The Limited Power of Monetary Policy in a Pandemic

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Abstract

We embed an extension of the canonical epidemiology model in a New Keynesian model with uninsurable income risk. In our framework, two factors contribute to making consumption less sensitive to real interest rate changes in a pandemic. First, individuals are less willing to take advantage of intertemporal substitution opportunities when doing so involves a risk of becoming sick. Second, households face pro-cyclical income risk and a precautionary savings motive tempers their responses to changes in future interest rates. In this context, forward guidance policies have only limited effects on real economic activity at the height of the pandemic. They can, however, help sustain the recovery once the virus starts to dissipate.

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1 Introduction

In response to the unprecedented declines in output and employment triggered by the COVID-19 pandemic, the Federal Open Market Committee (FOMC) cut the federal funds rate from a target range of 1-1/2 to 1-3/4 percent in January 2020 to its effective lower bound of 0 to 1/4 percent in March 2020. In subsequent communications, policymakers signaled that the federal funds rate is likely to remain at its effective lower bound for an extended period of time. For example, during the press conference following the June 2020 FOMC meeting, Chairman Powell declared *"We're not thinking about raising rates, we're not even thinking about thinking about raising rates"*. Recently published minutes from the July 2020 FOMC meeting also reveal that FOMC members are debating how to best formulate such forward guidance about the future path of the federal funds rate.

But, how effective can this accommodative stance of monetary policy be in the midst of a pandemic? Aside from its severity, the current recession is characterized by the unusual nature of the underlying shock. The decline in economic activity resulted from individuals' desire to minimize the risk of infection as well as from government interventions aiming at limiting the spread of the virus. Given this particular environment, should we expect monetary policy to transmit to real variables as in normal times?

To address this question, we embed an extension of the classic SIR (Susceptible, Infected, Recovered) epidemiology model in a New Keynesian model with uninsurable income risk. Two main features govern household decisions. First, the transition probability from being healthy (susceptible) to sick (infected) depends on households' consumption and labor supply decisions. Susceptible households cut back voluntarily on consumption and hours worked when the risk of infection becomes too large. Second, households face the prospect of a drop in income, against which they cannot insure, if they become seriously ill and cannot work. As a consequence, susceptible households build up their precautionary savings as the risk of becoming sick increases. These two effects imply that the economy experiences a large drop in output as the epidemic progresses, even in the absence of government interventions. In the long run, after the effects of the virus dissipate, all households are either susceptible or recovered and our model converges to the standard textbook New Keynesian model (Galí, 2008).

In standard models used for monetary policy analysis, monetary policy transmits exclusively through the intertemporal substitution channel: in response to a drop in the real interest rate, the returns to saving decrease and households want to consume more today. In our model, household's consumption becomes less sensitive to real interest rate changes during a pandemic because of two factors. First, the intertemporal substitution channel is partly impaired as increasing one's consumption increases the probability of becoming infected. Households weigh this heightened risk of infection against the benefits of taking advantage of intertemporal substitution opportunities. Second, households face pro-cyclical income risk. An expansionary monetary policy action stimulates economic activity, which brings more people in contact with each other and, in turn, translates into a build-up in new infections. In response to this rise in infection risk, susceptible households increase their precautionary savings, thereby depressing aggregate demand and counteracting the initial effects of the interest rate cut.

The importance of these two channels rises and falls nonlinearly according to the dynamics of the virus and, therefore, the extent to which monetary policy is less powerful than in normal times depends on the state of the pandemic. For example, at the onset of the epidemic, or after its peak, when the risk of infection is limited, the effectiveness of monetary policy is close to that in normal times. However, at the height of the epidemic, when the risk of infection is maximal, monetary policy has only limited effects on real economic activity. The effects of monetary policy are also persistent. This persistence arises from the influence of monetary policy on a key state variable of the model, the number of infected individuals, and implies that policymakers face an intertemporal tradeoff: stimulating economic activity today leads to new infections, which in turn depresses aggregate demand tomorrow.

