods. Other model parameters used here are reported later in [Table 1](#).

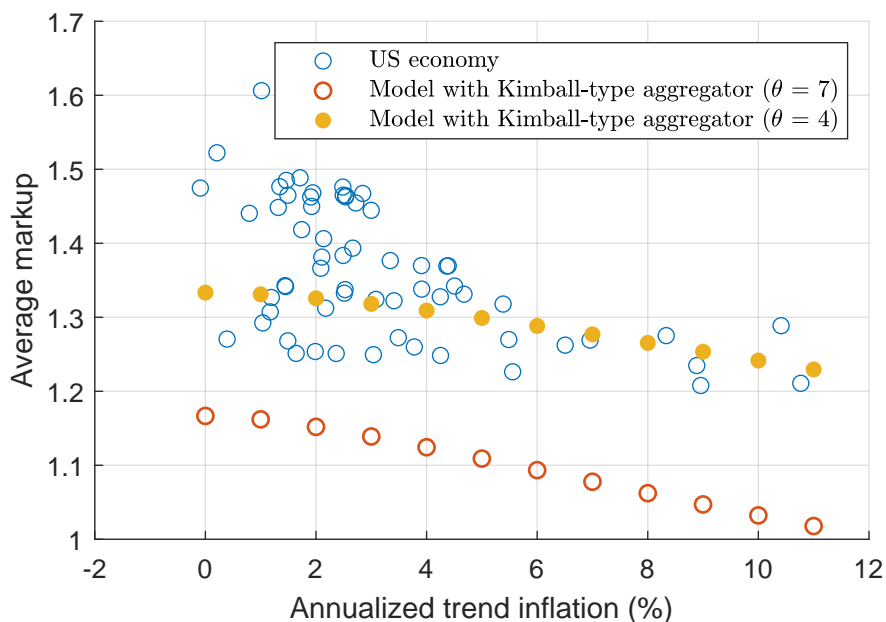
To mitigate these problems, [Shirota \(2015\)](#) and [Kurozumi and Van Zandweghe \(2016\)](#) suggest introducing, in staggered price models, a not necessarily CES aggregator of the sort proposed by [Kimball \(1995\)](#) and developed by [Dotsey and King \(2005\)](#) and [Levin et al. \(2008\)](#), which includes the CES aggregator as a special case.³ The non-CES aggregator provides a parsimonious way of incorporating variable (price) elasticity of demand, and has been widely used as a source of strategic complementarity in firms’ price-setting in the macroeconomic literature.⁴ As a consequence, *lower* trend inflation gives the models’ Phillips

³Moreover, staggered price models with CES aggregators lead higher trend inflation to induce a higher likelihood of indeterminacy of equilibrium, as argued by [Ascari and Ropele \(2009\)](#) and [Coibion and Gorodnichenko \(2011\)](#). [Kurozumi and Van Zandweghe \(2016\)](#) show that the equilibrium indeterminacy induced by higher trend inflation is largely prevented in the presence of the Kimball-type non-CES aggregator.

⁴See, e.g., [Eichenbaum and Fisher \(2007\)](#) and [Smets and Wouters \(2007\)](#).

curves a *flatter* slope, in line with the empirical evidence.⁵ Moreover, *lower* trend inflation *decreases* steady-state output by increasing the average markup, which is consistent with the empirical evidence. De Loecker et al. (2020) show that markups in the United States have increased substantially since 1980, a period during which inflation has trended down.⁶ The thin (blue) circles in Figure 2 display the negative relationship between their estimate of the average markup and the annual average inflation rate during the period 1955–2016.

Figure 2: Relationship between average or trend inflation and the average markup.



Notes: The thin (blue) circles plot the average markup estimated by De Loecker et al. (2020) (in their Figure 1) against the annual average inflation rate of the PCE price index from 1955 to 2016. The thick (red) circles and the filled (orange) circles show predictions of our model with the Kimball-type non-CES aggregator, respectively for two values of the parameter θ that governs the elasticity of substitution between goods. Other model parameters used here are reported later in Table 1.

The thick (red) circles and the filled (orange) circles in Figures 1 and 2 are predictions of our model with the Kimball-type non-CES aggregator using two common values of the parameter θ that governs the elasticity of substitution between goods. While the value of θ affects the size of the Phillips curve’s slope and of the average markup under high trend

⁵To address the “missing deflation” during the Great Recession and the “missing reflation” during the subsequent expansion, recent research examines the possibility of a flattening of Phillips curves. See, e.g., Lindé and Trabandt (2019), who employ a Kimball-type aggregator to that end.

⁶Likewise, Hall (2018) shows that markups in the US have increased from 1988 to 2015.

inflation, the direction of their relationships with trend inflation aligns closely with the empirical evidence. The figures therefore indicate that the non-CES aggregator generates empirically plausible short- and long-run trade-offs between output and inflation.

Given the positive implications of the non-CES aggregator illustrated in Figures 1 and 2, our paper examines its welfare implications in a staggered price model. To this end, the paper follows Woodford (2003) and Alves (2014) to derive the welfare function as a second-order approximation to the representative household's utility function in the model. The model-based welfare function captures three welfare costs: the steady-state cost, the cost induced by inflation-related variability, and that induced by output(-gap) variability. The magnitude of these three welfare costs then depends on the rate of trend inflation.

The paper shows that the Kimball-type non-CES aggregator substantially alters how higher trend inflation affects the first two of the welfare costs. The non-CES aggregator causes *higher* trend inflation to decrease the average markup as noted above, which *reduces* the steady-state welfare cost of higher trend inflation. It also causes *higher* trend inflation to *decrease* the weight on inflation-related variability in the welfare function, thus lowering the welfare cost of the variability stemming from higher trend inflation. The decrease in the inflation-related welfare weight arises because in the model there is an inverse relationship between that weight and the slope of the Phillips curve that is similar to those in Woodford (2003) and Alves (2014), who consider the special case of the CES aggregator, and because the slope of the Phillips curve becomes steeper for higher trend inflation as noted above.

With the two features of the welfare function generated by the non-CES aggregator, the optimal rate of trend inflation is moderately positive under a monetary policy rule of the sort proposed by Taylor (1993), even without considering the ZLB on nominal interest rates. Under a baseline calibration of the model's parameters, the optimal trend inflation rate is 2.4 percent (annually) without considering the ZLB. Once taking it into account, the optimal rate rises mildly to 3.3 percent. These results contrast sharply with those in the case of the CES aggregator. In this case, *higher* trend inflation *significantly raises* the steady-state welfare cost by increasing both average markup and relative price distortion. Moreover, *higher* trend inflation *increases* the weight on inflation variability in the model-based welfare function, because of the aforementioned inverse relationship between the weight and the model-implied Phillips curve's slope, the latter of which becomes flatter for higher trend inflation as noted

above. Consequently, the optimal trend inflation rate with the CES aggregator is zero in the absence of the ZLB and increases more substantially to 1.5 percent in the presence of it. The latter results are in line with those of [Coibion et al. \(2012\)](#), whose study of the optimal inflation rate in New Keynesian models with the CES aggregator is a natural benchmark for our analysis.

In recent years, some practical proposals, such as those by [Blanchard et al. \(2010\)](#), [Ball \(2013\)](#), and [Krugman \(2014\)](#), have called for raising the Federal Reserve’s inflation target from the current 2 percent to 4 percent or even higher. We examine such proposals by following [Ascari et al. \(2018\)](#) to calculate the difference of welfare under 2 percent and 4 percent trend inflation in our model. We find that the welfare difference is much smaller than in the case of the CES aggregator. This implies no crucial welfare difference between *setting* 2 percent and 4 percent inflation targets in our model. One caveat is that the welfare difference takes no account of transition costs, including the cost of making the 4 percent inflation target credible, so the welfare difference may underestimate the full cost of *raising* the inflation target from 2 percent to 4 percent.

The remainder of the paper proceeds as follows. Section 2 presents a staggered price model with a Kimball-type non-CES aggregator. Section 3 derives a welfare function from the model. Section 4 investigates optimal trend inflation and its determinants in the model. Section 5 concludes.

2 Model with Kimball-type Aggregator

This section presents a staggered price model with a [Kimball \(1995\)](#)-type, not necessarily CES, aggregator. The model consists of households, composite-good producers, firms, and a monetary authority. A key feature of the model is that, each period, a fraction of individual goods’ prices remains unchanged in line with the micro evidence, while the other prices are set given demand curves with variable elasticity arising from the non-CES aggregator.⁷ In

⁷For a microeconomic foundation of variable elasticity of demand, see [Benabou \(1988\)](#), [Heidhues and Koszegi \(2008\)](#), and [Gourio and Rudanko \(2014\)](#), among others. Benabou develops a model of customer search, where a search cost gives rise to a reservation price above which a customer continues to search for a seller. Heidhues and Koszegi consider customers’ loss aversion, which increases the price responsiveness of demand at higher relative to lower market prices. Gourio and Rudanko construct a model of customer capital, where firms have a long-term relationship with customers whose demand is unresponsive to a low price.

what follows, each economic agent's behavior is described in turn.

2.1 Households

There is a representative household that consumes a composite good C_t , supplies labor services $\{l_t(f)\}$ specific to firms $f \in [0, 1]$, and purchases one-period bonds B_t so as to maximize the utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \int_0^1 \frac{(l_t(f))^{1+1/\eta}}{1+1/\eta} df \right) \quad (1)$$

subject to the budget constraint

$$P_t C_t + B_t = \int_0^1 P_t W_t(f) l_t(f) df + B_{t-1} r_{t-1} \exp(z_{b,t}) + T_t,$$

where E_t denotes the expectation operator conditional on information available in period t , $\beta \in (0, 1)$ is the subjective discount factor, $\eta > 0$ is the elasticity of labor supply, P_t is the price of the composite good, $W_t(f)$ is the real wage rate of labor service $l_t(f)$, r_t is the monetary policy rate, $z_{b,t}$ is a risk premium shock, and T_t consists of lump-sum taxes and transfers and firm profits received.

The first-order conditions for utility maximization with respect to consumption, labor supply, and bond holdings are given by

$$\Lambda_t = \frac{1}{C_t}, \quad (2)$$

$$W_t(f) = \frac{(l_t(f))^{1/\eta}}{\Lambda_t}, \quad \forall f \in [0, 1], \quad (3)$$

$$1 = E_t \left(\frac{\beta \Lambda_{t+1}}{\Lambda_t} \frac{r_t}{\pi_{t+1}} \exp(z_{b,t}) \right), \quad (4)$$

where Λ_t denotes the marginal utility of consumption and $\pi_t \equiv P_t/P_{t-1}$ is the gross inflation rate of the composite good's price.

2.2 Composite-good producers

There are a representative composite-good producer and a continuum of firms $f \in [0, 1]$, each of which produces an individual differentiated good $Y_t(f)$ and is subject to staggered price-setting that is detailed in the next subsection. As in [Kimball \(1995\)](#), the composite

good Y_t is produced by aggregating individual differentiated goods $\{Y_t(f)\}$ with

$$\int_0^1 F\left(\frac{Y_t(f)}{Y_t}\right) df = 1. \quad (5)$$

Following [Dotsey and King \(2005\)](#) and [Levin et al. \(2008\)](#), the function $F(\cdot)$ is assumed to be of the form

$$F\left(\frac{Y_t(f)}{Y_t}\right) = \frac{\gamma}{(1+\epsilon)(\gamma-1)} \left((1+\epsilon)\frac{Y_t(f)}{Y_t} - \epsilon \right)^{\frac{\gamma-1}{\gamma}} + 1 - \frac{\gamma}{(1+\epsilon)(\gamma-1)},$$

where $\gamma \equiv \theta(1+\epsilon)$ is a composite parameter.⁸ The parameter ϵ governs the curvature ($-\epsilon\theta$) of the demand curve for each individual good. In the special case of $\epsilon = 0$, the aggregator (5) is reduced to the CES one $Y_t = [\int_0^1 (Y_t(f))^{\theta-1} df]^{\theta/(\theta-1)}$, where $\theta > 1$ represents the elasticity of substitution between individual differentiated goods. The case of $\epsilon < 0$ is of particular interest in this paper because it gives rise to strategic complementarity in firms' price-setting.

The composite-good producer maximizes profit $P_t Y_t - \int_0^1 P_t(f) Y_t(f) df$ subject to the aggregator (5), given individual goods' prices $\{P_t(f)\}$. Combining the first-order conditions for profit maximization and the aggregator (5) leads to

$$\frac{Y_t(f)}{Y_t} = \frac{1}{1+\epsilon} \left[\left(\frac{P_t(f)}{P_t} \right)^{-\gamma} + \epsilon \right], \quad (6)$$

$$d_t = \left[\int_0^1 \left(\frac{P_t(f)}{P_t} \right)^{1-\gamma} df \right]^{\frac{1}{1-\gamma}}, \quad (7)$$

$$1 = \frac{1}{1+\epsilon} d_t + \frac{\epsilon}{1+\epsilon} e_t, \quad (8)$$

where d_t is the Lagrange multiplier on the aggregator (5) and

$$e_t \equiv \int_0^1 \frac{P_t(f)}{P_t} df. \quad (9)$$

The Lagrange multiplier d_t represents the real marginal cost of producing the composite good (or aggregating individual differentiated goods), and consists of the aggregate of relative prices of individual goods that corresponds to the aggregator (5), as shown in (7). In the special case of $\epsilon = 0$, where the aggregator (5) becomes the CES one as noted above, eqs. (6)–

⁸See also [Shirota \(2015\)](#) and [Kurozumi and Van Zandweghe \(2016, 2019\)](#).

