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# Generalized Rotemberg Price-Setting

## Abstract

We propose a generalized Rotemberg pricing scheme which is able to explain important aspects of the observed nonlinear behavior of price adjustment at the macroeconomic level, such as higher pass-through in response to larger shocks, a positive impact of trend inflation on price flexibility, and the relationship between announcement and implementation effects. This is achieved by replacing the linear marginal adjustment cost in Rotemberg pricing by a monotonically increasing, but bounded marginal cost function, specifically some version of a sigmoid function. Conditional on computing a nonlinear model solution, the generalized pricing function is equally tractable as Rotemberg pricing, and equivalent to it for small shocks around a zero-inflation steady state. We show that a suitable calibration of the model has similar effects on macroeconomic variables as standard versions of the menu cost model. It replicates the effect of trend inflation on the impulse response to money supply shocks that has been established in the literature in a model of logit-price dynamics.

JEL-Codes: E130, E310.

Keywords: price setting, nominal rigidities, inflation.

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# 1 Introduction

In recent years, significant progress has been made in explaining microfacts of price-setting behavior, using models of heterogeneous firms with often rather complex state-dependent pricing behavior. Menu costs of price adjustment are a typical ingredient of these models. In contrast, medium-scale DSGE models either assume time-dependent staggered pricing a la Calvo (1983), where firm heterogeneity can be analytically aggregated, or assume a representative firm, following Rotemberg (1982). These approaches are much more tractable and provide good approximations to the aggregate responses to small shocks around a zero-inflation steady state. However, it is well known that they fail to capture the observed nonlinear aspects of pricing behavior.

The main contribution of our paper is to propose a generalization of the Rotemberg pricing model (abbreviated GRP in the following) that is equally tractable as the Rotemberg model, but is able to capture the observed nonlinear features of inflation dynamics, which are relevant in the presence of large shocks or positive trend inflation. The generalization consists in replacing the linear marginal cost function by a symmetric sigmoid function, where marginal pricing costs are monotonically increasing but bounded. Using the sigmoid marginal cost function, we derive the pricing problem and the New Keynesian Pillips curve in discrete and continuous time. The model is equivalent to the Rotemberg model up to second-order perturbations around a zero-inflation steady state. To analyze the model, it is therefore necessary to use nonlinear solution techniques such as nonlinear perfect foresight paths, higher-order perturbation solutions or global nonlinear models. In our examples, we compare impulse responses to large shocks obtained from higher-order perturbation and perfect foresight solutions.

What are the well-established nonlinear features of inflation dynamics? The literature has established three stylized facts which are explained by some version of state-dependent models but are inconsistent with the simple pricing models of Calvo and Rotemberg.[1] First, Ascari and Haber (2022) document the nonlinear pass-through of cost shocks to prices. Alvarez et al. (2017) point out that this is a key implication of state-dependent pricing models: large shocks propagate faster than small shocks, because the larger the shock, the more firms should find it profitable to adjust their prices. Cavallo et al. (2023) highlight the importance of this mechanism in explaining the inflation surge observed in 2022, as their data show a notable increase in the frequency of price changes following large shocks. They explain this using a New Keynesian model incorporating state-dependent price-setting. Second, a growing body of empirical evidence suggests that higher trend

[1] A more recent finding is that positive trend inflation induces an asymmetric response to shocks. Alexandrov (2022) shows this analytically for menu cost models and empirically using US sector data. In Section 4.5, we show that GRP is able to reproduce this implication of menu cost models. Similarly, there is empirical evidence for asymmetric pass-through of VAT changes, but no consensus in the literature, as we discuss in Section 5.4.

inflation is associated with a steeper New Keynesian Phillips curve (Benati, 2007; Ball and Mazumder, 2011; Gemma et al., 2023; Blanco et al., 2024b). Already Ball et al. (1988) argued that a higher trend inflation rate implies smaller real effects of nominal shocks. Their model illustrates how higher trend inflation induces firms to adjust prices more frequently, thereby mitigating the effects of nominal shocks. Similar mechanisms are present in recent state-dependent price-setting models such as Costain and Nakov (2019), which implies that higher trend inflation amplifies the impact of monetary policy shocks on inflation while dampening their effect on consumption. A second stylised fact is therefore that higher trend inflation leads to greater aggregate price flexibility. Third, the announcement effects of VAT reforms are comparatively small and the pass-through occurs mainly during implementation, as several recent empirical papers document (Benzarti et al., 2020; Benedek et al., 2020). One possible reason may be that a large share of fixed menu costs in total price adjustment costs leads to a lower incentive to smooth price adjustments over time (Karadi and Reiff, 2019). Another reason may be that firms find it easier to justify price adjustments to their customers during and after the implementation of the VAT reform.

We analyze the properties of the GRP model in three directions. First we investigate to what extent the model can replicate the aggregate implications of state-dependent pricing models. Despite being very parsimoniously parameterized, we show that the model has qualitatively and quantitatively very similar inflation dynamics as standard forms of menu cost models, if properly calibrated. Both models explain the observed nonlinear pass-through of cost shocks to prices and the greater aggregate price flexibility as well as the asymmetric response under positive trend inflation. Second, we embed the generalized Rotemberg model into a basic DSGE framework. We show that the GRP model goes a long way in explaining the above mentioned stylized facts, in contrast to the standard Rotemberg or the Calvo model. Third, we check whether the model can reproduce the relationship between trend inflation and price flexibility in the case of high rates of trend inflation. We show that our model has similar aggregate implications as the model of logit pricing in Costain and Nakov (2019), which is successful in explaining the firm level evidence for Mexican data with trend inflation rates of up to 80 percent annually.

Our approach builds on Rotemberg (1982), who developed a theory proposing that firms, concerned about upsetting their customers, attribute quadratic costs to price changes. Zbaracki et al. (2004) provided detailed microeconometric evidence that supports such a convex relationship. Their research suggests that menu costs, as traditionally understood, constitute only a small portion of the overall costs associated with setting prices. Instead, the study highlights the significance of managerial costs, such as information gathering, decision-making, and communication costs, as well as customer costs like communication and negotiation expenses. Importantly, Zbaracki et al. (2004) demonstrate that many components of these managerial and customer costs are convex in the size of the price adjustment. Stipulating quadratic costs, as Rotemberg originally did, is overly restrictive.[2] Our approach improves on this by allowing for a more general and more plausible class of convex functions.

To build on the Rotemberg rather than the Calvo approach may need some justification. Comparing the two models from an empirical point of view, the literature provides some support for Rotemberg pricing, suggesting that it is not inferior to the Calvo model. We review this literature in Section 2.2. Our main argument for using the Rotemberg model is that it allows a nonlinear generalization in a straightforward and tractable way. Generalizing the Calvo model is a walk on a knife's edge, because the analytic aggregation over the price distribution has to be maintained. Gasteiger and Grimaud (2023) endogenize the price setting frequency in a Calvo model. They make the model tractable by using the short-cut that the benefit of updating the price is computed not in comparison to the old price of the individual firm, but relative to the average old price in the economy. Recently, Blanco et al. (2024b) have found a novel way to generalize the Calvo model so as to account for the nonlinear responses of inflation to shocks. In their model, there is a continuum of firms and each firm produces a continuum of goods. The elasticity of substitution is the same between the goods of the same firm and across firms. Each firm can choose how many prices they adjust, but not which prices; this preserves the exact aggregation property of Calvo pricing.

In the Rotemberg model, further generalizations are much easier to do, because there is no price dispersion to take care of. For example, Arndt and Enders (2024) find in a regime switching model, estimated on US data, that the Phillips curve is steeper in times of high volatility of inflation rather than high trend inflation, as was already argued in Hall (2023). A natural way to explain this is that in times of volatile inflation, firms reduce price adjustment costs, for example by writing contracts of shorter duration. Allowing firms to invest in a technology that reduces price adjustment costs, an enlarged GRP model can potentially account for such a behavior, at the cost of an additional state variable. This is an interesting avenue for future research.

The paper proceeds as follows. After the literature review in Section 2, Section 3 introduces the generalization of Rotemberg pricing by means of a sigmoid marginal cost function. In section 4 we use a partial equilibrium industry model to compare the pass-through in the generalised Rotemberg model with that in a menu cost model. Section 5 embeds generalized Rotemberg pricing into a simple New Keynesian DSGE model, to explain the aforementioned stylized facts. The case study in Section 6 demonstrates the ability of the generalized Rotemberg model to reproduce the implications of trend inflation in the model of Costain and Nakov (2019). Section 7 concludes.

[2] Rotemberg refined his arguments in later work (Rotemberg, 2005, 2010, 2011).

# 2 Related Literature

## 2.1 Models of price setting

There is now an extensive literature devoted to models in which price rigidity is based on menu costs. An important topic of this literature is whether and how menu costs at the micro level lead to monetary non-neutrality in the aggregate. The former has been questioned by Caplin and Spulber (1987) and Golosov and Lucas (2007), the latter has been investigated by e.g. Caballero and Engel (2007), who study the importance of selection effects versus adjustments to the extensive margin, and Nakamura and Steinsson (2010), who include additional model components and in this way increase monetary non-neutrality.

Recently, the literature has generalized these models, making it possible, for example, to derive sufficient statistics for the effects of monetary policy (Alvarez et al. (2016)). In addition, Alvarez et al. (2022) have shown that in a large class of sticky price models the price-setting behavior of firms can be described by a generalized hazard function, and Auclert et al. (2024) have investigated to what extent the Calvo model can approximate menu costs models with appropriate calibration. We will discuss in section 3.4 how this literature can be used to calibrate the generalized Rotemberg model.

As data availability has improved at the micro level, a large literature has emerged that attempts to explain the detailed stylized facts reported by, for example, Klenow and Malin (2010), by constructing increasingly complex models of price setting. Nakamura and Steinsson (2013) provided an early review of this literature, important recent contributions have been made by Costain and Nakov (2019), Karadi and Reiff (2019), Ilut et al. (2020) and Dotsey and Wolman (2020). These are complex state-dependent models of price-setting, in which price adjustments occur at both the intensive and the extensive margin, in which possible selection effects are taken into account and which may or may not be based on menu costs. In Section 6, we show that our generalized Rotemberg model is able to reproduce the behavior of Costain and Nakov's model in the presence of high trend inflation, a model in which price rigidities are not based on menu costs but on error-prone decision making.

## 2.2 Rotemberg versus Calvo

Due to the widespread use of both the Calvo and Rotemberg model in macroeconomics, there is a rich and still active literature comparing and empirically testing both price-setting models. It has been shown that although both models are equivalent up to a first-order approximation around the zero inflation steady state, there can be large differences between the two when non-linearities are taken into account.[3]

[3]The details of our nonlinear implementation of the Calvo model are given in Appendix A.2.

A main difference between the two models is that the Calvo model introduces an additional state variable in the form of price dispersion, for which there is no equivalent in the Rotemberg model. The price dispersion induces misallocation and is the main driver of the welfare costs of inflation in this model. It is obvious that there is price dispersion in reality, as not all firms set their prices symmetrically. However, empirical results from Nakamura et al. (2018) suggest that the Calvo model greatly exaggerates price dispersion. They test the implication of the model that the absolute size of price changes should increase with inflation and do not find this confirmed in US data from the 1970s and 1980s. Furthermore, the Calvo model assumes that firms must always satisfy demand, which is inconsistent with profit-maximising behaviour when long-run inflation is positive. Hahn (2022) shows that in a model where firms do not have to satisfy demand, this implies a significantly lower loss in total effective productivity compared to a benchmark model without the possibility of rationing. To summarise, while the Rotemberg model generates no price dispersion, the Calvo model generates too much of it, and it is not clear which one is closer to reality in this respect.

More generally, the literature presents mixed results regarding the empirical performance of both models. Ascari et al. (2011) come to the conclusion that the Calvo model is empirically superior to the Rotemberg model when the model is estimated in the presence of positive trend inflation. However, as they also report, this only applies if price adjustment costs are interpreted as real resource costs (see also section B.4). Moreover, Ascari (2004) shows that trend inflation in the Calvo model has a large influence on the steady state output and there is a surprisingly low threshold value that trend inflation cannot exceed, depending on the model calibration. This limits the usefulness of the Calvo model when analysing models involving trend inflation. Richter and Throckmorton (2016) find that the Rotemberg model explains the macroeconomic data from 2008-2011 better because it endogenously generates more volatility at the zero lower bound. Similarly, Sims and Wolff (2017) conclude that fiscal multipliers in the Rotemberg model are more volatile between the states of the economy than in the Calvo model. Miao and Ngo (2021), in turn, conclude that both models produce very similar results at the zero lower bound if the price adjustment costs are refunded to households in the Rotemberg model. Furthermore, Oh (2020) shows that the two models have different dynamics in response to uncertainty shocks. In the Rotemberg model, uncertainty shocks lead to a decline in output and inflation, which is consistent with his empirical results. In contrast, uncertainty shocks in the Calvo model lead to a decrease in output but an increase in inflation as firms set higher prices as a precautionary measure. Iania et al. (2023) show that in the Calvo model the inflation cost channel produces the desired term premium moments but has non-trivial, counterintuitive approximation errors in the price dispersion function, whereas the Rotemberg model can successfully accommodate the intuition of the inflation cost channel while maintaining comparable term premium dynamics.

Considering both micro- and macroeconomic evidence, these results show that no model dominates the other one. While Calvo's (1983) model seems to have been used more frequently overall, the Rotemberg model has recently become popular in the Heterogeneous Agents New Keynesian (HANK) literature. Indeed, it is used in important milestones of this literature such as Kaplan et al. (2018) and Bhandari et al. (2021). We closely follow the continuous time framework in Kaplan et al. (2018) to derive the New Keynesian Phillips Curve for our model in Section 3.3.

