Fiscal Policy Under Convex Supply Curves*

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Abstract: Recent empirical evidence suggests that supply curves are convex. Supply curve convexity is at odds with conventional Phillips curves, which rely on an infinitely elastic underlying supply curve. This paper explores the effect of supply curve convexity on the transmission of fiscal policy to inflation. This convexity is generated by capacity constraints on firm production, which we embed in a Heterogeneous Agent New Keynesian model. We apply the model to understand the role of fiscal policy in generating the high inflation during COVID-19 and its aftermath. In the model with a convex supply curve, fiscal policy generates 40% more inflation than the model with a conventional Phillips curve at the inflation peak in 2021Q2 and the model can account for 80% of this peak. In contrast, the model with a conventional Phillips curve can only account for 40% of the inflation peak. Convexity matters most for the timing of inflation, not the cumulative increase in the price level: fiscal policy generates a similar amount of cumulative inflation in both models over the period from 2020Q2–2023Q4.

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1 Introduction

From 2020 to 2022, the U.S. engaged in a level of fiscal expansion unprecedented in the last several decades. Over this three-year time frame, the federal government spent about \$4.6 trillion, or about 20% of 2019 Gross Domestic Product (GDP), on the COVID-19 response.[1] At the same time, inflation spiked to 6% (annualized) in the second quarter of 2021, and remained between 4.5% and 6% until the second quarter of 2023, significantly higher than the Federal Reserve's 2% target.[2] While some prominent commentators such as Summers (2021) see these developments as linked, others have expressed doubts that fiscal policy could be responsible for much of this inflation, in part due to the pre-2020 consensus that the Phillips curve is flat – that is, the relationship between aggregate demand (usually captured by the unemployment rate or output gap) and inflation is weak (see, for instance, Hazell et al. 2022). If this relationship is weak, then fiscal policy, which works by stimulating aggregate demand, could not have substantially increased inflation.

We contribute to this debate by quantifying the transmission from fiscal policy to inflation in a Heterogeneous Agent New Keynesian (HANK) model, where the supply curve is disciplined to match the quasi-experimentally identified convexity estimated in Boehm and Pandalai-Nayar (2022). A model where such convexity is generated by firms facing constraints on their production capacity generates 40% more inflation than a model with a conventional Phillips curve at the inflation peak in 2021Q2. Overall, the model with capacity constraints can account for 80% of this inflation peak while the model with a conventional Phillips curve only accounts for 40%. However, the primary differences between the two models is in the timing of inflation, not cumulative inflation. Fiscal policy generates similar amounts of cumulative inflation in both models, and each only explains one third of the 7.1 percentage points of cumulative inflation from 2020Q2-2023Q4.

The key distinction generating these results is that under the conventional model, aggregate demand can only increase inflation via changes in the real wage, whereas in a model with capacity constraints, demand shocks additionally increase inflation by pushing firms closer to their production constraint. A conventional Phillips curve arises from an underlying flat static supply curve. That is, monopolistically competitive producers supply any level of output as long as they can charge their desired markup over marginal cost. When production relies only on labor and exhibits constant returns to scale, this marginal cost is just the wage. However, a flat supply curve is at odds with the empirical evidence that short-run supply curves are convex: the elasticity of prices to output is increasing in output. When firms face occasionally binding capacity constraints as in Boehm and Pandalai-Nayar (2022), higher aggregate demand causes more firms to reach their constraint. These constrained firms cannot produce more and so respond to further increases in demand by increasing prices rather than increasing output, thereby increasing inflation independent of any effect on the real wage.

Furthermore, these micro-foundations allow for a coherent notion of a capacity shock, defined as a shock that lowers producers' maximum output. Supply chain disruptions during the COVID-19 pandemic are a prime example of such a shock. If a producer cannot get an essential input due to supply chain disruptions or because their suppliers shut down factories due to public health restrictions, that limits the amount of output they can produce and results in further convexity in the supply curve. In a conventional model with a flat static supply curve, these capacity shocks are typically modeled as mark-up shocks or amorphous cost-push shocks that enter the Phillips curve as residuals. Properly modeling the supply side with empirically valid micro-foundations is important to understand the effect of fiscal stimulus during the pandemic, since the stimulus

[1] https://www.gao.gov/products/gao-23-106647.

[2] Throughout the paper, we use the Personal Consumption Expenditure Price Index, Excluding Food and Energy (Core PCE) as our measure of inflation.

coincided with supply chain disruptions that tightened capacity.

The transmission of fiscal stimulus to inflation relies on three main objects. The first is a mapping from the stimulus to aggregate demand, which we model with the Intertemporal Keynesian Cross (IKC) from Auclert et al. (forthcoming). In the IKC with a constant real rate, the matrix of intertemporal marginal propensities to consume (iMPCs) is a sufficient statistic to first order for the impact of fiscal policy on GDP, which we discipline with quasi-experimental evidence (see Havranek and Sokolova 2020 for a review). To emphasize the role of convexity in the supply curve, we will solve our model non-linearly, so the matrix of iMPCs is not sufficient for the GDP response to fiscal policy, but it is still the key observable object that disciplines this reaction. Given a path of GDP, the other two objects – the wage and price Phillips curves – mutually determine the path of wages and inflation. We will use a standard wage Phillips curve derived from monopolistically competitive unions facing quadratic Rotemberg wage adjustment costs. Our main innovation is to combine the IKC and standard wage Phillips curve with a price Phillips curve based on a convex supply curve that we can quantitatively discipline from the estimates in Boehm and Pandalai-Nayar (2022).

An observationally equivalent micro-foundation to capacity constraints for generating a convex supply curve is a production technology with convex marginal costs. Then, the production function exhibits diminishing marginal product in labor. Here, a capacity shock exacerbates the decreasing returns to scale. The economic interpretation of this shock remains the same: if a producer cannot get an essential input due to supply chain disruptions, any extra labor will be less productive. The Boehm and Pandalai-Nayar (2022) estimates apply equally to a supply curve generated with these micro-foundations and the authors emphasize that their analysis cannot distinguish between convex marginal costs and hard capacity constraints. While both micro-foundations lead to identical static supply curves, they lead to different inflation dynamics when embedded into firms' dynamic price setting problem under nominal rigidities (in our case, quadratic price adjustment costs). As such, we quantify the transmission from fiscal stimulus to inflation under both plausible micro-foundations of supply curve convexity. We refer to the micro-foundation with firm-level capacity constraints as the "capacity-constraint model" and the one with firm-level convex marginal costs as the "marginal-cost model" – even though we emphasize that both models share an identical static convex supply curve.

The response of inflation to fiscal shocks demonstrates significant size and state dependence only under the capacity-constraint model, while the marginal-cost model generates greater persistence in inflation than both the capacity-constraint model and the one with a conventional Phillips curve. In the capacity-constraint model, the marginal on-impact response of inflation to a fiscal expansion is increasing. High fiscal expenditures push the economy to the steep part of the aggregate supply curve so that any additional fiscal shock has an outsized effect on inflation. This stands in contrast to a conventional Phillips curve, which yields a constant marginal on-impact response of inflation to a fiscal shock – even when solved non-linearly – and thus a low inflationary response even to large fiscal shocks. However, in the capacity-constraint model, after the initial burst of inflation, as the constraints slacken, producers quickly drop their prices and inflation declines quite steeply. Overall, the three-year cumulative price increase in response to a fiscal expansion is quite similar between the model with hard capacity constraints and the model with a conventional Phillips curve.

In addition to size dependence, the inflation response in the capacity-constraint model also exhibits state dependence: fiscal policy is more inflationary when layered on top of a capacity tightening shock. A capacity tightening shock makes more firms constrained, pushing the economy to the steep part of the supply curve. As with size dependence, state dependence primarily affects the on-impact inflation response but does not meaningfully affect cumulative price growth.

On the other hand, the marginal-cost model does not exhibit quantitatively meaningful size or state dependence in the contemporaneous inflation response, but does generate more cumulative inflation than both the capacity-constraint and conventional models. The difference in the path of inflation between the capacity-constraint model and the marginal-cost model can be traced to the dynamics of price setting: since there are no hard capacity constraints in the marginal-cost model, firms spread out their price increases over a longer period of time to minimize adjustment costs.

To isolate the effect of the different supply sides on inflation, the structure of the IKC – which determines the GDP response – is identical across all three models. As in Auclert et al. (forthcoming), we assume that households hold real assets and that they are proportionally exposed to both profits and the wage in accordance with their idiosyncratic productivity. Furthermore, because households contract their labor to monopolistically competitive unions which set the wage, households are off their labor supply curve and will provide as much labor as firms demand given the wage. So, the sequence of aggregate consumption depends only on the sequences of real interest rates, GDP, and fiscal transfers. In order to isolate the effects of fiscal policy independent of endogenous monetary policy reaction, we also assume that the monetary authority follows a real rate rule and exogenously sets the path of real interest rates.

After this impulse response analysis, we quantify the effect of the fiscal stimulus on inflation during the COVID-19 pandemic and its aftermath (2020Q2 – 2023Q4). As mentioned earlier, the effect of fiscal stimulus on inflation depends on the IKC block disciplined by MPC estimates, a price Phillips curve based on an underlying convex supply curve disciplined by the estimates in Boehm and Pandalai-Nayar (2022), and a conventional wage Phillips curve. Additionally, we need the observed path of government expenditures, government transfers, real interest rates, and capacity shocks, all of which we take directly from the data. Because Congress did not specify any explicit financing for the fiscal stimulus during the pandemic, we leave the average income tax rate at its steady state level for the simulation. Debt returns to steady state because of the endogenous GDP response to fiscal policy. Finally, because non-linearities play a crucial role in the supply side of the economy, we need to discipline the overall level of aggregate demand. Motivated by the fact that the COVID-19 recession was generated by households' inability to spend on services and the corresponding spike in the savings rate, we solve for the discount rate shocks such that the model generates the observed cyclical movements of GDP given the observed paths of fiscal and monetary policy. We then compare model-implied inflation with and without fiscal policy to quantify the effect of fiscal stimulus on inflation.

In the data, core PCE inflation peaked during the second quarter of 2021. In the capacity-constraint model, fiscal policy generates 5.4 percentage points of (annualized) inflation in this quarter, compared to 4.9 percentage points with the marginal-cost model. As a benchmark, fiscal policy only generates 3.9 percentage points of inflation in the model featuring a conventional Phillips curve. From 2020Q2 to 2023Q4, fiscal policy generates 9.6 percentage points of cumulative inflation in the capacity-constraint model; however, most of this cumulative inflation comes from preventing substantial disinflation in the absence of fiscal policy. The full model with all shocks – including deflationary forces such as the discount rate shock capturing the fall in demand directly associated with COVID-19 – only generates 2.4 percentage points of inflation over this time horizon. Results are similar in the conventional model where fiscal policy generates 9.9 percentage points of cumulative inflation and the full model generates 2.4 percentage points. Inflation is more persistent in the marginal-cost model: fiscal policy generates 10.8 percentage points and the full model generates 2.9 percentage points of inflation. The main takeaway from these results is that under convex supply curves, fiscal policy can account for much more of the initial spike in inflation than in a conventional model. However, it does not account for the persistence of inflation throughout the pandemic episode.

The interaction between capacity shocks and fiscal expansion is also relevant in the model with capacity constraints, as capacity shocks exacerbate the effect of fiscal policy on the inflationary spike. Specifically, absent a concurrent capacity shock, the contribution of fiscal policy to inflation is 7% lower and the model with all shocks explains 20% less of the spike overall. However, the biggest role capacity plays is simply that it does not expand in accordance with the fiscal stimulus, thus causing the constraint to bind for more firms in response to the demand shock. The capacity shocks also primarily impact the timing of inflation, not the cumulative price increase.

While the focus of the quantitative exercise is to explain inflation during the pandemic, our model also shows that in the absence of fiscal stimulus, the initial decline in real GDP during the pandemic recession would have been 7 percent larger (as a share of steady state output) and the economy would have taken 11 quarters longer to recover. In total, without fiscal stimulus, there would have been an additional cumulative GDP decline equal to 13% of steady state quarterly output from 2020Q2-2023Q4.

Literature: This paper contributes to three strands of the literature. First, there is significant research on the nonlinearity of the Phillips curve. Our modeling strategy and primary empirical motivation comes from Boehm and Pandalai-Nayar (2022), who showed that industry-level supply curves are convex. Other time-series approaches have also suggested that the Phillips curve is convex, such as Debelle and Laxton (1997) and Benigno and Eggertsson (2023).[3] Lein and Köberl (2009) use firm-level data to show that under capacity constraints, firms' supply curves are convex at high output levels (and concave when there is excess supply). Recently, Bohr (2024) showed how investments in capacity buffers flattened the Phillips curve until this buffer effectively disappeared during the pandemic, thereby raising the slope of the curve. Our contribution is to incorporate a convex supply curve into a HANK model and to demonstrate the quantitative implications for fiscal policy.

Second, there is a burgeoning literature on the effects of fiscal policy on inflation, particularly during the pandemic. Our contribution is to study these effects in combination with an empirically realistic supply curve. di Giovanni et al. (2023) study the effects of fiscal policy on inflation during the pandemic in a Two-Agent New Keynesian model (TANK), but without considering the general equilibrium effects of government spending. de Soyres et al. (2023) show some reduced-form evidence that fiscal expansion increased demand, which was not met with a sufficient increase in production and thus increased prices, consistent with the simulation from our model. Barro and Bianchi (2023) show that inflation was strongly correlated with a composite government-spending variable in 37 OECD countries from 2020 to 2023, consistent with our emphasis on fiscal policy in understanding inflation in the U.S. over this period. Also consistent with our emphasis on fiscal policy, Hazell and Hobler (2024) use an event study around the 2021 Georgia senate run-offs to estimate a sizable causal effect of deficits on inflation. Fornaro (2024) builds a stylized, analytic model that illustrates some of our results about the relevance of capacity constraints for state and size dependence. Our quantitative model can speak to the importance of convexity for understanding the effects of fiscal policy during the COVID-19 pandemic and highlights the differences between two empirically valid approaches to modeling convexity, particularly regarding the timing of inflation.

Third, the determinants of inflation from 2021 to 2022 have been hotly debated. Bernanke and Blanchard (2023) attribute most of the initial inflation to commodity prices. Gagliardone and Gertler (2023) highlight the importance of oil price changes and accommodative monetary policy in stimulating inflation during the pandemic period. While our model does not feature an explicit role for oil prices, we show in Appendix C.3 that oil price changes can account for a substantial

[3] Many papers have shown that the Phillips curve is convex (either smoothly or via kinks in the slope) using time-series and cross-sectional approaches. For some other references, see Byrne and Zekaite (2020), Smith et al. (2023), Forbes et al. (2021), Cristini and Ferri (2021), Lai (1990), Bishop and Greenland (2021).

share of the unexplained inflation persistence in 2022, after the peak. In contrast, Bardóczy et al. (2024) find a substantial role for a demand mechanism. Their work characterizes the path of spending excess savings, which is related to our focus on the fiscal transfer shock. Other papers like Baqaee and Farhi (2022) similarly isolate the effects of supply and demand shocks, but do not consider the link between fiscal policy and demand like we do. Several papers discussing inflation have embraced the notion of capacity constraints and nonlinearity in the Phillips curve: Comin et al. (2023) show that in an open, multisector economy, binding capacity constraints can generate half of the observed inflation during the pandemic. We complement this analysis by endogenizing changes in demand due to fiscal policy and can thus speak to the effects of fiscal expenditures on inflation as well as the importance of the interaction between fiscal policy and capacity shocks during the pandemic. Harding et al. (2023) have a nonlinear Phillips curve arising from a kinked demand schedule that – combined with cost-push shocks – can generate higher inflation than the linearized model beginning in 2021Q2. We show that much of the inflationary spike during the pandemic can be explained by fiscal policy.