(8) can be reduced to $Y_t(f)/Y_t = (P_t(f)/P_t)^{-\theta}$, $P_t = \left[\int_0^1 (P_t(f))^{1-\theta} df \right]^{1/(1-\theta)}$, and $d_t = 1$, respectively. The last equation indicates that the real marginal cost is constant in the case of the CES aggregator. Moreover, if all firms share the same production technology (as assumed later) and all individual goods' prices are flexible, the prices are all identical and thus eqs. (7) and (8) imply that $d_t = 1$ even in the case of the non-CES aggregator, i.e., $\epsilon < 0$.

Eq. (6) is the demand curve for each individual good $Y_t(f)$ and features a variable (price) elasticity of demand for the good given by $\theta_t(f) = \theta [1 + \epsilon - \epsilon (Y_t(f)/Y_t)^{-1}]$. When $\epsilon < 0$, the elasticity $\theta_t(f)$ varies inversely with relative demand $Y_t(f)/Y_t$. That is, relative demand for each individual good becomes more price-elastic for an increase in the relative price of the good, whereas the relative demand becomes less price-elastic for a decrease in the relative price. As is well understood, this feature induces strategic complementarity in firms' price-setting, because firms that face the increasing elasticity keep their goods' relative prices near those of other firms (when they can adjust prices).⁹ In the special case of $\epsilon = 0$, the demand curve is reduced to $Y_t(f)/Y_t = (P_t(f)/P_t)^{-\theta}$ and the elasticity of demand becomes constant: $\theta_t(f) = \theta$.

Figure 3 illustrates the log of the inverse demand curve

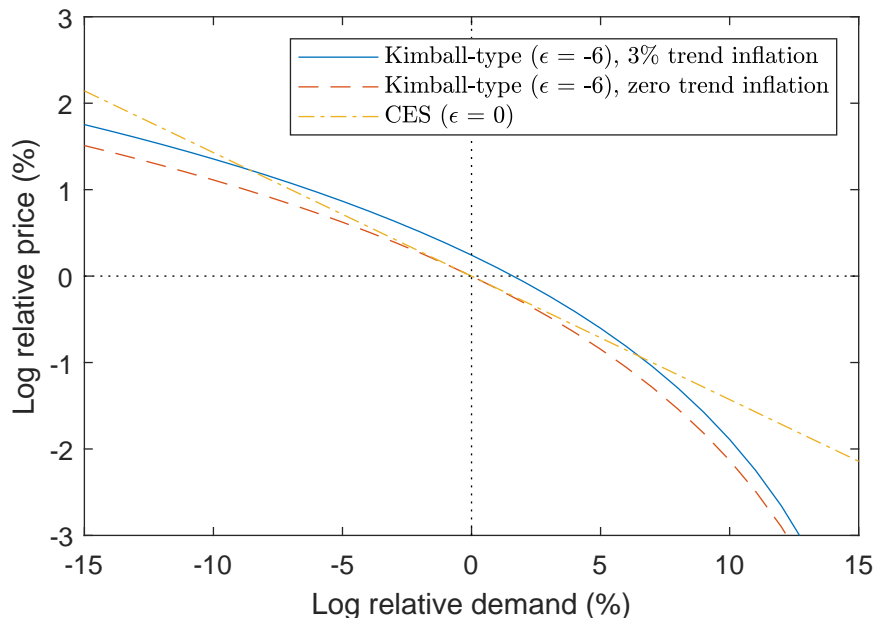
$$\frac{P_t(f)}{P_t} = \left[\frac{(1 + \epsilon) Y_t(f)}{Y_t} - \epsilon \right]^{-\frac{1}{\gamma}} d_t$$

implied by (6), keeping the real marginal cost of aggregating goods d_t at its steady-state value under firms' staggered price-setting. For each good $Y(f)$, the left-hand side of the inverse demand curve is its relative price and the right-hand side consists of its marginal product (i.e., $[(Y_t(f)/Y_t)(1 + \epsilon) - \epsilon]^{-1/\gamma}$) and the real marginal cost. The figure uses two values of the curvature parameter, $\epsilon = 0$ (the dashed-dotted line) and $\epsilon = -6$. For the latter, the inverse demand curve is shown under a trend inflation rate of zero (the dashed line) and 3 percent annually (the solid line).

Under zero trend inflation, the steady-state real marginal cost is unity, and thus the

⁹Models incorporating strategic complementarity are sometimes criticized for inducing unrealistically small absolute price changes. See [Klenow and Willis \(2016\)](#) for the criticism applied to the [Kimball \(1995\)](#)-type aggregator and [Nakamura and Steinsson \(2010\)](#) for an in-depth discussion. Although the Kimball-type aggregator dampens firms' price changes in our model, nonzero trend inflation amplifies them by eroding firms' relative prices between price changes.

Figure 3: Demand curves.



Notes: The figure illustrates demand curves in steady state. The case of the Kimball-type non-CES aggregator with $\epsilon = -6$ is shown by the dashed and the solid lines, which respectively assume a trend inflation rate of zero and 3 percent annually. The case of the CES aggregator (i.e., $\epsilon = 0$) is displayed by the dashed-dotted line. The values of other model parameters used here are reported later in Table 1.

dashed line of Figure 3 shows that the relative price is equal to the marginal product. When the trend inflation rate rises to 3 percent annually, the real marginal cost becomes higher than unity, so that the solid line of the figure shows that the inverse demand curve moves up, that is, the relative price becomes greater than the marginal product. The higher marginal cost is associated with an increase in price dispersion under the higher trend inflation rate and firms' staggered price-setting. Indeed, higher trend inflation induces higher dispersion in relative prices, as price-adjusting firms set a higher price and nonadjusting firms have their relative prices eroded by inflation. The higher price dispersion induces a shift in demand from goods with higher relative prices toward goods with lower ones. However, the shift is asymmetric because the non-CES aggregator implies variable elasticity of demand, so that a small increase in demand for goods with lower relative prices is more than offset by a sharp decline in demand for goods with higher ones. Hence, to meet the demand for aggregate output, the composite-good producer must increase its demand for individual goods, which stimulates the increase in demand for goods with lower relative prices and mitigates the

decline in demand for goods with higher ones. The increase in demand for individual goods raises their relative prices above marginal products and thus raises the real marginal cost of aggregating the goods.¹⁰

The output of the composite good is equal to the household's consumption:

$$Y_t = C_t. \quad (10)$$

2.3 Firms

Each firm f produces one kind of differentiated good $Y_t(f)$ using the production technology

$$Y_t(f) = A_t l_t(f), \quad (11)$$

where A_t represents the level of technology and is assumed to be identical among firms and governed by the stochastic process

$$\log \left(\frac{A_t}{A_{t-1}} \right) = \log(a_t) = \log(a) + z_{a,t}, \quad (12)$$

where $a_t (\equiv A_t/A_{t-1})$ is the gross rate of technological change and $z_{a,t}$ is a (non-stationary) technology shock.

The firm minimizes cost $P_t W_t(f) l_t(f)$ subject to the production technology (11), given the wage rate $P_t W_t(f)$. The first-order condition for cost minimization yields firm f 's real marginal cost of producing its differentiated good

$$mc_t(f) = \frac{W_t(f)}{A_t}. \quad (13)$$

In the face of the demand curve (6) and the marginal cost (13), firms set their products' prices on a staggered basis as in Calvo (1983). In each period, a fraction $\alpha \in (0, 1)$ of firms keeps prices unchanged, while the remaining fraction $1 - \alpha$ sets the price $P_t(f)$ so as to maximize the relevant profit

$$E_t \sum_{j=0}^{\infty} \alpha^j Q_{t,t+j} \left(\frac{P_t(f)}{P_{t+j}} - mc_{t+j}(f) \right) \frac{Y_{t+j}}{1 + \epsilon} \left[\left(\frac{P_t(f)}{P_{t+j} d_{t+j}} \right)^{-\gamma} + \epsilon \right],$$

¹⁰Likewise, an increase in the degree of price rigidity would increase price dispersion and the real marginal cost of aggregating goods. Conversely, if all individual goods' prices are flexible and all firms share the same production technology (as assumed later), the real marginal cost is unity even in the case of the non-CES aggregator as noted above, thus resulting in no shift in the inverse demand curve.

where $Q_{t,t+j}$ is the (real) stochastic discount factor between period t and period $t+j$, which meets the equilibrium condition $Q_{t,t+j} = \beta^j \Lambda_{t+j} / \Lambda_t$. Using (2) and (10), the first-order condition for profit maximization can be rewritten as

$$E_t \sum_{j=0}^{\infty} (\alpha\beta)^j \left[\left(\frac{p_t^*}{d_{t+j}} \prod_{k=1}^j \frac{1}{\pi_{t+k}} \right)^{-\gamma} \left(p_t^* \prod_{k=1}^j \frac{1}{\pi_{t+k}} - \frac{\gamma}{\gamma-1} mc_{t+j}^* \right) - \frac{\epsilon}{\gamma-1} p_t^* \prod_{k=1}^j \frac{1}{\pi_{t+k}} \right] = 0, \quad (14)$$

where p_t^* is the relative price set by firms that can change prices in period t , and mc_{t+j}^* is the firms' real marginal cost in period $t+j$. From (2), (3), (6), (11), and (13), it follows that the marginal cost is given by

$$mc_{t+j}^* = \frac{1}{A_{t+j} \Lambda_{t+1}} \left\{ \frac{Y_{t+j}}{(1+\epsilon)A_{t+j}} \left[\left(\frac{p_t^*}{d_{t+j}} \prod_{k=1}^j \frac{1}{\pi_{t+k}} \right)^{-\gamma} + \epsilon \right] \right\}^{1/\eta}. \quad (15)$$

Furthermore, under staggered price-setting, eqs. (7) and (9) can be reduced to, respectively,

$$d_t^{1-\gamma} = \alpha \pi_t^{\gamma-1} d_{t-1}^{1-\gamma} + (1-\alpha)(p_t^*)^{1-\gamma}, \quad (16)$$

$$e_t = \alpha \pi_t^{-1} e_{t-1} + (1-\alpha) p_t^*. \quad (17)$$

By considering flexible prices, that is, setting $\alpha = 0$ in (14), (16), and (17) and combining the resulting equations, (8), and (15), the natural rate of output can be written as

$$Y_t^n = \left(\frac{\theta-1}{\theta} \right)^{\frac{1}{1+1/\eta}} A_t, \quad (18)$$

regardless of whether the aggregator is CES or non-CES.

2.4 Monetary authority

The monetary authority conducts policy according to a Taylor (1993)-type rule. This rule adjusts the target interest rate r_t^* in response to inflation, the output gap, and output growth and allows for policy inertia:

$$\begin{aligned} \log(r_t^*) &= \phi_{r1} \log(r_{t-1}^*) + \phi_{r2} \log(r_{t-2}^*) + (1 - \phi_{r1} - \phi_{r2}) \log(r) \\ &+ (1 - \phi_{r1} - \phi_{r2}) \left[\phi_{\pi} (\log(\pi_t) - \log(\pi)) + \phi_y \log\left(\frac{Y_t}{Y_t^n}\right) + \phi_{gy} \left(\log\left(\frac{Y_t}{Y_{t-1}}\right) - \log(a) \right) \right] + z_{r,t}, \end{aligned} \quad (19)$$

where $\phi_{r1}, \phi_{r2}, \phi_{\pi}, \phi_y, \phi_{gy} \geq 0$ represent the degrees of first and second policy-rate smoothing and policy responses to inflation, the output gap, and output growth, and $z_{r,t}$ is a monetary policy shock. The actual interest rate is subject to the ZLB, so that it is given by

$$\log(r_t) = \max(\log(r_t^*), 0). \quad (20)$$

An interest rate rule such as (19) is widely regarded as a reasonable description of the Federal Reserve's stabilization policy in recent decades, so with it we separate the question about the optimal trend inflation rate from the distinct question of how stabilization policy should be conducted.

2.5 Equilibrium conditions and steady state

The equilibrium conditions consist of (2), (4), (8), (10), (12), (14)–(20), as well as univariate stationary first-order autoregressive processes for the shocks $z_{j,t}$, $j \in \{a, b, r\}$:

$$z_{j,t} = \rho_j z_{j,t-1} + \varepsilon_{j,t},$$

where $\rho_j \in [0, 1)$ is the persistence parameter and $\varepsilon_{j,t} \sim i.i.d. N(0, \sigma_j^2)$ is a disturbance.

To derive the steady state of the model explicitly from the equilibrium conditions, it is assumed hereafter that the elasticity of labor supply is unity, i.e., $\eta = 1$, which is a widely used value in the macroeconomic literature. Moreover, for the steady state to be well defined, the following condition is assumed to be satisfied:

$$\alpha \max(\pi^{2\gamma}, \pi^\gamma, \pi^{\gamma-1}, \pi^{-1}) < 1. \quad (21)$$

This condition is rewritten as $\alpha \max(\pi^\theta, \pi^{\theta-1}) < 1$ in the special case of the CES aggregator (i.e., $\epsilon = 0$), while the condition is always met in the special case of zero trend inflation (i.e., $\pi = 1$).