# 3 Generalization of Rotemberg price-setting

In the following, we first describe the profit maximisation problem of firms in general terms, including a brief description of the Rotemberg case as a reference. We then present our proposal of a sigmoid marginal cost function, which is a generalization of the latter as it nests it as a limiting case. To improve our understanding of the implications of the GRP, we then derive a continuous-time New Keynesian Phillips curve. Finally, we discuss ways to calibrate the GRP.

## 3.1 Price-setting by firms facing price adjustment costs

We assume a monopolistically competitive environment where profit-maximising firms face a demand function with constant elasticity $-\varepsilon$. Marginal costs $MC_t$ are independent of output, exogenous to the firm and the same for all firms. Firm $i$ sets its price $P_{i,t}$ and receives $P_{i,t}/(1+\tau_t)$ for each unit sold, where $\tau_t$ is the value added tax (VAT). If the firm changes its price including VAT, it must pay price adjustment costs of $F\left(P_{i,t}/P_{i,t-1}-1\right)Y_tP_t$, where the nominal industry output $Y_tP_t$ serves as adjustment cost base. The firm discounts future profits with the stochastic nominal discount factor $\Lambda_{t,t+j}$. This results in the following dynamic pricing problem:

$$\max_{\{P_{i,t}\}_{t=0}^{\infty}} E_t \sum_{j=0}^{\infty} \Lambda_{t,t+j} \left\{ \left( \frac{P_{i,t+j}}{1+\tau_t} - MC_{t+j} \right) \left( \frac{P_{i,t+j}}{P_{t+j}} \right)^{-\varepsilon} Y_{t+j} - F\left( \frac{P_{i,t+j}}{P_{i,t+j-1}} - 1 \right) Y_{t+j} P_{t+j} \right\}$$

By taking the derivative with respect to $P_{i,t}$ and using that $P_{i,t} = P_t$ in equilibrium because of symmetry, we can write the aggregate first order condition in real terms as

$$\frac{(1-\varepsilon)}{1+\tau_t} + \varepsilon\, mc_t + \Lambda_{t,t+1} f\left(\pi_{t+1}\right)\left(1+\pi_{t+1}\right)^2 \frac{y_{t+1}}{y_t} = f\left(\pi_t\right)\left(1+\pi_t\right), \qquad (1)$$

where $mc_t = MC_t/P_t$ denotes real marginal costs inflation is defined as $\pi_t = P_t/P_{t-1} - 1$. In the classical Rotemberg model, the absolute cost function is assumed to be quadratic, $F(\pi) = (\theta_R/2)\pi_t^2$, which implies that the marginal cost of price adjustment $f(\pi) = \theta_R \pi$ is linear in $\pi$.

### 3.2 The sigmoid marginal cost function

For the marginal cost of price adjustment we propose to use a *sigmoid* function, which is defined as a function on the real line with the following properties:

- it is bounded
- it is monotonically increasing
- it is differentiable
- there is exactly one inflection point $x_0$, and $\Sigma(x)$ is convex for $x \leq x_0$ and concave for $x \geq x_0$

We restrict attention to sigmoid functions $\Sigma$ with inflection point $x_0 = 0$ that are symmetric in the sense that $\Sigma(-x) = -\Sigma(x)$, although one could easily allow for non-symmetric cost functions. We write the marginal cost function in general form as

$$f(\pi) = \theta_R \theta_S \, \Sigma\left(\frac{\pi}{\theta_S}\right), \qquad \theta_R \geq 0, \quad \theta_S > 0 \tag{2}$$

where $\Sigma : \Re- > [-1, 1]$ stands for any symmetric sigmoid function normalized such that $\Sigma(0) = 0$, $\Sigma'(0) = 1$ and $\lim_{\pi->\infty} \Sigma(\pi) = 1$. The total cost function is then given by $F(\pi) = \int_0^\pi f(x)dx$. Since

$$f'(\pi) = \theta_R \Sigma'\left(\frac{\pi}{\theta_S}\right) \geq 0 \tag{3}$$

the Rotemberg cost parameter $\theta_R$ determines the derivative of the marginal cost function at the origin. The speed parameter $\theta_S$ determines the speed at which it approaches the upper limit. The product $\theta_R\theta_S$ is the upper limit of the marginal cost function. Symmetry implies $\Sigma''(0) = 0$ and therefore $f''(0) = 0$. Since classical Rotemberg has marginal cost function $\theta_R\pi$, this implies that GRP is equivalent to the classical linear Rotemberg model up to a quadratic approximation at the origin. The model delivers the same dynamics as the classical Calvo and Rotemberg models for sufficiently small shocks. In a perturbation around a zero-inflation steady state, the difference between classical and generalized Rotemberg therefore only appears at order 3 or higher.

To interpret the value of $\theta_S$, notice that it is the inflation level at which the Rotemberg marginal cost equals the upper bound of the generalized Rotemberg marginal cost. Since this depends on the model frequency, it is natural to express $\theta_S$ in annual terms. For example, if the model period is one month, we use the conversion $\theta_S^{ann} \equiv (1 + \theta_S)^{12} - 1$.

The marginal cost function (2) nests four pricing models as special or limit cases. (i) If $\theta_S$ goes to infinity, our model converges to the classical Rotemberg model in the sense that $f'(\pi) \to \theta_R$ for any $\pi$. (ii) If $\theta_R = 0$, it holds that $F(\pi) = f(\pi) = f'(\pi) = 0$ and thus prices are flexible. (iii) If $\theta_R \to \infty$ for any fixed $\theta_S$, total costs of price adjustment go to $\infty$ for any $\pi > 0$, and thus optimal prices are constant in the limit. (iv) If $\theta_S \to 0$ with $\theta_R\theta_S > 0$ fixed, the marginal cost of price adjustment converges to $\theta_R\theta_S$ for every $\pi > 0$ and to $-\theta_R\theta_S$ for every $\pi < 0$. The absolute cost function is linear with a kink at $\pi = 0$.

Prominent examples of normalized sigmoid functions are

$$\Sigma_1(x) = \text{erf}\left(\frac{\sqrt{\bar{\pi}}}{2}x\right), \qquad \bar{\pi} = arccos(-1) \tag{4}$$

$$\Sigma_2(x) = \left(\frac{1 - e^{-2x}}{1 + e^{-2x}}\right) = \tanh(x) \tag{5}$$

$$\Sigma_3(x) = \frac{x}{\sqrt{1 + x^2}} \tag{6}$$

$$\Sigma_4(x) = \frac{2}{\bar{\pi}} \arctan\left(\frac{\bar{\pi}}{2}x\right), \qquad \bar{\pi} = arccos(-1) \tag{7}$$

$$\Sigma_5(x) = \frac{x}{1 + |x|} \tag{8}$$

Here, erf denotes the error function, $\Sigma_2(x)$ is a scaled and shifted version of the logistic function, and $\Sigma_3(x)$ is an algebraic function. Since $\pi$ denotes inflation, as is common in the macroeconomic literature, we write the mathematical constant of the same name in $\Sigma_4(x)$ as $\bar{\pi}$. Functions $\Sigma_1(x)$ to $\Sigma_4(x)$ are all smooth in the sense of infinitely often differentiable, but $\Sigma_5(x)$ is not, it is only once differentiable at the origin. Smoothness is necessary if the solution is to be computed by a perturbation approach.

Any function $\Sigma(x) = 2(F(x) - 0.5)$ with $F$ being the distribution function of a symmetric probability distribution satisfies our definition. Of the examples above, $\Sigma_1$ corresponds to the normal distribution, $\Sigma_2$ to the logistic distribution and $\Sigma_4$ to the Cauchy distribution. Figure 1 graphically illustrates the various sigmoid marginal cost functions and their corresponding absolute cost functions, and compares them to the classic Rotemberg quadratic absolute and linear marginal cost functions. The price changes (in percent) are plotted on the x-axis and the function value is plotted on the y-axis. We set $\theta_S^{ann}$ to 7 percent and normalize the function to an upper bound of 1 by setting $\theta_R = 1/\theta_S$.

Depending on the properties of the corresponding probability distributions, the different sigmoid functions approach the upper bound at different speed. Since the normal distribution has thin tails, $\Sigma_1(x)$ converges quickly to the upper bound. The Cauchy distribution does not have finite moments, so $\Sigma_4(x)$ converges slowly to the upper bound. This is illustrated in Table 1. For example, if a company makes a price change equal to $\theta_S$ and its marginal cost function is based on the arc tan function, then it must pay a marginal cost equal to 63.9 percent of the maximum marginal cost $\theta_S\theta_R$.

Since any convex combination of these sigmoid functions gives again a sigmoid function, one could search the combination of sigmoid functions that fits best the data. However, despite the differences shown in the table, it turns out that the various sigmoid

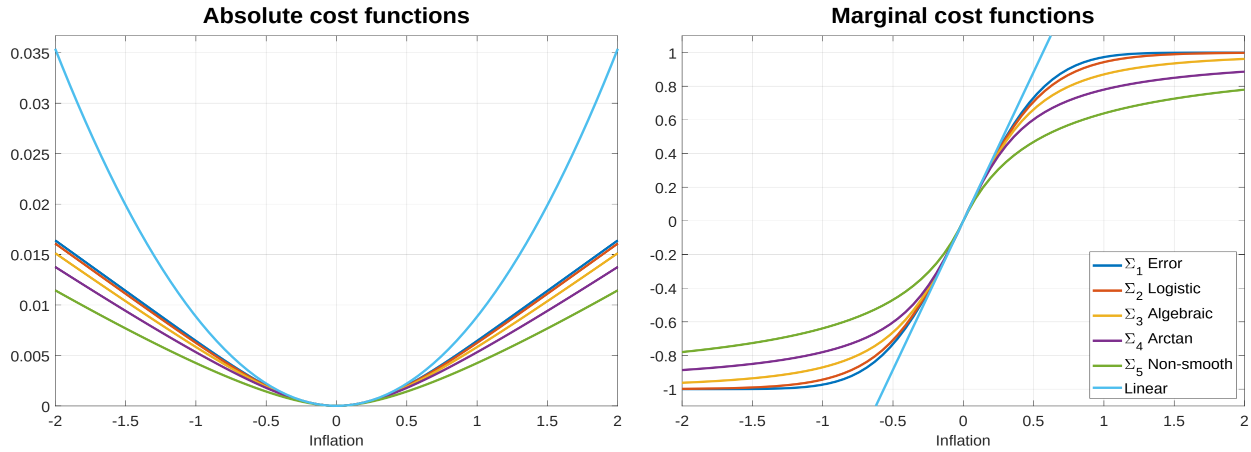


Figure 1: Comparison of various absolute and marginal cost functions

| $\frac{1}{8}\theta_S$ | $\frac{1}{4}\theta_S$ | $\frac{1}{2}\theta_S$ | $\theta_S$ | $2\theta_S$ | $4\theta_S$ | $8\theta_S$ | $16\theta_S$ |
|---|---|---|---|---|---|---|---|
| **Error function $\Sigma_1$** | | | | | | | |
| 12.4 | 24.6 | 46.9 | 79.0 | 98.8 | 100.0 | 100.0 | 100.0 |
| **Logistic function $\Sigma_2$** | | | | | | | |
| 12.4 | 24.5 | 46.2 | 76.2 | 96.4 | 99.9 | 100.0 | 100.0 |
| **Algebraic function $\Sigma_3$** | | | | | | | |
| 12.4 | 24.3 | 44.7 | 70.7 | 89.4 | 97.0 | 99.2 | 99.8 |
| **Arctan function $\Sigma_4$** | | | | | | | |
| 12.3 | 23.8 | 42.4 | 63.9 | 80.4 | 90.0 | 94.9 | 97.5 |
| **Non-smooth function $\Sigma_5$** | | | | | | | |
| 11.1 | 20.0 | 33.3 | 50.0 | 66.7 | 80.0 | 88.9 | 94.1 |

Table 1: Speed of approach to upper bound

functions lead to similar results after recalibration of the parameters. We therefore think that it would be very difficult to empirically identify the best shape of the sigmoid function. For this reason, we did not followe up on this idea. We tend to favor the arctan function, which approaches the bound relatively slowly, as the empirically most plausible approach, since it generates impulse responses that change relatively smoothly with the shock size.

## 3.3 The New Keynesian Phillips curve

To analyze the consequences of GRP, it is useful to derive a version of the New Keynesian Phillips curve. To obtain an exact nonlinear formula, we consider the continuous time limit of our model.[4] We abstract from value added taxes to keep the notation simple. The model is then analogous to Kaplan et al. (2018). Closely following their steps (cf.

[4]The linearized discrete-time Phillips curve has similar properties, but is algebraically more complicated, cf. Appendix C.2.

Appendix C.1 for details), we derive the Phillips curve

$$\left(r - \frac{\dot{Y}}{Y}\right) f(\pi) = \varepsilon\,(m - \bar{m}) + f'(\pi)\dot{\pi}, \qquad \bar{m} \equiv \frac{\varepsilon - 1}{\varepsilon} \tag{9}$$

where $r$ is the real interest rate and $m$ denotes real marginal costs $MC/P$, with $\bar{m}$ defined as flexible price optimum of the latter. $f(\pi)$ are sigmoid marginal costs as defined in Equation (2). Time subscripts are dropped, and the dot denotes time derivatives.

To see that (9) is a nonlinear generalization of Equation (19) in Kaplan et al. (2018), multiply it with $\pi/f(\pi)$ to get

$$\left(r - \frac{\dot{Y}}{Y}\right) \pi = \frac{\pi}{f(\pi)} \varepsilon\,(m - \bar{m}) + \eta^f_\pi \dot{\pi} \tag{10}$$

where $\eta^f_\pi$ denotes the elasticity of $f$ w.r.t. $\pi$. For $\pi \to 0$, GRP converges to the classical Rotemberg case, namely $\frac{\pi}{f} \to 1/\theta_R$ and $\eta^f_\pi \to 1$. This limit conforms to Equation (19) in Kaplan et al. (2018). For $\pi > 0$, the properties of the marginal adjustment cost function $f$ imply that $\frac{\pi}{f(\pi)}$ is increasing in $\pi$, and $\eta^f_\pi$ is decreasing in $\pi$. This means that the weight of the current marginal cost $m$ is increasing compared to the effect of the rise in inflation. Since $f(\pi)$ is bounded, $\frac{\pi}{f(\pi)} \to \infty$ for $\pi \to \infty$, which means that prices follow marginal costs instantaneously.