The rest of the paper proceeds as follows. In section 2, we describe the micro-foundations for a convex, static supply curve under the assumption of firm-level hard capacity constraints (the "capacity-constraint model") vis-à-vis firm-level convex marginal costs (the "marginal-cost model"). We then show how to incorporate this static supply curve into the dynamic price setting problem with nominal rigidities to generate a price Phillips curve, which we compare to the conventional Phillips curve. We also describe the rest of the model, namely the inter-temporal Keynesian cross, the wage Phillips curve, fiscal policy, and monetary policy. In section 3, we isolate the effects of fiscal policy shocks and discuss the mechanisms driving the impulse responses. Section 4 simulates inflation during the pandemic given the observed sequence of fiscal and monetary shocks, thereby measuring the contribution of fiscal policy to inflation under the three models. Section 5 concludes.

2 Models

We propose a Heterogeneous Agent New Keynesian (HANK) model with a supply side featuring convex supply curves. Its parameters are calibrated to match existing estimates in the literature. We explore two ways to generate convexity: firm-level capacity constraints and firm-level convex marginal costs. We then compare these two models to a model with a conventional Phillips curve.

2.1 The Supply Curve

This subsection derives the convex supply curve via both firm-level capacity constraints and firm-level convex marginal costs. Both approaches yield an identical static, nominal supply curve that we calibrate with the estimates in Boehm and Pandalai-Nayar (2022).

2.1.1 Capacity Constraints

Production is two-tiered and features capacity constraints and nominal price rigidity for the intermediate inputs producers. Intermediate producers are monopolistically competitive, face idiosyncratic demand shocks, and also differ in their existing price level. These demand shocks can move some firms close to the constraint while leaving others unconstrained. This will generate a static aggregate supply curve that is smooth and convex.

A competitive final goods sector produces a uniform consumption good, Y_t, by aggregating a unit continuum of intermediate input varieties $\{Y_{jt}\}_{j\in[0,1]}$ with a constant elasticity of substitution

(CES) γ:

$$Y_t = \left(\int v_{jt}^{\frac{1}{\gamma}} Y_{jt}^{\frac{\gamma-1}{\gamma}} \ dj \right)^{\frac{1}{\gamma-1}} \tag{1}$$

v_{jt} are idiosyncratic shocks for intermediate input j, which can be interpreted as taste shocks coming from consumers or productivity shocks for using the specific variety j. The distribution for v_j is log-normal with mean $E[v_j] = 1$ and $sd(\log(v_j)) = \sigma_v$. The demand curve faced by intermediate producer j is then:

$$Y_{jt} = \left(\frac{P_{jt}}{P_t} \right)^{-\gamma} v_{jt} Y_t, \quad P_t = \left(\int v_{jt} P_{jt}^{1-\gamma} \ dj \right)^{\frac{1}{1-\gamma}} \tag{2}$$

Above, Y_t is the quantity of consumption goods produced at time t and Y_{jt} is the corresponding quantity of input j demanded. P_{jt} is the nominal price set by producer j while P_t is the aggregate price index. The production function is

$$Y_{jt} = N_{jt} \quad s.t. \quad Y_{jt} \leq \overline{Y}_t \tag{3}$$

where N_{jt} is labor demand and $\overline{Y}_t$ is capacity, an exogenous limit to feasible production. This is the key ingredient for generating convex supply curves. Given a nominal wage W_t and the price index P_t, intermediate producers solve the standard monopoly problem with the added capacity constraint, re-expressed as a price floor:

$$\max_{P_{jt}} P_{jt} \left(\frac{P_{jt}}{P_t} \right)^{-\gamma} v_{jt} Y_t - W_t \left(\frac{P_{jt}}{P_t} \right)^{-\gamma} v_{jt} Y_t \quad s.t. \quad P_{jt} \geq \left(\frac{Y_t v_{jt}}{\overline{Y}_t} \right)^{\frac{1}{\gamma}} P_t. \tag{4}$$

The price floor becomes binding once the idiosyncratic demand shock v_{jt} exceeds a certain threshold value $\bar{v}_t$. The first order condition for this problem results in

$$P_{jt} = \max \left\{ \frac{\gamma}{\gamma - 1} W_t, \left(\frac{Y_t v_{jt}}{\overline{Y}_t} \right)^{\frac{1}{\gamma}} P_t \right\}. \tag{5}$$

This condition and the equation for the price index leads to

$$P_t(Y_t) = \frac{\gamma}{\gamma - 1} W_t \cdot M(\bar{v}(Y_t)). \tag{6}$$

The conventional static supply curve would be perfectly elastic at the unit cost of production W_t, marked up by the CES-factor $\frac{\gamma}{\gamma-1}$. With the presence of capacity constraints, the entire sector faces a cost multiplier $M(\bar{v}(Y_t))$. This reflects the notion that additional consumption goods Y_t become harder to produce as more and more suppliers become capacity-constrained:

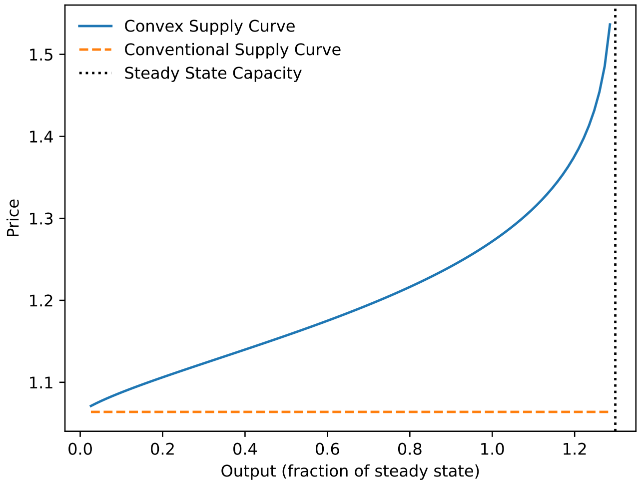
$$M(\bar{v}_t) \equiv M(\bar{v}(Y_t)) = \left(\int_0^{\bar{v}_t} v_{jt} dv_j + \bar{v}_t^{\frac{\gamma-1}{\gamma}} \int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}} dv_j \right)^{\frac{1}{1-\gamma}} \tag{7}$$

where $\bar{v}_t \equiv \bar{v}_t(Y_t)$ is the threshold demand shock above which firms are capacity-constrained, which is decreasing in Y_t.[4] Instead of $\bar{v}_t$ or $M(\bar{v}_t(Y_t))$, in practice, researchers and policymakers observe the time series for capacity utilization, so it is helpful to define capacity utilization in this model as:

$$u_t = \frac{Y_t}{\overline{Y}_t^{agg}}$$

[4]See Appendix A.1 or Boehm and Pandalai-Nayar (2022) for the full derivation.

Figure 1: Static Nominal Supply Curve



Note: This plot assumes a nominal wage normalized to 1 as well as our calibration for γ, σ_v and the steady state for $\overline{Y}_t$. The x-axis is the level of output expressed as a fraction of steady state output, which we normalize to 1.

where $\overline{Y}_t^{agg}$ is aggregate productive capacity. That is, aggregate output when all firms produce at their constraint $\overline{Y}_t$. One can show that $\overline{Y}_t^{agg} = \Theta\overline{Y}_t = \left(\int_0^\infty v_{jt}^{\frac{1}{\gamma}} dj\right)^{\frac{\gamma}{\gamma-1}} \overline{Y}_t$. There is a one-to-one mapping between total output Y_t, the productivity threshold $\bar{v}_t \equiv \bar{v}(Y_t)$ for binding constraints, and aggregate capacity utilization $u_t \equiv u(\bar{v}(Y_t))$[5]:

$$u_t \equiv u(\bar{v}_t) = \frac{Y_t}{\Theta\overline{Y}_t} = \frac{1}{\Theta\bar{v}_t}\left(\int_0^{\bar{v}_t} v_{jt} dj + \bar{v}_t^{\frac{\gamma-1}{\gamma}} \int_{\bar{v}_t} v_{jt}^{\frac{1}{\gamma}} dj\right)^{\frac{\gamma}{\gamma-1}} \tag{8}$$

$$\bar{v}_t = u^{-1}(u_t) = \underbrace{u^{-1}\left(\frac{Y_t}{\Theta\overline{Y}_t}\right)}_{\bar{v}(Y_t)} \tag{9}$$

We can thus write the induced static, nominal supply curve as

$$P_t(Y_t) = \frac{\gamma}{\gamma - 1} W_t \cdot M\left(u^{-1}\left(\frac{Y_t}{\Theta\overline{Y}_t}\right)\right). \tag{10}$$

Figure 1 plots the curve given our calibration for γ and σ_v and the steady state $\overline{Y}_t$ along with the conventional flat supply curve for reference. The calibration is discussed in Section 2.5.

2.1.2 Convex Marginal Costs

Equation (10) would be the exact same nominal supply curve we would derive from a unit mass of identical monopolistically competitive firms facing marginal cost given by

$$C_t'(Y_t) = W_t \cdot M\left(u^{-1}\left(\frac{Y_t}{\Theta\bar{Y}_t}\right)\right). \tag{11}$$

[5] Derivations can be found in Appendix A.1.

The inverse production function (with labor being the single production factor that is the labor demand function) that leads to this marginal cost curve is

$$N(Y_t) = \int_0^{Y_t} M\left(u^{-1}\left(\frac{y}{\Theta \bar{Y}_t}\right)\right) dy. \tag{12}$$

The second-order approximation of equation (10) forms the estimation equation in Boehm and Pandalai-Nayar (2022). Their evidence thus cannot distinguish between convexity driven by capacity constraints and convex marginal costs, which is why we explore both models. We find that the models generate very different quantitative results when we embed the two static supply curves into the firms' dynamic price setting problem.

2.2 From Supply Curve to Price Phillips Curve

This subsection derives a price Phillips curve from the firms' price-setting problem in each of the three models: (1) the conventional supply curve, (2) the "capacity-constraint model" from section 2.1.1 where heterogeneous firms face occasionally binding capacity constraints in section 2.1.1, and (3) the "marginal-cost model" in section 2.1.2 where identical firms face convex marginal costs.

2.2.1 Conventional Price Phillips Curve

In the model with a conventional Phillips curve with inertia, the monopolistically competitive producers solve a dynamic price setting problem with quadratic price adjustment costs of the form

$$K(P_{jt}, P_{jt-1}) = Y_t \frac{\phi}{2}\left(\frac{P_{jt}}{P_{jt-1}} - \pi_{t-1}^{\xi}\pi^{1-\xi}\right)^2 \tag{13}$$

where $\pi_t = \frac{P_t}{P_{t-1}}$ is the gross inflation rate, π is steady state inflation, and ξ reflects indexation to the previous period's inflation. Let $p_{jt} = \frac{P_{jt}}{P_t}$ be the relative price for intermediate producer j. Given sequences for the real interest rate r_t, the real wage w_t, and inflation π_t, all intermediate producers solve the following, identical price setting problem:

$$\max_{\{p_{jt}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty}\left(\prod_{s=0}^{t-1}\frac{1}{1+r_s}\right)\left(\underbrace{(p_{jt}-w_t)p_{jt}^{-\gamma}Y_t}_{\text{variable profit}} - \underbrace{Y_t\frac{\phi}{2}\left(\frac{p_{jt}\pi_t}{p_{j,t-1}} - \pi_{t-1}^{\xi}\pi^{1-\xi}\right)^2}_{\substack{\text{price}\\ \text{adjustment costs}}}\right) \tag{14}$$

Because every firm faces an identical optimization problem, they will all choose the same price; hence $p_{jt} = 1$ for all j by the price index equation (2). The solution to this maximization leads to the conventional Phillips curve:

$$\left(\pi_t - \pi_{t-1}^{\xi}\pi^{1-\xi}\right)\pi_t = \frac{\gamma-1}{\phi}\left(\frac{\gamma}{\gamma-1}w_t - 1\right) + \frac{1}{1+r_t}\frac{Y_{t+1}}{Y_t}\left(\pi_{t+1} - \pi_t^{\xi}\pi^{1-\xi}\right)\pi_{t+1} \tag{15}$$

where $\frac{\gamma}{\gamma-1} - 1$ is the price markup.[6] The slope of the log-linearized price Phillips curve is $\kappa^p = \frac{\gamma-1}{\phi}$.

[6]Details of the derivation are in Appendix A.2.

2.2.2 Price Phillips Curve of the Capacity-Constraint Model

In the dynamic problem, we will assume that variety-specific demand shocks, v_{jt}, evolve according to an AR(1) process in logs with persistence ρ_ν:

$$\log v_{jt} = \rho_v \log v_{j,t-1} + \varepsilon_{v_j,t}, \quad \varepsilon_{v_j,t} \overset{i.i.d.}{\sim} \mathcal{N}(0, \sigma^2) \tag{16}$$

where the stationary distribution for v_j is log-normal with mean $E[v_j] = 1$ and $sd(\log(v_j)) = \sigma_v$. Given sequences for π_t, w_t, and r_t, we can express the dynamic price setting problem recursively as

$$V_t(v_{jt}, p_{j,t-1}) = \max_{p_{jt}} \underbrace{(p_{jt} - w_t)p_{jt}^{-\gamma} v_{jt} Y_t}_{\text{variable profit}} - \underbrace{Y_t \frac{\phi}{2}\Big(\frac{p_{jt}\pi_t}{p_{j,t-1}} - \pi_{t-1}^{\xi}\pi^{1-\xi}\Big)^2}_{\substack{\text{price}\\ \text{adjustment costs}}} + \underbrace{\frac{1}{1+r_t} E\Big[V_{t+1}(v_{j,t+1}, p_{jt})|v_{jt}\Big]}_{\substack{\text{discounted}\\ \text{continuation value}}} .$$
$$s.t. \quad p_{jt} \geq \left(v_{jt}\frac{Y_t}{\overline{Y}_t}\right)^{\frac{1}{\gamma}} \tag{17}$$

This problem does not have an analytic Phillips curve representation like equation (15), but we can solve it numerically with the endogenous grid-point method. Fundamentally, the Phillips curve is just a mapping from sequences $\{w_t\}_{t=0}^{\infty}$, $\{Y_t\}_{t=0}^{\infty}$, and $\{r_t\}_{t=0}^{\infty}$ to a sequence of inflation $\{\pi_t\}_{t=0}^{\infty}$. The maximization in equation (17) results in a sequence space mapping into the index of real prices $\{p_t\}_{t=0}^{\infty}$:

$$\left\{\left(\int p_{jt}^{1-\gamma} v_{jt} dj\right)^{\frac{1}{1-\gamma}}\right\}_{t=0}^{\infty} = \mathcal{P}\left(\{w_t\}_{t=0}^{\infty}, \{Y_t\}_{t=0}^{\infty}, \{r_t\}_{t=0}^{\infty}, \{\pi_t\}_{t=0}^{\infty}\right). \tag{18}$$

The "Phillips curve" solves for the sequence of inflation $\{\pi_t\}_{t=0}^{\infty}$ such that the price index equation (2) holds period by period:

$$1 = \mathcal{P}\left(\{w_t\}_{t=0}^{\infty}, \{Y_t\}_{t=0}^{\infty}, \{r_t\}_{t=0}^{\infty}, \{\pi_t\}_{t=0}^{\infty}\right). \tag{19}$$

We still need to calculate aggregate real flow profits, as they will constitute part of the households' income.

$$\begin{aligned}
\Pi_t &= \int (p_{jt} - w_t)p_{jt}^{-\gamma} v_{jt} Y_t - Y_t \frac{\phi}{2}\Big(\frac{p_{jt}\pi_t}{p_{j,t-1}} - \pi_{t-1}^{\xi}\pi^{1-\xi}\Big)^2 \, dj \\
&= Y_t - w_t \Delta_t^p Y_t - K_t \\
\text{where} \quad K_t &= Y_t \frac{\phi}{2} \int \Big(\frac{p_{jt}\pi_t}{p_{j,t-1}} - \pi_{t-1}^{\xi}\pi^{1-\xi}\Big)^2 \, dj \\
\Delta_t^p &= \int v_{jt} p_{jt}^{-\gamma} \, dj
\end{aligned}$$

Above, K_t reflects aggregate price adjustment costs and Δ_t^p price dispersion, with $N_t = \Delta_t^p Y_t$. Thus, real GDP, X_t, can be written as

$$X_t = Y_t - K_t. \tag{20}$$

2.2.3 Price Phillips Curve of the Marginal-Cost Model

With firm-level convex marginal costs, the dynamic price setting problem is

$$\max_{\{p_{jt}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \left(\prod_{s=0}^{t-1} \frac{1}{1+r_s} \right) \left(\underbrace{p_{jt}^{1-\gamma} Y_t - c_t \left(p_{jt}^{-\gamma} Y_t \right)}_{\text{variable profit}} - \underbrace{Y_t \frac{\phi}{2} \Big(\frac{p_{jt}\pi_t}{p_{j,t-1}} - \pi_{t-1}^{\xi} \pi^{1-\xi} \Big)^2}_{\substack{\text{price}\\ \text{adjustment costs}}} \right) \tag{21}$$

where

$$c_t(y_{jt}) = w_t \int_0^{y_j} M \left(u^{-1} \left(\frac{y}{\Theta \overline{Y}_t} \right) \right) dy. \tag{22}$$

is the real cost curve. As in the conventional model, all price setters choose $p_{jt} = 1$. The result of the price setting problem is thus the following Phillips curve:

$$\left(\pi_t - \pi_{t-1}^{\xi} \pi^{1-\xi} \right) \pi_t = \underbrace{\frac{\gamma - 1}{\phi}}_{\kappa^p} \left(\frac{\gamma}{\gamma - 1} c_t'(Y_t) - 1 \right) + \frac{1}{1+r_t} \frac{Y_{t+1}}{Y_t} \left(\pi_{t+1} - \pi_t^{\xi} \pi^{1-\xi} \right) \pi_{t+1} \tag{23}$$

where

$$c_t'(Y_t) = w_t M \left(u^{-1} \left(\frac{Y_t}{\Theta \overline{Y}_t} \right) \right) \tag{24}$$

is real marginal cost. Aggregate labor demand is

$$N_t(Y_t) = \int_0^{Y_t} M \left(u^{-1} \left(\frac{y}{\Theta \overline{Y}_t} \right) \right) dy. \tag{25}$$

2.3 The Intertemporal Keynesian Cross

In this subsection, we describe the ingredients required to derive the intertemporal Keynesian cross following Auclert et al. (forthcoming): a household consumption-savings problem, fiscal policy, and monetary policy.