Using the equilibrium conditions rewritten in terms of detrended variables (e.g., $y_t \equiv Y_t/A_t$, $y_t^n \equiv Y_t^n/A_t$), detrended output y and its natural rate y^n in the steady state with trend inflation π can be written as

$$y = y^n \left[\frac{\frac{1-\alpha\beta\pi^{2\gamma}}{1-\alpha\beta\pi^{\gamma-1}} \left(\frac{1-\alpha}{1-\alpha\pi^{\gamma-1}} \right)^{\frac{\gamma}{\gamma-1}} \frac{(\gamma-1-\epsilon_2)(1+\epsilon)}{(\gamma-1-\epsilon)(1+\epsilon_3)}}{\frac{1}{1+\epsilon} \left(\frac{1-\alpha\pi^{\gamma-1}}{1-\alpha} \right)^{\frac{1}{\gamma-1}} + \frac{\epsilon}{1+\epsilon} \frac{1-\alpha}{1-\alpha\pi^{-1}}} \right]^{\frac{1}{2}}, \quad y^n = \left(\frac{\theta-1}{\theta} \right)^{\frac{1}{2}},$$

where $\epsilon_1 \equiv \epsilon[(1 - \alpha)/(1 - \alpha\pi^{\gamma-1})]^{\gamma/(\gamma-1)}$, $\epsilon_2 \equiv \epsilon_1(1 - \alpha\beta\pi^{\gamma-1})/(1 - \alpha\beta\pi^{-1})$, and $\epsilon_3 \equiv \epsilon_1(1 - \alpha\beta\pi^{2\gamma})/(1 - \alpha\beta\pi^\gamma)$. Note that the rate of trend inflation and the CES or non-CES aggregator are irrelevant to the natural rate of steady-state output y^n .

Steady-state output loss induced by higher trend inflation can be prevented in the presence of the Kimball-type non-CES aggregator, as shown by [Kurozumi and Van Zandweghe \(2016\)](#). To see this, values of parameters in the quarterly model are chosen. The parameter values are set at the baseline values of [Coibion et al. \(2012\)](#) to facilitate the comparison with their results.¹¹ The elasticity of labor supply has already been fixed at $\eta = 1$. The subjective discount factor is set at $\beta = 0.998$; the parameter governing the elasticity of substitution between individual differentiated goods is chosen at $\theta = 7$, implying a static markup equal to 17 percent; and the probability of no price change is set at $\alpha = 0.55$. As for the parameter governing the curvature of demand curves, we choose a value of $\epsilon = -6$ that implies, given our assumption for θ , curvature of $-\epsilon\theta = 42$. This degree of curvature is intermediate between those implied by the two estimates of [Guerrieri et al. \(2010\)](#).¹² To meet the assumption (21) under the parameter values presented above, the trend inflation rate needs to be greater than -3.4 percent annually. Table 1 summarizes the calibration of parameters. The parameters in the bottom panel of the table are explained in Section 4.

Figure 4 illustrates how steady-state (detrended) output y changes with the annualized rate of trend inflation π in the cases of the Kimball-type non-CES aggregator with $\epsilon = -6$ (the solid line) and the CES aggregator (the dashed line), using the values of model parameters presented in Table 1. In the case of the CES aggregator (i.e., $\epsilon = 0$), higher trend inflation—more generally, a larger deviation from zero trend inflation—induces a larger loss in steady-state output (even relative to its natural rate y^n , which is displayed by the dashed-dotted line), as pointed out by [Ascari \(2004\)](#) and [Levin and Yun \(2007\)](#). By contrast, the non-CES aggregator causes steady-state output to increase with higher trend inflation. As [Kurozumi and Van Zandweghe \(2016\)](#) indicate, the non-CES aggregator alters the effect

¹¹Aside from the non-CES aggregator, our model differs from that of [Coibion et al. \(2012\)](#) by abstracting from consumption habits and government spending. This difference, however, leads to little change in the results on optimal trend inflation.

¹²These authors use international trade data and the New Keynesian Phillips curve of an open-economy model to estimate the degree of curvature and obtain two estimates, based on different assumptions for the static markup implied by θ . Their baseline and alternative estimates assume $\theta = 6$ and $\theta = 11$ and imply curvature of 16.7 and 65.9, respectively.

Table 1: Calibration of parameters in the quarterly model.

Parameter	Description	Value
η	Elasticity of labor supply	1
β	Subjective discount factor	0.998
θ	Parameter governing the elasticity of substitution between goods	7
α	Probability of no price change	0.55
ϵ	Parameter governing the curvature of demand curves	-6
ϕ_π	Policy response to inflation	2.5
ϕ_y	Policy response to output gap	0.43/4
ϕ_{gy}	Policy response to output growth	1.5
ϕ_{r1}	First policy-rate smoothing coefficient	1.05
ϕ_{r2}	Second policy-rate smoothing coefficient	-0.13
a	Steady-state rate of technological change	$1.015^{1/4}$
ρ_a	Persistence of technology shock	0
ρ_b	Persistence of risk premium shock	0.947
ρ_r	Persistence of monetary policy shock	0
σ_a	Standard deviation of technology shock disturbance	0.009
σ_b	Standard deviation of risk premium shock disturbance	0.0024
σ_r	Standard deviation of monetary policy shock disturbance	0.0024

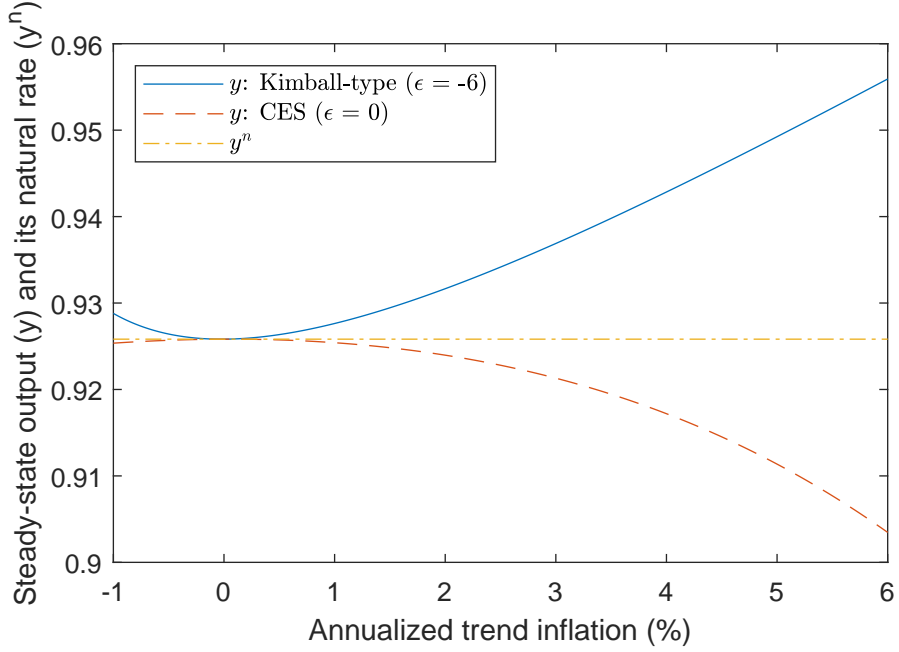
of trend inflation on the steady-state average markup. Higher trend inflation causes price-adjusting firms to choose a higher markup and erodes non-adjusting firms' markups more severely. The steady-state average markup decreases in the case of the non-CES aggregator because the effect of non-adjusting firms' more severely eroding markups dominates that of price-adjusting firms' higher markups, whereas the opposite holds in the case of the CES aggregator.¹³ Recall that the inverse relationship between trend inflation and the average markup generated by the non-CES aggregator is in line with the empirical evidence reported by [De Loecker et al. \(2020\)](#), as illustrated in [Figure 2](#).

2.6 New Keynesian Phillips curve

By log-linearizing the equilibrium conditions rewritten in terms of detrended variables around the steady state with trend inflation π and rearranging the resulting conditions, we can derive

¹³To be precise, in the case of the CES aggregator, steady-state output increases with trend inflation for very low rates of trend inflation. In [Figure 4](#), steady-state output is maximized at a slightly positive trend inflation rate of 0.06 percent annually, consistent with [King and Wolman \(1999\)](#).

Figure 4: Steady-state output and its natural rate.



Notes: The solid and the dashed lines illustrate steady-state (detrended) output respectively in the cases of the Kimball-type non-CES aggregator with $\epsilon = -6$ and the CES aggregator (i.e., $\epsilon = 0$), while the dashed-dotted line displays the natural rate of steady-state output. The values of other model parameters used here are reported in Table 1.

the New Keynesian Phillips curve (henceforth NKPC)

$$\hat{\pi}_t = \beta\pi^{1+\gamma} E_t \hat{\pi}_{t+1} + \kappa_y \hat{y}_t + \kappa_d \hat{d}_t + \hat{d}_{t-1} + \beta\pi^{1+\gamma} E_t \hat{d}_{t+1} + \varphi_t + \zeta_t + \psi_t, \quad (22)$$

where hatted variables denote log-deviations from steady-state values; and φ_t , ζ_t , and ψ_t are auxiliary variables that are additional drivers of inflation under nonzero trend inflation and evolve according to the forward-looking equations

$$\varphi_t = \alpha\beta\pi^{\gamma-1} E_t \varphi_{t+1} + \kappa_\varphi \left[(\gamma - 1) E_t \hat{\pi}_{t+1} + \gamma(1 - \alpha\beta\pi^{\gamma-1}) E_t \hat{d}_{t+1} \right], \quad (23)$$

$$\zeta_t = \alpha\beta\pi^\gamma E_t \zeta_{t+1} + \kappa_{\epsilon\zeta} \left[\gamma E_t \hat{\pi}_{t+1} + (1 - \alpha\beta\pi^\gamma) \left(2E_t \hat{y}_{t+1} + \gamma E_t \hat{d}_{t+1} \right) \right], \quad (24)$$

$$\psi_t = \alpha\beta\pi^{-1} E_t \psi_{t+1} + \kappa_{\epsilon\psi} E_t \hat{\pi}_{t+1}. \quad (25)$$

The law of motion of the real marginal cost of aggregating goods is given by

$$\hat{d}_t = \rho_d \hat{d}_{t-1} + \kappa_{\epsilon d} \hat{\pi}_t. \quad (26)$$

The coefficients in these five equations (22)–(26) are presented in Appendix A.¹⁴

The other log-linearized equilibrium conditions consist of the spending Euler equation

$$\hat{y}_t = E_t \hat{y}_{t+1} - (\hat{r}_t - E_t \hat{\pi}_{t+1}) + E_t z_{a,t+1} - z_{b,t}, \quad (27)$$

and the Taylor-type rule¹⁵

$$\hat{r}_t^* = \phi_{r1} \hat{r}_{t-1}^* + \phi_{r2} \hat{r}_{t-2}^* + (1 - \phi_{r1} - \phi_{r2}) [\phi_{\pi} \hat{\pi}_t + \phi_y \hat{y}_t + \phi_{gy} (\hat{y}_t - \hat{y}_{t-1} + z_{a,t})] + z_{r,t} \quad (28)$$

with the ZLB

$$\hat{r}_t = \max(\hat{r}_t^*, -\log(r)) = \max\left(\hat{r}_t^*, -\log\left(\frac{a\pi}{\beta}\right)\right). \quad (29)$$

In the special case of the CES aggregator (i.e., $\epsilon = 0$), we have $\hat{d}_t = \zeta_t = \psi_t = 0$. Then the NKPC (22) and the auxiliary variable φ_t 's equation (23) are reduced, respectively, to

$$\hat{\pi}_t = \beta\pi^{1+\theta} E_t \hat{\pi}_{t+1} + \kappa_{y0} \hat{y}_t + \varphi_t, \quad (30)$$

$$\varphi_t = \alpha\beta\pi^{\theta-1} E_t \varphi_{t+1} + \kappa_{\varphi 0} (\theta - 1) E_t \hat{\pi}_{t+1}, \quad (31)$$

where κ_{y0} and $\kappa_{\varphi 0}$ take the values of κ_y and κ_{φ} at $\epsilon = 0$, while the spending Euler equation (27) and the Taylor-type rule (28) with the ZLB (29) remain unchanged.