Notice that $f'(\pi)\dot{\pi}$ is the time derivative of $f$, so that (9) can be used to derive the analogy to Equation (20) in Kaplan et al. (2018):

$$f(\pi)Y_t = \varepsilon \int_t^\infty e^{-\int_t^s r_\tau d\tau} Y_s(m_s - \bar{m})\, ds \tag{11}$$

The marginal cost of price adjustment, $f(\pi)Y_t$, equals the discounted present value of future gains of the price increase, $Y_s(m_s - \bar{m})$, which are positive when $m_s$ is larger than $\bar{m}$. Classical Rotemberg pricing implies that inflation is a linear function of future marginal costs. With GRP, the inverse of marginal adjustment costs $f^{-1}(\pi)$ is a strictly convex function for $\pi > 0$ and a strictly concave function for for $\pi < 0$. Therefore (11) implies that inflation reacts more than linearly to changes in discounted future marginal costs and thus explains the faster pass-through of large shocks.

To study the effect of steady state inflation $\pi^*$, we look at balanced growth paths with $g \equiv \frac{\dot{Y}}{Y}$ and $\dot{\pi} = \pi^*$. We assume that price adjustment costs are a function of total inflation $\pi$, not of $\pi - \pi^*$. Then we get

$$(r - g)\,\pi^* = \frac{\pi^*}{f(\pi^*)} \varepsilon\,(m^* - \bar{m}) \tag{12}$$

$\pi^* = 0$ implies that real marginal costs in steady state equal $m^* = \bar{m}$, since $\frac{\pi}{f(\pi)} \to 1/\theta_R$.

More generally,

$$m^* = \bar{m} + \frac{r-g}{\varepsilon} f(\pi^*) \tag{13}$$

Positive steady state inflation is only possible if real marginal costs $m$ are above the static equilibrium value $\bar{m}$. The required $m$ grows more slowy under GRP than under classical Rotemberg pricing, because $f(\pi) < \theta_R \pi$ for $\pi > 0$. It should be noted that the model only makes economic sense if firm profits are non-negative in steady state, which requires $F(\pi^*) \leq 1 - m^*$. For a given $\theta_R$, this puts a limit on the possible steady state inflation rate (see also Footnote7 below). Since both $F(\pi^*)$ and $m^*$ increase more slowly under GRP, a larger steady state inflation is possible. Nevertheless, it is clear that GRP is not compatible with hyper inflations for any realistic level of $\theta_R$, as long as one sticks with the assumption of increasing marginal price adjustment costs.

As explained in the introduction, it is a robust empirical finding that the slope of the Phillips curve increases in the level of trend inflation. This result is intuitive: firms have to adjust their prices more often anyway in the presence of trend inflation. Moreover, trend inflation provides an argument that firms can use to justify higher price adjustments to their customers, which is a relevant argument in the logic of the Rotemberg model. To derive this result in the GRP model, linearize (9) at the steady state inflation $\pi^*$ and the balanced growth path with $g \equiv \frac{\dot{Y}}{Y}$. After rearranging we get

$$(r-g)\,\tilde{\pi} = \frac{\varepsilon}{f'(\pi^*)}\tilde{m} + \dot{\tilde{\pi}}, \tag{14}$$

where the tilde denotes deviations from steady state. The slope of the Phillips curve equals $\varepsilon/f'(\pi^*)$, which increases in $\pi^*$. Since $f'(\pi^*)$ is not zero any longer, trend inflation affects the dynamics of the model already in a first-order approximation, and the equivalence of GRP and Calvo breaks down even for small shocks. We will show in the next section how (14) can be used for calibrating the speed parameter $\theta_S$.

## 3.4 Calibrating the parameters of the marginal cost function

The marginal cost function (3) has two free parameters, $\theta_R$ and $\theta_S$. Using the equivalence first order equivalence of Rotemberg and Calvo, $\theta_R$ is linked to the Calvo parameter $\theta_C$ by $\theta_R = (\varepsilon - 1)\theta_C/((1-\beta\theta_C)(1-\theta_C))$. Compared to Calvo or Rotemberg pricing, a DSGE model using GRP only has to estimate one additional parameter, $\theta_S$.

An interesting alternative is to calibrate the parameters using additional information from micro data. Alvarez et al. (2016) demonstrate that the cumulative impulse response of the price level to a permanent nominal cost shock in continuous time depends only on the ratio of the kurtosis to the frequency of price changes. Auclert et al. (2024) show that this also holds almost exactly in discrete time. They also show that in a broad class of menu cost models, the first-order dynamics of aggregate inflation in response to arbitrary shocks to aggregate costs are almost the same as in Calvo models. For this, the Calvo parameter must be set as

$$\theta_C = \frac{kurt/freq - 3}{kurt/freq + 3} \tag{15}$$

where kurtosis $kurt$ and frequency $freq$ can be obtained directly from price data, possibly controlling for unobserved heterogeneity and sales (see e.g. Alvarez et al., 2022; Cavallo et al., 2023). Alternatively, $kurt$ and $freq$ can be taken from a menu cost model that has been found to be a good approximation to the true data generating process.

To complete the calibration, information is needed about $\theta_S$. This is more difficult, because it rests on the nonlinear properties of the model. A promising idea is to exploit the relationship between trend inflation and the Phillips curve. For example, Blanco et al. (2024b) find that the slope of the quarterly Phillips curve increases by a factor of five if steady state inflation is 10 percent annually rather than 0 percent. We found in Section 3.3 that the slope of the Phillips curve is given by $\varepsilon/f'(\pi^*)$. Generating the result of Blanco et al. (2024b) in our model requires $f'(0.1) = 0.2f'(0)$ or equivalently $\Sigma'(0.1/\theta_S) = 0.2$. This is satisfied by $\theta_S = 0.0785$ (at an annual rate) in the case of the arctan function. One should not take this result too literally, since the slope of the Phillips curve is model-dependent, and Blanco et al. (2024b) are using a model that is not consistent with the simple model of Section 3.3.

More generally, whenever a pricing model is identified that is successful in matching data at the micro level, the parameters $\theta_R$ and $\theta_S$ can be chosen so as to yield aggregate implications as close as possible to the micro model. In Section 4 we show how to do this in hypothetical menu cost models. In Section 6 we apply it to a model calibrated to Mexican data.

# 4 Generalized Rotemberg pricing versus menu costs

Menu cost models have solid micro-foundations, and have become the workhorse for explaining pricing behavior at the micro level. They also imply strongly nonlinear behavior on the aggregate level. Since in general they give rise to firm heterogeneity that cannot be aggregated analytically, they are difficult to integrate into medium- or large scale macroeconomics models. It would therefore be useful to have a tractable approximation that implies nonlinear aggregate dynamics similar to menu cost models, if properly calibrated. In this section we examine whether GRP satisfies this requirement. The focus is not on whether GRP explains any stylized facts, but to what extent the generalized Rotemberg pricing model is able to replicate the macroeconomic consequences of menu cost pricing, especially under large shocks and potentially non-zero steady state inflation.

## 4.1 The menu cost model

To study the effects of different price setting mechanisms in isolation from general equilibrium effects, we consider an industry under monopolistic competition subject to a sudden permanent increase in marginal costs. The industry is populated by a continuum of ex ante identical firms. Firm $i$ is producing output $y_i$ with labor as the only input:

$$y_{i,t} = \xi_{i,t} L_{i,t} \tag{16}$$

The log of firm-specific productivity $\xi_{i,t}$ follows an AR(1) process $\log \xi_{i,t} = \rho \log \xi_{i,t-1} + \varepsilon_{i,t}$ which is independent across firms. The nominal wage $w_t$ is exogenous to the industry, so that the nominal marginal costs of firm $i$ are given by $w_t/\xi_{i,t}$. Monopolistic competition in the industry implies that firm demand is given by $(p_{i,t}/P_t)^{-\epsilon} Y_t$, where the aggregate price index $P_t$ is given by the Dixit-Stiglitz aggregator $P_t = \left(\int p_{i,t}^{1-\epsilon}\right)^{1/(1-\epsilon)}$. Industry demand $Y_t$ follows $Y_t = P_t^{-\eta}$.

The only endogenous firm-specific state is the nominal price $p_{i,t}$. Changing the price is subject to menu costs $\kappa_{i,t}$ which are potentially stochastic and independent over time and across firms. We treat adjustment costs here as "deliberation costs", affecting the decision of the firm but not costing physical resources or lowering output. Since the model here is in partial equilibrium with exogenous aggregate demand, this does not make a difference for inflation dynamics. Nominal profits are discounted at the constant rate $\beta$, implicitly assuming that the dynamics of this specific industry does not affect the stochastic discount factor of the representative share holder.

In the numerical experiments below, we abstract from aggregate uncertainty and assume that the path of industry wages $w_t$ is known. Industry price level $P_t$ and demand $Y_t$ are determined in a perfect foresight equilibrium. Firm $i$ chooses a state-contingent path of prices $p_{i,t}$ and output $y_{i,t}$ to maximize

$$\mathrm{E} \sum_{t}^{\infty} \beta^t \left[ y_{i,t} \left( p_{i,t} - w_t/\xi_{i,t} \right) - \kappa_{i,t} I \left\{ p_{i,t} \Pi^* - p_{i,t-1} \right\} \right] \tag{17}$$

where $I\{x\}$ is the indicator function with $I\{0\} = 0$ and $I\{x\} = 1$ for $x \neq 0$. If trend inflation is positive, so $\Pi^* > 1$, we define $p_{i,t}$, $P_t$ and $w_t$ as relative to the trend of the price level. In a steady state, industry price $P_t$ and industry wage $w_t$ grow at the aggregate rate of inflation $\Pi^*$. If firm $i$ does not adjust its price, $p_{i,t}$ diminishes at the rate of inflation, and therefore adjustment costs have to be paid if $p_{i,t}\Pi^* \neq p_{i,t-1}$.

## 4.2 Industry model with Rotemberg pricing

The industry model with Rotemberg pricing can be summarized in the following three equations:

$$P_t = P_{t-1}\frac{\Pi_t}{\Pi^*} \tag{18}$$

$$Y_t = P_t^{-\eta} \tag{19}$$

$$(1-\epsilon) + \epsilon\frac{w_t}{P_t} = \theta_R \Sigma\left(\pi_t/\theta_S\right)\Pi_t - \beta^{-1}\frac{Y_{t+1}}{Y_t}\theta_R\Sigma\left(\pi_{t+1}/\theta_S\right)\Pi_{t+1}, \qquad \pi_t \equiv \Pi_t - 1 \tag{20}$$

Equations (18) and (19) express the fact that $P_t$ is defined relative to the trend price level, and this is what industry demand depends on. Equation (20) is the first order condition for price setting, equivalent to (1), where $\Sigma(.)$ is one of the sigmoid functions presented in Section 3.2. Notice that marginal adjustment costs are a function of absolute inflation $\Pi$, not relative to trend $\Pi^*$.

## 4.3 Functional forms and parameters

For the numerical experiments, we take most parameter values from Costain and Nakov (2019). Autocorrelation of firm productivity is set to $\rho = 0.95$ at monthly frequency, and the variance of the shock process $\varepsilon$ is set to $0.06^2(1-\rho^2)$ so that the unconditional standard deviation of $\log\xi$ equals 0.06. The cost parameter $\bar{\kappa}$ is set in all three cases such that the frequency of price adjustment in the stationary state equals 10.2 percent per month.

For the stochastic price adjustment cost, we consider several distribution functions:

1. **LogN(0.01):** Log-normal distribution with parameters $\sigma = 0.01$ and mean $\mu$ being calibrated to yield 10.2 percent frequency of price adjustment. With $\sigma$ being very low, this is a slightly smoothed version of a fixed menu cost.

2. **LogN(1.0):** Log-normal distributed with parameters $\sigma = 1.0$ and mean $\mu$ being calibrated to yield 10.2 percent frequency of price adjustment.

3. **LogN(1.0), freq=5.1:** Log-normal distributed with parameters $\sigma = 1.0$ and mean $\mu$ being calibrated to yield 5.1 percent frequency of price adjustment.

4. **LogN(3.0):** Log-normal distributed with parameters $\sigma = 3.0$ and mean $\mu$ being calibrated to yield 10.2 percent frequency of price adjustment. The cost distribution is widely dispersed, a significant fraction of firms faces prohibitive adjustment costs, similar to a Calvo model.

5. **Uniform:** The menu cost is zero with probability $\lambda = 0.051$, and uniformly distributed on the interval $[0, \bar{\mu}]$ with probability $1-\lambda$, where again $\mu$ is calibrated to

yield 10.2 percent frequency of price adjustment.

These distributions are illustrated in Fig. 2.