To illustrate the quantitative relevance of these mechanisms, we examine the effects of delaying lift-off from the effective lower bound on nominal interest rates by one year compared to our baseline economy. Under perfect foresight, the more accommodative stance of monetary policy ignites an economic expansion early in the pandemic when the risk of infection is low. However, at the peak of the pandemic, the contraction in output is larger under the forward guidance policy than in the baseline economy. This arises for two reasons: *i)* forward guidance is ineffective at propping up economic activity when the risk of infection is high; and *ii)* policy interventions early in the pandemic lead to an additional build-up in infections that depresses demand compared to the baseline economy. Once the worst of the pandemic is over and the effects of the virus start to dissipate, forward guidance helps accelerate the recovery in economic activity.

Our paper is related to the literature on the macroeconomic implications of the COVID-19 health crisis. This literature is already too vast to be easily summarized. Instead, we point the reader to studies that are close to ours in terms of focus and modeling choices. Several authors starting with Eichenbaum, Rebelo and Trabandt (2020) have modified the standard SIR model to introduce a feedback between individuals' economic decisions and epidemic dynamics and have embedded such an extended framework in macroeconomic models. Eichenbaum, Rebelo and Trabandt (2020) and Jones, Philippon and Venkateswaran (2020) study the trade-off between public health objectives and the economic costs of the pandemic. Using a rich heterogeneous agent model, Kaplan, Moll and Violante (2020) emphasize that the trade-off is not only between lives and livelihoods, but also over who should bear the burden of the economic costs. Bodenstein, Corsetti and Guerrieri (2020) show instead that social distancing measures may improve economic outcomes, as an unchecked epidemic could incapacitate core sectors and result in a steep fall in economic activity.

Levin and Sinha (2020) and Woodford (2020) focus on the stabilizing role of monetary policy during the current health crisis and reach a similar conclusion to ours: monetary policy may be less effective during a pandemic than in normal times. However, the channels put forward by these authors differ from those we emphasize. Levin and Sinha (2020) stress that several issues such as the myopia of economic agents or limited commitment by the central bank may be especially relevant in the current environment, thereby weakening the power of forward guidance. Woodford (2020) argues that monetary policy is ineffective at restoring the first-best allocation when the effects of a shock are sectorially concentrated, as is the case today. Instead, our argument rests on the idea that households' consumption behavior has significantly changed since the onset of the pandemic.

Our paper is also related to the literature on the "forward guidance puzzle" (Del Negro, Giannoni, and Patterson, 2015) – the observation that forward guidance policies have unrealistically powerful effects in standard New Keynesian models (Eggertsson and Woodford, 2003, Calstrom, Fuerst, and Paustian, 2015). Different rationalizations to this puzzle based, for example, on departures from the rational expectations hypothesis (Woodford, 2018, Angeletos and Lian, 2018, Fahri and Werning, 2018, Gabaix, 2020), sticky information (Chung, Herbst, and Kiley, 2015, Kiley, 2016), and the presence of incomplete markets (McKay, Nakamura, and Steinsson, 2016, Werning, 2015, Bilbiie, 2019, 2020, Hagedorn et al., 2019) have been proposed in the literature. For the reasons outlined above, our model with COVID-19 effects does not suffer from the forward guidance puzzle.

The paper is organized as follows. Section 2 describes the model. Section 3 calibrates the model, simulates a pandemic of moderate size, and examines its consequences on economic activity. Section 4 performs several monetary policy exercises and shows that the effects of monetary policy are weaker in a pandemic than in normal times. Section 5 considers two extensions involving *i)* better health policies and *ii)* endogenous lockdowns. Section 6 concludes.

2 The Model

Our model economy is populated by *(i)* households: who are subject to the evolution of a pandemic, that is, start being susceptible to the virus, can become infected, can recover, and can die from the virus; *(ii)* monopolistically competitive firms facing price adjustment costs; *(iii)* a government; and *(iv)* a central bank conducting monetary policy subject to the effective lower bound on nominal interest rates.

2.1 Epidemics: The extended SIR model

In standard epidemiological models, transitions between different health status are exogenous. However, in reality, individuals may be able to reduce the probability of becoming infected by cutting down on activities that involve interacting with others, such as the purchase of consumption goods and work. Eichenbaum, Rebelo and Trabandt (2020) propose an extension of the Kermarck and McKendrick (1927) SIR (Susceptible, Infected, Recovered) model where the transition probability from being healthy (susceptible) to sick (infected) depends on people's economic decisions.