A substantial difference between the NKPC (22) in the case of the non-CES aggregator and the one (30) in the case of the CES aggregator is the slope of the NKPC, that is, κ_y in (22) and κ_{y0} in (30):

$$\kappa_y \equiv \frac{2(1 + \epsilon_1)(1 - \alpha\pi^{\gamma-1})(1 - \alpha\beta\pi^{2\gamma})}{\alpha\pi^{\gamma-1}\{(1 + \epsilon_3)[1 - \epsilon_2\gamma/(\gamma - 1 - \epsilon_2)] + \gamma\}}, \quad \kappa_{y0} \equiv \frac{2(1 - \alpha\pi^{\theta-1})(1 - \alpha\beta\pi^{2\theta})}{\alpha\pi^{\theta-1}(1 + \theta)}.$$

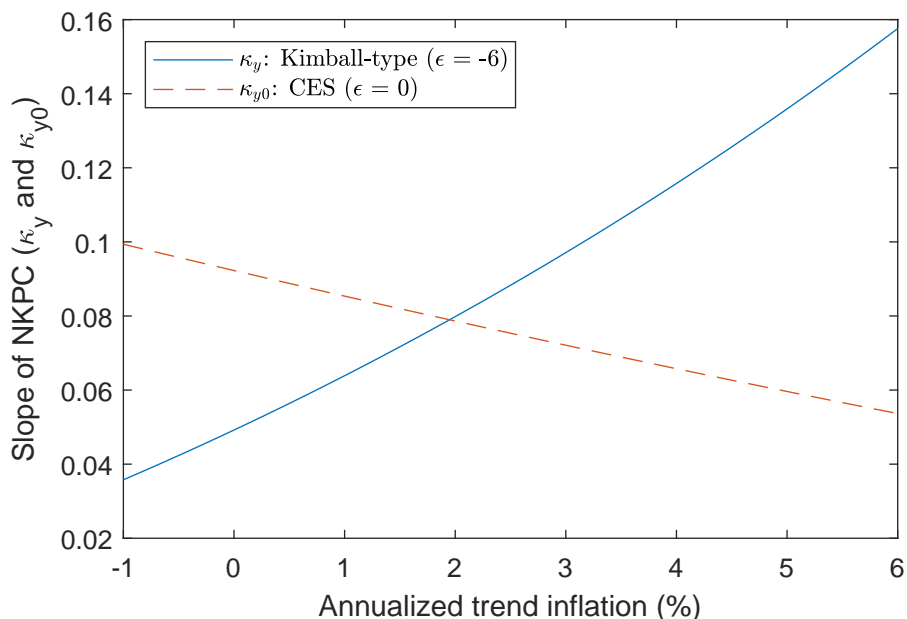
Figure 5 illustrates how these slope coefficients change with the annualized rate of trend inflation. When trend inflation declines, the slope κ_y *flattens* in the case of the Kimball-type non-CES aggregator with $\epsilon = -6$, whereas the slope κ_{y0} *steepens* in the case of the CES aggregator (i.e., $\epsilon = 0$), as indicated by Shirota (2015). Therefore, the non-CES

¹⁴Using the law of motion (26) to substitute for the current, past, and expected future real marginal costs of aggregating goods— d_t , d_{t-1} , $E_t d_{t+1}$ —in (22) introduces lags of inflation in the NKPC. Therefore, the model provides a theoretical justification for intrinsic inertia in inflation without relying on ad hoc backward-looking price-setting behavior (e.g., price indexation), as pointed out by Kurozumi and Van Zandweghe (2019).

¹⁵Note that the natural rate of output is given by $\hat{y}_t^n = 0$.

aggregator leads lower trend inflation to give rise to a flatter slope of the NKPC. This positive relationship between trend inflation and the slope of the Phillips curve is consistent with the empirical evidence reported by, for example, [Benati \(2007\)](#), [Ball and Mazumder \(2011\)](#), the [International Monetary Fund \(2013\)](#), and [Matheson and Stavrev \(2013\)](#) (see [Figure 1](#)).

Figure 5: Slope of the New Keynesian Phillips curve (NKPC).



Notes: The solid and the dashed lines display the NKPCs' slopes κ_y and κ_{y0} respectively in the cases of the Kimball-type non-CES aggregator with $\epsilon = -6$ and the CES aggregator (i.e., $\epsilon = 0$). The values of other model parameters used here are reported in [Table 1](#).

3 Welfare Function

This section derives a welfare function from the model presented in the preceding section. The welfare function is a second-order approximation to the household's utility function (1) around the steady state with trend inflation π (in the case of unit elasticity of labor supply, i.e., $\eta = 1$). It extends the welfare function derived by [Alves \(2014\)](#), who considers the case of the CES aggregator, to the general case of the Kimball-type aggregator.

3.1 Second-order approximation to households' utility function

Using (10) and (11), the utility function (1) with $\eta = 1$ can be rewritten as

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \int_0^1 \frac{(l_t(f))^2}{2} df \right) = E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(y_t A_t) - \frac{y_t^2 \Delta_t}{2} \right),$$

where Δ_t represents relative price distortion and meets

$$\Delta_t \equiv \int_0^1 \left(\frac{Y_t(f)}{Y_t} \right)^2 df. \quad (32)$$

Thus, the relative price distortion captures the dispersion of relative demand. Values of the relative price distortion greater than one reflect inefficiency in producing the composite good from individual differentiated goods due to the dispersion of relative prices of the latter; the distortion is minimized at one if prices are all flexible. Using (6), the relative price distortion can be rewritten as

$$\Delta_t = \int_0^1 \left\{ \frac{1}{1+\epsilon} \left[\left(\frac{P_t(f)}{P_t d_t} \right)^{-\gamma} + \epsilon \right] \right\}^2 df = \frac{s_t + 2\epsilon s_{\epsilon,t} + \epsilon^2}{(1+\epsilon)^2},$$

where

$$s_t \equiv d_t^{2\gamma} \int_0^1 \left(\frac{P_t(f)}{P_t} \right)^{-2\gamma} df, \quad s_{\epsilon,t} \equiv d_t^\gamma \int_0^1 \left(\frac{P_t(f)}{P_t} \right)^{-\gamma} df.$$

The relative price distortion is influenced by the real marginal cost of aggregating individual goods d_t because the latter influences how dispersion in the relative prices of the goods affects dispersion in the relative demand for them, as can be seen from the shift in the inverse demand curve illustrated in Figure 3. Under staggered price-setting, the last two equations can be reduced, respectively, to

$$d_t^{-2\gamma} s_t = \alpha \pi_t^{2\gamma} d_{t-1}^{-2\gamma} s_{t-1} + (1-\alpha)(p_t^*)^{-2\gamma}, \quad (33)$$

$$d_t^{-\gamma} s_{\epsilon,t} = \alpha \pi_t^\gamma d_{t-1}^{-\gamma} s_{\epsilon,t-1} + (1-\alpha)(p_t^*)^{-\gamma}. \quad (34)$$

Moreover, the three variables Δ_t , s_t , and $s_{\epsilon,t}$ in the steady state with trend inflation π are given by

$$\Delta = \frac{s + 2\epsilon s_\epsilon + \epsilon^2}{(1+\epsilon)^2}, \quad s = \frac{1-\alpha}{1-\alpha\pi^{2\gamma}} \left(\frac{1-\alpha\pi^{\gamma-1}}{1-\alpha} \right)^{\frac{2\gamma}{\gamma-1}}, \quad s_\epsilon = \frac{1-\alpha}{1-\alpha\pi^\gamma} \left(\frac{1-\alpha\pi^{\gamma-1}}{1-\alpha} \right)^{\frac{\gamma}{\gamma-1}}.$$

As shown in Appendix B, the utility function can then be approximated up to the second order as

$$\begin{aligned}
& E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \int_0^1 \frac{(l_t(f))^2}{2} df \right) \\
& \approx \frac{\Gamma_{ss} + \Gamma_{dev}}{1 - \beta} - \frac{1}{2} E_0 \sum_{t=0}^{\infty} \beta^t \left[\Gamma_{\pi} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} - \Phi_{\pi} \right)^2 + 2 \left(\hat{y}_t - \frac{\Phi_y}{2} \right)^2 \right] + tip, \quad (35)
\end{aligned}$$

where *tip* stands for terms independent of policy and the coefficients and constants are presented in Appendix B. This shows that the real marginal cost of aggregating goods \hat{d}_t influences the welfare of the representative household in the model, as it affects the relative price distortion. Based on the function (35), the welfare W is measured as

$$\begin{aligned}
W & \equiv (1 - \beta) E \left[E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \int_0^1 \frac{(l_t(f))^2}{2} df \right) \right] \\
& \approx \Gamma_{ss} + \Gamma_{dr} + tip = \Gamma_{ss} - \left[\frac{\Gamma_{\pi}}{2} Var(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}) + Var(\hat{y}_t) \right] + tip. \quad (36)
\end{aligned}$$

In the special case of the CES aggregator (i.e., $\epsilon = 0$), the second-order approximated utility function (35) can be reduced to

$$\begin{aligned}
& E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \int_0^1 \frac{(l_t(f))^2}{2} df \right) \\
& \approx \frac{\Gamma_{ss0} + \Gamma_{dev0}}{1 - \beta} - \frac{1}{2} E_0 \sum_{t=0}^{\infty} \beta^t \left[\Gamma_{\pi0} (\hat{\pi}_t - \Phi_{\pi0})^2 + 2 \left(\hat{y}_t - \frac{\Phi_{y0}}{2} \right)^2 \right] + tip, \quad (37)
\end{aligned}$$

where the coefficients and constants are presented in Appendix B.¹⁶ Thus the welfare measure (36) can also be reduced to

$$W \approx \Gamma_{ss0} + \Gamma_{dr0} + tip = \Gamma_{ss0} - \left[\frac{\Gamma_{\pi0}}{2} Var(\hat{\pi}_t) + Var(\hat{y}_t) \right] + tip. \quad (38)$$

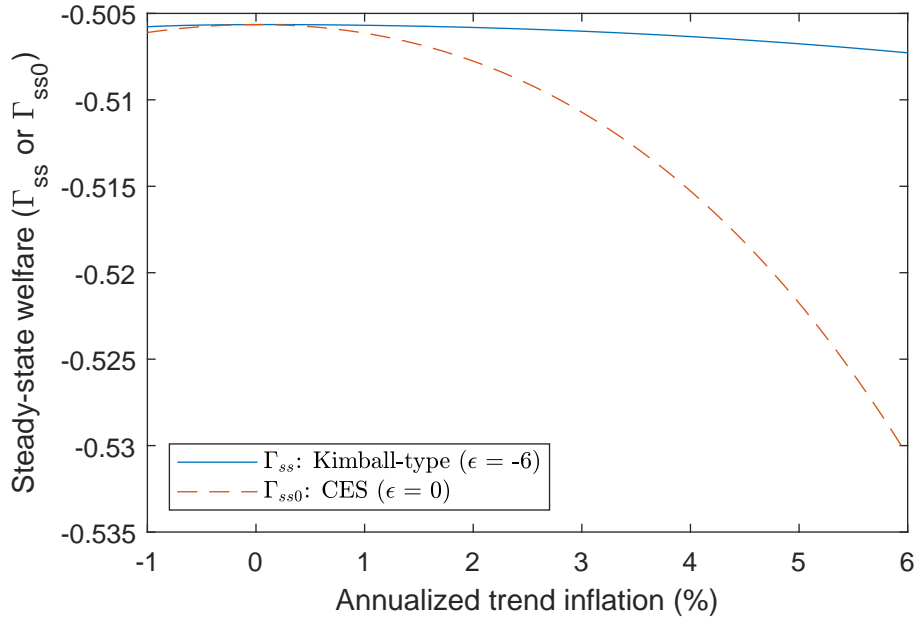
The distinct welfare functions (35) and (37) indicate that the non-CES aggregator alters the welfare function substantially. We investigate the differences between the welfare functions more closely by focusing on the steady-state welfare level Γ_{ss} and the inflation-related welfare weight Γ_{π} .

¹⁶The case of the CES aggregator is considered by Alves (2014) and the welfare function (37) is consistent with his when the elasticities of intertemporal substitution and labor supply are both unity and the shock to consumption preferences is absent.

3.2 Steady-state welfare and inflation-related welfare weight

We begin by investigating optimal trend inflation that maximizes steady-state welfare. Figure 6 illustrates how steady-state welfare changes with the annualized rate of trend inflation, using the values of model parameters presented in Table 1. The solid line shows that the optimal rate of trend inflation that maximizes steady-state welfare Γ_{ss} ($\equiv \log(y) - y^2\Delta/2$) is 0.11 percent annually in the case of the Kimball-type non-CES aggregator (with $\epsilon = -6$). Moreover, welfare Γ_{ss} is insensitive to higher trend inflation. In the special case of the CES aggregator, displayed by the dashed line, the optimal trend inflation rate that maximizes steady-state welfare Γ_{ss0} is almost zero—0.01 percent annually—and welfare Γ_{ss0} decreases rapidly as trend inflation becomes higher. Therefore, the non-CES aggregator reduces the steady-state welfare cost of higher trend inflation.

Figure 6: Steady-state welfare.



Notes: The solid and the dashed lines illustrate the steady-state welfare levels Γ_{ss} and Γ_{ss0} respectively in the cases of the Kimball-type non-CES aggregator with $\epsilon = -6$ and the CES aggregator (i.e., $\epsilon = 0$). The values of other model parameters used here are reported in Table 1.

To understand the effect of trend inflation on steady-state welfare, let us consider the model's two steady-state distortions, average markup and relative price distortion, in steady state. For higher trend inflation, the steady-state average markup decreases in line with

the empirical evidence provided by [De Loecker et al. \(2020\)](#) in the case of the non-CES aggregator, whereas with the CES one the markup increases (except for very low rates of trend inflation). This is why higher trend inflation has different effects on steady-state output between the two cases illustrated in [Figure 4](#). As for the steady-state relative price distortion, while it always increases with trend inflation, the non-CES aggregator dampens its increase, as illustrated in [Figure 7](#). Intuitively, higher trend inflation increases steady-state price dispersion. Then, in the presence of the non-CES aggregator, the steady-state real marginal cost of aggregating goods rises, which subdues the increase in steady-state demand dispersion—that is, the steady-state relative price distortion—associated with the increase in steady-state price dispersion. Therefore, the increase in steady-state output and the subdued increase in the steady-state relative price distortion make steady-state welfare relatively insensitive to higher trend inflation in the case of the non-CES aggregator. Consequently, higher trend inflation has the positive effect on steady-state welfare through higher steady-state output in the case of the non-CES aggregator, but not in the case of the CES one (except for very low rates of trend inflation).