2.3.1 Households

There is a unit continuum of households, indexed by $i \in [0, 1]$, which each face idiosyncratic shocks to their productivity, e_{it}, following an AR(1) process in logs with persistence ρ_e.

$$\log e_{it} = \rho_e \log e_{it-1} + \varepsilon_{e,it}, \quad \varepsilon_{e,it} \sim \mathcal{N}(0, \sigma_e^2). \tag{26}$$

The stationary distribution for e_i is log-normal with $E[e_i] = 1$ and $sd(\log(e_i)) = \sigma_e$. Each household belongs to labor unions that set the wage and choose the number of hours worked. Thus, household i provides labor N_{ikt} to a unit measure of unions $k \in [0, 1]$. Each household provides an equal amount of labor to all labor unions. Since households' labor supply choice is determined by unions and productivity is exogenous, households take their disposable income z_{it} as given. Households suffer disutility $v(\int N_{ikt} dk)$ from working and discount future utility by β.

Households must choose consumption in the current period c_{it} and savings in safe assets (government bonds) a_{it}, which pay a real interest rate r_{t+1} in the next time period. They face a borrowing constraint $\underline{a}$, which is the minimum asset level they must have. Thus, households choose c_{it} and a_{it} to maximize utility subject to the budget constraint and borrowing constraint:

$$\begin{aligned} V_t(e_{i,t-1}, a_{i,t-1}) = \max_{c_{it}, a_{it}} u(c_{it}) - v\left(\int N_{ikt}\, dk\right) + \beta E\left[V_{t+1}(e_{it}, a_t)|e_{it}\right] \\ s.t. \quad c_{it} + a_{it} \le (1 + r_t)a_{it-1} + z_{it}(e_{it}) \\ a_{it} \ge \underline{a} \end{aligned} \tag{27}$$

Real disposable income z_{it}, taken as given, is made up of labor income paid at wages $\{w_{kt}\}_k$ for each efficiency unit of labor, profits (Π_t) paid in proportion to productivity, and targeted transfers, all in real terms. We assume that transfers are dispensed via fixed sharing rules based on labor income. Specifically, each household with productivity e_{it} receives a fraction $\gamma^T(e_{it})$ of aggregate transfers T_t, where $\int \gamma^T(e_{it})di = 1$. Wage and profit income is taxed at a proportional rate τ. Thus,

$$z_{it} = (1 - \tau)\left(\int w_{kt} N_{ikt} e_{it} dk + \Pi_t e_{it}\right) + \gamma^T(e_{it})T_t \tag{28}$$

$$= (1 - \tau)\left(w_t N_t e_{it} + \Pi_t e_{it}\right) + \gamma^T(e_{it})T_t \tag{29}$$

$$= (1 - \tau)X_t e_{it} + \gamma^T(e_{it})T_t. \tag{30}$$

Note that

$$w_t = \left(\int w_{kt}^{1-\varepsilon} dk\right)^{\frac{1}{1-\varepsilon}}$$

where ε is the elasticity of substitution between unions for the labor aggregators that hire the workers from them.[7] Because all households contribute the same mass of workers to every union and labor aggregators hire the same number of workers from each of them:

$$N_{ikt} = N_t = \int\int N_{ikt} dk di$$

for all i, k, with N_t being aggregate labor demand. Finally,

$$X_t = w_t N_t + \Pi_t$$

is real GDP. We can solve this problem numerically using the endogenous grid point method to derive a consumption policy function $\mathcal{C}\left((1-\tau)\{X_t\}_{t=0}^{\infty}, \{T_t\}_{t=0}^{\infty}, \{r_t\}_{t=0}^{\infty}\right)$, expressed in sequence space, which for any given paths of GDP, transfers, and real interest rate outputs a path of aggregate consumption.

2.3.2 Fiscal and Monetary Policy

The government sets real government spending, G_t, and transfers, T_t, exogenously. This spending is financed by income taxation and government debt by issuing real bonds B_t. The government's budget constraint is

$$G_t + T_t + (1 + r_t)B_{t-1} \le B_t + \tau X_t. \tag{31}$$

The government does not actively try to bring down the debt in response to a fiscal stimulus. Instead, debt returns to steady state due to the endogenous movement of GDP in response to the

[7] See section 2.4 for further details.

shock. We will show that our main results are robust to considering an active fiscal rule that slowly raises tax rates in response to spending increases in Appendix C.1.

As in Auclert et al. (forthcoming), the central bank follows a real rate rule, setting $\{r_t\}_{t=0}^{\infty}$ exogenously. This is equivalent to a Taylor rule of the form

$$\log(1 + i_t) = \log(1 + r + \hat{r}_t) + \log(\pi_{t+1}) \tag{32}$$

where $\hat{r}_t$ are exogenous deviations from the steady state real interest rate r. Since monetary policy is not the primary focus of this paper, this approach simplifies the interpretation of the impulse responses to fiscal shocks by removing effects coming from endogenous monetary reactions.

Goods market clearing is given by

$$C_t + G_t = X_t \tag{33}$$

Asset market clearing implies

$$A_t = B_t \tag{34}$$

where C_t and A_t are aggregate consumption and asset demand respectively. The household and two policy blocks together fully determine the path of GDP through the Intertemporal Keynesian Cross (IKC):

$$\mathcal{C}\Big((1-\tau)\{X_t\}_{t=0}^{\infty}, \{T_t\}_{t=0}^{\infty}, \{r_t\}_{t=0}^{\infty}\Big) + \{G_t\}_{t=0}^{\infty} = \{X_t\}_{t=0}^{\infty}. \tag{35}$$

To see why the matrix of iMPCs is the fundamental object disciplining the GDP response to fiscal stimulus, differentiate both sides of equation (35) with respect to the sequence of transfers $\mathbf{T}$ to get

$$(1-\tau)\frac{d\mathcal{C}}{d(1-\tau)\mathbf{X}}\frac{d\mathbf{X}}{d\mathbf{T}} + \frac{d\mathcal{C}}{d\mathbf{T}} = \frac{d\mathbf{X}}{d\mathbf{T}}.$$

where bold variables denote sequences. We can see that the general equilibrium response of GDP to transfer shocks, $\frac{d\mathbf{X}}{d\mathbf{T}}$ depends on two related objects, $\frac{d\mathcal{C}}{d(1-\tau)\mathbf{X}}$ and $\frac{d\mathcal{C}}{d\mathbf{T}}$, which are both based on the distribution of underlying individual iMPCs. An individual's iMPC is the fraction she consumes at a given horizon out of an unexpected shock to her income at another horizon. Formally, $\frac{d\mathcal{C}}{d(1-\tau)\mathbf{X}}$ is the matrix of *weighted* iMPCs because we can derive it by averaging over all the individual iMPCs weighted by individual productivity e_{it}. This procedure works because aggregate after tax income, $(1-\tau)X_t$, enters household income proportionally to e_{it} (see equation 30). On the other hand, $\frac{d\mathcal{C}}{d\mathbf{T}}$ is the matrix of unweighted iMPCs because we derive it by summing over the iMPCs of everyone who receives the transfer without multiplying by productivity. Quasi-experimental estimates of iMPCs using micro data tend to estimate $\frac{d\mathcal{C}}{d(1-\tau)\mathbf{X}_0}$, the response of consumption at each time horizon to an unanticipated income shock (see Fagereng et al. 2021 for an example). We will discipline our model-implied iMPCs by explicitly matching a standard estimate of $\frac{d\mathcal{C}_0}{d(1-\tau)\mathbf{X}_0}$, the contemporaneous response.

2.4 The Wage Phillips Curve

Households provide labor to unions, which set wages and hours and whose output is packaged by a competitive sector of labor aggregators. Thus, this sector aggregates labor $\{N_{kt}\}_{k\in[0,1]}$ from specialized unions k into a homogeneous labor input N_t with constant elasticity of substitution ε:

$$N_t = \left(\int N_{kt}^{\frac{\varepsilon-1}{\varepsilon}}\; dk\right)^{\frac{\varepsilon}{\varepsilon-1}} \tag{36}$$

Table 1: Calibrated Parameters

Parameter	Description	Value	Rationale
π	Steady state gross inflation	1	Standard
φ	Labor supply shifter	.83	Normalize ss output (Y) to 1
β	Discount factor	.93	2% ss annual real interest rate
τ	Income tax rate	.24	MPC of .16
G	ss government spending	.109	Avg. G/GDP 2010-2019
T	ss transfers	.117	Avg. T/GDP 2010-2019
$\bar{Y}$	Capacity Constraint	1.473	77% avg. cap. util. rate (2010-2019)
γ	Elasticity of subs. intermediates	16.65	Local convexity of supply curve
ε	Elasticity of subs. between unions	100	Wage markup in ss of 1.01
σ	Inverse elasticity of intertemp sub	2	Standard
ν	Inverse Frisch	1	Standard
ϕ	Price adjustment costs	830	.019 slope of price Phillips curve
ξ	Indexation to past inflation	0	Standard
ψ	Wage adjustment costs	11,205	.008 slope of wage Phillips curve
ρ_e	Persistence of productivity	.966	Persistence of log earnings
σ_e	SD of productivity stationary distribution	.92	SD of log gross earnings
ρ_v	Persistence of intermediary demand	.999	Minimize ss price adjustment costs (Y $\approx$ GDP)
σ_v	SD of demand stationary distribution	2.05	Local steepness of supply curve
a_{min}	Borrowing limit	0	Standard
p_{min}	Min price grid-point	.001	Close to 0

These aggregators exist so that firms just choose N_t given some aggregate nominal wage W_t, instead of choosing N_{kt} for each union given nominal wages for each union $\{W_{kt}\}_{k\in[0,1]}$. Expenditure minimization yields the labor demand curve:

$$N_{kt} = \left(\frac{w_{kt}}{w_t}\right)^{-\varepsilon} N_t, \quad w_t = \left(\int w_{kt}^{1-\varepsilon}\, dk\right)^{\frac{1}{1-\varepsilon}} \tag{37}$$

Unions thus set wages to maximize households' utility taking the labor demand curve, aggregate labor N_t, inflation π_t, and the real interest rate, r_t, as given. Unions also face quadratic nominal wage adjustment costs. For a given path of real wages, $\{w_{kt}\}_{k,t}$, let $V_i = V_t(e_{it}, a_{it}, \{w_{kt}\}_{k,t})$ from equation (27). Thus, union k solves:

$$\max_{\{w_{kt}\}_{t=0}^{\infty}} \int V_i\, di - \sum_{t=0}^{\infty} \beta^t \Big\{ \frac{\psi}{2}\Big(\frac{w_{kt}\pi_t}{w_{kt-1}} - 1\Big)^2 \Big\} \tag{38}$$

We assume that all unions hire the same representative collection of household members across $i \in [0,1]$, so that all unions solve the same optimization problem and set the same wage $w_{kt} = w_t\ \forall k$ each period. The solution to the union problem yields the wage Phillips curve:[8]

$$\begin{aligned}\left(\frac{w_t}{w_{t-1}}\pi_t - 1\right)\frac{w_t}{w_{t-1}}\pi_t = \frac{\varepsilon}{\psi} N_t \left(v'(N_t) - \frac{\varepsilon-1}{\varepsilon}(1-\tau_t)\, w_t \int u'(c_{it}) e_{it} di\right) \\ + \beta\left(\frac{w_{t+1}}{w_t}\pi_{t+1} - 1\right)\frac{w_{t+1}}{w_t}\pi_{t+1}\end{aligned} \tag{39}$$

The average wedge in the households' labor supply curve is a measure of slack:

$$v'(N_t) - \frac{\varepsilon-1}{\varepsilon}(1-\tau_t)\, w_t \int u'(c_{it}) e_{it} di$$

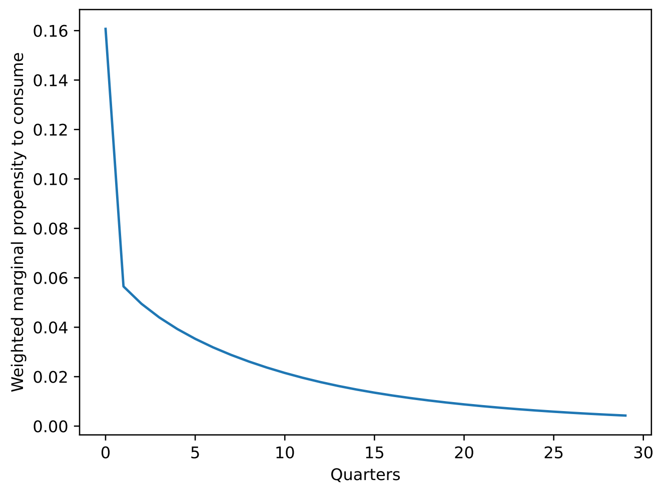
where $\frac{\varepsilon}{\varepsilon-1} - 1$ is the wage markup. The slope of the log-linearized wage Phillips curve is $\kappa^w = \frac{\varepsilon}{\psi} N v'(N)$.

2.5 Calibration

All parameters are calibrated to match either existing empirical evidence or standard values in the literature at a quarterly frequency. Table 1 lists the calibrated values for each parameter as well as

[8] See Appendix A.3 for the derivation

Figure 2: Intertemporal Marginal Propensities to Consume (First Column)



Note: This figure plots the first column of the Jacobian of the sequence space consumption function with respect to GDP: $\frac{d\mathbf{C}}{d(1-\tau)\mathbf{X}_0}$.

the rationale for each. We use the standard functional forms

$$u(c) = \frac{c^{1-\sigma}}{1-\sigma}, \quad v(N) = \varphi\frac{N^{1+\nu}}{1+\nu}$$

and choose conventional values for ν (an inverse Frisch elasticity of 1) and σ (an inverse elasticity of inter-temporal substitution of 2). The labor supply shifter φ is calibrated to normalize steady state output, Y, to 1. The discount factor β is calibrated to be consistent with a steady state annualized real interest rate, r, of 2%. The steady state tax rate, τ, is chosen to achieve a level of liquidity consistent with a quarterly (weighted) MPC of about .15, which is a typical quasi-experimental estimate in the literature (Havranek and Sokolova 2020). Figure 2 plots the productivity-weighted partial equilibrium response of consumption at time t to an income shock at time 0 (iMPCs). We calibrate government spending G and transfers T each to 10.9 and 11.7 percent of GDP, respectively, matching the average ratios from 2010-2019. Data on government expenditures data, transfers, and GDP come from the Bureau of Economic Analysis (BEA).