Following Eichenbaum, Rebelo and Trabandt (2020), the total number of newly infected people T_t is given by

$$T_t = \pi_{s1}\left(S_t c_{s,t}\right)\left(I_t c_{i,t}\right) + \pi_{s2}\left(S_t n_{s,t}\right)\left(I_t n_{i,t}\right) + \pi_{s3} S_t I_t. \tag{1}$$

where S_t is the number of susceptible households, I_t is the number of infected households, R_t is the number of recovered people, c_t is consumption, and n_t is hours worked. The technological parameters π_{s1}, π_{s2} denote the probability of contracting the virus while purchasing consumption goods and supplying hours worked, respectively. The parameter π_{s3} captures both how likely one is to become infected in random interactions and the intensity of these interactions. Group-specific variables are denoted with a subscript $k = S, I, R$.

The number of susceptible people, S_t, evolves according to

$$S_{t+1} = S_t - T_t. \tag{2}$$

Let π_r be the per-period probability of recovering after being infected and π_d be the per-period probability of dying if infected. The number of infected people at time $t+1$ is equal to the number of infected people at time t plus the number of newly infected, T_t, minus the number of infected people who either recovered, $\pi_r I_t$, or died, $\pi_d I_t$,

$$I_{t+1} = \left(1 - \pi_r - \pi_d\right) I_t + T_t. \tag{3}$$

The number of recovered people at time $t+1$ is the number of recovered people at time t plus the number of infected people who just recovered $\pi_r I_t$

$$R_{t+1} = R_t + \pi_r I_t. \tag{4}$$

The number of deceased people at time $t+1$ is the number of deceased people at time t plus the number of infected people who just died $\pi_d I_t$

$$D_{t+1} = D_t + \pi_d I_t. \tag{5}$$

Total population evolves according to

$$POP_{t+1} = POP_t - \pi_d I_t. \tag{6}$$

A useful statistic to summarize the transmissibility of a virus and, hence, quantify the potential intensity of an outbreak, is the basic reproduction number: $\mathcal{R}_0$. $\mathcal{R}_0$ is defined as the number of new infections generated by the first ill person in a population where everyone is susceptible. A large $\mathcal{R}_0$ implies a rapid spread of the virus. In the standard SIR model, where the probability of getting sick is exogenous and constant, $\mathcal{R}_0$ is also constant over time. Instead, in our model, individuals can reduce the probability of becoming infected by cutting down on consumption and hours worked. As a result, $\mathcal{R}_{0,t}$ is time-varying and given by

$$\mathcal{R}_{0,t} = \frac{\pi_{s1} c_{s,t} c_{i,t} + \pi_{s2} n_{s,t} n_{i,t} + \pi_{s3}}{\pi_r + \pi_d}. \tag{7}$$

After rearranging equation 3, we can express the dynamics of infections as a function of $\mathcal{R}_{0,t}$,

$$\frac{I_{t+1} - I_t}{I_t} = (\pi_r + \pi_d)\left(\mathcal{R}_{0,t} S_t - 1\right). \tag{8}$$

This equation states that the number of infected people grows when the *effective* reproduction number, $\mathcal{R}_{0,t} S_t$, is larger than one, and subsides when it is lower than one. For a given $\mathcal{R}_{0,t}$, the virus dies out naturally as S_t decreases and society reaches herd immunity. Alternatively, the spread of the virus may be halted temporarily or permanently if voluntary or government-induced changes in individual behavior are effective in reducing $\mathcal{R}_{0,t}$. Note, however, that our specification captures only endogenous social distancing through consumption and work activities. Changes in the intensity of social interactions not involving consumption or work will be modeled through shocks to the parameter π_{s3}.