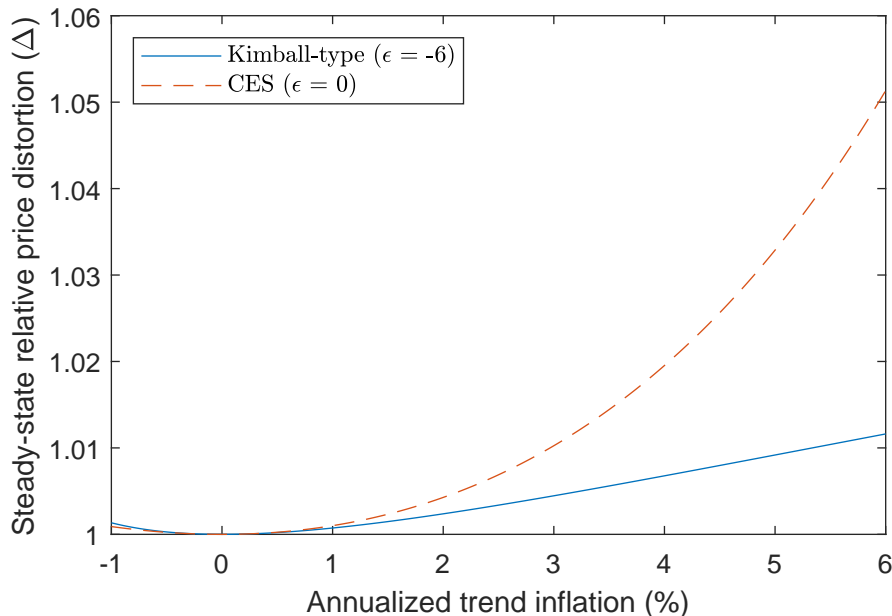
Next, we examine the implications of the non-CES aggregator for the welfare weight on inflation-related variability:

$$\Gamma_\pi \equiv \frac{1}{\Delta(1+\epsilon)^2} \frac{\gamma\alpha\pi^{\gamma-1}}{(1-\alpha\pi^{\gamma-1})^2} \left(\frac{s(1-\alpha\pi^{2\gamma})(1+\gamma)}{1-\alpha\beta\pi^{2\gamma}} + \frac{\epsilon s_\epsilon(1-\alpha\pi^\gamma)}{1-\alpha\beta\pi^\gamma} \right).$$

[Figure 8](#) displays how the inflation-related weight Γ_π in the second-order approximated utility function [\(35\)](#) changes with the annualized rate of trend inflation, using the values of model parameters presented in [Table 1](#). The solid line shows that the weight *decreases* as trend inflation rises (in the case of the non-CES aggregator with $\epsilon = -6$). This feature of the inflation-related weight contrasts sharply with that in the special case of the CES aggregator (i.e., $\epsilon = 0$). In the latter case, the inflation weight $\Gamma_{\pi 0}$ in the second-order approximated utility function [\(37\)](#) *increases* with trend inflation, as illustrated by the dashed line.

The stark contrast between the two cases is attributable primarily to the different way in which the NKPC's slope (i.e., its coefficient on output \hat{y}_t) changes with trend inflation—for higher trend inflation, the slope increases in the case of the non-CES aggregator, whereas it decreases in the special case of the CES aggregator (i.e., $\epsilon = 0$). As demonstrated by

Figure 7: Steady-state relative price distortion.



Notes: The solid and the dashed lines illustrate the steady-state relative price distortion Δ in the cases of the Kimball-type non-CES aggregator with $\epsilon = -6$ and the CES aggregator (i.e., $\epsilon = 0$). The values of other model parameters used here are reported in Table 1.

Woodford (2003) and Alves (2014), who consider the CES aggregator case, there is an inverse relationship between the inflation-related weight Γ_π and the NKPC's slope κ_y (in (22)):

$$\Gamma_\pi = \frac{2\gamma}{\kappa_y} \frac{1 - \alpha\pi^{2\gamma}}{1 - \alpha\pi^{\gamma-1}} \frac{s}{\Delta(1 + \epsilon)^2} \frac{(1 + \epsilon_1)(1 + \epsilon_3 + \gamma)}{(1 + \epsilon_3)[1 - \epsilon_2\gamma/(\gamma - 1 - \epsilon_2)] + \gamma},$$

which can be reduced to

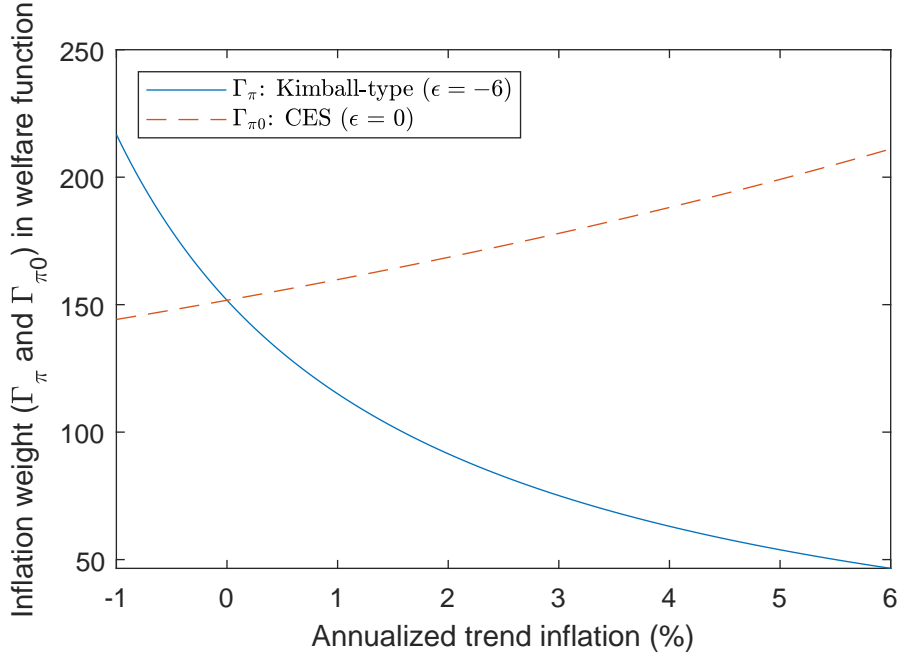
$$\Gamma_{\pi 0} = \frac{2\theta}{\kappa_{y0}} \frac{1 - \alpha\pi^{2\theta}}{1 - \alpha\pi^{\theta-1}}$$

in the case of the CES aggregator, where κ_{y0} denotes the slope of the NKPC (30). The above inverse relationship then shows that the difference in how the slope changes with the trend inflation rate leads to the difference in how the inflation-related weight changes with the rate.

4 Welfare Implications of Kimball-type Aggregator

Having derived the welfare function from the model, we use it in this section to examine the optimal trend inflation rate that maximizes (total) welfare, and its determinants. We then

Figure 8: Inflation weight in the second-order approximated utility function.



Notes: The solid and the dashed lines illustrate the welfare functions' inflation weights Γ_π and $\Gamma_{\pi 0}$ respectively in the cases of the Kimball-type non-CES aggregator with $\epsilon = -6$ and the CES aggregator (i.e., $\epsilon = 0$). The values of other model parameters used here are reported in Table 1.

analyze the welfare difference between the cases of 2 percent and 4 percent trend inflation.

4.1 Optimal rate of trend inflation

For the analysis of optimal trend inflation that maximizes welfare (36), we continue to use the calibration of model parameters presented in Table 1. We calibrate the coefficients in the monetary policy rule, the shocks, and the steady-state rate of technological change using the values set by Coibion et al. (2012). That is, the policy responses to inflation, the output gap, and output growth are $\phi_\pi = 2.5$, $\phi_y = 0.11$, and $\phi_{gy} = 1.5$, respectively, and the policy-rate smoothing coefficients are $\phi_{r1} = 1.05$ and $\phi_{r2} = -0.13$. The parameters of the technology shock are $\rho_a = 0$ and $\sigma_a = 0.009$, those of the risk premium shock are $\rho_b = 0.947$ and $\sigma_b = 0.0024$, and those of the monetary policy shock are $\rho_r = 0$ and $\sigma_r = 0.0024$. The steady-state rate of technological change, which determines the steady-state rate of real interest, is 1.5 percent annually. To solve the model in the presence of the ZLB constraint, we use the piecewise linear perturbation method described in Guerrieri and Iacoviello (2015),

which is the same as that employed in [Coibion et al. \(2012\)](#).

The calibrated model accounts for key business cycle moments. The top panel of [Table 2](#) presents standard deviations, autocorrelations, and cross-correlations of inflation, the nominal interest rate, and HP-filtered output based on data for the US economy from 1954:Q3 to 2019:Q3. To evaluate the model against the US data, we set the trend inflation rate at its annualized historical average rate of $\bar{\pi} = 3.1$ percent. The middle panel of the table shows that the model’s business cycle statistics are reasonably close to their empirical counterparts. However, the nominal interest rate in the model is at the ZLB only 4.7 percent of the time, which is arguably less than the US experience, where the federal funds rate was at its effective lower bound 11.1 percent of the time in the sample. Because the ZLB episode (2008:Q4 to 2015:Q4) occurred later in the sample period, when the trend inflation rate was likely below its sample average, the bottom panel of the table shows the model’s business cycle statistics obtained with the annualized trend inflation rate of $\bar{\pi} = 2$ percent. The lower trend inflation rate does not change the statistics much, but leads the nominal interest rate to be at the ZLB 9.2 percent of the time, closer to the US experience.

Table 2: Model fit at the baseline calibration.

x	Inflation	Interest rate	Output
US data			
$Std(x)$	0.0063	0.0089	0.0155
$Corr(x, x_{-1})$	0.8229	0.9710	0.8547
$Corr(x, y)$	0.1083	0.1566	1.0000
Model ($\bar{\pi} = 3.1$)			
$Std(x)$	0.0056	0.0076	0.0202
$Corr(x, x_{-1})$	0.8522	0.9667	0.6478
$Corr(x, y)$	0.6332	0.1442	1.0000
Model ($\bar{\pi} = 2$)			
$Std(x)$	0.0060	0.0074	0.0215
$Corr(x, x_{-1})$	0.8408	0.9660	0.6484
$Corr(x, y)$	0.6586	0.1382	1.0000

Notes: The table shows, for each variable x , its standard deviation $Std(x)$, autocorrelation $Corr(x, x_{-1})$, and cross-correlation with output $Corr(x, y)$. The US data for x are the PCE inflation rate, the federal funds rate, and the HP-filtered nominal GDP per capita deflated by the PCE price index, from 1954:Q3 to 2019:Q3, and its statistics are shown in the top panel. The other panels show the results of model simulations using the values of model parameters reported in [Table 1](#).

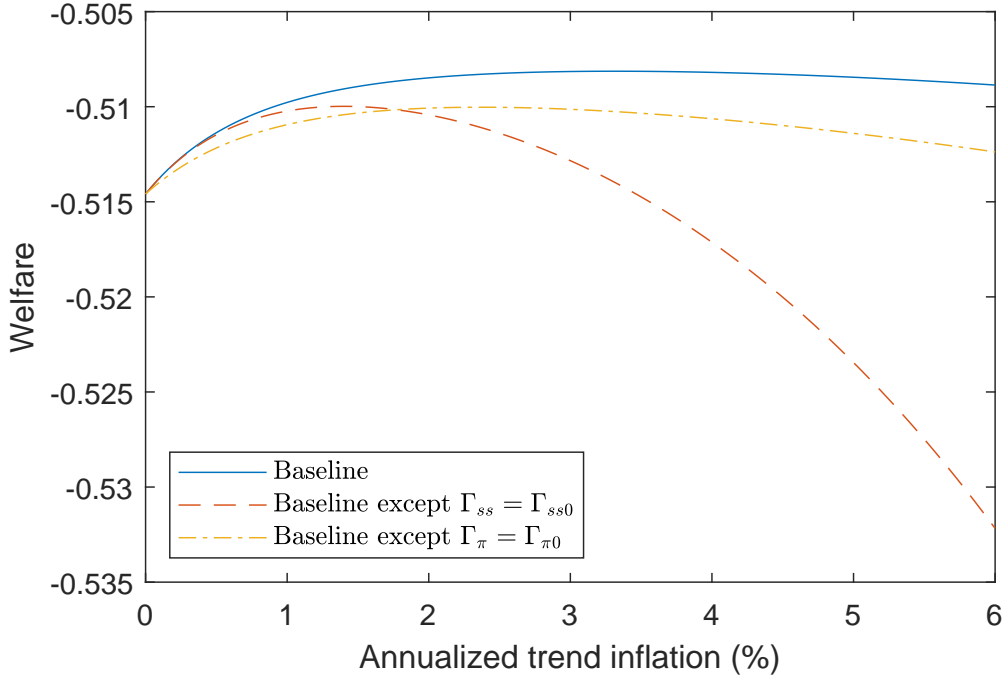
The optimal trend inflation rate, which maximizes welfare [\(36\)](#), is 3.32 percent annually

under the baseline calibration of parameters summarized in Table 1. This level exceeds most central banks’ inflation targets in advanced economies and is close to the historical average of inflation in the United States. The non-CES aggregator increases the optimal trend inflation rate substantially. In the case of the CES aggregator, the optimal rate is only 1.48 percent, consistent with the level reported by Coibion et al. (2012). The solid line in Figure 9 plots $\Gamma_{ss} + \Gamma_{dr}$ in the welfare function (36) (generated with the non-CES aggregator). To highlight the effects of the aggregator on steady-state welfare Γ_{ss} and on the inflation-related welfare weight Γ_{π} , the figure also shows two “hybrid” welfare functions obtained by successively replacing Γ_{ss} and Γ_{π} with their counterparts in the case of the CES aggregator. The dashed line shows that replacing Γ_{ss} with Γ_{ss0} reduces the optimal trend inflation rate substantially (to 1.40 percent), while the dashed-dotted line shows that replacing Γ_{π} with $\Gamma_{\pi0}$ reduces the optimal rate less (to 2.36 percent). This indicates that the primary effect of the non-CES aggregator is to reduce the steady-state welfare cost of higher trend inflation and its additional effect is to reduce the dynamic welfare cost of inflation-related variability.