We discretize e_{it} to a ten-point grid and given our calibration for ρ_e and σ_e, the bottom four points account for 25% of the income distribution, the fifth and sixth points each account for 25% each, and the top four points account for the remaining 25%. Motivated by the fact that the pandemic stimulus checks went to all households earning under $150,000, or the bottom 80% of the income distribution, we assume that everyone with idiosyncratic productivity in the bottom 6 grid points receives the same amount of transfers.[9] Specifically, we set $\gamma^T(e_{it}) = 1.34$ for the bottom six grid points and $\gamma^T(e_{it}) = 0$ for the top four.

Appendix A.1 shows how estimates of the supply curve in Boehm and Pandalai-Nayar (2022) identify γ and σ_v given a value for capacity utilization. Specifically, we match the first derivative of the log markup, $\log M\left(u^{-1}\left(e^{\log u}\right)\right)$, with respect to log-utilization, to equal their estimate of .27 and the second derivative to equal their estimate of .93. We choose the steady state value of

[9] https://www.statista.com/statistics/203183/percentage-distribution-of-household-income-in-the-us/

$\overline{Y}$ to approximate the average industrial capacity utilization rate (77%) from 2010-2019 according to the series from the Board of Governors. ε is set to 100 to bring the steady state wage markup $(\frac{1}{\varepsilon-1})$ over households' marginal rate of substitution close to 0. Changes in the debt level due to fiscal policy do not result in a change in tax rates. In the long run, the debt is still paid off because deficit-financed fiscal stimulus creates a boom in output which increases tax revenues and thus reduces the debt burden.

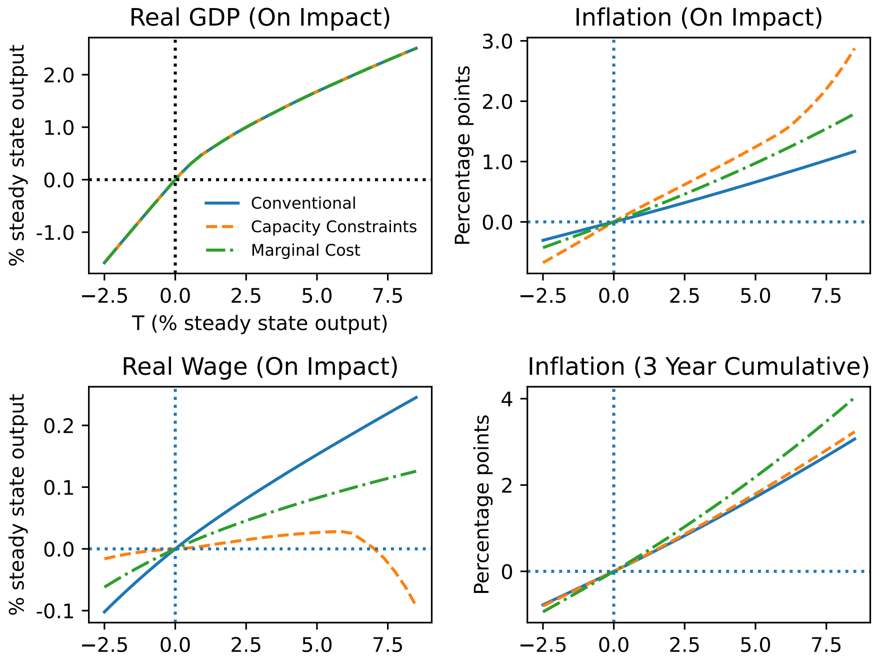
Price adjustment costs ϕ and wage adjustment costs ψ are set to match estimates of the slopes of the linearized price and wage Phillips curves respectively. We follow the procedure in Auclert et al. (forthcoming) for constructing these estimates. In a Calvo pricing model, these slopes are equal to $\frac{1}{1+\Gamma}\left(1-\frac{1}{1+r}(1-\text{freq})\right)\frac{\text{freq}}{1-\text{freq}}$ where freq is the quarterly frequency of price adjustment and Γ captures real rigidites. We use Auclert et al. (forthcoming)'s preferred estimate of $\Gamma = 5$. For the frequency of price adjustments, we convert the monthly value of .105 from Nakamura and Steinsson (2008) to a quarterly value of .28.[10] For the frequency of wage adjustments, we use a quarterly value of .194 from Grigsby et al. (2021). The resulting slopes are $\kappa^p = .025$ and $\kappa^w = .008$. We also make the conventional choice to have no indexation to past inflation in the price Phillips curve and set $\xi = 0$, although we show that our results are robust to including indexation in Appendix C.2.

The choice for $\rho_e = .966$ comes from an estimate in Floden and Lindé (2001) converted to quarterly by McKay et al. (2016). As in Auclert et al. (forthcoming), we calibrate $\sigma_e = .92$ based on an estimate of the standard deviation of log-gross earnings in the United States. We also make the conventional choice of setting $a_{min} = 0$ to prevent borrowing. Finally we set $\rho_v = .999$ to make steady state price adjustment costs as close as possible to zero. The reason they are not automatically zero in steady state is because individual firms continue to receive new idiosyncratic demand shocks v_{jt} and adjust their prices accordingly. In the comparison models, there is a representative price setter with no idiosyncratic demand so price adjustment costs are zero in steady state. We thus set ρ_v very high to facilitate comparison. With price adjustment costs close to zero, we have that $Y \approx \text{GDP}$ in steady state.[11] The calibration is otherwise identical across all three models we consider, with the exception of φ and ψ which have to be adjusted in each model to achieve $Y = 1$ and $\kappa^w = .008$.

3 Impulse Responses

In this section, we document that our capacity-constraint model exhibits quantitatively meaningful size and state dependence in response to fiscal policy shocks. The marginal response of inflation to fiscal stimulus increases with the size of the stimulus. Moreover, in the presence of a capacity tightening shock, inflation is more sensitive to expansionary fiscal shocks. However, the persistence of inflation following a fiscal shock is lower in the capacity-constraint specification than in the conventional model and the cumulative inflationary effect is similar. On the other hand, the marginal-cost model exhibits neither meaningful size nor state dependence, but generates much more persistence in inflation and thus more cumulative inflation than the conventional model. We obtain impulse responses by solving the model nonlinearly given unanticipated perfect-foresight shocks, using the sequence space Jacobian approach outlined in Auclert et al. (2021).

Figure 3: Size Dependent Response to a one-quarter Transfer Shock



Note: "Conventional" refers to the model with a conventional Phillips curve, "Capacity Constraints" refers to the model with firm-level capacity constraints, and "Marginal Cost" refers to the model with firm-level convex marginal costs. On-impact inflation is annualized.

3.1 Size Dependence

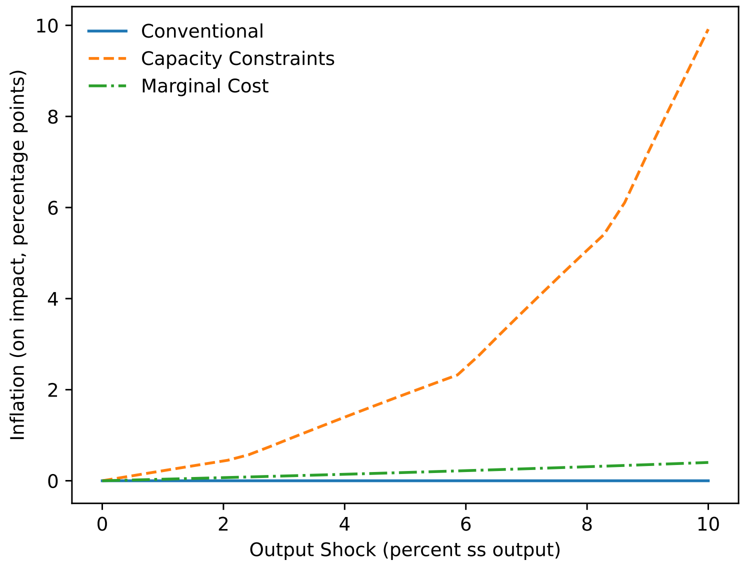
Figure 3 shows the on-impact response to a one-quarter unanticipated transfer shock, varying the size of the transfer shock. With the capacity-constraint micro-foundation, the inflation response is convex in the size of the transfer shock, while in both the conventional model and the marginal cost model the response is approximately linear. The different inflation responses between the three models do not become quantitatively relevant until the transfer shock is at least 2% of GDP. For reference, the cyclical component of transfers (from a Hodrick-Prescott filter) was 7.8% in 2020Q2 and 8.8% in 2021Q1, whereas it was at most 1.6% in any quarter during the Great Recession. Thus, the strong convexity in the proposed capacity-constraint model was highly relevant during the pandemic, but not so for the fiscal expansion during the Great Recession. Similar results can be found for government expenditure, G, in Appendix B.

Figure 3 also shows that the GDP response is the same across the models since GDP does not depend on the supply side of the economy; however, the real wage response differs significantly. With a conventional Phillips curve, the real wage is the forcing variable, so increased demand can only lead to increased inflation via an increase in the real wage. In both the capacity-constraint model and the marginal-cost model, an increase in aggregate demand can increase inflation independent of the real wage, although that effect is far more pronounced with price setting under firm-level capacity constraints. Figure 4 shows this result in partial equilibrium, holding the real

[10] They estimate a range of .09-.12 so we take the mid point. Let f_m be the monthly frequency. The quarterly frequency is then $1-(1-f_m)^3$.

[11] GDP differs from Y because it subtracts price adjustment costs.

Figure 4: Partial Equilibrium On-Impact Inflation Response to an Output Shock



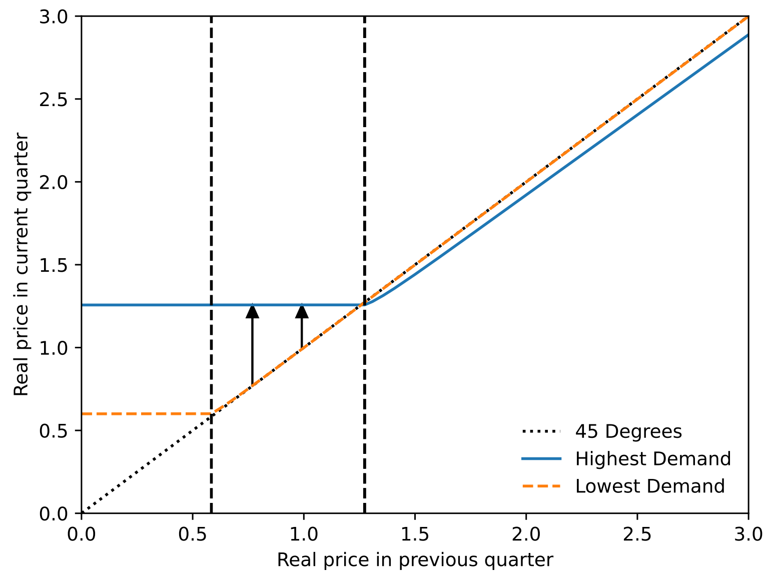
Note: Impulse Response of annualized inflation to an output shock at time $t = 0$, holding the wage fixed. "Conventional" refers to the model with a conventional Phillips curve, "Capacity Constraints" refers to the model with firm-level capacity constraints, and "Marginal Cost" refers to the model with firm-level convex marginal costs. On-impact inflation is annualized.

wage fixed. Because nominal wages are quite sticky, if inflation is high enough, it can overcome the increase in nominal wages from higher output and produce a negative real wage response.

To understand convexity in the capacity-constraint model depicted in figure 4, it is useful to look at the partial equilibrium pricing function $p(v_{jt}, p_{j,t-1})$ in the capacity-constraint model (as derived in implicit form in 2.2.2) in steady state. This pricing function is shown in figure 5, plotting the relative price that firms choose, conditional on their price in the previous quarter $p_{j,t-1}$ and their current level of idiosyncratic demand v_{jt}; aggregate values such as output Y_t and inflation π_t are at steady-state. Quadratic price adjustment costs imply that firms adjust prices slowly, causing the lines to be near the 45-degree line. But crucially, the capacity constraint creates a price floor regardless of the previous quarter price. This floor exists because at a price set below the floor, the quantity demanded would exceed the firm's production capacity. The binding price floors are visible as the flat parts of the pricing functions. The pricing function for each v_{jt} bisects the 45-degree line once; that is the fixed point which a firm j's price p_{jt} would converge to if it were to keep drawing the same v_{jt}. In a discretized distribution for v_{jt}, as we use in our computations, the steady state distribution of firm-level prices p_{jt} has its support bounded by the fixed points of the pricing functions for the lowest and highest demand, at roughly $(0.84, 1.26)$.

To visualize increased price sensitivity when close to capacity, consider a firm in steady-state whose demand changes from lowest to highest. Depending on its past period price, we can delineate three zones marked by the vertical dashed lines. The left zone is where all firms are constrained and is not very interesting for this purpose. The right zone is where the firm remains unconstrained even when facing high demand. Any change in prices here is modest due to price adjustment frictions. The middle zone is where this particular demand change causes a previously unconstrained firm to

Figure 5: Steady State Pricing Function in Capacity-Constraint Model



Note: "Lowest demand" and "Highest demand" refer to the lowest and highest value of the discretized grid for firm-level demand v_{jt}. The dashed line for lowest demand appears to coincide with the 45-degree line when unconstrained, but this is numerical; it bisects the latter at around 0.84.

become constrained: the price floor forces a jump, so firms that have too low a price are much more price-sensitive than those that are already close to the price floor. An aggregate shock can suddenly place a lot of firms onto the left side of the middle zone, increasing aggregate price sensitivity.[12] Therefore, aggregate price sensitivity to a demand shock increases when demand becomes larger, or mathematically: $\frac{\partial^2(\mathcal{P}_t)}{\partial Y_t^2} > 0$. If the real wage is held fixed, the only way for equation (19) to hold is for inflation to rise and put countervailing downward pressure on $\mathcal{P}_t$.

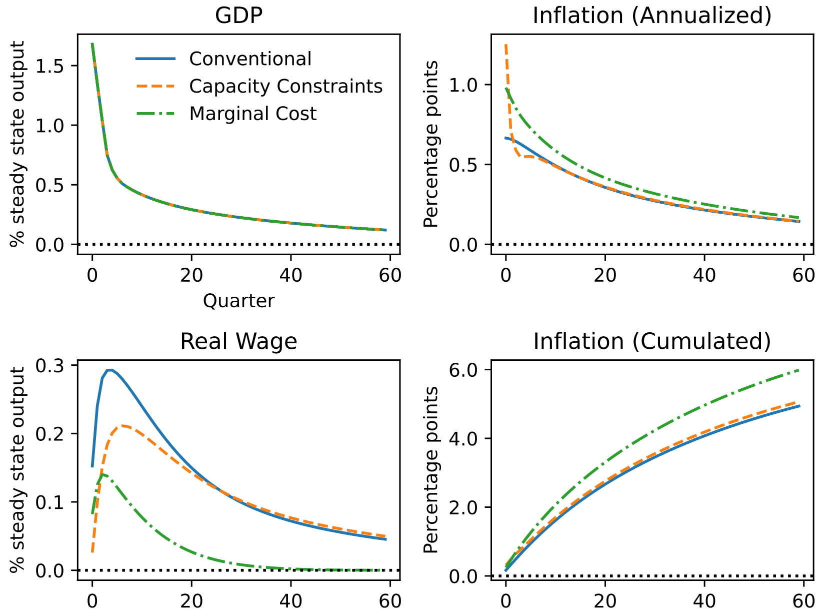
Lastly, the bottom-right panel of figure 3 shows that the cumulative inflation response over three years is quite similar between the conventional and capacity-constraint models even at high levels of transfers. As will be discussed next, this occurs because after the transfer shock dissipates, the capacity constraints slacken and previously constrained firms are relieved of their pressure to increase prices. Notably, however, the cumulative response is greater under the marginal-cost model and this discrepancy grows in the size of the transfer shock.