2.2 Households

The economy is initially populated by a continuum of households with measure one. Prior to the epidemic, all households are identical and their momentary utility function is given by

$$u(c_t, n_t) = log(c_t) - \chi \frac{n_t^{1+1/\varphi}}{1+1/\varphi}, \tag{9}$$

where φ is the Frisch elasticity of labor supply. The consumption level c_t is a Dixit-Stiglitz aggregator of the different varieties of goods produced by firms, $c_t \equiv \left[\int_0^1 c_t(j)^{\frac{\theta-1}{\theta}} dj\right]^{\frac{\theta}{\theta-1}}$, where θ is the elasticity of substitution between varieties and $c_t(j)$ is the consumption of goods produced by firm j. The optimal allocation of income to each variety is given by $c_t(j) = \left[\frac{P_t(j)}{P_t}\right]^{-\theta} c_t$, where $P_t = \left[\int_0^1 P_t(j)^{\frac{\theta-1}{\theta}} dj\right]^{\frac{\theta}{\theta-1}}$ is the aggregate price index and $P_t(j)$ is the price of variety j.

Once the epidemic starts, households are divided in four groups: *(i)* susceptible households, S_t, who have not yet been exposed to the disease; *(ii)* infected households, I_t, who have contracted the disease; *(iii)* recovered households, R_t, who have survived and acquired immunity.[1]; and *(iv)* deceased households, D_t, who we assume are not replaced. Households in the first three categories face different optimality problems.

[1]There is no consensus in the medical and scientific communities about the duration of immunity. We acknowledge assuming long-lasting, perpetual in our case, immunity after recovering from the disease is a simplifying assumption.

2.2.1 Susceptible households

Their lifetime utility is given by

$$U_{s,t} = u(c_{s,t}, n_{s,t}) + \beta \left[(1 - \tau(c_{s,t}, n_{s,t})) \, U_{s,t+1} + \tau(c_{s,t}, n_{s,t}) U_{i,t+1} \right], \tag{10}$$

where β is the discount factor and $\tau(c_{s,t}, n_{s,t})$ is the per-period probability of getting infected by the virus. Susceptible households understand that this probability depends on their consumption and labor supply choices. The per-period probability of infection is equal to

$$\tau \left(c_{s,t}, n_{s,t} \right) = \pi_{s1} c_{s,t} \left(I_t c_{i,t} \right) + \pi_{s2} n_{s,t} \left(I_t n_{i,t} \right) + \pi_{s3} I_t. \tag{11}$$

All households have access to one-period nominal bonds $b_{s,t}$ that promise a unit of currency tomorrow and cost $(1 + r_t)^{-1}$ today. Households receive firm dividends $\Upsilon_{s,t}$ and transfers $\Gamma_{s,t}$ from the government in the form of lump-sump payments. The budget constraint of susceptible households is given by

$$\left(1 + \mu_t\right) c_{s,t} + \frac{b_{s,t}}{P_t \left(1 + r_t\right)} = \frac{b_{s,t-1}}{P_t} + w_t \phi_s n_{s,t} + \Gamma_{s,t} + \Upsilon_{s,t}, \tag{12}$$

where μ_t is the tax rate on consumption, ϕ_s is the labor productivity of susceptible households, and w_t is the wage per efficient hour. We assume that the labor productivity of susceptible households is equal to 1. Eichenbaum, Rebelo and Trabandt (2020) interpret μ_t as a proxy for containment measures aimed at reducing social interactions and, hence, refer to it as the containment rate. Mandatory social distancing measures, such as lockdown policies, can be introduced in the model through the containment rate.

Susceptible households face the following borrowing constraint:

$$b_{s,t} \geq -\psi_s, \quad \text{with} \quad \psi_s \geq 0. \tag{13}$$

Susceptible households choose consumption and bond holdings to maximize equation 10 subject to equations 11, 12, and 13. Their labor supply condition is given by

$$w_t = \frac{\chi n_s^{1/\varphi} + \beta \tau_{n_{s,t}} \left[U_{i,t+1} - U_{s,t+1}\right]}{\frac{\frac{1}{c_{s,t}} + \beta \tau_{c_{s,t}} \left[U_{i,t+1} - U_{s,t+1}\right]}{1+\mu_t}}, \tag{14}$$

where $\tau_{n_{s,t}} = \partial \tau \left(c_{s,t}, n_{s,t}\right) / \partial n_{s,t} > 0$ and $\tau_{c_{s,t}} = \partial \tau \left(c_{s,t}, n_{s,t}\right) / \partial c_{s,t} > 0$. This equation equates the wage per efficient hour with the marginal rate of substitution between hours worked and consumption for susceptible households. The marginal disutility of labor, the numerator, includes an additional term compared to a case without the virus. By working longer hours, individuals have more chances of becoming infected, in which case they suffer a loss in lifetime utility since $U_{i,t+1} - U_{s,t+1} < 0$. Thus, as the pandemic progresses through the population, susceptible households willingly cut back on hours worked. Similarly, the marginal utility of consumption, the denominator, depends on the probability that individuals will become infected through their consumption activities.