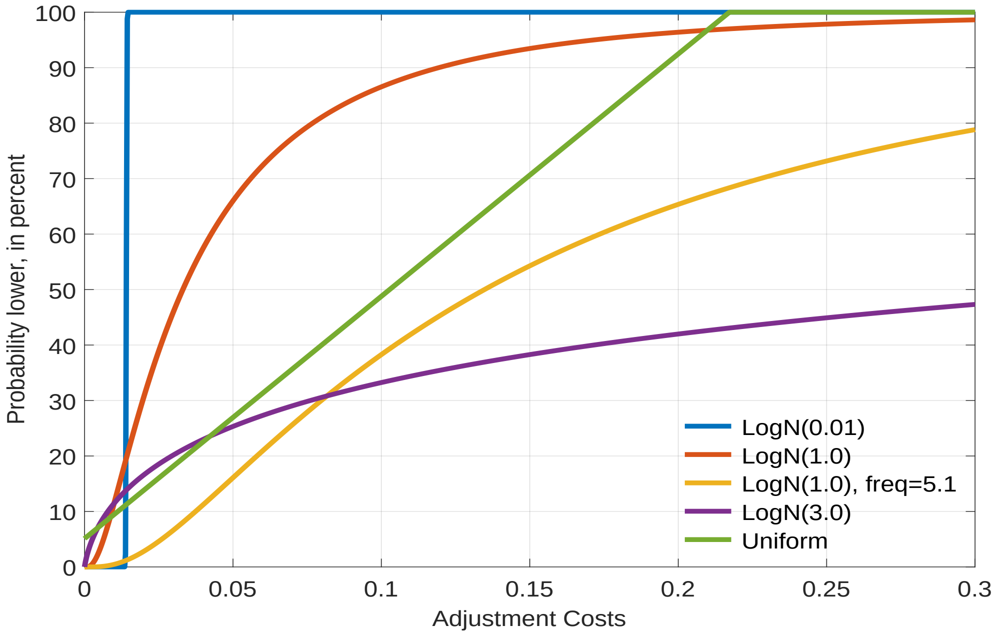


Figure 2: Menu Cost Distributions

## 4.4 Approximating menu costs with Rotemberg pricing

In the numerical exercise we investigate to what extent the generalized Rotemberg model can mimic the behavior of the menu cost model with respect to the aggregate consequences of a one-time permanent shock to the nominal wage, which is a shock to the nominal marginal cost of each firm in either model. We assume the economy starts out in the stationary state. If there is positive trend inflation, it is understood that nominal price and nominal wage increase with trend inflation in the absence of a shock. Then an unexpected shock hits in period 0 which increases the nominal wage permanently by $x$ percent, where $x$ varies between 1 and 20 percent. We solve for the perfect foresight equilibrium path of $P$ after the shock. In the long run, the industry price also increases by $x$ percent, both in the menu cost and the Rotemberg model. The question is the speed of this adjustment.

Figure 3 shows impulse responses of annualized inflation for different shock sizes ranging from 1 percent to 20 percent. Impulse responses are scaled by the size of the shock, so that they are comparable to the response of a 1 percent shock. In the zero-inflation stationary state, responses to negative shocks are roughly symmetric and therefore not shown here. Rows 1–5 in the graph refer to the five parameterizations of the menu cost distributions as described in Section 4.3. The left column shows the impulse responses

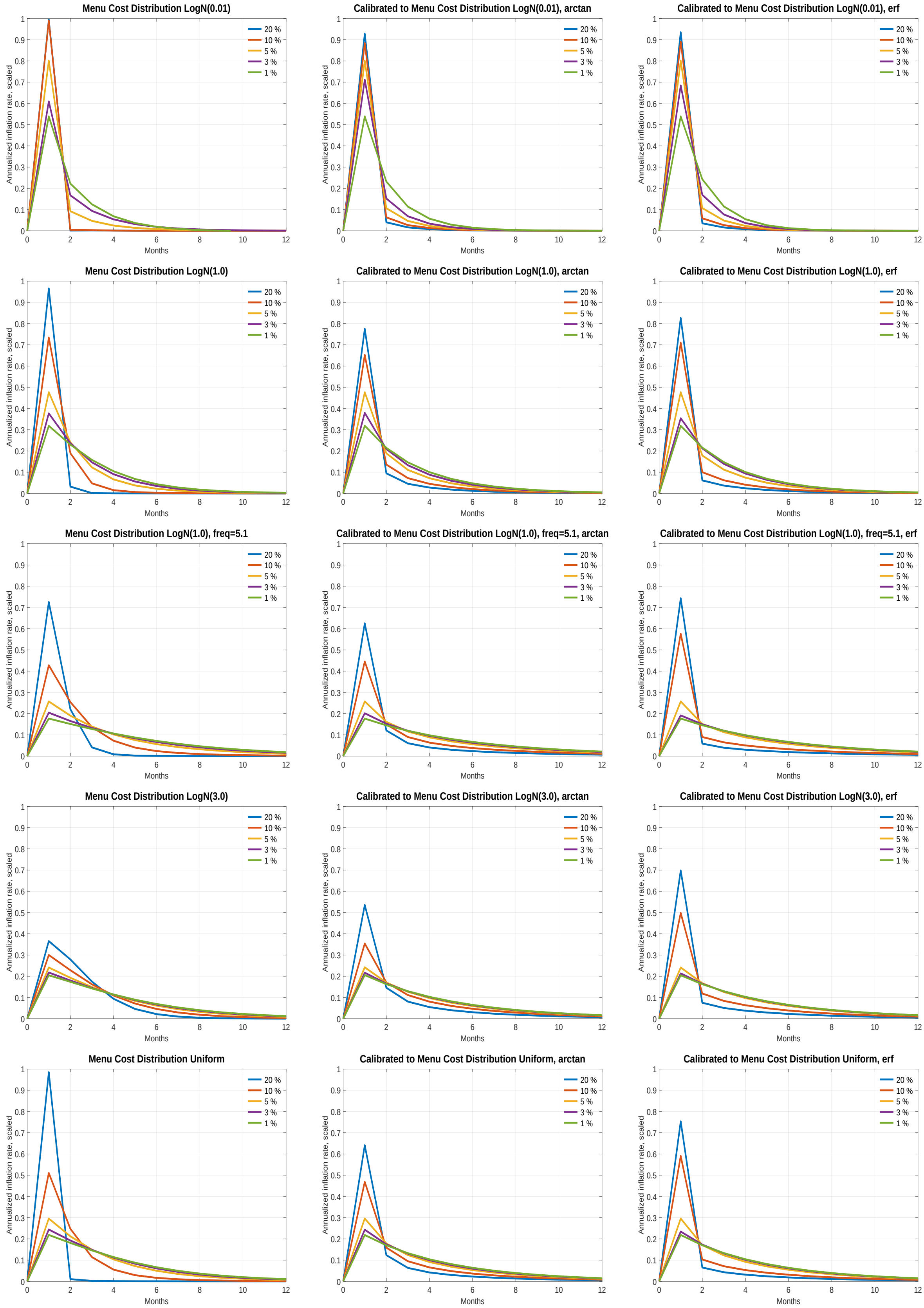


Figure 3: Impulse responses to marginal cost shocks, zero trend inflation

of the menu cost model, the middle column those of the calibrated Rotemberg model using the arctan function, the right column those of the Rotemberg model using the erf function. The functions arctan and erf are the two extreme cases among the smooth sigmoid functions shown in Section 3.2.

In all cases, the Rotemberg model was calibrated so as to perfectly match the one-percent and five-percent impulse responses of the menu cost model on impact, but the other impulse responses were not targeted. The following main conclusions arise. First, the Rotemberg model captures very well the qualitative feature that larger shocks lead to faster adjustment to the new equilibrium level, in other words, a higher pass-through of the shock. The models differ in how smoothly the pass-through increases with the shock size. In the menu cost model with uniform adjustment costs, and more so with narrowly concentrated lognormal costs, the pass-through goes up to almost 100 percent very quickly for shocks of 10 percent or more. On the opposite side, very widely dispersed lognormal costs show a rather small increase of the pass-through, getting closer in this respect to a Calvo model. Because of the smoothness of the marginal adjustment costs, the impulse responses in the Rotemberg model move relatively smoothly with the shock size, more so with the arctan function than with the error function. The Rotemberg models come closest to menu cost models with lognormal costs of moderate dispersion (the case LogN(1.0)). Only having two free parameters, it is clear that the different calibrations of the Rotemberg model cannot exactly replicate the various results of the menu cost models.

Table 2 displays the parameter values of the different calibrations of the Rotemberg models. While the menu cost models were calibrated to obtain an average frequency of price adjustment of 0.102 percent monthly, which conforms to a $\theta_C = 0.898$, the calibrated $\theta_C$ is consideraly lower in all cases. This reflects the fact that a menu cost model implies much higher price flexibility than a Calvo model with the same adjustment frequency, because the endogenous selection of firms who adjust. Even when the menu cost model is calibrated to 0.0051 percent monthly, $\theta_C$ is still below 0.898. The case of the wide lognormal distribution is closest to Calvo, which shows in a relatively high value of $\theta_C$. The $\theta_C$'s do not vary much between different sigmoid functions. The speed parameter

| Model | $\theta_C$, monthly | | | | $\theta_S^{ann}$,in percent | | | |
|---|---|---|---|---|---|---|---|---|
| | Atan | Algebr | Logist | Erf | Atan | Algebr | Logist | Erf |
| LogN(0.01) | 0.508 | 0.493 | 0.483 | 0.477 | 11.8 | 11.9 | 12.2 | 12.6 |
| LogN(1.0) | 0.690 | 0.688 | 0.687 | 0.686 | 17.2 | 15.2 | 14.2 | 14.1 |
| LogN(1.0),freq=5.1 | 0.828 | 0.827 | 0.828 | 0.827 | 12.0 | 10.4 | 9.4 | 9.2 |
| LogN(3.0) | 0.798 | 0.799 | 0.798 | 0.798 | 21.5 | 17.0 | 14.8 | 13.7 |
| Uniform | 0.786 | 0.785 | 0.785 | 0.785 | 16.3 | 13.8 | 12.3 | 11.8 |

Table 2: Calibrated parameters in Rotemberg model

$\theta_S^{ann}$ gives an idea of the curvature of the marginal adjustment cost function. It varies across calibrations between 10 and 20 percent, which means that the classical Rotemberg function would hit the upper bound of the cost function at an annualize inflation rate of 10 to 20 percent. In this range, the cost function becomes essentially flat, so that there is almost no inflation smoothing incentive left.

### 4.5 Variations in trend inflation

In our next experiment, we consider exactly the same models, but now assume a trend inflation rate of about 3 percent annually (the exact number was chosen so as to conform to a integer number of steps in the price grid of the firms). The industry nominal wage follows the same trend. For both models, we use the same calibration as in the zero-inflation steady state, no re-calibration.

Alexandrov (2022) shows theoretically that the response of inflation to shocks is asymmetric in menu cost models under positive trend inflation, and provides empirical evidence for this effect with US industry data. This result is intuitive: with 3 percent trend inflation, a positive shock of 3 percent requires a 6 percent change in nominal prices over the course of a year; while total adjustment costs are high, marginal adjustment are relatively flat in this region. Conversely, a negative shock of 3 percent now requires no change in nominal prices after a year, but since the shock is immediate, and inflation accumulates gradually to 3 percent, there is still some adjustment necessary during the year. While total adjustment costs are small, the cost function is very convex at this point, providing strong incentives to smooth adjustment over time. Comparing the economy with positive trend inflation to the case of zero trend inflation, we can therefore expect that firms react more strongly on impact to a positive shock, less strongly to a negative shock.

| Model | ShockSize | Menu | Atan | Algebr | Logist | Erf |
|---|---|---|---|---|---|---|
| LogN(0.01) | 3 | 9.5 | 5.9 | 6.2 | 6.7 | 7.0 |
| | -3 | -8.2 | -6.9 | -6.7 | -6.7 | -6.9 |
| LogN(1.0) | 3 | 4.3 | 5.6 | 5.6 | 5.4 | 5.1 |
| | -3 | -3.7 | -4.9 | -4.4 | -3.8 | -3.3 |
| LogN(1.0),freq=5.1 | 3 | 4.0 | 5.2 | 5.3 | 5.3 | 5.1 |
| | -3 | -3.1 | -3.0 | -2.6 | -2.2 | -1.9 |
| LogN(3.0) | 3 | 2.1 | 2.2 | 2.3 | 2.2 | 2.2 |
| | -3 | -2.3 | -1.5 | -1.4 | -1.3 | -1.2 |
| Uniform | 3 | 3.2 | 4.0 | 4.0 | 3.9 | 3.8 |
| | -3 | -2.6 | -2.7 | -2.5 | -2.2 | -1.9 |

Table 3: Comparison trend inflation 3 percent

Table 3 shows this comparison for positive and negative shocks of 3 percent, comparing the menu cost model under different distributions of the adjustment costs to the generalized Rotemberg model. Again, the response is scaled by the size of the shock and expressed in percent (i.e., multiplied by 100). For example, the number 5.9 for the Rotemberg model with atan function means that the impact response is higher by 5.9 percent of 3 percent (the shock size). With negative shocks, a negative number means that the response is less negative under trend inflation. The stated hypothesis above is fulfilled in all cases.[5] The different sigmoid functions lead to somewhat different impulse responses, but there is no clear pattern with respect to what function leads to results closer to the menu cost model. Moreover, the Rotemberg model gives quantitatively similar predictions as the Menu cost models. This is remarkable given that both models use the same parameters as in the zero trend inflation case.

# 5 Explaining the Stylized Facts

As described in the introduction, three stylized facts stand out which the Calvo and classical Rotemberg models do not explain. First, the pass-through of large shocks is faster than of small shocks. Second, the higher the trend inflation, the steeper the slope of the New Keynesian Phillips curve, and thus the smaller the real impact of nominal shocks. Third, VAT changes are largely passed through at implementation, with little announcement effects.[6]

## 5.1 A basic DSGE model

Following much of the literature, we embed the price setting model into a standard DSGE framework, which is described in more detail in Appendix B.

**Households** maximize discounted expected lifetime utility with current utility function $C_t^{1-\sigma}/(1-\sigma) - \chi N_t$, where $C$ denotes the consumption bundle and $N$ is household labor supply. Their period budget constraint, expressed in terms of the consumption good, is given by

$$m_t + \frac{b_t}{R_t} = w_t N_t + \frac{m_{t-1} - C_{t-1} + b_{t-1}}{1+\pi_t} + T_t,$$

where $m_t$ are real money balances of the household, $b_t$ denotes bond holdings, $R_t$ is the nominal interest rate and $w_t$ is the real wage. They receive the lump-sum transfer $T_t$, which includes the central bank's seignorage profit, the government's VAT revenue

[5] For small shock sizes of $\pm 1$ percent (results not shown here), some of the menu cost models appear to have the opposite sign than what is expected. Since the effects are quantitatively very small, this discrepancy may be due to the discrete approximations of the menu cost.