3.2 Persistence

Figure 6 plots the impulse response of inflation over time to a 5% (of steady-state output) transfer shock in period $t = 0$. Consistent with the results in figure 3, the contemporaneous response is greatest in the capacity-constraint model and lowest in the conventional model. However, the response in the capacity-constraint model is far less persistent than in the model with firm-level convex marginal costs. The main reason for this difference comes from the different price setting dynamics. Under capacity constraints, constrained firms are forced to immediately increase prices until they reach the price floor. Under convex marginal costs, without hard constraints, those firms

[12] Note that outside of steady state, the exact locations of the zones and the policy functions change.

Figure 6: Impulse Response of Inflation to a Transfer Shock



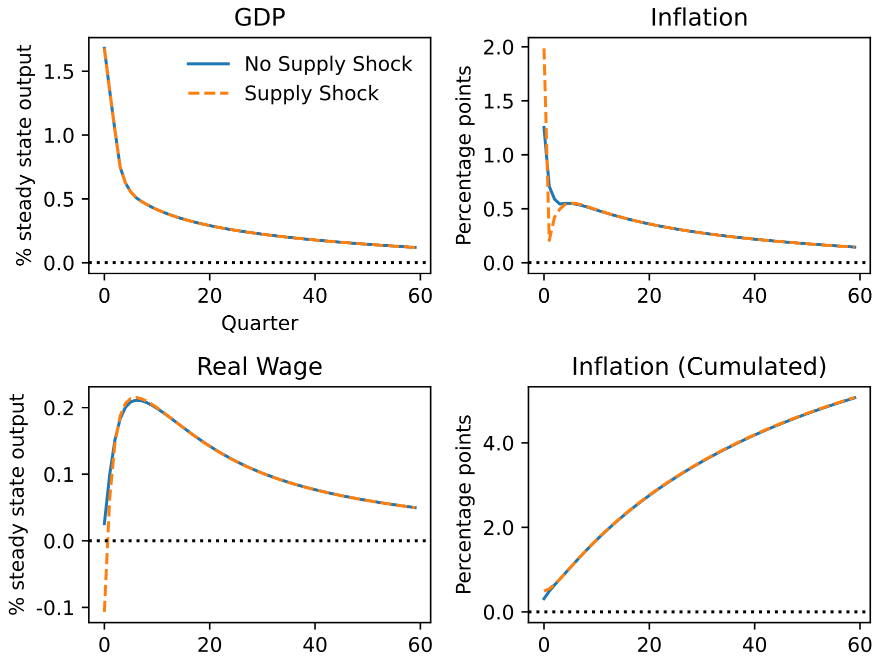
Note: Impulse Response of annualized inflation to a 5% (of output) rise in transfers at time 0. "Conventional" refers to the model with a conventional Phillips curve, "Capacity Constraints" refers to the model with firm-level capacity constraints, and "Marginal Cost" refers to the model with firm-level convex marginal costs.

can adjust gradually, which they prefer because of the quadratic price adjustment costs. In the capacity-constraint model, once demand starts to fall and capacity constraints slacken, firms drop their prices quite steeply. The drop is sufficiently steep that 3-year cumulative inflation is the same in both the capacity-constraint and the conventional models. In the marginal-cost model, firms also drop their prices much more gradually as they never had to sharply raise them in the first place; thus, inflation is more persistent. Similar results can be found for government expenditures, G, in Appendix B.

3.3 State Dependence

While the earlier results highlighted the dependence of the inflation and wage responses in the capacity-constraint model on the size of the transfer shock, figure 7 shows that these responses also depend on the state of the economy: it considers the marginal contribution of a transfer shock when capacity concurrently falls by 2% of steady state output with an AR(1) persistence of 0.5. We then compare the impulse response to an increase in transfers of 5% of steady state output with the same transfer shock but without the concurrent fall in capacity. For reference, as will be discussed in Section 4, capacity decreased by a maximum of 2.7% of steady state output during the pandemic. When firms are more constrained, the contemporaneous inflation response is larger because the constrained firms must adjust prices rapidly. Real wages fall on impact because nominal wage rigidities prevent nominal wages from increasing as much as inflation does, just like before. As in the previous analysis, firms that become constrained from the capacity shock raise their prices sharply on impact but also decrease their prices sharply once the constraints slacken. While the contemporaneous effect of the fiscal stimulus on inflation depends on the capacity shock, the

Figure 7: State-Dependence in the Capacity-Constraint Model



Note: Impulse Response of annualized inflation to a 5% (of steady-state GDP) increase in transfers at time $t = 0$. The "Supply Shock" line includes an additional 2% (of steady-state output) capacity tightening shock at time 0 with AR(1) persistence coefficient equal to .5. The supply shock lines net out the effect of capacity shocks on their own. On-impact inflation is annualized.

cumulative effect is very similar with and without a capacity shock. Similar results can be found for government expenditure, G, in Appendix B. By definition there is no such state dependence with the conventional Phillips curve as production capacity plays no role in that model. Production capacity does play a role in the marginal-cost model through the definition of marginal costs in equation (11). However, this model does not exhibit quantitatively meaningful state dependence because the adjustment of prices is more gradual since firms are never completely constrained and so do not raise prices rapidly.

4 Effects of Fiscal Policy During the Pandemic

In this section, we explore the role of fiscal policy in generating the inflation dynamics during the COVID-19 pandemic and its aftermath. As mentioned before, the effect of fiscal policy on inflation depends primarily on three objects. The first is a mapping from fiscal stimulus to GDP, which we model via the IKC disciplined by estimates of the marginal propensity to consume. The second object is a price Phillips curve derived from an underlying convex supply curve that we discipline with the estimates in Boehm and Pandalai-Nayar (2022), and the third object is a conventional wage Phillips curve. The necessary inputs for these three objects are the sequences of observed changes in capacity, real interest rates, government expenditures, and government transfers. We take all of these series directly from the data as explained in Appendix A.4. Finally, because non-linearities are crucial in the supply side of our model, the effect of fiscal stimulus on inflation will depend on the overall level of demand in the economy. Given the observed paths of fiscal and monetary policy, we solve for the discount rate shocks such that the model generates the observed cyclical movements of GDP. We use the discount rate shocks since it captures the increase in households' savings rate due to constraints on households' ability to spend on services.

To get the observed changes, we calculate log-deviations of government spending (G_t), transfers (T_t), and capacity ($\overline{Y}_t$) from their trend values. We map these deviations in the data to deviations from steady state in the model. For the real interest rate (r_t) we calculate the deviation from the mean in the data and map it to the percentage point deviation from steady state in the model. The data on government spending and transfers come from the BEA while capacity comes from the Board of Governors' industrial capacity index.[13] Interest rates come from the effective Federal Funds Rate. We benchmark the model against core PCE inflation since the model lacks a separate food or energy sector. For consistency, GDP and interest rates are converted to real terms using core PCE inflation as well.

The deviations from trend for GDP, capacity, government spending, and transfers are calculated using a Hodrick-Prescott filter on the logged series beginning in 1960Q1.[14] Specifically, for a variable x_t, we HP-filter $\log x_t$ to get the cyclical component $\hat{x}_t$. The model is written in levels with steady state output normalized to 1, so shocks are interpreted as percent deviations from steady state output. To map the empirical $\hat{x}_t$ to model deviations from steady state, we perform the following transformation: $x_t - x_{ss} = (e^{\hat{x}_t} - 1)x_{ss}$. For real interest rates, we use the mean value from 1990 onward as the steady-state level and for inflation, we use the commonly-accepted value of 2% as steady-state inflation. We choose 1990 to exclude the high real interest rates in the 1980s, especially since it is well known that the natural rate of interest has fallen since (for example, see Del Negro et al. 2019).

To highlight the surprise nature of the extent of fiscal stimulus, fiscal policy shocks are treated as fully unanticipated each quarter whereas changes in capacity, discount rates, and real interest rates are set to be fully anticipated beginning in 2020Q2. The change in the discount rate is estimated to match GDP in the data given the other shocks and is necessary to generate the recession. Figure 8 displays the path of GDP in the data along with the observed capacity and policy shocks, computed discount factor shocks, and implied savings rates, which are consistent across all three models. Households looked significantly more patient in 2020Q2-Q3 and in 2021Q2-Q3. This is consistent with the origins of the recession as an inability of households to spend on services due to the pandemic, which lead to increased savings. There was indeed a large spike in the personal savings rate in the data in 2020Q2. Agents believe that each shock series will converge to steady state in 2024Q1. The economy is assumed to start at steady state before 2020Q2 because it is the first full quarter of the pandemic.[15]

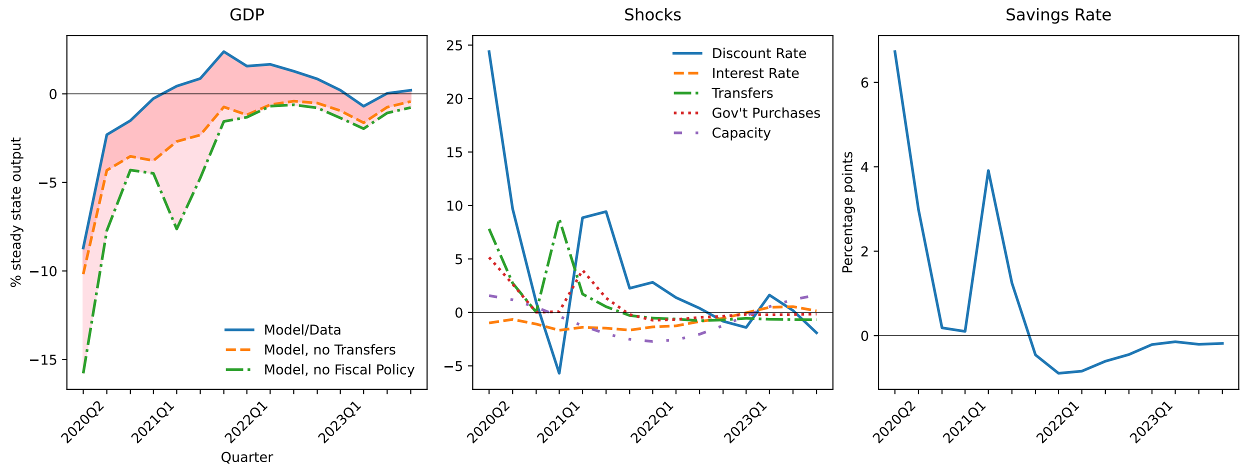
Figure 9 shows the resulting processes for inflation from 2020Q2 to 2023Q4 in each of the three models with and without fiscal policy shocks and Table 2 summarizes the key results. Observed core PCE inflation peaked at 6% (annualized) in the second quarter of 2021. With hard capacity constraints, fiscal policy generates 5.5 percentage points (annualized) of inflation in this quarter and with convex marginal cost it generates 4.9 percentage points. In contrast, fiscal policy only accounts for 3.9 percentage points of inflation in the conventional model. With all shocks, the

[13] Technically this capacity index is analogous to $\Theta\overline{Y_t}$ in the model, which is aggregate output assuming all firms produce at their capacity constraint. However, we want to feed in shocks directly to $\bar{Y}_t$ in the model. Fortunately, because Θ is a constant, it drops out when we take log-deviations from trend so we can interpret these log deviations in $\bar{Y}_t$ space.

[14] Because of data availability, capacity begins in 1967Q1.

[15] Because of the perfect anticipation of discount rate changes, beginning in 2020Q1 would also change households' behavior in that quarter even though in reality, the pandemic appeared too late for behavior in that quarter to change significantly.

Figure 8: GDP and Shocks During the Pandemic



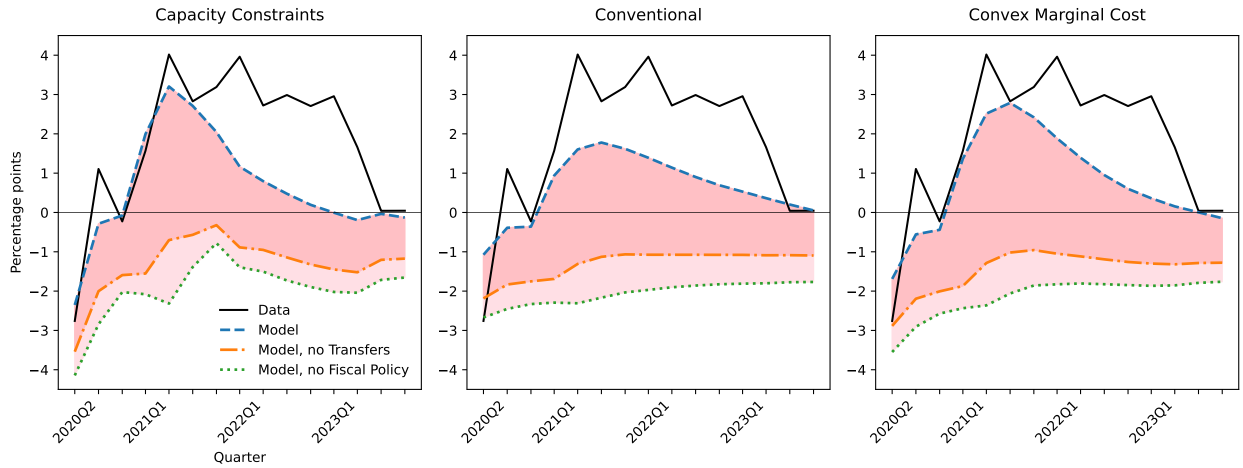
Note: The left-most panel plots GDP as percent deviation from steady state. Specifically, the discount factor shocks are chosen so the model path of GDP exactly matches the cyclical component of GDP in the data given the observed values of the other shocks (middle panel). With the exception of the discount factor, the shocks are plotted in level deviations from steady state. Because steady state output is normalized to 1, we can interpret the transfer, government spending, and capacity shocks as percent deviations from steady state output. We can interpret the interest rate shock in percentage point deviations from steady state. The discount factor shock is plotted as percent deviation from the steady state discount factor of .923. The rightmost panel shows the model implied savings rate given the discount factor shocks, which is plotted as a percentage point deviation from steady state.

capacity-constraint model accounts for 80% of the spike in inflation, the convex marginal cost model accounts for 60%, and the conventional model only accounts for 40%.

In total from 2020Q2-2023Q4, core PCE grew by 7.1 percentage points above target (2% annual) in the data. In the model with capacity constraints, fiscal policy generates 9.6 percentage points of core PCE growth; however most of this inflation comes from preventing substantial disinflation in the absence of fiscal policy. The model with all shocks only generates 2.4 percentage points of inflation over this time horizon. Cumulative inflation is actually similar in the model with a conventional Phillips curve as fiscal policy generates 9.9 percentage points of core PCE growth and the full model generates 2.4 percentage points. Consistent with the impulse response in figure 6, fiscal policy leads to more persistent inflation in the model with convex marginal costs. Specifically, fiscal policy generates 10.8 percentage points of core PCE growth and the model with all shocks accounts for 2.9 percentage points. These results demonstrate that under convex supply curves, fiscal policy can account for much more of the initial spike in inflation than in a conventional model but that it cannot account for persistence of inflation and cumulative price growth during the pandemic.

The models do not generate the high persistence we see in inflation after 2021Q2. One explanation is unmodeled supply shocks such as a rise in oil prices. While we use core inflation, which eliminates the direct effects of oil price changes on inflation, it does not remove the indirect effects since oil is an important input into many products that are included in core inflation. These indirect effects can be quantitatively important, as noted by Minton and Wheaton (2023) and shown in Figure 16 in Appendix C.3. Filtering the inflation series to remove the indirect effects of oil reduces the persistence of inflation considerably, as seen in Figure 17. This suggestive evidence is consistent with our model results that the spike in inflation in 2021 was largely due to fiscal policy but not the persistence.

Figure 9: Model-Implied Inflation During the Pandemic



Note: The figure plots annualized inflation in each model from 2020Q2 to 2023Q4 as a percentage point deviation from steady state given the filtered shocks. Annualized inflation in the data is plotted as a percentage point deviation from 2%.

A popular narrative is that capacity declined during 2021 and 2022, for example because of supply chain disruptions. The capacity data indicates a decline in $\bar{Y}_t$ of up to 2.7% of steady state GDP. Tighter capacity amplifies the effect of a fiscal shock by constraining more firms in response to a demand shock, increasing price pressure in the economy. Figure 10 suggests that the peak inflation response would have been lower without the capacity tightening in the data. Specifically, the capacity-constraint model generates only 60% of the spike in inflation in that case. As discussed in Section 3.3, capacity shocks are not quantitatively important in either the conventional or marginal-cost model.