The Euler equation for susceptible households is given by:

$$\begin{aligned} \frac{1}{c_{s,t}} + \overbrace{\beta \tau_{c_{s,t}} \left[U_{i,t+1} - U_{s,t+1}\right]}^{\text{consumption vs. risk}} \geq \; & \beta \left(\frac{1+r_t}{\Pi_{t+1}}\right) \frac{1+\mu_t}{1+\mu_{t+1}} \left(\frac{1}{c_{s,t+1}} + \overbrace{\beta \tau_{c_{s,t+1}} \left[U_{i,t+2} - U_{s,t+2}\right]}^{\text{consumption vs. risk}}\right) \\ & \cdot \underbrace{\left[1 - \tau_t + \tau_t \frac{1/c_{i,t+1}}{1/c_{s,t+1} + \beta \tau_{c_{s,t+1}} \left[U_{i,t+2} - U_{i,t+1}\right]}\right]}_{\text{precautionary savings}}, \end{aligned} \tag{15}$$

where $\Pi_{t+1} = \frac{P_{t+1}}{P_t}$ is the gross inflation rate between period t and t+1. This equation holds with equality if susceptible households are not borrowing-constrained.

The Euler equation of susceptible households includes two new motives. First, the consumption versus risk motive, which states that households prefer to consume more when the risk of getting infected is low. Depending on whether the outlook for the virus is about to improve or worsen, this motive could make them more patient or impatient, respectively. Second, susceptible households engage in precautionary savings out of fear of losing income if they become infected. We capture the idea that a fraction of infected individuals will become too sick to report to work by assuming that individuals are less productive when infected with the virus. Since there is no market to insure themselves against this risk of income loss, susceptible households seek to partially insure themselves by holding bonds.

2.2.2 Infected households

Their lifetime utility is given by

$$U_{i,t} = u(c_{i,t}, n_{i,t}) + \beta \left[(1 - \pi_r - \pi_d) U_{i,t+1} + \pi_r U_{r,t+1} + \pi_d U_d \right]. \tag{16}$$

We assume that the probability of recovering, π_r, and the probability of dying, π_d, are independent of the choices made by infected households. To calibrate the cost of death using estimates of the statistical value of a life, we include a psychological cost U_d so that the cost of death comprises both the foregone utility of consumption and hours worked and this psychological cost.

The budget constraint of infected households is given by

$$(1 + \mu_t) c_{i,t} + \frac{b_{i,t}}{P_t (1 + r_t)} = \frac{b_{i,t-1}}{P_t} + w_t \phi_i n_{i,t} + \Gamma_{i,t} + \Upsilon_{i,t}, \tag{17}$$

where ϕ_i is their labor productivity. We assume that $\phi_i < \phi_s = \phi_r = 1$, that is, infected households are less productive than susceptible and recovered households[2].

Infected households face the following borrowing constraint

$$b_{i,t} \geq -\psi_i, \quad \text{with} \quad \psi_i \geq 0 \tag{18}$$

The labor supply supply condition for infected households is given by

$$\phi_i w_t = \frac{\chi n_{i,t}^{1/\varphi} c_{i,t}}{1 + \mu_t} \tag{19}$$

[2] For simplicity, we assume recovered households are as productive as susceptible ones.

and their Euler equation by

$$\frac{1}{c_{i,t}} \geq \beta \frac{1+r_t}{\Pi_{t+1}} \frac{1+\mu_t}{1+\mu_{t+1}} \left[(1-\pi_r-\pi_d) \frac{1}{c_{i,t+1}} + \pi_r \frac{1}{c_{r,t+1}} \right], \tag{20}$$

which holds with equality if infected households are not borrowing-constrained.