[6] It is an established empirical finding that monetary policy shocks have delayed and persistent effects on inflation and output (cf. Friedman and Schwartz (1963), Romer and Romer (1989) and Christiano et al. (1999), among many others). Dotsey and King (2005) have shown that such dynamics can occur in a menu cost model with state-dependent pricing, but not in Calvo or Rotemberg pricing models. The problem applies to GRP as well, as it is equivalent to Calvo and Rotemberg for small inflation rates. However, the literature has taken a different path, starting with Christiano et al. (2005), explaining these dynamic features by other model components or rigidities, such as wage rigidities and variable capital utilisation.

$T_t^{VAT} = \tau_t/(1+\tau_t)Y_t$ and corporate profits. Unless stated otherwise, we assume in model variants with Rotemberg pricing that the household is reimbursed for price adjustment costs $F(\pi_t)\,Y_t$, but our results do not depend on this assumption.[7] Monetary policy has real effects because households are subject to the cash-in-advance constraint $C_t = m_t$.

**Firms**' production function has constant returns to scale, using labor $N_t$ as the only input, with exogenous labor productivity $z_t$. Real marginal costs are given by $mc_t = \frac{s_t}{z_t} w_t$, where $s_t$ is a price dispersion factor which equals 1 in the Rotemberg model, but is generally larger than 1 in the Calvo model.

**Monetary policy** sets real money balances according to

$$\frac{m_t}{m_{t-1}} = \frac{\mu e^{u_{m,t}}}{1+\pi_t}, \tag{21}$$

where $\mu$ is the steady state growth rate of money supply, and $u_{m,t}$ is an AR(1) process with autocorrelation $\phi_m$. The central bank's seignorage revenue $T_t^m = m_t - \frac{m_{t-1}}{1+\pi_t}$ is reimbursed to households.

**Parameter values**. The model period is one month, in line with the menu cost literature. The discount factor $\beta$ is set to $1.04^{-1/12}$, the steady state growth rate of the money supply equals $\mu = 1.00$, unless stated otherwise. The elasticity of substitution in consumption, $\varepsilon$, is set to 7 in accordance with Costain and Nakov (2019). We follow Nakamura and Steinsson (2010) in setting the intertemporal elasticity of consumption to $\sigma = 1$, and the inverse of the Frisch elasticity of labor supply to 0. The latter is common in the menu cost literature. Karadi and Reiff (2019) justify this assumption, for example, by the resulting complete long-term pass-through of VAT shocks in line with empirical evidence. The steady state VAT $\tau$ is set to zero and the parameter $\chi$ only scales output and is irrelevant for our purposes.

## 5.2 Large versus small shocks

Figure 4 compares the impulse responses after productivity shocks of the generalized Rotemberg model with different calibrations to those of the Calvo model. The Rotemberg parameter $\theta_R$ of the generalized Rotemberg model is always calibrated such that the model is equivalent to the Calvo model to a first order approximation (see section 3.4). The figures then show impulse responses for different speed parameters. When the speed parameter $\theta_S^{ann}$ is set to 20 percent (or, in monthly terms, $\theta_S$ is set to 1.53 percent),

[7] The problem is that price adjustment costs can occasionally be very high, especially in the case of quadratic price adjustment costs. Eggertsson and Singh (2019) show that the Rotemberg model therefore cannot generate the Great Depression, because a 10 percent deflation, as observed in the Great Depression, would absorb over 100 percent of output. See also the discussion in Eggertsson and Singh (2019) on the consequences for the slope of the AS and AD equations and the interpretation of price adjustment costs. Already Ascari and Rossi (2012) have suggested a similar interpretation of price adjustment costs not as real resource costs, as this improves the empirical performance of the Rotemberg model in the presence of trend inflation.

the model, at least for the cases considered here, is almost equivalent to the classical Rotemberg and Calvo models. The lower the speed parameter and the larger the shock or the larger the trend inflation, the more the generalized Rotemberg model deviates from the classical Rotemberg and Calvo model.

The first two rows of figure 4 compare the impulse responses of the generalized Rotemberg model using different calibrations with those of the Calvo model for large versus small shocks. The impulse responses of inflation and consumption (second and third columns of the figure) are each divided by the size of the shock. The productivity shock has a persistence of 0.95. The first row shows the impulse responses following a small negative productivity shock of 0.5 percent. It can be seen that all model calibrations produce almost the same impulse responses as the Calvo model. The pass-through is about 7 percent in the first period. The Calvo parameter is $\theta_C = 0.8980$, which means that only 10.2 percent of the firms can adjust their prices immediately.However, firms do not fully pass through the shock because in the Calvo case they do not know exactly when they can make the next adjustment, so they may have too high prices in the future when the shock has faded out. In the Rotemberg model, firms adjust their prices slowly because small price adjustments have low marginal costs. In both cases, therefore, consumers have to reduce their consumption only gradually because of the slow pace of price increases.

The second row of the figure shows the impulse responses to a large, negative productivity shock of 5 percent. Clear differences between the model calibrations can now be observed. While the Calvo model and the generalized Rotemberg model with $\theta_S^{ann} = 20\%$ show only little difference to the first line, i.e. the pass-through increases at about 11 percent, the variants with speed parameter of 7% or less show considerably larger pass-throughs in the first shock period. Consumers must then also reduce their consumption at a faster rate. The sharp rise in inflation is only short-term and the model variants with a faster pass-through at the beginning show slightly lower inflation rates in later months, as prices are already closer to the flexible price optimum.

## 5.3 Impulse Respones under Different Levels of Trend Inflation

In Section 3.3 we derived an analytical relationship between trend inflation and the slope of the Phillips curve in a continuous time model. The third and fourth rows of Figure 4 show impulse responses for small negative productivity shocks of -0.5 %, for levels of trend inflation of 2 % or 4 %. We restrict ourselves here to the case of low trend inflation, as they are typical for developed countries. Low trend inflation allows us to compare the results with the Calvo model.[8] We will consider high trend inflation rates in Section 6.

[8] Ascari (2004) shows that in the Calvo model, only low trend inflation rates are compatible with a steady state. And even with trend inflation sufficiently low for a steady state, complex roots and the resulting oscillating behavior can occur.

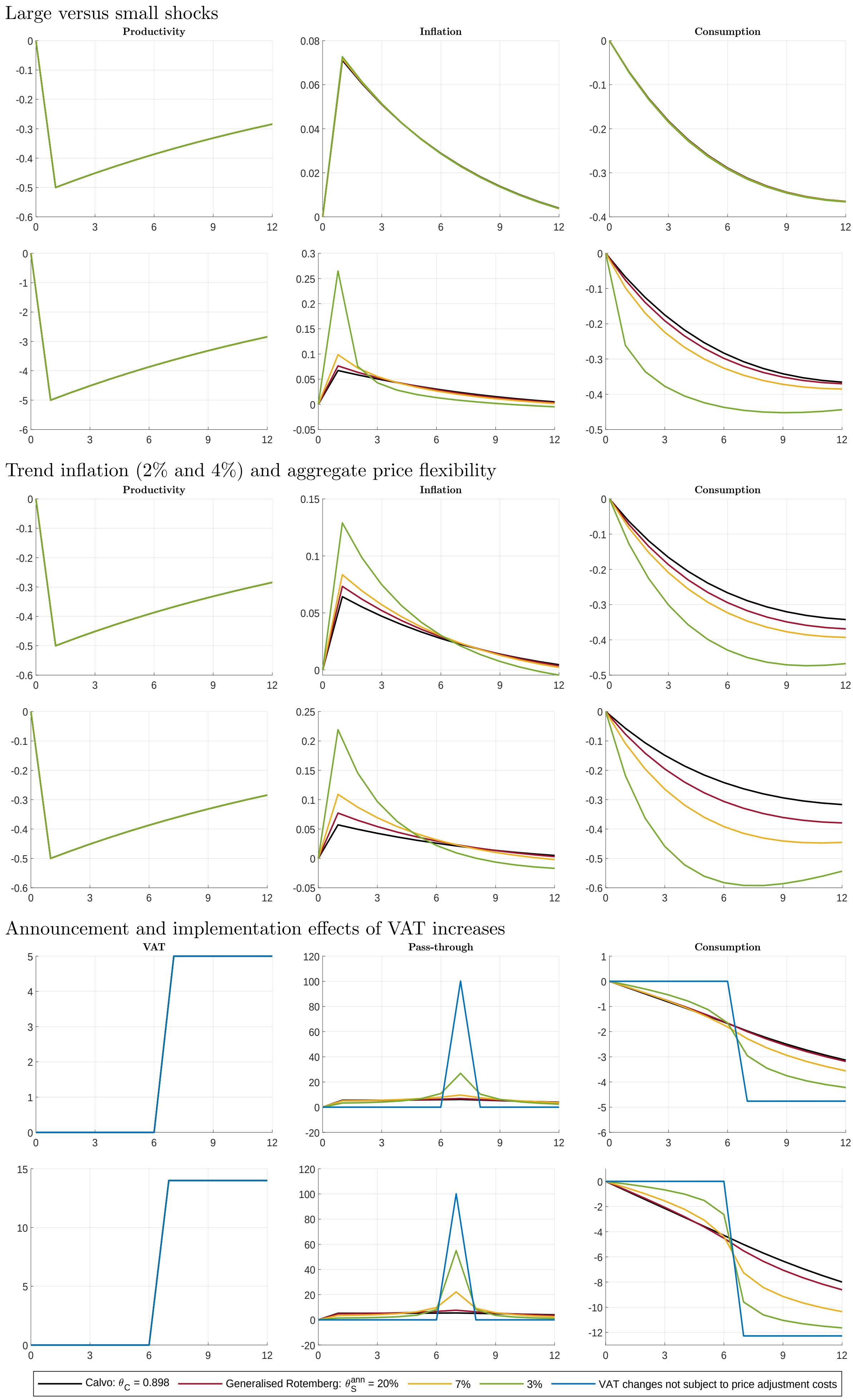


Figure 4: Generalized Rotemberg and the stylized facts of price setting

The third row of figure 4 shows impulse responses for 2 percent trend inflation, the fourth row shows impulse responses for 4 percent trend inflation, and the first row of the figure shows the same shock assuming zero trend inflation. As before, all impulse responses are divided by the shock size. It turns out that trend inflation has little effect on the impulse responses of the Calvo model. In the GRP model, it depends on the speed parameter: the lower it is, the greater the impact of trend inflation on the impulse responses. Thus, with a low speed parameter, even low trend inflation can significantly steepen the NKPK and thus increase aggregate price flexibility. The higher the trend inflation, the greater the effect on aggregate price flexibility in the generalized Rotemberg model, but the differences between zero and 2 % are larger than the differences between 2 % and 4 % trend inflation. This is in line with discussion of the slope of the NCPK above.The first result, i.e. the lack of an effect of trend inflation on the impulse responses of the Calvo model, seems to contradict the results of the literature. Ascari and Rossi (2012) find that in the Calvo model the responses of output and inflation become stronger and more persistent when trend inflation increases, even for a first-order Taylor approximation of the model. Moreover, they report a strong effect on output directly in the first period, which then slowly fades out in the following periods. In contrast, we report a hump-shaped impulse response for consumption, which is equal to output in our model. The difference is that, in contrast to Ascari and Rossi (2012), we consider a money supply growth rule. Using their Taylor rule, we arrive at similar results as they do; The corresponding impulse responses are shown in Fig E.7 in the appendix. At this point it should only be emphasized that our main result reported here, that in the generalized Rotemberg model with trend inflation price flexibility increases with lower speed parameters, remains the same. By selecting the speed parameter, one can then obtain a similar or even larger effect of the technology shock than in the Calvo model. However, relative to the effect on impact, the Calvo model always generates a greater persistence of this effect.

### 5.4 VAT pass-through

Several studies have recently been published on the pass-through of VAT changes to prices. The authors have come across some clear contradictions to current economic theory. For example, Benzarti et al. (2020) document an asymmetric pass-through, i.e. negative VAT changes are only passed through half as much as positive changes, which can hardly be explained by trend inflation alone.[9] In addition, they show a very persistent effect of VAT changes that cannot be explained by adjustment costs. They also show large sectoral and firm-specific differences, with their estimated pass-throughs being relatively

[9] It has been known since Ball and Mankiw (1994) that positive trend inflation can explain an asymmetric pass-through, at least to a certain extent and in the short term.

low between 29 and 55 percent for VAT increases, and only half as high for decreases. In contrast, Karadi and Reiff (2019) report pass-throughs of 33 percent for VAT reductions and 74 to 99 percent for VAT increases. They explain this with a menu-cost model that features trend inflation and fat-tailed product-level shocks. However, this model predicts high price flexibility with respect to monetary policy shocks, so they report doubts about the ability of menu cost models to explain the price rigidities supported by time-series evidence. Benedek et al. (2020) document large differences in the pass-through of VAT shocks, estimating the total pass-through to be only about 25 percent when all VAT changes are treated equally. On closer analysis, they come to the conclusion for the standard rate VAT that even full pass-through cannot be ruled out, while for the reduced rates, for example, there is only a pass-through of about 30 percent. They find no evidence of asymmetric pass-through.

Our aim here is not to resolve the major discrepancies in empirical estimates or to resolve the inconsistencies with existing models, but rather to show that generalized Rotemberg pricing provides a flexible, yet simple and unified framework to study macroeconomic consequences of VAT changes. Notice that one can generate a very high pass-through directly in the implementation period by assuming that price adjustments in the Calvo or Rotemberg models do not refer to after tax prices, but to before tax prices, so that passing on VAT changes does not imply any costs. Alternatively, the modeler can assume that firms have to bear the full adjustment costs for VAT changes, as for all other price changes. As Karadi and Reiff (2019) document, and is confirmed in the results for the Calvo model below, this implies a low pass-through in the implementation period and comparatively large anticipatory and follow-up effects. The literature cited above largely agrees that there is little evidence of price adjustments in the run-up to a VAT change, i.e. after announcement but before implementation, that a large part of the pass-through occurs immediately upon implementation, and that almost all price changes are completed after a few months.