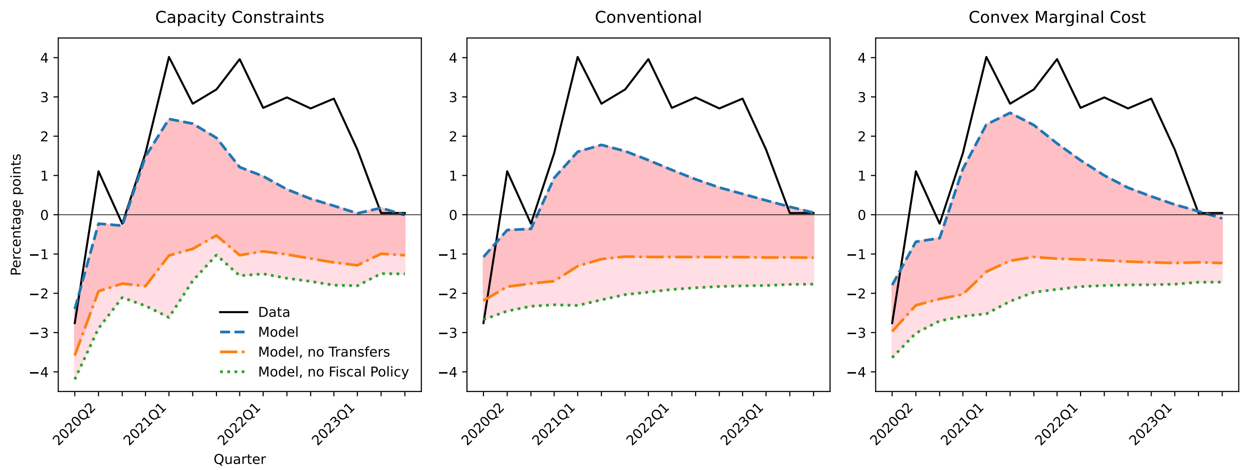
Table 2: Inflation Under Counterfactual Simulations: 2020Q2–2023Q4

Outcome	Inflation at Spike (2021Q2)			Cumulative Inflation		
Model	CC	Conventional	MC	CC	Conventional	MC
Data (Deviation From 2%)	4			7.1		
All Shocks	3.2	1.6	2.5	2.4	2.4	2.9
No Fiscal Shocks	-2.3	-2.3	-2.4	-7.2	-7.5	-7.9
Contribution of Fiscal Policy	5.5	3.9	4.9	9.6	9.9	10.8
No Capacity Shocks	2.4	1.6	2.3	2.2	2.4	2.7
No Capacity or Fiscal Shocks	-2.6	-2.3	-2.5	-7.3	-7.5	-8
Contribution of Fiscal Policy	5	3.9	4.8	9.5	9.9	10.7

Note: All numbers are in percentage points. Inflation at the spike is annualized. "CC" refers to the model with capacity constraints, and "MC" refers to the model with convex marginal costs. On-impact inflation is annualized.

Next, we consider the effects of fiscal policy on GDP in figure 8. Since real GDP is determined

Figure 10: Model-Implied Inflation during the Pandemic: No Capacity Shocks



Note: The figure plots annualized inflation in each model from 2020Q2 to 2023Q4 as a percentage point deviation from steady state without shocks to capacity. Annualized inflation in the data is plotted as a percentage point deviation from 2%.

by the demand side of the economy, this decomposition is identical across the models. GDP during the pandemic would have been persistently lower without the support from fiscal policy. In 2020Q2, quarterly real GDP would have been 7% lower (as a percent of steady state output) without fiscal policy and taken 11 quarters longer to return to its steady-state value. Cumulatively, this implies a loss in GDP from 2020Q2 through 2023Q4 equal to 13% of steady state annual output. For reference the sum of all fiscal policy shocks over this period is 6.5% of steady state annual GDP.

5 Conclusion

Recent empirical evidence suggests that supply curves are convex. This paper has shown that under such convexity, large levels of fiscal expenditures or expenditures when firms are close to their capacity constraints can generate much higher inflation than a conventional Phillips Curve would suggest. This mechanism is quantitatively important, particularly in understanding the effects of fiscal policy on inflation from 2020 to 2021. We shed further light on the debate about whether inflation during the pandemic was driven by supply or demand-side factors. We show that an increase in demand due to the higher government spending can explain much of the inflation during this period, particularly when augmented by a modest decline in capacity.

Our model does not generate the high persistence we see in inflation well after the fiscal shock ended (2021Q3–2023Q4) and therefore attributes the residual inflation to unmodeled cost-push shocks. While we discuss some evidence that oil shocks account for part of this persistence, future work should further investigate the matter further. One possibility is that our model lacks frictions like the sticky household expectations that Auclert et al. (2020) suggest are important to match aggregate impulse responses. We chose not to incorporate such frictions out of a desire for conceptual clarity and to emphasize the role of convexity. It is possible, however, that such frictions would enable the model to match the persistence of inflation.

This paper also shows that two natural ways of generating convexity lead to different impulse responses – even when yielding the same static supply curve. Empirical work distinguishing between the importance of capacity constraints and convexity in marginal costs would thus be welcome.

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Appendix

A Additional Model Details

A.1 Static Nominal Supply Curve with Capacity Constraints

Here we reproduce a derivation from the appendix of Boehm and Pandalai-Nayar (2022). Given demand $Y_{jt} = \left(\frac{P_{jt}}{P_t}\right)^{-\gamma} v_{jt} Y_t$, price setters solve

$$\max_{P_{jt}} P_{jt} \left(\frac{P_{jt}}{P_t}\right)^{-\gamma} v_{jt} Y_t - W_t \left(\frac{P_{jt}}{P_t}\right)^{-\gamma} v_{jt} Y_t \quad s.t. \quad P_{jt} \geq \left(\frac{Y_t v_{jt}}{\bar{Y}_t}\right)^{\frac{1}{\gamma}} P_t =$$

$$\max_{P_{jt}} P_{jt}^{1-\gamma} - W_t P_{jt}^{-\gamma} \quad s.t. \quad P_{jt} \geq \left(\frac{Y_t v_{jt}}{\bar{Y}_t}\right)^{\frac{1}{\gamma}} \quad s.t. \quad P_{jt} \geq \left(\frac{Y_t v_{jt}}{\bar{Y}_t}\right)^{\frac{1}{\gamma}} P_t$$

The derivative of the objective function is

$$(1-\gamma) + \gamma W_t P_{jt}^{-1} < 0 \iff P_{jt} > \frac{\gamma}{\gamma - 1} W_t.$$

So, if

$$\frac{\gamma}{\gamma - 1} W_t > \left(\frac{Y_t v_{jt}}{\bar{Y}_t}\right)^{\frac{1}{\gamma}} P_t$$

the price setter will choose $P_{jt} = \frac{\gamma}{\gamma-1} W_t$ but if

$$\frac{\gamma}{\gamma - 1} W_t \leq \left(\frac{Y_t v_{jt}}{\bar{Y}_t}\right)^{\frac{1}{\gamma}} P_t$$

they will choose $P_{jt} = \left(\frac{Y_t v_{jt}}{\bar{Y}_t}\right)^{\frac{1}{\gamma}} P_t$. The value of v_{jt} at which the price setter is at their constraint is given by

$$\frac{\gamma}{\gamma - 1} W_t = \left(\frac{Y_t \bar{v}_t}{\bar{Y}_t}\right)^{\frac{1}{\gamma}} \iff \bar{v}_t = \left(\frac{\gamma - 1}{\gamma} \frac{W_t}{P_t}\right)^{\gamma} \frac{\bar{Y}_t}{Y_t}.$$

Note that for unconstrained firms with $v_{jt} < \bar{v}_t$ we have that

$$\bar{v}_t = \left(\frac{P_{jt}}{P_t}\right)^{\gamma} \frac{\bar{Y}_t}{Y_t} = \frac{\bar{Y}_t}{Y_{jt}} v_{jt} \implies Y_{jt} = \bar{Y}_t \frac{v_{jt}}{\bar{v}_t}.$$

Recall that

$$Y_t = \left(\int v_{jt}^{\frac{1}{\gamma}} Y_{jt}^{\frac{\gamma-1}{\gamma}} dj\right)^{\frac{\gamma}{\gamma-1}}$$

Thus,

$$Y_t = \left(\int_0^{\bar{v}_t} v_{jt}^{\frac{1}{\gamma}} \left(\frac{v_{jt}}{\bar{v}_t}\bar{Y}_t\right)^{\frac{\gamma-1}{\gamma}} dv_j + \int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}} \bar{Y}_t^{\frac{\gamma-1}{\gamma}}\right)^{\frac{\gamma}{\gamma-1}} = \bar{Y}_t \left(\bar{v}_t^{\frac{1-\gamma}{\gamma}} \int_0^{\bar{v}_t} v_{jt} dv_j + \int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}}\right)^{\frac{\gamma}{\gamma-1}}.$$

Aggregate capacity is determined by output when all firms produce at $\bar{Y}_t$ and is thus equal to

$$\bar{Y}_t \underbrace{\left(\int_0^{\infty} v_{jt}^{\frac{1}{\gamma}} dv_j\right)^{\frac{\gamma-1}{\gamma}}}_{\Theta}$$

Capacity utilization is thus given by

$$u_t = \frac{Y_t}{\Theta \bar{Y}_t} = \frac{1}{\Theta}\left(\bar{v}_t^{\frac{1-\gamma}{\gamma}} \int_0^{\bar{v}_t} v_{jt} dv_j + \int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}}\right)^{\frac{\gamma}{\gamma-1}}$$

which implicitly establishes an invertible mapping between utilization and the demand shock at which firms become constrained: $u_t = u(\bar{v}_t)$. Next recall that the CES price index is

$$P_t = \left(\int P_{jt}^{1-\gamma} v_{jt} dj\right)^{\frac{1}{1-\gamma}}.$$

So,

$$\begin{aligned}
P_t &= \left(\int_0^{\bar{v}_t} v_{jt} \left(\frac{\gamma}{\gamma-1} W_t\right)^{1-\gamma} dv_j + \int_{\bar{v}_t}^{\infty} \left(\left(\frac{Y_t v_{jt}}{\bar{Y}_t}\right) P_t\right)^{1-\gamma} dv_j\right)^{\frac{1}{1-\gamma}} \\
&= \left(\int_0^{\bar{v}_t} v_{jt} \left(\frac{\gamma}{\gamma-1} W_t\right)^{1-\gamma} dv_j + \int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}} \left(\frac{Y_t}{\bar{Y}_t}\right)^{\frac{1-\gamma}{\gamma}} P_t^{1-\gamma} dv_j\right)^{\frac{1}{1-\gamma}} \\
&= \left(\int_0^{\bar{v}_t} v_{jt} \left(\frac{\gamma}{\gamma-1} W_t\right)^{1-\gamma} dv_j + \int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}} \bar{v}_t^{\frac{\gamma-1}{\gamma}} \left(\frac{\gamma}{\gamma-1} W_t\right)^{1-\gamma} dv_j\right)^{\frac{1}{1-\gamma}} \\
&= \frac{\gamma}{\gamma-1} W_t \underbrace{\left(\int_0^{\bar{v}_t} v_{jt} dv_j + \bar{v}_t^{\frac{\gamma-1}{\gamma}} \int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}} dv_j\right)^{\frac{1}{1-\gamma}}}_{M(\bar{v}_t)}
\end{aligned}$$

and

$$\log(P_t) = \log(W_t) + \log\left(\frac{\gamma}{\gamma-1}\right) + \underbrace{\log M\left(u^{-1}\left(e^{\log u_t}\right)\right)}_{\mathcal{M}(\log u_t)}.$$

The estimation in Boehm and Pandalai-Nayar (2022) identifies $\mathcal{M}'(\log u_t)$ and $\mathcal{M}''(\log u_t)$. We can see that

$$\mathcal{M}'(\log u_t) = (\log M)'(\bar{v}_t)\frac{u_t}{u'(\bar{v}_t)} = \frac{1}{\gamma}\bar{v}_t^{\frac{\gamma-1}{\gamma}}\frac{\int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}}dv_j}{\int_0^{\bar{v}_t} v_{jt}dv_j} \equiv \chi(\bar{v}_t)$$

and

$$\mathcal{M}''(\log u_t) = \frac{\chi'(\bar{v}_t)}{u'(\bar{v}_t)}u_t$$

where

$$u'(\bar{v}_t) = -\frac{1}{\Theta\bar{v}_t^2}\left(\int_0^{\bar{v}_t} v_{jt}dv_j + \bar{v}_t^{\frac{\gamma-1}{\gamma}}\int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}}dv_j\right)^{\frac{1}{\gamma-1}}\int_0^{\bar{v}_t} v_{jt}dv_j$$

and

$$\chi'(\bar{v}_t) = \frac{\frac{\gamma-1}{\gamma}\bar{v}_t^{-\frac{1}{\gamma}}\int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}}dv_j\int_0^{\bar{v}_t} v_{jt}dv_j - \bar{v}_t g(\bar{v}_t)\left(\int_0^{\bar{v}_t} v_{jt}dv_j + \bar{v}_t^{\frac{\gamma-1}{\gamma}}\int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}}dv_j\right)}{\gamma\left(\int_0^{\bar{v}_t} v_{jt}dv_j\right)^2}$$

where $g(\cdot)$ is the log-normal density function.

For computation, we need to repeatedly evaluate the integrals:

- Theta
$$\Theta = \left(\int v_{jt}^{\frac{1}{\sigma}}dj\right)^{\frac{\gamma}{\gamma-1}}$$
- upper integral
$$\int_{\bar{v}_t}^{\infty} v_{jt}^{\frac{1}{\gamma}}\ dj = \int_{\bar{v}_t}^{\infty} \nu^{\frac{1}{\gamma}}dv$$
- lower integral
$$\int_0^{\bar{v}_t} v_{jt}\ dj = \int_0^{\bar{v}_t} v\ dv$$

We use analytical expressions in our code, making use of the following derivations: Let $X \sim log\mathcal{N}(\mu,\sigma^2)$, i.e. with density $f(x) = \frac{1}{x\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right)$. To compute the integral $h(k) = \int_0^k xf(x)\ dx$:

$$h(k) = \int_0^k \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right)\ dx$$

Employ a change of variable: $y = \frac{\ln x-\mu}{\sigma} \longrightarrow x = \exp(y\sigma+\mu) \longrightarrow dx = \sigma\exp(y\sigma+\mu)\ dy$.

$$\begin{aligned}
h(k) &= \int_0^{\frac{\ln k-\mu}{\sigma}} \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{y^2}{2}\right)\ \sigma\exp(y\sigma+\mu)\ dy \\
&= \int_0^{\frac{\ln k-\mu}{\sigma}} \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{y^2}{2}+y\sigma+\mu\right)\ dy \\
&= \int_0^{\frac{\ln k-\mu}{\sigma}} \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{1}{2}(y-\sigma)^2+\mu+\frac{1}{2}\sigma^2\right)\ dy \\
&= \exp\left(\mu+\frac{1}{2}\sigma^2\right)\frac{1}{\sqrt{2\pi}}\int_0^{\frac{\ln k-\mu}{\sigma}} \exp\left(-\frac{1}{2}(y-\sigma)^2\right)\ dy
\end{aligned}$$

To phrase things in terms of standard normal objects, employ another change of variable: $u = y - \sigma \longrightarrow y = u + \sigma \longrightarrow dy = du$.

$$\begin{aligned} h(k) &= \exp\big(\mu + \frac{1}{2}\sigma^2\big)\frac{1}{\sqrt{2\pi}}\int_0^{\frac{\ln k - \mu}{\sigma} - \sigma} \exp\big(-\frac{1}{2}u^2\big)\ du \\ &= \exp\big(\mu + \frac{1}{2}\sigma^2\big)\ \Phi\Big(\frac{\ln k - \mu - \sigma^2}{\sigma}\Big) \end{aligned}$$

by courtesy of an anonymous editor on Wikipedia. So we have the expression for the lower integral, where $v_j \sim \log\mathcal{N}(0, \sigma_z^2)$:

$$\int_0^{\overline{v}_t} v\ dv = \exp\big(\frac{1}{2}\sigma_z^2\big)\ \Phi\Big(\frac{\ln \overline{v}_t - \sigma_z^2}{\sigma_z}\Big)$$