2.2.3 Recovered households

Their lifetime utility is given by

$$U_{r,t} = u(c_{r,t}, n_{r,t}) + \beta U_{r,t+1} \tag{21}$$

The budget constraint of recovered households is as follows

$$(1+\mu_t)\, c_{r,t} + \frac{b_{r,t}}{P_t\,(1+r_t)} = \frac{b_{r,t-1}}{P_t} + w_t \phi_r n_{r,t} + \Gamma_{r,t} + \Upsilon_{r,t}, \tag{22}$$

They face the following borrowing constraint

$$b_{r,t} \geq -\psi_r, \quad \text{with} \quad \psi_r \geq 0. \tag{23}$$

The labor supply condition for recovered households is given by

$$w_t = \frac{\chi n_{r,t}^{1/\varphi} c_{r,t}}{1+\mu_t}, \tag{24}$$

and their Euler equation by

$$\frac{1}{c_{r,t}} \geq \beta \left(\frac{1+r_t}{\Pi_{t+1}} \right) \frac{1+\mu_t}{1+\mu_{t+1}} \frac{1}{c_{r,t+1}}, \tag{25}$$

which holds with equality if they are not borrowing-constrained.

2.3 Firms

A continuum of monopolistic firms, indexed by j, produce differentiated goods according to a linear technology

$$Y_t(j) = A\left(S_t n_{s,t}(j) + \phi I_t n_{i,t}(j) + R_t n_{r,t}(j)\right), \tag{26}$$

where A is the (constant) level of technology. Firms face quadratic price adjustment costs

$$\Phi_t(j) = \frac{\phi^p}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \Pi^*\right)^2 Y_t. \tag{27}$$

These costs have the same composition as the aggregate consumption basket and are proportional to aggregate output. Firms discount future profits using households' discount factor β. Firms choose a price $P_t(j)$ to maximize the expected discounted sum of future profits

$$V_t^p\left(P_{t-1}(j)\right) = max_{P_t(j)}\frac{P_t(j)}{P_t}Y_t(j) - \frac{w_t}{A}Y_t(j) - \frac{\phi^p}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \Pi^*\right)^2 Y_t + \beta V_{t+1}^p\left(P_t(j)\right), \tag{28}$$

subject to the demand for their variety $Y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\theta} Y_t^d$, where Y_t^d is aggregate demand and Π^* is the inflation target of the monetary authority.

In equilibrium, all firms face a similar problem and choose the same price, which implies that $Y_t = \int_0^1 Y_t(j)dj = Y_t^d$. The Phillips curve is given by

$$1 - \theta + \theta\frac{w_t}{A} - \phi^p\Pi_t\left(\Pi_t - \Pi^*\right) + \beta\phi^p\Pi_{t+1}\left(\Pi_{t+1} - \Pi^*\right)\frac{Y_{t+1}}{Y_t} = 0. \tag{29}$$

We assume that price adjustment costs do not result in a loss of resources although firms behave as if they did. Following Hagedorn et al. (2019), we make this assumption to avoid "price-adjustment booms" that would arise from large price movements in a liquidity trap.

2.4 Government and monetary policy

The government does not issue debt and balances its budget constraint in every period

$$\mu_t\left(S_t c_{s,t} + I_t c_{i,t} + R_t c_{r,t}\right) = S_t \Gamma_{s,t} + I_t \Gamma_{i,t} + R_t \Gamma_{r,t}. \tag{30}$$

The monetary authority sets the short-term nominal interest rate and responds to deviations of inflation and output from their respective targets using the following rule

$$1 + r_t = max\left\{(1 + r^*)\left[\left(\frac{\Pi_t}{\Pi^*}\right)^{\delta_\pi}\left(\frac{Y_t}{Y_t^*}\right)^{\delta_y}\right], 1 + r_{min}\right\}, \tag{31}$$

where the max operator captures the presence of the effective lower bound, fixed at r_{min}. Because the size of the population evolves through time, so does the steady-state value of output. The following process for Y_t^* captures the idea that policy-makers learn gradually about this steady-state shift

$$Y_t^* = \rho_y Y_{t-1}^* - (1 - \rho_y)\widetilde{Y}, \tag{32}$$

where $\widetilde{Y}$ is the new steady-state value of output after the pandemic.