Figure 4 shows simulation results for 5 percent VAT increases (fifth row) and 14 percent VAT increases (sixth row) announced 6 months before implementation. The order of magnitude corresponds to that examined in the literature, e.g. 14 percent VAT changes in the Finnish hairdressing industry were examined by Benzarti et al. (2020), 5 percent changes were examined by Karadi and Reiff (2019). As can be seen in the second column, the pass-through, defined as $(\pi_t - \pi)/|\Delta \text{VAT}|$, is always below 100 percent during the implementation period. This is because the model predicts that part of the incidence of the tax will be borne by producers, they will reduce their producer prices somewhat and therefore the total pass-through remains below 100 percent. The column also shows that the generalized Rotemberg model implies a pass-through immediately after implementation that, depending on the speed parameter, lies between the low pass-through implied by the Calvo model and the high pass-through implied by a model in which VAT changes do not cause price adjustment costs. This has significant effects on consumption, as the third column shows. While consumption in the Calvo model evolves very smoothly over time, so that the implementation period is not recognizable as such, a model in which VAT changes do not cause price adjustment costs leads to a sudden change when the VAT change is implemented. Consumption in the generalized Rotemberg model falls between the two extremes.

### 5.5 Solving Generalized Rotemberg models by perturbation methods

The impulse responses presented in this section so far have been obtained using Dynare's perfect foresight solver. For stochastic simulations, the most widely used solution method is perturbation around the steady state. Since the generalized Rotemberg pricing implies strong nonlinearities, we want to investigate how well those are captured by perturbation solutions. In Figure 5 we compare the impulse responses after a negative productivity shock; the top row shows a large negative productivity shock of -5 % and zero trend inflation, while the bottom row shows a small productivity shock of -0.5 % with trend inflation of 4 %. In order to make the impulse responses obtained by perturbation comparable to the perfect foresight case, we compute the perturbation under the assumption of zero shock variance, to eliminate precautionary behavior of firms. Under these assumptions, the perturbation solution is an approximation of the perfect foresight solution.

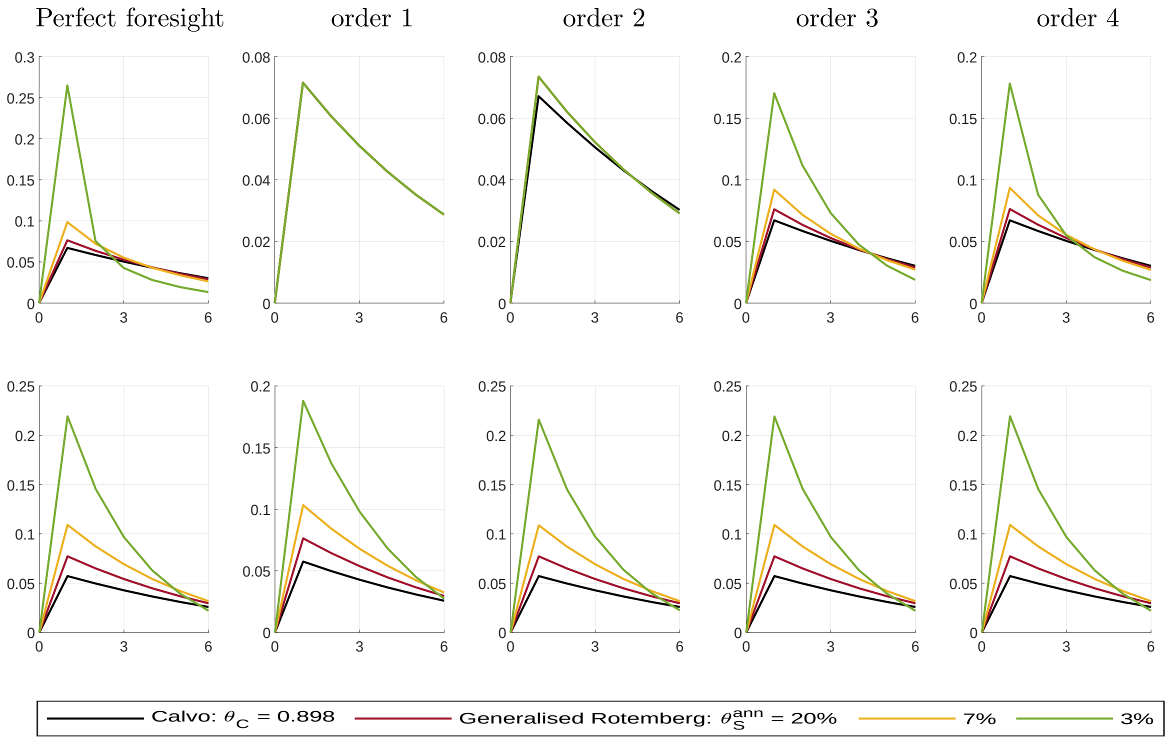


Figure 5: Perfect foresight versus perturbation solutions

The first column of Figure 5 shows the previously presented impulse response using the perfect foresight solution. In both cases, the lower $\theta_S$, the more abrupt the inflation response. The second column shows the results obtained by first order perturbations. In the case of the large shock, the results for the different model variants do not differ; the curves lie exactly on top of each other. The Rotemberg and Calvo models are exactly equivalent here, and the different calibrations of the Rotemberg model are lost due to the approximation. On the other hand, non-zero trend inflation leads to different results even when a first order perturbation is used. The reason for this has already been explained in section 3.3 for the continuous time case, but it also holds in discrete time (see Appendix C.2): Trend inflation affects the parameter of the New Keynesian Phillips curve.

For the large shock, the second-order perturbation leads to almost the same result as the first-order perturbation, although there are slight differences between the Rotemberg and Calvo models. Only from the third-order perturbation onwards are there clear differences, with the response of inflation and consumption being smoothed over time to a much greater extent than in the perfect foresight solution. The fourth-order perturbation provides impulse responses that are close in shape to the perfect foresight solution, but are quantitatively still too small. In contrast, the impulse responses after a small shock and 4 % trend inflation are quantitatively almost indistinguishable from the perfect foresight results already using a second order perturbation.

# 6 High Levels of Trend Inflation

In this section, we use Rotemberg pricing to reproduce a result from Costain and Nakov (2019), who show how price flexibility increases with higher trend inflation. This case is interesting because it considers very high trend inflation of up to 80 percent, which is the range actually observed in Mexico. Costain and Nakov offer a new theoretical perspective by modeling price rigidity as the result of costly, error-prone decision making, rather than of price adjustment costs. Apart from price setting, their model framework is very similar to ours, so that a comparison requires only a few adjustments. In the following we want to investigate whether our generalized Rotemberg model is able to deliver similar results at the aggregate level to Costain and Nakov's comparatively complex model for both low and very high rates of trend inflation.

To adapt our model framework to Costain and Nakov (2019), we replace the cash-in-advance constraint and determine liquidity demand by including money in the utility function. Households then maximize

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[ \frac{C_t^{1-\sigma}}{1-\sigma} - \chi N_t + \nu \ln \left( \frac{M_t}{P_t} \right) \right],$$

subject to

$$C_t + m_t + \frac{b_t}{R_t} = w_t N_t + \frac{m_{t-1} + b_{t-1}}{1+\pi_t} + T_t.$$

The only difference to our previous model is that we replace the cash-in-advance constraint with the following first-order condition for money demand:

$$\frac{\nu}{m_t} = 1 - \frac{1}{R_t} \tag{22}$$

We set $\nu = 1$, $\sigma = 2$ and $\chi = 6$ as in Costain and Nakov (2019).

Figure 6 displays impulse responses of inflation and consumption after a 1 percentage point money supply growth shock with a persistence of $\rho_{u_m} = 0.8$, for different trend inflation rates of 0 to 80 percent. The first row shows the results of Costain and Nakov (2019), exactly replicated with their model. It can be seen that the higher the trend inflation, the stronger the response of inflation and the weaker the response of consumption.

For the results in the second line of the figure, we set our parameters $\theta_R$ and $\theta_S$ such that the mean square deviation between our inflation impulse responses and those of Costain and Nakov (2019) in the first 12 months after the shock is minimised. This results in $\theta_S^{ann} = 0.227$ and $\theta_R = 107$, which conforms to $\theta_C = 0.7907$ monthly. The model matches the impact response very well, i.e. just over 1 percentage point increase in inflation at zero or 2 percent trend inflation and over 3 percentage points at 80 percent trend inflation. However, the Costain and Nakov (2019) model generates less persistence at high inflation, with inflation even becoming slightly negative after 5 months. The generalized Rotemberg model, on the other hand, shows a very smooth impulse response. The two models are also close to each other for consumption, although the differences between consumption at high versus low trend inflation are somewhat smaller in the generalized Rotemberg Model.

Alternatively, we can parameterize $\theta_R$ similarly as in the previous section in accordance with the frequency of price adjustments, i.e. in accordance with $\theta_C = 0.898$ and optimize only $\theta_S$. This results in $\theta_R = 503$ and $\theta_S^{ann} = 0.0796$. In comparison to the GRP version, where both parameters are optimized, $\theta_R$ is fixed significantly higher here, making the prices more sticky. In order to achieve a good fit despite this, the optimized $\theta_S^{ann}$ is now significantly lower. The impulse responses of the GRP model are then somewhat further away from those of Costain and Nakov (2019), especially at low inflation rates of 0 and 2 percent, the money supply shock now has too weak an effect on inflation.

The success of GRP becomes clearer if we compare it to other models. The fourth row shows the classical Rotemberg model, but the parameter $\theta_R$ is calibrated using impulse response matching, just as described above for the generalized Rotemberg model. The result is that $\theta_R$ is set very small, which implies high price flexibility, and the impulse response lies roughly in the middle of the impulse responses of Costain and Nakov (2019).

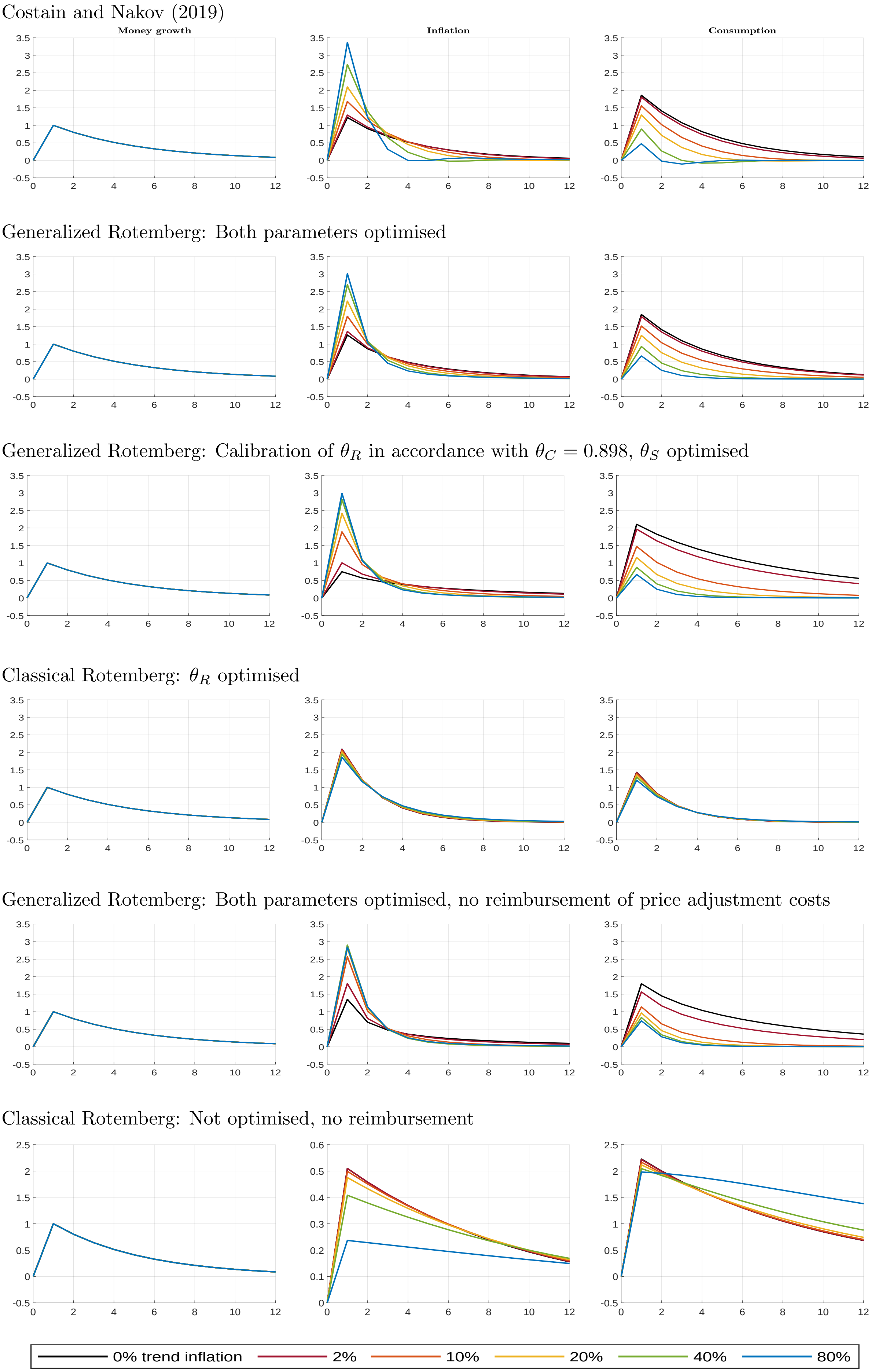


Figure 6: IR to 1 percent money supply shocking, different levels of trend inflation

However, as can also be seen in the figure, in the classical Rotemberg model, trend inflation has almost no effect on the impulse responses. The last two lines then show a similar exercise as in lines 2 and 3, only this time under the assumption that price adjustment costs are real resource costs and thus appear in the market clearing equation. This implies negative corporate profits for high trend inflation. Moreover, in the last line we set $\theta_R = 503$, in accordance with $\theta_C = 0.898$, thus we do not optimise the classical Rotemberg parameter. The impulse responses of the classic Rotemberg model now show the opposite relationship between price flexibility and trend inflation. Higher trend inflation accordingly leads to lower price flexibility. The generalized Rotemberg model, on the other hand, continues to produce very similar results to Costain and Nakov (2019); there is only a slight deterioration in the mean square deviations compared to the model with reimbursement of price adjustment costs.[10]

# 7 Conclusion

We have proposed a generalization of the well known Rotemberg pricing model and have shown that it can account for important aspects of the observed nonlinear behavior of price adjustment at the macroeconomic level, such as a higher pass-through in response to larger shocks, a positive impact of trend inflation on price flexibility, and the relationship between announcement and implementation effects of tax changes. Furthermore, we have shown that with an appropriate calibration of the model, it can generate similar effects on macroeconomic variables as standard versions of the menu cost model. It also generates effects of trend inflation on price flexibility very similar to a recent, substantially more complex model of logit-price dynamics.