For Θ and the upper integral: If $v \sim log\mathcal{N}(\mu_z, \sigma_z^2)$, i.e. $\log v \sim \mathcal{N}(\mu_z, \sigma_z^2)$, then $\log v^{\frac{1}{\gamma}} = \frac{1}{\gamma}\log v \sim \mathcal{N}\big(\frac{\mu_z}{\gamma}, \big(\frac{\sigma_z}{\gamma}\big)^2\big)$, so apply the prior formula with parameters $\mu = \frac{\mu_z}{\gamma}, \sigma^2 = \big(\frac{\sigma_z}{\gamma}\big)^2$.

$$\begin{aligned} \Theta &= \lim_{\overline{v}_t \to \infty}\Big\{\exp\Big(\frac{\mu_z}{\gamma} + \frac{1}{2}\Big(\frac{\sigma_z}{\gamma}\Big)^2\Big)\ \Phi\Big(\frac{-\ln \overline{v}_t + \frac{\mu_z}{\gamma} + \big(\frac{\sigma_z}{\gamma}\big)^2}{\frac{\sigma_z}{\gamma}}\Big)\Big\}^{\frac{\gamma}{\gamma-1}} \\ &= \Big\{\exp\Big(\frac{\mu_z}{\gamma} + \frac{1}{2}\Big(\frac{\sigma_z}{\gamma}\Big)^2\Big)\Big\}^{\frac{\gamma}{\gamma-1}} \end{aligned}$$

For the lower integral, to account for the integration bounds, do another change of variable $w = v^{\frac{1}{\gamma}}$, and w itself is lognormally distributed as above. The integration bound is given by when $v = \overline{v}_t$, which is when $w^\gamma = \overline{v}_t$. So in terms of w, the integration bound is when $w = \overline{v}_t^{\frac{1}{\gamma}}$. Consequently, we have, using a similar derivation for the integral:

$$\begin{aligned} \int_{\overline{v}_t}^{\infty} v^{\frac{1}{\gamma}}\ dv &= \int_{\overline{v}_t^{\frac{1}{\gamma}}}^{\infty} w\ dw \\ &= \exp\Big(\frac{\mu_z}{\gamma} + \frac{1}{2}\Big(\frac{\sigma_z}{\gamma}\Big)^2\Big)\ \Phi\Big(\frac{-\ln\big(\overline{v}_t^{\frac{1}{\gamma}}\big) + \frac{\mu_z}{\gamma} + \big(\frac{\sigma_z}{\gamma}\big)^2}{\frac{\sigma_z}{\gamma}}\Big) \\ &= \exp\Big(\frac{\mu_z}{\gamma} + \frac{1}{2}\Big(\frac{\sigma_z}{\gamma}\Big)^2\Big)\ \Phi\Big(\frac{-\frac{1}{\gamma}\ln\big(\overline{v}_t\big) + \frac{\mu_z}{\gamma} + \big(\frac{\sigma_z}{\gamma}\big)^2}{\frac{\sigma_z}{\gamma}}\Big) \end{aligned}$$

A.2 Conventional Price Phillips Curve

Each firm solves

$$\max_{p_{jt}} \sum_{t=0}^{\infty}\left(\prod_{s=0}^{t-1}\frac{1}{1+r_s}\right)\left(\left(p_{jt}^{1-\gamma}Y_t - w_t p_{jt}^{-\gamma}Y_t\right) - Y_t\frac{\phi}{2}\left(\frac{p_{jt}\pi_t}{p_{jt-1}} - \pi_{t-1}^{\xi}\pi^{1-\xi}\right)^2\right).$$

Note that because every firm faces an identical optimization problem, they will all choose the same price, thus by the price index equation $p_{jt} = 1$. Applying this fact to the first order condition, we get

$$Y_t(1-\gamma+\gamma w_t) - \phi Y_t\left(\pi_t - \pi_{t-1}^{\xi}\pi^{1-\xi}\right)\pi_t = -\frac{1}{1+r_t}Y_{t+1}\phi\left(\pi_{t+1} - \pi_t^{\xi}\pi^{1-\xi}\right)\pi_{t+1} \implies$$

$$(\pi_t - \pi_{t-1}^{\xi}\pi^{1-\xi})\pi_t = \frac{\gamma-1}{\phi}\left(\frac{\gamma}{\gamma-1}w_t - 1\right) + \frac{1}{1+r_t}\frac{Y_{t+1}}{Y_t}(\pi_{t+1} - \pi_t^{\xi}\pi^{1-\xi})\pi_{t+1}.$$

Aggregate price adjustment costs are

$$K_t = Y_t\frac{\phi}{2}(\pi_t - \pi_{t-1}^{\xi}\pi^{1-\xi})^2.$$

A.3 Wage Phillips Curve

This derivation is taken from the appendix in Auclert et al. (forthcoming). Union k solves

$$\max_{w_{kt}} \int V_i di - \sum_{t=0}^{\infty}\beta^t\frac{\psi}{2}\left(\frac{w_{kt}\pi_t}{w_{kt-1}} - 1\right)^2$$

Because every union solves the same optimization problem, they will all choose the same optimal wage each period, thus by the wage index equation we will have that $w_t = w_{kt}$ in equilibrium. Let λ_{it} is the Lagrange multiplier on the time t budget constraint for household i. By the first order condition with respect to c_{it}, we know $\lambda_{it} = Pr_{it}\beta^t u'(c_{it})$. By the envelope theorem, the first order condition with respect to w_{kt} is

$$\int E_0\left(\beta^t u'(c_{it})\frac{\partial z_{it}}{\partial w_{kt}}\right)di + \beta^t\varepsilon v'(N_t)\frac{N_t}{w_t} = \beta^t\psi\left(\frac{w_t}{w_{t-1}}\pi_t - 1\right)\frac{\pi_t}{w_{t-1}}$$
$$- \beta^{t+1}\psi\left(\frac{w_{t+1}}{w_t}\pi_{t+1} - 1\right)\frac{w_{t+1}\pi_{t+1}}{w_t^2}.$$

Applying the law of iterated expectation yields

$$\int\left(\beta^t u'(c_{it})\frac{\partial z_{it}}{\partial w_{kt}}\right)di + \beta^t\varepsilon v'(N_t)\frac{N_t}{w_t} = \beta^t\psi\left(\frac{w_t}{w_{t-1}}\pi_t - 1\right)\frac{\pi_t}{w_{t-1}}$$
$$- \beta^{t+1}\psi\left(\frac{w_{t+1}}{w_t}\pi_{t+1} - 1\right)\frac{w_{t+1}\pi_{t+1}}{w_t^2}di.$$

Now,

$$z_{it} = \frac{1}{A_t}(1-\tau_t)w_t^{\varepsilon}\left(\int w_{kt}^{1-\varepsilon}dk\right)N_t e_{it} + ...$$

So,

$$\frac{\partial z_{it}}{\partial w_{kt}} = \frac{1}{A_t}(1-\tau_t)(1-\varepsilon)N_{kt}e_{it} = \frac{1}{A_t}(1-\tau_t)(1-\varepsilon)N_t e_{it}$$

Thus, we can write the wage Phillips curve as

$$\left(\frac{w_t}{w_{t-1}}\pi_t - \left(\frac{w_{t-1}\pi_{t-1}}{w_{t-2}}\right)^{\xi_w}\pi^{1-\xi_w}\right)\frac{\pi_t}{w_{t-1}} = \frac{N_t}{\psi w_t}\left((1-\varepsilon)\frac{1}{A_t}(1-\tau_t)w_t\int u'(\tilde{c}_{it})e_{it}di + \varepsilon v'(N_t)\right)$$
$$+ \beta\left(\frac{w_{t+1}}{w_t}\pi_{t+1} - \left(\frac{w_t\pi_t}{w_{t-1}}\right)^{\xi_w}\pi^{1-\xi_w}\right)\frac{w_{t+1}\pi_{t+1}}{w_t^2}$$

After some algebra we get

$$\left(\frac{w_t}{w_{t-1}}\pi_t - \left(\frac{w_{t-1}\pi_{t-1}}{w_{t-2}}\right)^{\xi_w}\pi^{1-\xi_w}\right)\frac{w_t}{w_{t-1}}\pi_t = \frac{\varepsilon}{\psi}N_t\left(v'(N_t) - \frac{\varepsilon-1}{\varepsilon}(1-\tau_t)\frac{w_t}{A_t}\int u'(\tilde{c}_{it})e_{it}di\right)$$
$$+\beta\left(\frac{w_{t+1}}{w_t}\pi_{t+1} - \left(\frac{w_t\pi_t}{w_{t-1}}\right)^{\xi_w}\pi^{1-\xi_w}\right)\frac{w_{t+1}}{w_t}\pi_{t+1}.$$

A.4 Numerical Details

We discretize the AR(1) process for idiosyncratic productivity, e, on a 10-point grid using the Rouwenhorst method. The asset distribution is discretized on a 200-point, double-exponentially-spaced grid that goes from 0 to 1,000. The price distribution is similarly discretized on a 500-point, double-exponentially-spaced grid that goes from 0.001 to 20.

The shocks are calculated as follows: for the change in real interest rates, we divide one plus the effective Federal Funds Rate (FRED code: DFF) at quarter t (at a quarterly rate, averaging the value across days in the quarter) by one plus Core PCE inflation (FRED code: PCEPILFE) in quarter $t+1$ to get $1 + r_{t+1}$. We divide by inflation one quarter ahead since r_{t+1} reflects the real return one gets next quarter and so the appropriate change in the price index is the one from time t to $t+1$. The nominal interest rate is converted from an annualized to a quarterly rate as $(1+x)^{0.25}$.

Government transfers come from the BEA's federal government social benefits to persons (FRED code: B087RC1Q027SBEA). Government spending comes from subtracting the federal government's current expenditures (also from the BEA; FRED code: FGEXPND) by the transfers from earlier. Real GDP is calculated by dividing nominal GDP (FRED code: GDP) by the price level from the Core PCE price index in the same quarter. Lastly, $\bar{Y}$ comes from the Board of Governors of the Federal Reserve's industrial capacity index (FRED code: CAPB50001SQ). This measure is intended to capture the maximum sustainable level of output under a realistic work schedule and comes from dividing production by capacity utilization, which one gets from surveys of plants in the manufacturing, mining, and utilities sectors. In unreported results, we verified that the model-implied inflation during the COVID-19 pandemic is similar when using the Federal Reserve Bank of New York's Global Supply Chain Pressure Index (GSCPI).[16]

For the $Y, G, T, \bar{Y}$ series, we take logs before HP filtering the series from 1960Q1 (with capacity beginning in 1967Q1 because of data availability) to 2024Q2 before calculating $(e^{\hat{x}}-1)\bar{x}$ as described in Section 4, where $\hat{x}$ is the cyclical component of the series and $\bar{x}$ is the steady state value of the variable in the calibration. For the real rate, we use the mean real rate from 1990Q1 to 2024Q2 as the trend value.

The model is solved in the sequence space since the computational improvements from this method allow solving a model with heterogeneity in both the household and producer blocks. The model counterfactuals are obtained via the following approach: at each time t (beginning 2020Q2), pass in the sequence of $\bar{Y}, r, \beta$ shocks from time t to 2023Q4 so that these shocks are fully anticipated. At time t, the G and T shocks are taken from the data by the method described earlier. Agents expect the future deviations of these values from steady state to be 0. Then, solve for the impulse responses nonlinearly by iterating on the path of unknowns (in this case, Y, w, π,

[16]Note that the GSCPI is reported in terms of standard deviations from the mean which requires calculating the standard deviation relative to the mean to get deviations from steady state. To do this, we HP filtered the Board of Governors' industrial capacity series and divided the standard deviation of the cyclical component by the mean and multiplied by the steady state capacity in the model. We then multiplied the GSCPI by this number to get the deviation from steady state.

which must be chosen to clear the asset market, and match the wage and price Phillips curves). The impulse responses are also calculated via this iterative method.

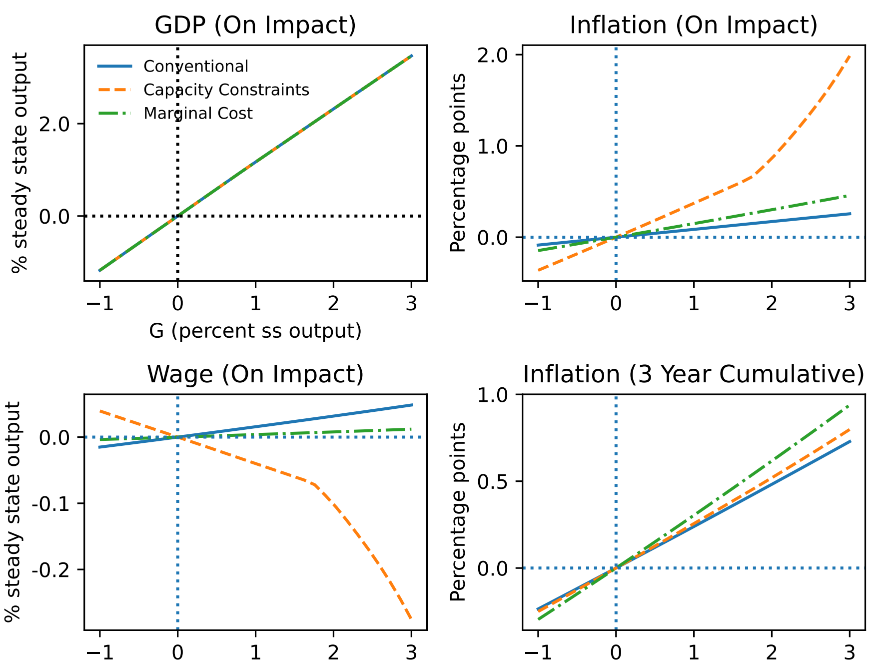
Note that the β shocks come from a fixed-point iteration to ensure that the model matches observed GDP from 2020Q2 to 2023Q4. Since the model's prediction for GDP only depends on the IKC block, which is the same across all three models, the estimated sequence of β shocks are also the same across the models.

We use the quasi-Newton method described in Auclert et al. (2021) which uses the Jacobian calculated at the steady state. In some cases, this does not converge to a solution. Then, we solve for the counterfactual values by re-computing the Jacobians at the current guess for the unknowns. Since there are $3T$ unknowns (where T is the number of time periods the model is solved for, which in our case is 200) and we have to perform this procedure for each quarter of interest (there are 15 quarters from 2020Q2 to 2023Q4), this iteration can be quite slow. We speed it up by parallelizing the Jacobian calculation across the $3T$ unknowns.

B Additional Results: Impulse Responses

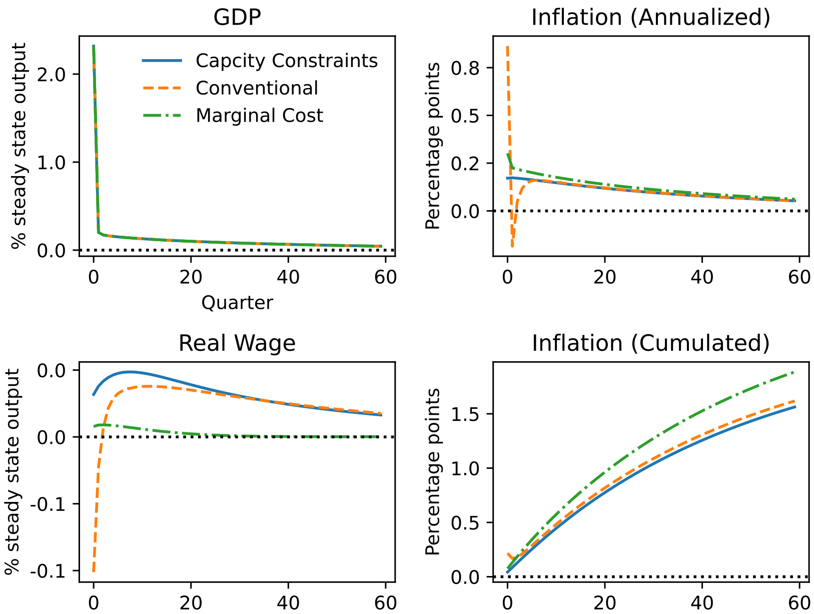
Here we replicate the exercises from Section 3 with a focus on government expenditure, G, as opposed to transfers, T.