4.2 Effects of the zero lower bound on nominal interest rates

Next, we examine the importance of the ZLB on nominal interest rates for optimal trend inflation. In the presence of the non-CES aggregator, the ZLB is not the only factor calling for a positive rate of optimal trend inflation: even without considering the ZLB, the optimal trend inflation rate is 2.44 percent annually. This level reflects two important factors: that the non-CES aggregator reduces the steady-state welfare cost of higher trend inflation, and that higher trend inflation decreases the weight on inflation-related variability in the welfare function, which lowers the welfare cost of this variability. Incidentally, the optimal rate of trend inflation is near the inflation targets adopted by many central banks in advanced economies in the past three decades. The ZLB then calls for a higher trend inflation rate of 3.32 percent annually. Because the optimal trend inflation rate with the non-CES aggregator is already positive without considering the ZLB, this constraint binds less frequently and thus calls for a smaller increase in the optimal rate—0.88 ($= 3.32 - 2.44$) percentage point—than in the case of the CES aggregator, where the optimal trend inflation rate is zero in the absence of the ZLB, so that its presence increases the optimal rate by 1.48 percentage points. Table 3 highlights that optimal trend inflation is only mildly affected by the ZLB, by showing optimal

Figure 9: Welfare function and effects of steady-state welfare Γ_{ss} and inflation-related weight Γ_{π} .



Notes: The solid line illustrates the welfare function in the case of the Kimball-type non-CES aggregator with $\epsilon = -6$. The dashed line shows the hybrid welfare function obtained by replacing the steady-state welfare Γ_{ss} with Γ_{ss0} in the case of the CES aggregator. The dashed-dotted line shows the hybrid welfare function obtained by replacing the inflation-related weight Γ_{π} with $\Gamma_{\pi0}$ in the case of the CES aggregator. The values of other model parameters used here are reported in Table 1.

trend inflation rates obtained with and without the lower bound for a range of values of the curvature parameter ϵ . Recall that a smaller value of ϵ implies a larger curvature of demand curves. As the curvature increases, optimal trend inflation rises in increasing increments, reaching 4.44 percent annually for $\epsilon = -8$ even without considering the ZLB. At the same time, the ZLB has a decreasing effect on optimal trend inflation—except for low degrees of curvature, for instance, from $\epsilon = 0$ to $\epsilon = -2$ in the table.

Figure 10 further illustrates the disparate effects of the ZLB on the welfare function in the cases of the non-CES aggregator with $\epsilon = -6$ and the CES aggregator (i.e., $\epsilon = 0$). The left three panels display the welfare function (36) or (38) in the top panel, the contribution of inflation-related variability (i.e., $-(\Gamma_{\pi}/2)Var(\pi_t + d_t - d_{t-1})$ or $-(\Gamma_{\pi0}/2)Var(\pi_t)$) in the middle panel, and the contribution of output variability (i.e., $-Var(y_t)$) in the bottom

Table 3: Optimal trend inflation rate and ZLB frequency (%).

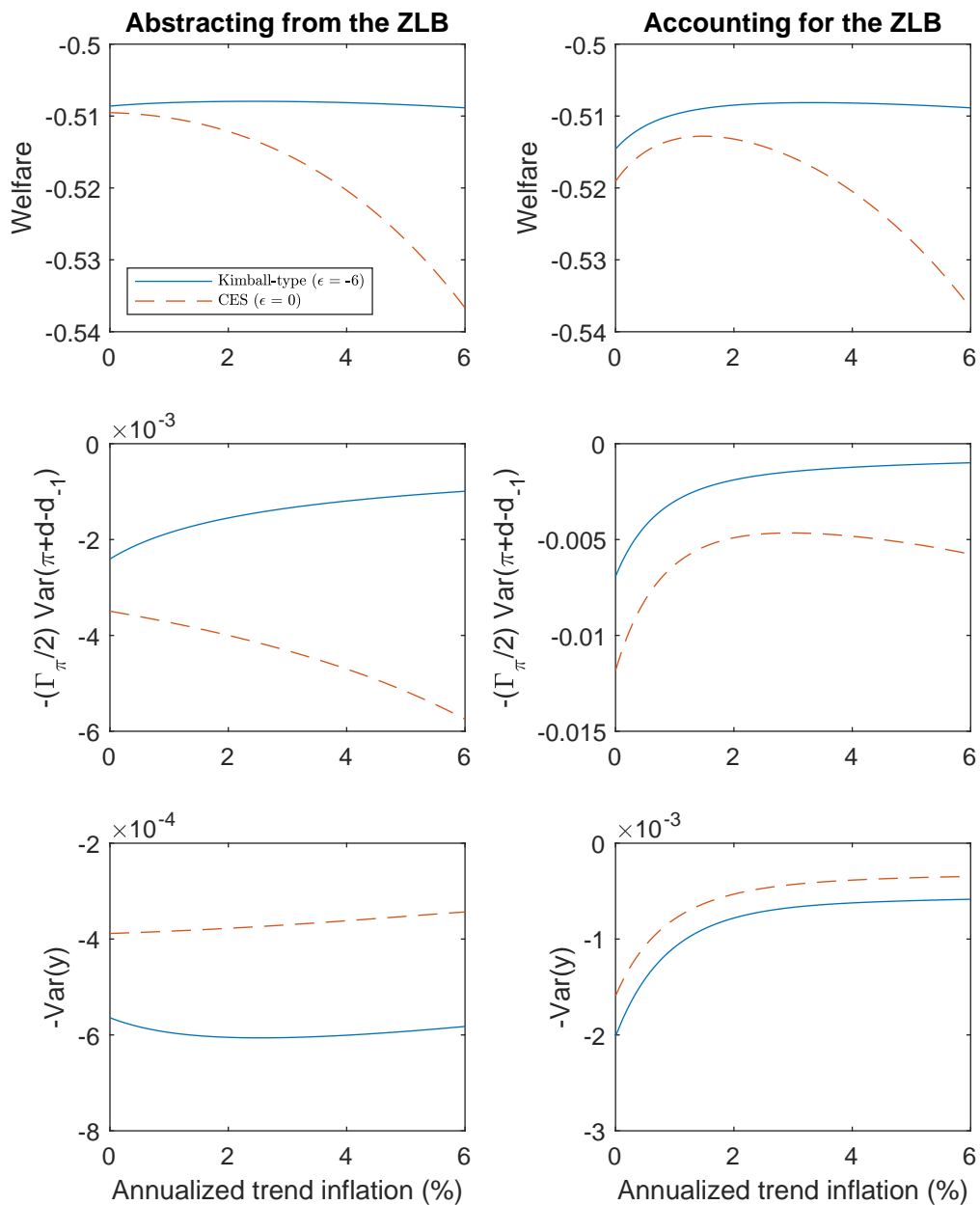
ϵ	$\bar{\pi}^*$ (No ZLB)	$\bar{\pi}^*$ (ZLB)	ZLB freq.
0	0.00	1.48	12.97
-2	0.32	1.88	10.14
-4	1.04	2.44	7.07
-6	2.44	3.32	3.99
-8	4.44	4.68	1.53

Note: The table shows the annualized optimal trend inflation rate $\bar{\pi}^*$ using the values of model parameters reported in Table 1, except for ϵ , when abstracting from the ZLB (the second column) and when accounting for the ZLB (the third column), along with the time spent at the ZLB in percent (the fourth column).

panel, when abstracting from the ZLB. The contribution of steady-state welfare Γ_{ss} or Γ_{ss0} has already been shown in Figure 6. In the case of the CES aggregator (the dashed lines), the middle left panel illustrates that the welfare contribution of inflation variability declines monotonically for higher trend inflation, reflecting that the variance of inflation and its welfare weight Γ_{π_0} increase with higher trend inflation. Combining this with the monotonically declining steady-state welfare displayed in Figure 6 and a small contribution of output variability shown in the bottom left panel leads the optimal rate of trend inflation to be zero. By contrast, in the case of the non-CES aggregator (the solid lines), the middle right panel illustrates that the contribution of inflation-related variability increases with higher trend inflation. Although higher trend inflation increases the inflation-related variance, the declining welfare weight Γ_{π} displayed in Figure 8 reduces the welfare cost of inflation variability arising from higher trend inflation. Then, because the non-CES aggregator makes the contribution of steady-state welfare relatively insensitive to higher trend inflation as shown in Figure 6, and because the welfare contribution of output variability is relatively small as in the bottom right panel, the welfare function is relatively flat for higher trend inflation as seen in the top left panel.

The right three panels of Figure 10 show the effect of the ZLB on the welfare function, by replicating the left three panels after introducing the lower bound. In the case of the CES aggregator, the middle right panel shows that the contribution of inflation variability is maximized at a positive rate of trend inflation. This is because for higher trend inflation, the ZLB causes the variance of inflation to decline, while the welfare cost of the variance increases with the higher welfare weight Γ_{π_0} . By contrast, in the case of the non-CES aggregator, the

Figure 10: Welfare function and contributions of variability related to inflation and output.



Notes: The solid and the dashed lines illustrate the welfare levels (the top panels) and the contributions of the variability related to inflation (the middle panels) and output (the bottom panels) respectively in the cases of the Kimball-type non-CES aggregator with $\epsilon = -6$ and the CES aggregator (i.e., $\epsilon = 0$). The values of other model parameters used here are reported in Table 1.

ZLB causes the welfare cost of inflation-related variance to decline more rapidly when trend inflation rises, as both the variance and its welfare weight decrease. The ZLB also makes the variance of output decline for higher trend inflation, although, as before, this variance is relatively small. Therefore, the ZLB generates a positive rate of optimal trend inflation in the case of the CES aggregator and increases the optimal rate in the case of the non-CES aggregator.

Since we have so far focused on the role of ϵ , we now analyze the robustness of the optimal trend inflation rate with respect to other structural parameters.¹⁷ Table 4 reports the optimal rate of trend inflation and the frequency of time at the ZLB for alternative parameter values, in the cases of the CES aggregator (the second and third columns) and the non-CES aggregator (the fourth and fifth columns). The optimal trend inflation rate obtained with the non-CES aggregator is consistently above the one with the CES aggregator for each parameter value, yet qualitatively we can distinguish three sets of parameters. First, the degree of price rigidity α has similar effects on optimal trend inflation in the CES and non-CES cases, as it affects welfare primarily via the relative price distortion. Second, the subjective discount factor β and the steady-state rate of technological change a have relatively large effects on optimal trend inflation in the case of the CES aggregator. These parameters determine the steady-state real interest rate and thus the frequency of hitting the ZLB. Likewise, the alternative values of the policy-rule coefficients (i.e., HKV policy rule), taken from the estimates of Hirose et al. (2020), raise optimal trend inflation more noticeably in the case of the CES aggregator, because the lower degree of policy inertia increases interest-rate volatility and thus the frequency of hitting the ZLB (at a given trend inflation rate).¹⁸ Third, the parameter governing the elasticity of substitution θ has an outsized effect on optimal trend inflation in the case of the non-CES aggregator. Reducing θ from 7 to 4 increases the static markup, which in this case raises the trend inflation rate that maximizes steady-state welfare Γ_{ss} from 0.11 to 6.00 percent.¹⁹ The optimal trend inflation rate is also 6.00 percent,

¹⁷Coibion et al. (2012) consider alternative structural parameter values and versions of their staggered price model. They conclude that the optimal inflation rate is “remarkably robust to changes in parameter values as long as these do not dramatically increase the implied frequency of being at the ZLB” (p. 1373). Given their extensive analysis, ours is more limited.

¹⁸Billi (2011) emphasizes that higher policy-rate smoothing in a Taylor-type rule reduces the optimal inflation rate.

¹⁹Note that the value of $\theta = 4$ causes the relationships of trend inflation with the steady-state markup

indicating that Γ_π and the ZLB become practically irrelevant. The steady-state effect of θ on optimal trend inflation is absent in the case of the CES aggregator. Overall, the findings that individual parameters affect the optimal trend inflation rate and the frequency of time at the ZLB indicate the importance of considering a combination of parameter values that reproduces the historical frequency for the US economy.

Table 4: Robustness with respect to structural parameters.