Compared to a standard Calvo or Rotemberg model our model only requires to estimate one additional parameter, which we call $\theta_S$. It can be interpreted as the level of inflation at which the marginal price adjustment cost of the Rotemberg model equals the upper limit of the marginal price in our model. This parameter will obviously depend on the model and the data used. Based on a variety of empirical evidence, we estimate it to be in the range of 5 to 20 percent in terms of annual inflation.

There are obvious limitations to the generalized Rotemberg model. By construction, it only explains aggregate price dynamics and cannot account for the cross-sectional price dispersion that arises in a model with heterogeneous firms and nominal frictions. For this

[10]The comparison between line 4 and line 6 of figure 6 shows the best result that can be achieved with the classic Rotemberg model, which, however, requires a very high degree of price flexibility, against a specification that is actually used in the literature, but which provides the opposite of the result of Costain and Nakov (2019). With optimization, the results of the classic Rotemberg model with reimbursement of the price adjustment costs would look almost exactly like the results of the classic Rotemberg model without reimbursement, since the price adjustment costs would be set very low and would then have only a very small effect.

reason, it is also not clear whether it implies realistic welfare losses of inflation. We leave an investigation of this issue for future research. We have also explained that this is not a model of hyper inflations.

We see a major application of our price-setting scheme in multi-industry DSGE models, because shocks at the industry level are larger than aggregate shocks, so that nonlinearities become very important. The size of these models makes it very difficult to handle heterogeneous firms, so that the tractability of the generalized Rotemberg model is a big advantage. Estimating such a model is part of our research agenda.

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# Appendix

# A Alternative price-setting models or model variants

## A.1 Price-setting by firms when price adjustments due to VAT changes are exempt from price adjustment costs

In section 5.4 we show results for a Rotemberg model in which price adjustments due to VAT changes are exempt from price adjustment costs. The firm's problem is similar to that described in section 3.1. The only difference is that firm $i$ pays the price adjustment costs on changes in the net price instead of the gross price. It must therefore pay price adjustment costs of $F\left((1+\tau_t)P_{i,t}/(1+\tau_{t-1})P_{i,t-1}-1\right)Y_tP_t$. The problem becomes:

$$\max_{\{P_{i,t}\}_{t=0}^{\infty}} E_t \sum_{j=0}^{\infty} \Lambda_{t,t+j}\left\{ \left(\frac{P_{i,t+j}}{1+\tau_{t+j}} - MC_{t+j}\right)\left(\frac{P_{i,t+j}}{P_{t+j}}\right)^{-\varepsilon} Y_{t+j} - F\left(\frac{(1+\tau_{t+j-1})P_{i,t+j}}{(1+\tau_{t+j})P_{i,t+j-1}}-1\right) Y_{t+j}P_{t+j}\right\}$$

By taking the derivative with respect to $P_{i,t}$ and using that $P_{i,t} = P_t$ in equilibrium because of symmetry, we can write the aggregate first order condition in real terms as

$$\frac{(1-\varepsilon)}{1+\tau_t} + \varepsilon\ mc_t + \Lambda_{t,t+1} f\left(\tilde{\pi}_{t+1}\right)\left(1+\tilde{\pi}_{t+1}\right)\left(1+\pi_{t+1}\right)\frac{y_{t+1}}{y_t} = f\left(\tilde{\pi}_t\right)\left(1+\tilde{\pi}_t\right), \tag{23}$$

where net inflation is defined as $\tilde{\pi}_t = (1+\tau_t)P_{i,t}/(1+\tau_{t-1})P_{i,t-1} - 1$.

## A.2 The Nonlinear Calvo Model

If firms are subject to Calvo pricing, only a fraction $(1-\theta_C)$ of these firms can change their price each period. Under the same conditions as above, but without price adjustment costs, the problem of optimal price setting of a firm $i$ that is able to set its price in a given period $t$ is given by

$$\max_{\{P_{i,t}\}_{t=0}^{\infty}} E_t \sum_{j=0}^{\infty} (\theta_C)^j \Lambda_{t,t+j}\left\{ \left(\frac{P_{i,t+j}}{1+\tau_t} - MC_{t+j}\right)\left(\frac{P_{i,t+j}}{P_{t+j}}\right)^{-\varepsilon} Y_{t+j}\right\}$$

the first order condition of the problem can be written recursively as

$$\varepsilon\ g_{1,t} = (\varepsilon-1)\, g_{2,t}, \tag{24}$$

with

$$g_{1,t} = mc_t\ Y_t + \theta_C E_t\left\{\Lambda_{t,t+1}\left(1+\pi_{t+1}\right)^{\varepsilon-1} g_{1,t+1}\right\} \tag{25}$$

and

$$g_{2,t} = \frac{p_t^*}{(1+\tau_t)} \, Y_t + \theta_C E_t \left\{ (1+\pi_{t+1})^{\varepsilon} \Lambda_{t,t+1} \frac{p_t^*}{p_{t+1}^*} g_{2,t+1} \right\} \tag{26}$$

$p_t^* = P_t^*/P_t$ is the price set by the firms that can change their price in period $t$. It evolves according to

$$p_t^* = \left[ \frac{1}{1-\theta_C} - \frac{\theta_C}{1-\theta_C} \left( \frac{1}{1+\pi_t} \right)^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}} \tag{27}$$

In the case of flexible prices, the respective first-order conditions, i.e. either in the Rotemberg price setting equation (1) or in the Calvo price setting equation (24), are reduced to the usual price rule, in which all firms set the same price as a mark-up on their marginal costs, given by $p_t^* = \frac{\varepsilon}{\varepsilon-1}(1+\tau_t)\, mc_t = 1$. The Calvo model additionally implies a price dispersion term in the aggregate production function, resulting from the different labour demands of firms. Specifically, if the production function of each firm $i$ is given by $Y_{i,t} = z_t N_{i,t}$, where $z_t$ is aggregate productivity, then the aggregate demand for labour is $N_t = \int_0^1 N_{i,t} d\, i = \int_0^1 \left(\frac{Y_{i,t}}{z_t}\right) d\, i = \frac{Y_t}{z_t} \int_0^1 \left(\frac{P_{i,t}}{P_t}\right)^{\varepsilon} d\, i$. We can define the price dispersion term as $s_t = \int_0^1 \left(\frac{P_{i,t}}{P_t}\right)^{\varepsilon} d\, i$, which becomes a state variable in the model with dynamic equation

$$s_t = \theta_C (1+\pi_t)^{\varepsilon} s_{t-1} + (1-\theta_C) \left(p_{i,t}^*\right)^{-\varepsilon}. \tag{28}$$

In the Rotemberg model, all firms can set their optimal price, i.e. the fraction of firms that are not allowed to change their price is $\theta_C = 0$. Thus, in this case, $p_{i,t}^*$ and $s_t$ must always be one, as can be seen in equations (27) and (28).

## A.3 The Calvo model, when VAT changes are automatically applied to all prices

As mentioned above, in section 5.4 we show results for a Rotemberg model in which price adjustments due to VAT changes are exempt from price adjustment costs. In this case, the pass-through occurs entirely when the VAT change is implemented. The same can be achieved by a Calvo model in which VAT changes lead directly to price changes, i.e. all prices adjust automatically when the tax changes. In this case, we can define the net price as $\tilde{P}_{t,i} = P_{t,i}/(1+\tau_t)$. Then we can express the problem of the firm that adjusts its price in period $t$ as follows:

$$\max_{\{P_{i,t}\}_{t=0}^{\infty}} E_t \sum_{j=0}^{\infty} (\theta_C)^j \Lambda_{t,t+j} \left\{ \left(\tilde{P}_{t,i} - MC_{t+j}\right) \left( \frac{(1+\tau_{t+j})\tilde{P}_{t,i}}{P_{t+j}} \right)^{-\varepsilon} Y_{t+j} \right\}$$

the first order condition of the problem can be written recursively as

$$\varepsilon \, g_{1,t} = (\varepsilon - 1)\, g_{2,t}, \tag{29}$$

with

$$g_{1,t} = \frac{mc_t}{(1+\tau_t)^{\varepsilon}} Y_t + \theta_C E_t \left\{ \Lambda_{t,t+1} (1+\pi_{t+1})^{\varepsilon-1} g_{1,t+1} \right\} \tag{30}$$

and

$$g_{2,t} = \frac{p_t^*}{(1+\tau_t)^{1+\varepsilon}} Y_t + \theta_C E_t \left\{ (1+\pi_{t+1})^{\varepsilon} \Lambda_{t,t+1} \frac{p_t^*}{p_{t+1}^*} \frac{(1+\tau_{t+1})}{(1+\tau_t)} g_{2,t+1} \right\} \tag{31}$$

$p_t^* = P_t^*/P_t$ is the price set by the firms that can change their price in period $t$. It evolves according to

$$p_t^* = \left[ \frac{1}{1-\theta_C} - \frac{\theta_C}{1-\theta_C} \left( \frac{(1+\tau_t)}{(1+\tau_{t-1})} \frac{1}{(1+\pi_t)} \right)^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}} \tag{32}$$

Price dispersion becomes

$$s_t = \theta_C \left[ (1+\pi_t) \frac{(1+\tau_{t-1})}{(1+\tau_t)} \right]^{\varepsilon} s_{t-1} + (1-\theta_C) (p_t^*)^{-\varepsilon}. \tag{33}$$

# B A basic DSGE model

We embed the pricing mechanisms described in section 3 in a general equilibrium framework that is kept as simple as possible. Our aim is to compare generalized Rotemberg pricing with other pricing mechanisms, and these, especially the complex, micro-data motivated pricing models, are usually also integrated into otherwise simple general equilibrium models.

## B.1 Households

Households maximize their utility by choosing consumption and leisure subject to a budget and a cash-in-advance constraint. The representative household maximizes

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[ \frac{C_t^{1-\sigma}}{1-\sigma} - \chi \frac{N_t^{1+\varphi}}{1+\varphi} \right],$$

where $C_t$ is the consumption bundle, $N_t$ is labor supplied by the household, $\sigma$ and $\varphi$ are the corresponding elasticities of substitution with respect to consumption and labor, $\chi$ is an index that we use to calibrate steady state labor supply and $\beta$ denotes the discount factor. The household can choose between an infinite number of consumer products, and substitutes them with the elasticity $\varepsilon$. This is the well-known Dixit-Stiglitz framework and ultimately implies the firms' markup price setting. The household's real period budget constraint is given by

$$m_t + \frac{b_t}{R_t} = w_t N_t + \frac{m_{t-1} - C_{t-1} + b_{t-1}}{1+\pi_t} + T_t.$$

$m_t$ are real money balances of the household, $b_t$ denotes bond holdings, $R_t$ is the nominal interest rate and $w_t$ is the real wage. $T_t$ denotes the lump-sum transfers to the household, which include the central bank's seignorage profit $T_t^m$, the government's VAT revenue $T_t^{VAT} = \tau_t/(1+\tau_t)Y_t$ and corporate profits. In some model variants with Rotemberg pricing, the household is also reimbursed for the price adjustment costs $F(\pi_t)Y_t$. Moreover, we follow Blanco et al. (2024a) and Rotemberg (1987) by assuming that the household is also subject to a cash-in-advance constraint given in real terms by

$$C_t = m_t.$$

In this form, the cash-in-advance constraint has a small effect on the results, in particular it does not distort the choice of labor supply (see Blanco et al., 2024a), it is almost always binding, at least as long as the interest rate does not become negative, and it is in principle close to the simple quantity equation and is therefore easy to interpret. This is very convienient for later examining the pass-through of money supply growth shocks into prices.

The household's first order conditions are

$$w_t = \frac{\chi N_t^{\varphi}}{C_t^{-\sigma}}, \tag{34}$$

$$C_t^{-\sigma} = \beta R_t \, \mathrm{E}_t \left[ \frac{C_{t+1}^{-\sigma}}{(1+\pi_{t+1})} \right] \tag{35}$$

Equation (34) equates the real wage with the marginal rate of substitution between consumption and labor and equation (35) is the standard Euler equation, i.e. the optimality condition for the one-period holding of bonds. The latter also determines the stochastic discount factor $\Lambda_{t,t+1}$, which firms use to discount their future profits.

## B.2 Firms

Firms use the labor supplied by households and produce the output $Y_t$ with productivity $z_t$. As shown in the section 2.2, it is also necessary to take the price dispersion $s_t$ into account in the Calvo model, whereby the latter is always equal to 1 in the Rotemberg model. Thus, the aggregate production function can be written as

$$Y_t = \frac{z_t}{s_t} N_t. \tag{36}$$

Cost minimization yields the following expression for marginal costs:

$$mc_t = \frac{s_t}{z_t} w_t \tag{37}$$

The profit maximization is described in the section 3.1 and leads to equation (1) as a first-order condition in the Rotemberg model and to equation (24) in the Calvo model.