Figure 11: On-Impact Response to a one-quarter Government Expenditure Shock



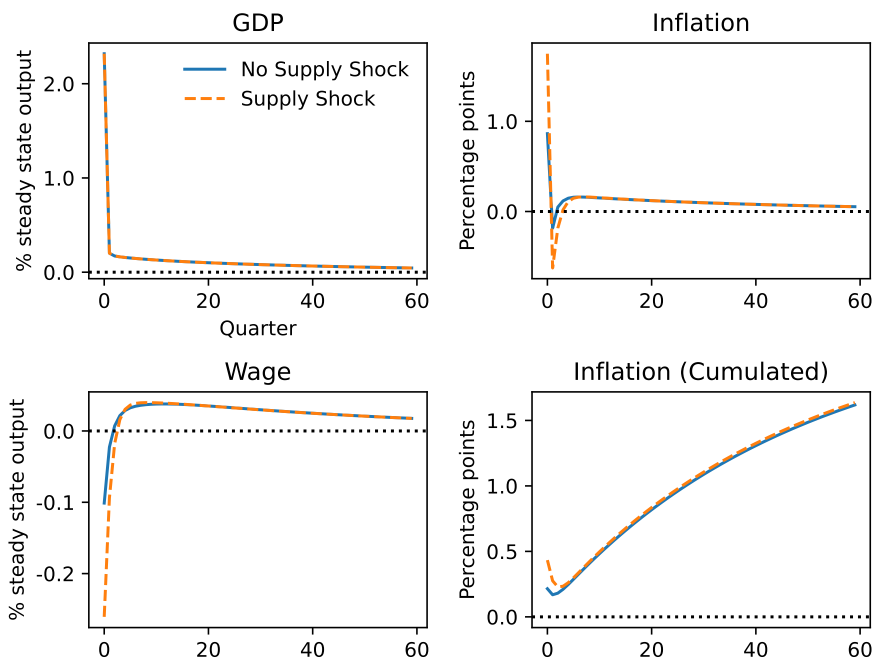
Note: "Conventional" refers to the model with a conventional Phillips curve, "Capacity Constraints" refers to the model with firm-level capacity constraints, and "Marginal Cost" refers to the model with firm-level convex marginal costs. On-impact inflation is annualized.

Figure 12: Impulse Response of Inflation to a Government Expenditure Shock



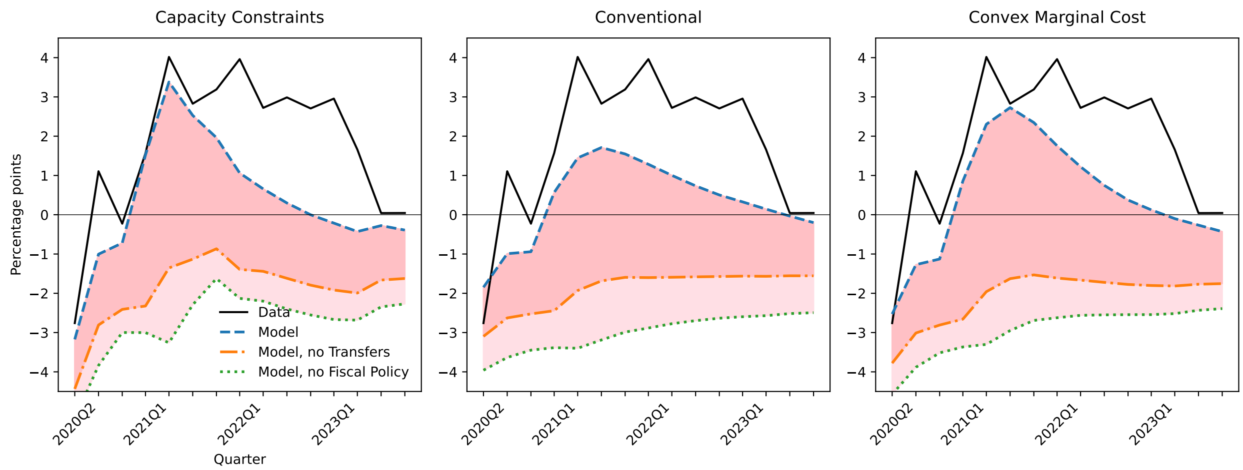
Note: Impulse Response of annualized inflation to a 2% (of steady-state output) rise in government spending at time 0. “Conventional” refers to the model with a conventional Phillips curve, “Capacity Constraints” refers to the model with firm-level capacity constraints, and “Marginal Cost” refers to the model with firm-level convex marginal costs.

Figure 13: State-Dependence in the Capacity-Constraint Model (Government Expenditure



Note: Impulse Response of annualized inflation to a 2% (of steady-state GDP) increase in government spending at time 0. The “Supply Shock” line includes an additional 2% (of steady-state output) capacity tightening shock at time 0 with AR-1 persistence coefficient equal to .5. On-impact inflation is annualized.

Figure 14: Model-Implied Inflation During the Pandemic: Active Fiscal Rule



Note: The figure plots annualized inflation in each model from 2020Q2 to 2023Q4 as a percentage point deviation from steady state given the filtered shocks. Annualized inflation in the data is plotted as a percentage point deviation from 2%.

C Additional Results: Pandemic Counterfactuals

C.1 Active Fiscal Rule

Instead of an unfunded fiscal shock, one could imagine that fiscal policy raised taxes depending on the level of debt, namely:

$$\mathcal{T}_t = \mathcal{T} + \alpha_{\mathcal{T}}(B_{t-1} - B)$$

$\mathcal{T}$ reflects tax revenues and $\alpha_{\mathcal{T}}$ reflects the level of revenue financing of fiscal policy. A higher $\alpha_{\mathcal{T}}$ means that the government increases taxes quickly in in response to a high level of debt accumulated in the past. In figure 14, we plot the inflation implied by the three models under this alternative rule. We calibrate $\alpha_{\mathcal{T}} = 0.025$ based on the coefficient estimate from a linear regression of quarterly federal tax revenue (FRED code: NA000327Q) on one-quarter-lagged federal debt (FRED code: GFDEBTN) from 2020Q1 to 2023Q4 (after HP filtering both series). The figure is very similar to that in figure 9, suggesting that the baseline results are robust to an alternative specification of fiscal rule.

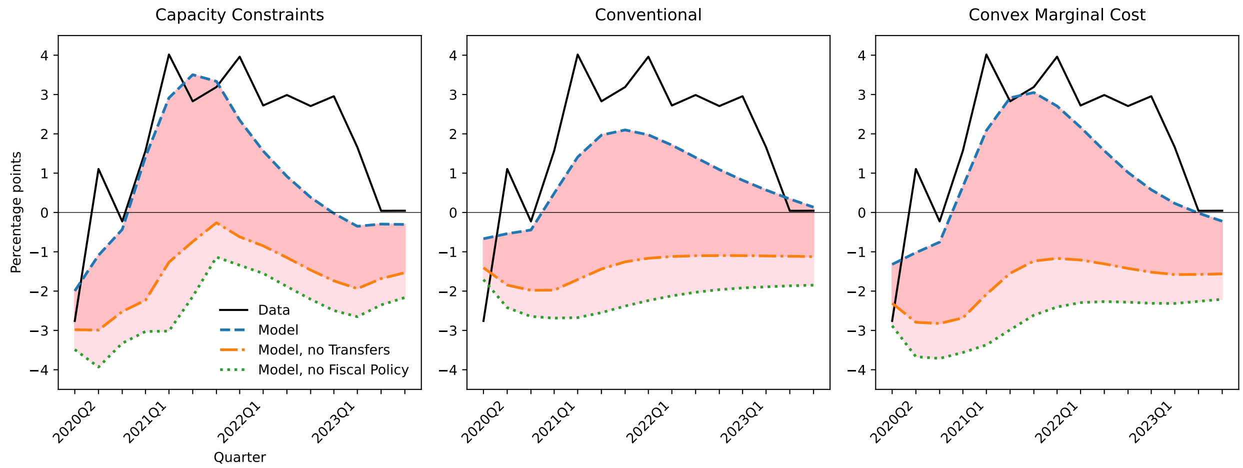
C.2 Inflation Indexation

Figure 15 shows that our main results are robust to including indexation to past inflation in the price Phillips curve. Specifically we consider the case where $\xi = .5$.

C.3 Removing the Effect of Oil on Inflation

Oil prices increased dramatically in 2021 and the first half of 2022. Since oil prices affect core inflation indirectly by increasing the marginal cost of other products and does so in a delayed manner (Minton and Wheaton, 2023), some of the persistence in inflation could be caused by this change in oil prices. We explore this possibility to test how plausible it is that fiscal policy does not contribute significantly to the high levels of core inflation in 2022, as the model simulations suggest.

Figure 15: Model-Implied Inflation during the Pandemic: $\xi = 0.5$



Note: The figure plots annualized inflation in each model from 2020Q2 to 2023Q4 as a percentage point deviation from steady state without shocks to capacity. Annualized inflation in the data is plotted as a percentage point deviation from 2%.

To do this, we extend the approach from Minton and Wheaton (2023) and perform the following two-stage instrumental variables regression:

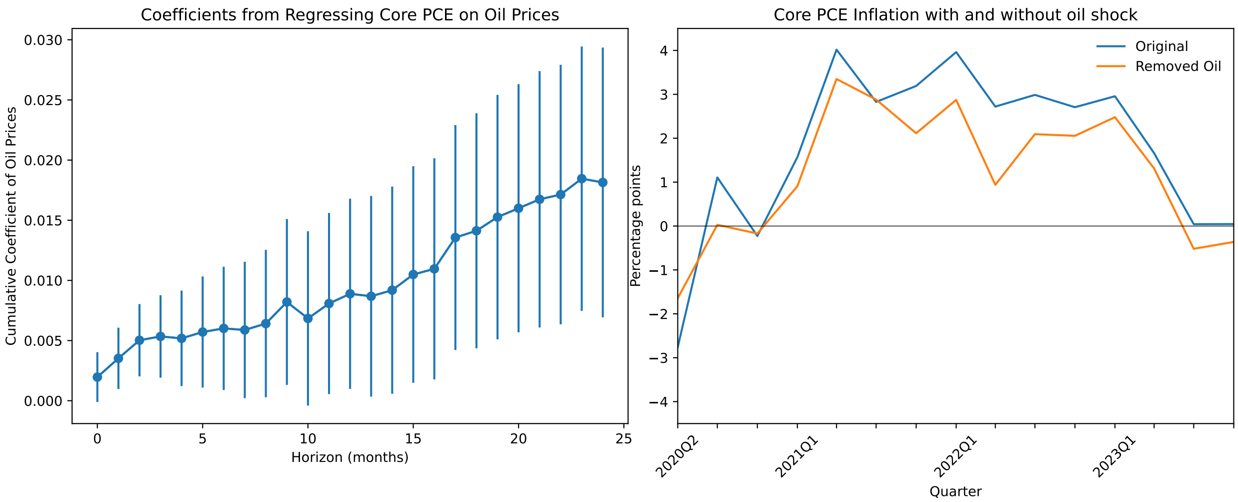
$$\Delta P_t = \alpha + \sum_{h=0}^{24} \beta_h \Delta P_{Oil,t-h} + \epsilon_t \tag{C.1}$$

Above, P_t is the core PCE inflation price index, P_{Oil} is the West Texas Intermediate crude oil prices in Cushing, Oklahoma (FRED code: DCOILWTICO). The price changes are calculated in percentage points so β_h reflects the percentage change in prices at time t from a 1% increase in oil prices in time $t-h$. $P_{Oil,t-h}$ is instrumented for using the Känzig (2021) oil supply news shock. The regression is run at the monthly level from January 1986 (first month with WTI crude oil prices) to December 2023 (last month for which the Känzig 2021 values are available).

Figure 16 plots the resulting values of the coefficients in the left panel. A 1% increase in oil prices increases the price index 2 years hence by approximately 0.02%. Note that the standard errors are large and we want to emphasize the suggestive nature of these results. The right panel shows that core PCE inflation would be lower in 2022 if we removed the effects of oil price changes using the point estimates from Equation C.1. Namely, we predict ΔP_t using oil price changes in the last 24 months (excluding the effect of the intercept) and subtract this value from actual core PCE inflation. Then, we aggregate to the quarterly level by calculating the average implied price index in each quarter and the subsequent percent change.

Figure 17 plots the baseline inflation results under the three models with this new oil-filtered inflation series. Since the inflation series is now lower, there is far less unexplained inflation in the first half of 2022, particularly in the models with convex supply curves. These results are consistent with our finding that the rapid increase in inflation in 2021 was due to fiscal policy but the persistence in 2022 was not, as the persistence can be largely driven by oil price increases. Note that we use the same shocks in this figure as in the baseline figure 9. We could have alternatively deflated nominal GDP and interest rates with this new oil-filtered measure of core inflation but it would have produced different values for the β and r shocks and thus be less comparable to the

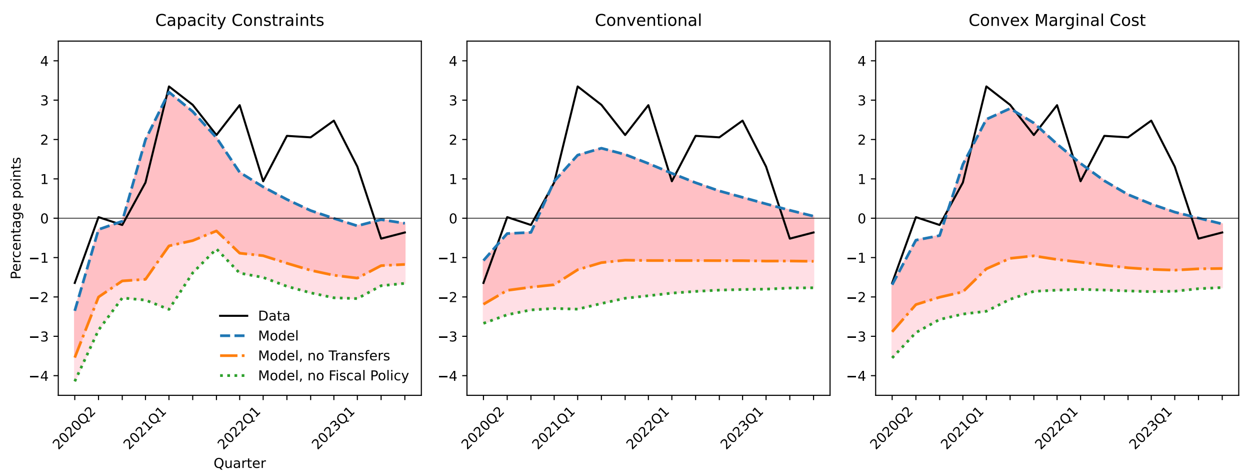
Figure 16: Effect of Oil Price Changes on Core PCE Inflation



Note: The left panel plots $\sum_{h=0}^{k} \beta_h$ for each k on the x-axis from Equation C.1. The right panel plots annualized inflation in each model from 2020Q2 to 2023Q4 as a percentage point deviation from steady state with and without filtering oil price changes. Annualized inflation in the data is plotted as a percentage point deviation from 2%. We report heteroskedasticity-robust standard errors for a 95% confidence interval and calculate standard errors for a given k as $\sqrt{\sum_{0 \leq h, h' \leq k} Cov(\beta_h, \beta_{h'})}$ to account for covariances since we are cumulating the coefficient estimates.

earlier results.

Figure 17: Model-Implied Inflation During the Pandemic: Removing Effects of Oil



Note: The figure plots annualized inflation in each model from 2020Q2 to 2023Q4 as a percentage point deviation from steady state with the "Data" line referring to core PCE inflation subtracting the effects of oil price changes. Annualized inflation in the data is plotted as a percentage point deviation from 2%.