Parameters	CES aggregator		non-CES aggregator	
	$\bar{\pi}^*$	ZLB freq.	$\bar{\pi}^*$	ZLB freq.
Baseline	1.48	12.97	3.32	3.99
$\alpha = 0.50$	1.64	12.21	3.64	3.42
$\alpha = 0.75$	0.68	17.02	1.88	7.75
$\beta = 0.995$	0.80	4.57	2.84	2.36
$\beta = 0.9999$	2.00	14.65	3.72	5.11
$a = 1.0075^{1/4}$	1.96	14.77	3.72	5.03
HKV policy rule	3.80	6.79	4.36	3.56
$\theta = 4$	1.84	11.11	6.00	0.06
$\theta = 11$	1.16	14.86	2.24	7.40

Notes: The table shows the annualized optimal trend inflation rate $\bar{\pi}^*$ and the frequency of time at the ZLB for the cases of the CES aggregator ($\epsilon = 0$) and the Kimball-type non-CES aggregator with $\epsilon = -6$. The values of model parameters are reported in Table 1, except for those listed in the first column. The “HKV policy rule” refers to [Hirose et al. \(2020\)](#)’s estimates of the policy-rule coefficients during the post-1982 period, $\phi = 2.995$, $\phi_y = 0.104$, $\phi_{gy} = 0.539$, $\phi_{r1} = 0.686$, and $\phi_{r2} = 0$.

4.3 Welfare difference between 2 and 4 percent inflation targets

The analysis of optimal trend inflation in our model with the non-CES aggregator indicates that a 2 percent inflation target may be somewhat low in the presence of the ZLB. This result may support recent practical proposals, such as those by [Blanchard et al. \(2010\)](#), [Ball \(2013\)](#), and [Krugman \(2014\)](#), to raise the Federal Reserve’s inflation target from the current 2 percent to 4 percent or even higher. This subsection thus focuses more directly on those proposals by following [Ascari et al. \(2018\)](#) to examine the difference in the welfare level between the cases of 2 percent and 4 percent trend inflation in our model with the non-CES aggregator.

and with the slope of the NKPC in the model to align closely with their empirical counterparts as shown in Figures 1 and 2.

As in [Ascari et al. \(2018\)](#), two metrics are used for the welfare comparison. Each measures welfare differences in consumption-equivalent units, as the fraction λ by which consumption would have to be adjusted each period if trend inflation is 2 percent to attain the welfare level associated with 4 percent trend inflation. Thus, positive (negative) values of λ indicate that welfare is higher (lower) at 2 percent trend inflation than at 4 percent. The first metric is based on steady-state welfare and is given by

$$\lambda_{ss} = 1 - \exp [(1 - \beta) (\Gamma_{ss}(\bar{\pi} = 4) - \Gamma_{ss}(\bar{\pi} = 2))],$$

where the arguments ($\bar{\pi} = j$) have been added to indicate that the welfare level corresponds to the trend inflation rate of $j = 2, 4$ percent. The other metric is based on the stochastic mean of welfare and is given by

$$\lambda_m = 1 - \exp [(1 - \beta) (W(\bar{\pi} = 4) - W(\bar{\pi} = 2))].$$

The metrics λ_{ss} and λ_m are computed using the calibration of model parameters reported in [Table 1](#) and the ZLB constraint is operative in the model.

The welfare difference between the cases of 2 percent and 4 percent trend inflation is much smaller with the non-CES aggregator than with the CES one. [Table 5](#) reports the levels of λ_{ss} and λ_m as a percentage for a range of values of the curvature parameter. Although the table indicates a very small welfare cost of higher trend inflation under the baseline calibration of other parameters (the second and third columns), the non-CES aggregator substantially affects the welfare cost. Lowering ϵ from 0 to -6 reduces the welfare cost of the higher trend inflation by an order of magnitude according to the steady state-based metric and even makes the higher trend inflation beneficial according to the stochastic mean-based metric. [Ascari et al. \(2018\)](#) report substantially larger welfare differences between the cases of 2 percent and 4 percent trend inflation using a medium-scale model. An alternative calibration using $\beta = 0.99$, $\theta = 11$, and $\alpha = 0.8$ likewise generates a large steady-state welfare difference in our model in the case of the CES aggregator (1.65 percent as shown in the last column). Then, the non-CES aggregator with $\epsilon = -6$ lowers the welfare difference dramatically (to 0.02 percent). Therefore, there is no crucial welfare difference between setting 2 percent and 4 percent inflation targets in our model.

Table 5: Welfare cost of 4 percent trend inflation relative to 2 percent.

ϵ	$100\lambda_{ss}$	$100\lambda_m$	$100\lambda_{ss}$ (alt. cal.)
0	0.0015	0.0015	1.6537
-2	0.0006	0.0004	0.0491
-4	0.0003	0.0001	0.0286
-6	0.0001	-0.0001	0.0216
-8	-0.0000	-0.0002	0.0177

Notes: The table shows the welfare cost of 4 percent trend inflation relative to 2 percent in consumption-equivalent units. The second and third columns use the values of model parameters other than ϵ reported in Table 1. The fourth column is based on the alternative parameter values $\beta = 0.99$, $\theta = 11$, and $\alpha = 0.8$.

Before proceeding to the concluding remarks on the paper, one caveat is worth noting. The welfare difference analyzed in this subsection takes no account of transition costs, including the cost of making the 4 percent inflation target credible. Thus, such a difference does not properly capture the full cost of raising the Federal Reserve’s inflation target from the current 2 percent to 4 percent.

5 Conclusion

This paper has examined the welfare implications of a non-CES aggregator of the sort proposed by [Kimball \(1995\)](#) in a staggered price model. Previous studies have shown that the non-CES aggregator bestows on staggered price models empirically plausible short- and long-run trade-offs between output and inflation. In the presence of the aggregator, lower trend inflation flattens Phillips curves derived from the models and decreases steady-state output by increasing the average markup, generating relationships with trend inflation that align with the empirical evidence. This paper has demonstrated that the non-CES aggregator reduces both the steady-state welfare cost of higher trend inflation and the inflation-related weight in a model-based welfare function for higher trend inflation. Consequently, the optimal rate of trend inflation is moderately positive even without considering the ZLB on nominal interest rates. Thus optimal trend inflation is only mildly affected by the ZLB. Moreover, the welfare difference between the cases of 2 percent and 4 percent trend inflation is much smaller than in the model with the CES aggregator.

Along with a few recent studies that show a positive rate of optimal trend inflation even in

the absence of the ZLB, such as [Adam and Weber \(2019\)](#) and [Bilbiie et al. \(2014\)](#), our paper suggests that further investigating the implications of microeconomic market structures is a fruitful avenue for future research on monetary economics and monetary policy.

Appendix

A Composite Coefficients in the New Keynesian Phillips Curve

The coefficients in the log-linearized equilibrium conditions (22)–(26) are given by

$$\begin{aligned}
\kappa_y &\equiv 2\kappa, & \kappa &\equiv \frac{(1 + \epsilon_1)(1 - \alpha\pi^{\gamma-1})(1 - \alpha\beta\pi^{2\gamma})}{\alpha\pi^{\gamma-1}\{(1 + \epsilon_3)[1 - \epsilon_2\gamma/(\gamma - 1 - \epsilon_2)] + \gamma\}}, \\
\kappa_d &\equiv \gamma \left[\kappa \left(1 + \frac{1}{1 + \epsilon_1} \right) - \tilde{\kappa}_d \right] - \alpha\beta\pi^{2\gamma} - \frac{1}{\alpha\pi^{\gamma-1}}, \\
\tilde{\kappa}_d &\equiv \frac{(1 + \epsilon_3)(1 - \alpha\pi^{\gamma-1})(1 - \alpha\beta\pi^{\gamma-1})}{\alpha\pi^{\gamma-1}\{(1 + \epsilon_3)[1 - \epsilon_2(1 + \gamma)/(\gamma - 1)] + \gamma[1 - \epsilon_2/(\gamma - 1)]\}}, \\
\kappa_\varphi &\equiv \frac{\beta(\pi^{1+\gamma} - 1)(1 + \epsilon_3)(1 - \alpha\pi^{\gamma-1})}{(1 + \epsilon_3)[1 - \epsilon_2(1 + \gamma)/(\gamma - 1)] + \gamma[1 - \epsilon_2/(\gamma - 1)]}, \\
\kappa_{\epsilon\zeta} &\equiv -\frac{\epsilon_3\beta\pi(\pi^\gamma - 1)(1 - \alpha\pi^{\gamma-1})}{(1 + \epsilon_3)[1 - \epsilon_2\gamma/(\gamma - 1 - \epsilon_2)] + \gamma}, \\
\kappa_{\epsilon\psi} &\equiv \frac{\epsilon_2\beta(\pi^{1+2\gamma} - 1)(1 + \epsilon_3)(1 - \alpha\pi^{\gamma-1})}{\pi^\gamma\{(1 + \epsilon_3)[\gamma - 1 - \epsilon_2(1 + \gamma)] + \gamma(\gamma - 1 - \epsilon_2)\}}, \\
\rho_d &\equiv \frac{\alpha\pi^{-1}(1 + \epsilon_1\pi^\gamma)}{1 + \epsilon_1}, & \kappa_{ed} &\equiv -\frac{\epsilon_1\alpha\pi^{-1}(\pi^\gamma - 1)}{(1 + \epsilon_1)(1 - \alpha\pi^{-1})}.
\end{aligned}$$

B Derivation of Second-order Approximated Utility Function (35)

This appendix derives a second-order approximation to the utility function (1) with unit elasticity of labor supply (i.e., $\eta = 1$),

$$E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(C_t) - \int_0^1 \frac{(l_t(f))^2}{2} df \right) = E_0 \sum_{t=0}^{\infty} \beta^t \left(\log(y_t A_t) - \frac{y_t^2 \Delta_t}{2} \right).$$

The period consumption utility function can be approximated up to the second order as

$$\log(y_t A_t) \approx \log(y) + \hat{y}_t + tip.$$

Therefore, the second-order approximation to the consumption part of the utility function is given by

$$E_0 \sum_{t=0}^{\infty} \beta^t \log(C_t) \approx \frac{\log(y)}{1 - \beta} + E_0 \sum_{t=0}^{\infty} \beta^t \hat{y}_t + tip. \quad (39)$$

Next turning to the labor part of the utility function, this paper extends the second-order approximation of [Alves \(2014\)](#)—who considers the case of the CES aggregator—to the general case of the Kimball-type aggregator. Log-linearizing the real marginal cost of aggregating goods d_t 's law of motion (16) yields

$$\hat{p}_t^* \approx \frac{\alpha\pi^{\gamma-1}}{1 - \alpha\pi^{\gamma-1}} \left(\hat{\pi}_t + \frac{1}{\alpha\pi^{\gamma-1}} \hat{d}_t - \hat{d}_{t-1} \right), \quad (40)$$

and the second-order approximation to (16) leads to

$$\hat{p}_t^* \approx \frac{\alpha\pi^{\gamma-1}}{1 - \alpha\pi^{\gamma-1}} \left[\hat{\pi}_t + \frac{1}{\alpha\pi^{\gamma-1}} \hat{d}_t - \hat{d}_{t-1} - \frac{1 - \gamma}{2(1 - \alpha\pi^{\gamma-1})} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right)^2 \right]. \quad (41)$$

Log-linearizing the variable s_t 's law of motion (33) yields

$$\hat{s}_t \approx \alpha\pi^{2\gamma} \hat{s}_{t-1} + \frac{2\gamma\alpha\pi^{\gamma-1}(\pi^{1+\gamma} - 1)}{1 - \alpha\pi^{\gamma-1}} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right).$$

Using these three equations, the second-order approximation to (33) leads to

$$\begin{aligned} \hat{s}_t \approx & \alpha\pi^{2\gamma} \hat{s}_{t-1} + \frac{2\gamma\alpha\pi^{\gamma-1}\Phi}{1 - \alpha\pi^{\gamma-1}} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right) + \frac{\gamma\alpha\pi^{\gamma-1}(1 - \alpha\pi^{2\gamma})(1 + \gamma + 2\gamma\Phi)}{(1 - \alpha\pi^{\gamma-1})^2} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right)^2 \\ & + 2\gamma\alpha\pi^{2\gamma}(1 - \alpha\pi^{2\gamma}) \left[\frac{1}{1 - \alpha\pi^{\gamma-1}} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right) \hat{s}_{t-1} + \frac{1}{4\gamma} \hat{s}_{t-1}^2 \right], \end{aligned}$$

where $\Phi \equiv \pi^{1+\gamma} - 1$. As in [Alves \(2014\)](#), it is assumed that Φ is of first order and \hat{s}_{-1} is of second order. Then, it follows that

$$\begin{aligned} \hat{s}_t \approx & \alpha\pi^{2\gamma} \hat{s}_{t-1} + \frac{2\gamma\alpha\pi^{\gamma-1}}{1 - \alpha\pi^{\gamma-1}} \Phi \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right) + \frac{\gamma\alpha\pi^{\gamma-1}(1 - \alpha\pi^{2\gamma})(1 + \gamma)}{(1 - \alpha\pi^{\gamma-1})^2} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right)^2 \\ & + 2\gamma\alpha\pi^{2\gamma}(1 - \alpha\pi^{2\gamma}) \left[\frac{1}{1 - \alpha\pi^{\gamma-1}} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right) \hat{s}_{t-1} + \frac{1}{4\gamma} \hat{s}_{t-1}^2 \right], \end{aligned}$$

which implies that \hat{s}_t is of second order. Consequently, the second-order approximation is reduced to

$$\begin{aligned} \hat{s}_t \approx & \alpha\pi^{2\gamma} \hat{s}_{t-1} + \frac{2\gamma\alpha\pi^{\gamma-1}}{1 - \alpha\pi^{\gamma-1}} \Phi \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right) + \frac{\gamma\alpha\pi^{\gamma-1}(1 - \alpha\pi^{2\gamma})(1 + \gamma)}{(1 - \alpha\pi^{\gamma-1})^2} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right)^2 \\ = & \sum_{j=0}^t (\alpha\pi^{2\gamma})^{t-j} \left[\frac{\gamma\alpha\pi^{\gamma-1}(1 - \alpha\pi^{2\gamma})(1 + \gamma)}{(1 - \alpha\pi^{\gamma-1})^2} \left(\hat{\pi}_j + \hat{d}_j - \hat{d}_{j-1} \right)^2 \right. \\ & \left. + \frac{2\gamma\alpha\pi^{\gamma-1}}{1 - \alpha\pi^{\gamma-1}} \Phi \left(\hat{\pi}_j + \hat{d}_j - \hat{d}_{j-1} \right) \right] + tip, \end{aligned}$$

and thus

$$\sum_{t=0}^{\infty} \beta^t \hat{s}_t \approx \sum_{t=0}^{\infty} \beta^t \left[\frac{\gamma \alpha \pi^{\gamma-1} (1 - \alpha \pi^{2\gamma}) (1 + \gamma)}{(1 - \alpha \pi^{\gamma-1})^2 (1 - \alpha \beta \pi^{2\gamma})} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1})^2 + \frac{2\gamma \alpha \pi^{\gamma-1}}{(1 - \alpha \pi^{\gamma-1}) (1 - \alpha \beta \pi^{2\gamma})} \Phi (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}) \right] + tip. \quad (42)$$