## B.3 Monetary policy

Real money balances evolve according to

$$\frac{m_t}{m_{t-1}} = \frac{\mu e^{u_{m,t}}}{1+\pi_t}, \tag{38}$$

where $\mu$ is the steady state growth rate of money supply and $u_{m,t}$ is a shock process to monetary policy which is given by

$$u_{m,t} = \phi_m u_{m,t-1} + \epsilon_t^{u_m} \tag{39}$$

with $0 < \phi_m < 1$ and $\epsilon_t^{u_m} \sim i.i.d.N(0, \sigma_m^2)$. The central bank's seignorage revenue $T_t^m = m_t - \frac{m_{t-1}}{1+\pi_t}$ is reimbursed to households.

## B.4 Market clearing

If price adjustment costs correspond to a loss of real resources, then this implies for the goods market clearing that all goods produced are either consumed or used to pay for price adjustments:

$$Y_t = C_t + F\left(\pi_t\right) Y_t \tag{40}$$

If, on the other hand, firms only behave as if there were price adjustment costs, or if these are reimbursed to households, all goods produced are also consumed:

$$Y_t = C_t \tag{41}$$

In the Calvo case, market clearing is achieved in any case by equation (41). Since bonds are in zero net supply, symmetry of the equilibrium implies $b_t = 0$.

## B.5 Calibration

In the following, we first briefly describe the calibration of the parameters of the model framework. Note that we parameterize our model to a monthly frequency, in line with the menu cost literature. We then go into detail on the calibration of the price adjustment cost parameters.

### B.5.1 Parameters of the model framework

The discount factor $\beta$ is set to $1.04^{-1/12}$, the steady state growth rate of the money supply $\mu = 1.00$, unless stated otherwise, and the elasticity of substitution $\varepsilon$ is set to 7 in accordance with Costain and Nakov (2019). We follow Nakamura and Steinsson (2010) in setting the intertemporal elasticity of consumption $\sigma = 1$ and the Frisch elasticity of labor supply $\varphi$ to 0. The latter is common in the menu cost literature. Karadi and Reiff (2019) justify this assumption, for example, by the resulting complete long-term pass-through of VAT shocks in line with empirical evidence. We set $\chi$ in a way that steady state labor supply is roughly 1/3. The steady state VAT $\tau$ is set to 20 percent in section 5.4, otherwise it is set to zero.

# C Deriving the New Keynesian Phillips curve

## C.1 Continuous time

We closely follow (Kaplan et al., 2018, Appendix B.2). Differentiating the Bellman equation

$$r(t)J(p,t) = \max_{\pi} \left\{ \left( \frac{p}{P(t)} - m(t) \right) \left( \frac{p}{P(t)} \right)^{-\varepsilon} Y(t) - F(\pi)Y(t) + J_p(p,t)p\pi + J_t(p,t) \right\} \tag{42}$$

w.r.t. $\pi$ we obtain the first order condition

$$J_p(p,t) = \frac{f(\pi)Y}{p} \tag{43}$$

Differentiating (42) w.r.t. $p(t)$ we obtain

$$r(t)J_p(p,t) = \left[ \left( \frac{p}{P(t)} \right)^{-\varepsilon} - \left( \frac{p}{P(t)} - m(t) \right) \varepsilon \left( \frac{p}{P(t)} \right)^{-\varepsilon-1} \right] \frac{Y}{P} + J_{pp}(p,t)p\pi + J_p(p,t)\pi + J_{tp}(p,t)$$

In symmetric equilibrium with $p = P(t)$ we get

$$\left(r(t) - \pi\right) J_p(p,t) = \left[1 - \left(1 - m(t)\right)\varepsilon\right] \frac{Y}{P} + J_{pp}(p,t)p\pi + J_{tp}(p,t) \tag{44}$$

Differentiation of (43) w.r.t. time gives

$$J_{pt}(p,t) + J_{pp}(p,t)\dot{p} = \frac{f'(\pi)Y}{p}\dot{\pi} + \frac{f(\pi)\dot{Y}}{p} - \frac{f(\pi)Y}{p^2}\dot{p} \tag{45}$$

Using $p\pi = \dot{p}$ and inserting (45) into (44) we get

$$(r(t) - \pi)\,\frac{f(\pi)Y}{p} = [1 - (1 - m(t))\,\varepsilon]\,\frac{Y}{P} + \frac{f'(\pi)Y}{p}\dot{\pi} + \frac{f(\pi)\dot{Y}}{p} - \frac{f(\pi)Y}{p}\pi$$

Dividing by $Y/p$ we get

$$(r(t) - \pi)\,f(\pi) = \varepsilon(m(t) - \bar{m}) + f'(\pi)\dot{\pi} + \frac{f(\pi)\dot{Y}}{Y} - f(\pi)\pi, \qquad \bar{m} \equiv \frac{\varepsilon - 1}{\varepsilon}$$

Rearranging gives Equ. (9) in the text.

## C.2 Discrete time

Equation (1) can be rearranged to

$$mc_t = \frac{1}{\varepsilon}f(\pi_t\,)(1 + \pi_t\,) - \frac{1}{\varepsilon}\Lambda_{t,t+1}f(\pi_{t+1})(1 + \pi_{t+1}\,)^2\frac{Y_{t+1}}{Y_t} - \frac{(1 - \varepsilon)}{\varepsilon(1 + \tau_t)} \tag{46}$$

A first-order Taylor expansion at the steady state with trend inflation $\pi$ and VAT $\tau$ yields

$$\begin{aligned} mc_t = mc + & \left(\frac{1}{\varepsilon}f'(\pi) + \frac{1}{\varepsilon}f'(\pi)\,\pi + \frac{1}{\varepsilon}f(\pi)\right)[\pi_t - \pi] \\ & - \frac{1}{\varepsilon}\Lambda\left[f'(\pi)\left(1 + 2\pi + \pi^2\right) + 2f(\pi)(1 + \pi)\right][\pi_{t+1} - \pi] \\ & - \frac{1}{\varepsilon}\Lambda\left(f(\pi) + f(\pi)\,2\pi + f(\pi)\,\pi^2\right)\frac{1}{Y}[Y_{t+1} - Y] \\ & + \frac{1}{\varepsilon}\Lambda\left(f(\pi) + f(\pi)\,2\pi + f(\pi)\,\pi^2\right)\frac{Y}{Y^2}[Y_t - Y] \\ & + \frac{(\varepsilon - 1)}{\varepsilon(1 + \tau)^2}[\tau_t - \tau], \end{aligned} \tag{47}$$

which we can rearrange to

$$\begin{aligned} \hat{\pi}_t = \varepsilon & \frac{mc}{(f'(\pi)(1 + \pi) + f(\pi))}\,\widehat{mc}_t \\ & + \Lambda\frac{[f'(\pi)(1 + 2\pi + \pi^2) + 2f(\pi)(1 + \pi)]}{(f'(\pi)(1 + \pi) + f(\pi))}\hat{\pi}_{t+1} \\ & - \Lambda\frac{\left(\frac{f(\pi)}{\pi} + f(\pi)\,2 + f(\pi)\,\pi\right)}{(f'(\pi)(1 + \pi) + f(\pi))}\Delta Y_{t+1|t} \\ & + \frac{(\varepsilon - 1)\tau}{(1 + \tau)^2}\hat{\tau}_t. \end{aligned} \tag{48}$$

Using $\Lambda = 1/(\beta(1+\pi))$ and steady state marginal costs

$$mc = \frac{(1 - \Lambda(1+\pi)) f(\pi)(1+\pi)}{\varepsilon} + \frac{(\varepsilon - 1)}{\varepsilon(1+\tau)} \tag{49}$$

we can derive the following expression for the New Keynesian Phillips curve:

$$\hat{\pi}_t = \gamma_{mc}\, \widehat{mc}_t + \gamma_\pi \hat{\pi}_{t+1} - \gamma_Y \Delta Y_{t+1|t} + \gamma_\tau \hat{\tau}_t \tag{50}$$

The hat represents the percentage deviation of the variable from its steady state or, in the case of inflation, the percentage point deviation from its steady state. $\Delta Y_{t+1|t}$ is in period $t$ expected change in output $(Y_{t+1} - Y_t)/Y$. $\gamma_{mc}$, $\gamma_\pi$, $\gamma_Y$ and $\gamma_\tau$ are parameters that depend on the model and its calibration. Especially relevant for our analysis is $\gamma_{mc}$, which determines the slope of the New Keynesian Phillips curve with respect to marginal costs. It is given by

$$\gamma_{mc} = \frac{(\varepsilon - 1)/(1+\tau)}{f'(\pi)(1+\pi) + f(\pi)} + \frac{(1-\beta) f(\pi)(1+\pi)}{f'(\pi)(1+\pi) + f(\pi)} \tag{51}$$

With zero trend inflation, this expression becomes $\gamma_{mc} = (\varepsilon - 1)/(f'(0)(1+\tau)) = (\varepsilon - 1)/(\theta_R(1+\tau))$. If the slope $f'(\pi)$ of the marginal costs decrease fast enough, as is the case in GRP models with suitable parameters, $\gamma_{mc}$ is decreasing in inflation, i.e., the Phillips curve is steeper under positive trend inflation. Numerical calculations show that $\gamma_{mc}$ rises slowly with positive trend inflation until a limit is reached, where it remains constant. Through its influence on the slope of the New Keynesian Phillips curve, trend inflation influences the dynamics of the model already in a first-order approximation, so that the equivalence of GRP and Calvo breaks down even for small shocks. The remaining parameters are given by:

$$\gamma_\pi = \frac{[f'(\pi)(1 + 2\pi + \pi^2) + 2f(\pi)(1+\pi)]}{\beta(1+\pi)(f'(\pi)(1+\pi) + f(\pi))} \tag{52}$$

$$\gamma_Y = \frac{\left(\frac{f(\pi)}{\pi} + f(\pi)2 + f(\pi)\pi\right)}{\beta(1+\pi)(f'(\pi)(1+\pi) + f(\pi))} \tag{53}$$

$$\gamma_\tau = \frac{(\varepsilon - 1)\tau}{(1+\tau)^2} \tag{54}$$

# D Computational Details

## D.1 Menu cost model of Section 4.1

The problem is to compute an industry equilibrium path from one stationary state to a new stationary state after a permanent cost shock. Given a time path of industry price level $P_t$ (or a fixed level $P^*$ for the stationary state), the firm problem is solved by discrete dynamic programming on a finite grid of 501 points in the endogenous state (price) and 21 points in the exogenous state (firm productivity). To achieve smoothness and guarantee existence of an industry equilibrium, the solution is slightly perturbed by allowing that several actions (prices) are taken with positive probability if their level of utility is very close. The terminal condition is set by assuming that after 120 periods (ten years), the value function of the firm is that of the new steady state with the persistently higher level of marginal costs. The path of industry price level $P_t$ is then found by simple fixed point iteration.

Solving for the perfect-foresight path of the Rotemberg model of Section 4.2 is standard and can be done, for example, in Dynare.

# E Monetary policy conducted by means of a Taylor rule

Fig E.7 displays impulse responses under the assumption that monetary policy follows a Taylor rule, to show that our results are compatible with Ascari and Rossi (2012), cf. Section 5.3.

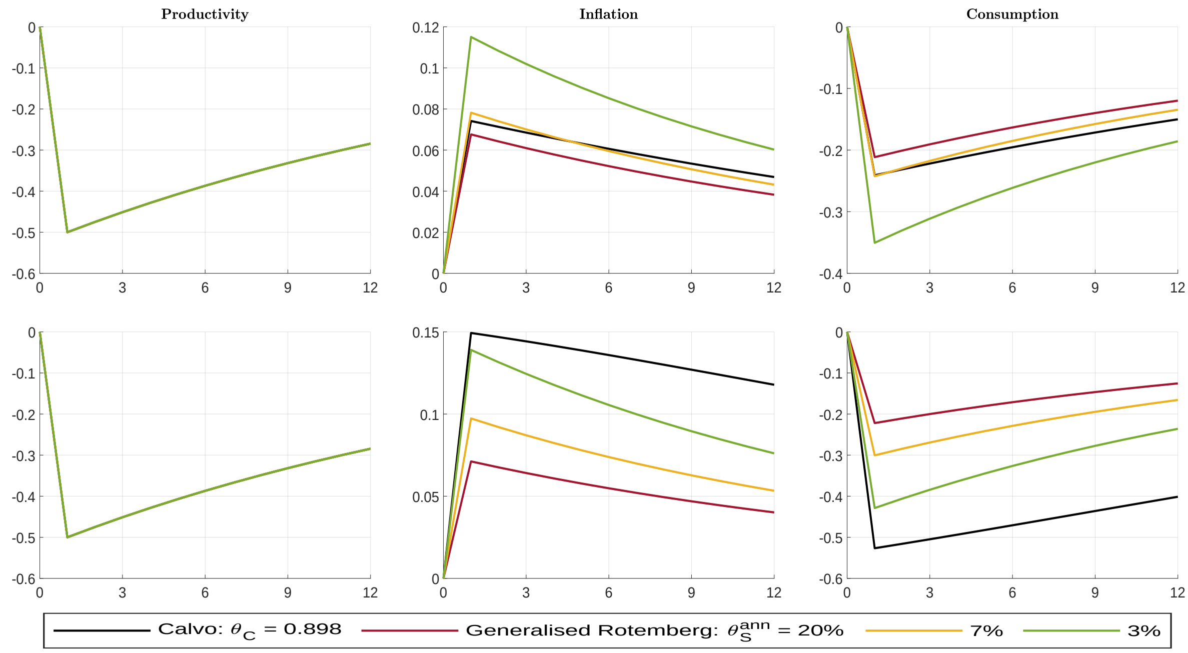


Figure E.7: Trend inflation and price flexibility when monetary policy is conducted by means of a Taylor rule