Similarly to s_t , log-linearizing the variable $s_{\epsilon,t}$'s law of motion (34) yields

$$\hat{s}_{\epsilon,t} \approx \alpha \pi^\gamma \hat{s}_{\epsilon,t-1} + \frac{\gamma \alpha \pi^{\gamma-1} (\pi - 1)}{1 - \alpha \pi^{\gamma-1}} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}).$$

Using this equation as well as (40) and (41), the second-order approximation to (34) leads to

$$\begin{aligned} \hat{s}_{\epsilon,t} \approx & \alpha \pi^\gamma \hat{s}_{\epsilon,t-1} + \frac{\gamma \alpha \pi^{\gamma-1} \Phi_\epsilon}{1 - \alpha \pi^{\gamma-1}} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}) + \frac{\gamma \alpha \pi^{\gamma-1} (1 - \alpha \pi^\gamma) (1 + \gamma \Phi_\epsilon)}{2(1 - \alpha \pi^{\gamma-1})^2} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1})^2 \\ & + \gamma \alpha \pi^\gamma (1 - \alpha \pi^\gamma) \left[\frac{1}{1 - \alpha \pi^{\gamma-1}} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}) \hat{s}_{\epsilon,t-1} + \frac{1}{2\gamma} \hat{s}_{\epsilon,t-1}^2 \right], \end{aligned}$$

where $\Phi_\epsilon \equiv \pi - 1$. Under the assumption that Φ_ϵ is of first order and $\hat{s}_{\epsilon,-1}$ is of second order, it follows

$$\begin{aligned} \hat{s}_{\epsilon,t} \approx & \alpha \pi^\gamma \hat{s}_{\epsilon,t-1} + \frac{\gamma \alpha \pi^{\gamma-1}}{1 - \alpha \pi^{\gamma-1}} \Phi_\epsilon (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}) + \frac{\gamma \alpha \pi^{\gamma-1} (1 - \alpha \pi^\gamma)}{2(1 - \alpha \pi^{\gamma-1})^2} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1})^2 \\ & + \gamma \alpha \pi^\gamma (1 - \alpha \pi^\gamma) \left[\frac{1}{1 - \alpha \pi^{\gamma-1}} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}) \hat{s}_{\epsilon,t-1} + \frac{1}{2\gamma} \hat{s}_{\epsilon,t-1}^2 \right], \end{aligned}$$

which implies that $\hat{s}_{\epsilon,t}$ is of second order. Consequently, the second-order approximation is reduced to

$$\begin{aligned} \hat{s}_{\epsilon,t} \approx & \alpha \pi^\gamma \hat{s}_{\epsilon,t-1} + \frac{\gamma \alpha \pi^{\gamma-1}}{1 - \alpha \pi^{\gamma-1}} \Phi_\epsilon (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}) + \frac{\gamma \alpha \pi^{\gamma-1} (1 - \alpha \pi^\gamma)}{2(1 - \alpha \pi^{\gamma-1})^2} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1})^2 \\ = & \sum_{j=0}^t (\alpha \pi^\gamma)^{t-j} \left[\frac{\gamma \alpha \pi^{\gamma-1} (1 - \alpha \pi^\gamma)}{2(1 - \alpha \pi^{\gamma-1})^2} (\hat{\pi}_j + \hat{d}_j - \hat{d}_{j-1})^2 + \frac{\gamma \alpha \pi^{\gamma-1}}{(1 - \alpha \pi^{\gamma-1})} \Phi_\epsilon (\hat{\pi}_j + \hat{d}_j - \hat{d}_{j-1}) \right] + tip, \end{aligned}$$

and thus

$$\sum_{t=0}^{\infty} \beta^t \hat{s}_{\epsilon,t} \approx \sum_{t=0}^{\infty} \beta^t \left[\frac{\gamma \alpha \pi^{\gamma-1} (1 - \alpha \pi^\gamma)}{2(1 - \alpha \pi^{\gamma-1})^2 (1 - \alpha \beta \pi^{2\gamma})} (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1})^2 + \frac{\gamma \alpha \pi^{\gamma-1}}{(1 - \alpha \pi^{\gamma-1}) (1 - \alpha \beta \pi^{2\gamma})} \Phi_\epsilon (\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}) \right] + tip. \quad (43)$$

Then, the period labor disutility function can be approximated up to the second order as

$$\frac{y_t^2 \Delta_t}{2} \approx \frac{y^2 \Delta}{2} \left(1 + 2(\hat{y}_t + \hat{y}_t^2) + \frac{s \hat{s}_t + 2\epsilon s_\epsilon \hat{s}_{\epsilon,t}}{s + 2\epsilon s_\epsilon + \epsilon^2} \right),$$

since s_t , $s_{\epsilon,t}$, and Δ_t are of second order. Using this equation as well as (42) and (43), the second-order approximation to the labor part of the utility function is given by

$$\begin{aligned}
E_0 \sum_{t=0}^{\infty} \beta^t \int_0^1 \frac{(l_t(f))^2}{2} df &= E_0 \sum_{t=0}^{\infty} \beta^t \frac{y_t^2 \Delta_t}{2} \approx E_0 \sum_{t=0}^{\infty} \beta^t \frac{y^2 \Delta}{2} \left(1 + 2(\hat{y}_t + \hat{y}_t^2) + \frac{s \hat{s}_t + 2\epsilon s_{\epsilon} \hat{s}_{\epsilon,t}}{s + 2\epsilon s_{\epsilon} + \epsilon^2} \right) \\
&\approx \frac{y^2 \Delta}{2(1-\beta)} + y^2 \Delta E_0 \sum_{t=0}^{\infty} \beta^t (\hat{y}_t^2 + \hat{y}_t) + \frac{y^2}{2(1+\epsilon)^2} \left(s E_0 \sum_{t=0}^{\infty} \beta^t \hat{s}_t + 2\epsilon s_{\epsilon} E_0 \sum_{t=0}^{\infty} \beta^t \hat{s}_{\epsilon,t} \right) \\
&\approx \frac{y^2 \Delta}{2(1-\beta)} + y^2 \Delta E_0 \sum_{t=0}^{\infty} \beta^t (\hat{y}_t^2 + \hat{y}_t) \\
&\quad + \frac{y^2}{2(1+\epsilon)^2} \frac{\gamma \alpha \pi^{\gamma-1}}{(1-\alpha \pi^{\gamma-1})^2} \left(\frac{s(1-\alpha \pi^{2\gamma})(1+\gamma)}{1-\alpha \beta \pi^{2\gamma}} + \frac{\epsilon s_{\epsilon}(1-\alpha \pi^{\gamma})}{1-\alpha \beta \pi^{\gamma}} \right) \\
&\quad \times E_0 \sum_{t=0}^{\infty} \beta^t \left[\left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right)^2 - 2\Phi_{\pi} \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} \right) \right] + tip,
\end{aligned}$$

where

$$\Phi_{\pi} \equiv \frac{(1-\alpha \pi^{\gamma-1})[s(1-\alpha \beta \pi^{\gamma})\Phi + \epsilon s_{\epsilon}(1-\alpha \beta \pi^{2\gamma})\Phi_{\epsilon}]}{s(1-\alpha \pi^{2\gamma})(1-\alpha \beta \pi^{\gamma})(-1-\gamma) - \epsilon s_{\epsilon}(1-\alpha \pi^{\gamma})(1-\alpha \beta \pi^{2\gamma})}.$$

Because both Φ and Φ_{ϵ} are of first order, so is Φ_{π} . Following [Woodford \(2003\)](#) and [Alves \(2014\)](#), the inefficiency degree Φ_y of steady-state output in our model satisfies

$$\frac{1}{y} (1 - \Phi_y) = y \Delta \quad \Leftrightarrow \quad \Phi_y = 1 - y^2 \Delta.$$

Moreover, it is assumed that Φ_y is of first order. Hence, it follows

$$\begin{aligned}
E_0 \sum_{t=0}^{\infty} \beta^t \int_0^1 \frac{(l_t(f))^2}{2} df &\approx \frac{y^2 \Delta}{2(1-\beta)} + E_0 \sum_{t=0}^{\infty} \beta^t [\hat{y}_t^2 + (1-\Phi_y) \hat{y}_t] \\
&\quad + \frac{\Gamma_{\pi}}{2} E_0 \sum_{t=0}^{\infty} \beta^t \left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1} - \Phi_{\pi} \right)^2 - \frac{\Gamma_{\pi}}{2(1-\beta)} \Phi_{\pi}^2 + tip, \quad (44)
\end{aligned}$$

where

$$\Gamma_{\pi} \equiv \frac{1}{\Delta(1+\epsilon)^2} \frac{\gamma \alpha \pi^{\gamma-1}}{(1-\alpha \pi^{\gamma-1})^2} \left(\frac{s(1-\alpha \pi^{2\gamma})(1+\gamma)}{1-\alpha \beta \pi^{2\gamma}} + \frac{\epsilon s_{\epsilon}(1-\alpha \pi^{\gamma})}{1-\alpha \beta \pi^{\gamma}} \right).$$

Therefore, from (39) and (44), the second-order approximation to the utility function

leads to (35), where the coefficients and constants are given by

$$\begin{aligned}\Gamma_{ss} &\equiv \log(y) - \frac{y^2\Delta}{2}, & \Gamma_{dev} &\equiv \frac{2\Gamma_\pi\Phi_\pi^2 + \Phi_y^2}{4}, \\ \Gamma_\pi &\equiv \frac{1}{\Delta(1+\epsilon)^2} \frac{\gamma\alpha\pi^{\gamma-1}}{(1-\alpha\pi^{\gamma-1})^2} \left(\frac{s(1-\alpha\pi^{2\gamma})(1+\gamma)}{1-\alpha\beta\pi^{2\gamma}} + \frac{\epsilon s_\epsilon(1-\alpha\pi^\gamma)}{1-\alpha\beta\pi^\gamma} \right), \\ \Phi_\pi &\equiv \frac{(1-\alpha\pi^{\gamma-1})[s(\pi^{1+\gamma}-1)(1-\alpha\beta\pi^\gamma) + \epsilon s_\epsilon(\pi-1)(1-\alpha\beta\pi^{2\gamma})]}{s(1-\alpha\pi^{2\gamma})(1-\alpha\beta\pi^\gamma)(-1-\gamma) - \epsilon s_\epsilon(1-\alpha\pi^\gamma)(1-\alpha\beta\pi^{2\gamma})}, & \Phi_y &= 1 - y^2\Delta.\end{aligned}$$

In the special case of the CES aggregator (i.e., $\epsilon = 0$), the second-order approximated utility function can be reduced to (37), where the coefficients and constants are given by

$$\begin{aligned}\Gamma_{ss0} &\equiv \log(y) - \frac{y^2\Delta}{2}, & \Gamma_{dev0} &\equiv \frac{2\Gamma_{\pi0}\Phi_{\pi0}^2 + \Phi_{y0}^2}{4}, & \Gamma_{\pi0} &\equiv \frac{\theta\alpha\pi^{\theta-1}(1-\alpha\pi^{2\theta})(1+\theta)}{(1-\alpha\pi^{\theta-1})^2(1-\alpha\beta\pi^{2\theta})}, \\ \Phi_{\pi0} &\equiv -\frac{(\pi^{1+\theta}-1)(1-\alpha\pi^{\theta-1})}{(1-\alpha\pi^{2\theta})(1+\theta)}, & \Phi_{y0} &= 1 - y^2\Delta, \\ y &= \left[\frac{\theta-1}{\theta} \frac{1-\alpha\beta\pi^{2\theta}}{1-\alpha\beta\pi^{\theta-1}} \left(\frac{1-\alpha}{1-\alpha\pi^{\theta-1}} \right)^{\frac{\theta+1}{\theta-1}} \right]^{\frac{1}{2}}, & \Delta &= \frac{1-\alpha}{1-\alpha\pi^{2\theta}} \left(\frac{1-\alpha\pi^{\theta-1}}{1-\alpha} \right)^{\frac{2\theta}{\theta-1}}.\end{aligned}$$

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