2.5 Equilibrium

Aggregate consumption is a weighted average of the consumption of each household type

$$C_t = S_t c_{s,t} + I_t c_{i,t} + R_t c_{r,t}. \tag{33}$$

Firm dividends are equal to

$$div_t = (A - w_t)\left(S_t n_{s,t} + \phi I_t n_{i,t} + R_t n_{r,t}\right) = S_t \Upsilon_{s,t} + I_t \Upsilon_{i,t} + R_t \Upsilon_{r,t}. \tag{34}$$

Thus, given that government bonds are in zero net supply, we can use the household budget constraints 12, 17, 22, the government budget constraint 30, and the expression of dividends 34 to derive an aggregate resource constraint

$$C_t = Y_t. \tag{35}$$

Finally, we assume that the proceeds from the consumption tax are redistributed proportionally to agents' consumption levels and that dividends are redistributed proportionally to agents' productive hours. This implies $\Gamma_{k,t} = \mu_t c_{k,t}$ and $\Upsilon_{k,t} = (A - w_t)\,\phi_k n_{k,t}$ for $k = S, I, R$.

We now characterize the equilibrium in the asset market. We follow Krusell, Mukoyama and Smith (2011) and assume that households are not able to borrow ($\psi_s = \psi_i = \psi_r = 0$). Under this assumption, there is no saving vehicle available to households and, in equilibrium, since individuals cannot issue debt, all households consume their income every period. Given this no-borrowing constraint, the wealth distribution is degenerate, which helps keep the model tractable. The equilibrium real interest rate that sustains the equilibrium must, in each period, ensure that no household has an incentive to save. Therefore, any real interest rate below that, consistent with the Euler equation of the household with the greater desire to save holding with equality is consistent with equilibrium. However, small positive levels of liquidity would require the equilibrium real interest rate to be unique and consistent with the Euler equation of the marginal saver (Werning, 2015). We focus on such an equilibrium with "vanishing liquidity".

Which household is likely to be the marginal saver? On the one hand, infected households are naturally impatient. They currently have low income and expect to have higher income in the future once they, hopefully, recover. They want to borrow against this future higher income to smooth consumption intertemporally. On the other hand, recovered households do not risk getting infected and face stable income (in the absence of aggregate shocks) going forward. Thus, they are likely to be more patient than infected households. The situation of susceptible households is ambiguous. As noted before, their Euler equation features two motives. First susceptible households prefer consuming when the risk of getting infected is low. Depending on whether the outlook for the virus is about to improve or worsen, this could make them more patient or impatient, respectively. Second, they anticipate that their labor income will drop if they become infected. Since there is no market to insure themselves against this risk, they seek to partially insure themselves by holding bonds. On balance, it is unclear which motive dominates. If the first motive prevails, susceptible households will be more impatient than recovered households. If the second precautionary savings motive prevails, susceptible households will be more patient than recovered households.

We conjecture that infected households will never be on their Euler equations and check that our conjecture holds in simulations. We then allow for the model to switch endogenously between the Euler equations of susceptible and recovered households depending on the circumstances. In most cases, susceptible households will be on their Euler equation as the precautionary savings motive dominates and impacts equilibrium quantities through the real interest rate.

3 The baseline economy

In this section, we calibrate the model and simulate the effects of a pandemic on the economy.

3.1 Calibration

Each time period corresponds to a week. We first choose parameters for the New Keynesian side of the model. The elasticity of substitution between goods is set to $\theta = 6$, implying that price markups are equal to 20% in steady state. The inflation target and the steady-state real interest rate are equal to 2% at an annual frequency, which correspond to gross rates of $1.02^{\frac{1}{52}}$ at a weekly frequency. The monetary authority responds to deviations of inflation and output from target with coefficient $\delta_\pi = 1.5$ and $\delta_y = 1/52$. The Frisch elasticity of labor supply φ is set to a value of $1/2$ and the productivity levels of each type of household is fixed as in Eichenbaum, Rebelo and Trabandt (2020): $\phi_s = \phi_r = 1$ and $\phi_i = 0.8$. We calibrate the price adjustment cost parameter ϕ^p according to the following logic. The current COVID-19 pandemic was an unprecedented shock to the economy but did not result in a deflationary spiral. Thus, we wish to have a relatively flat Phillips curve in order to prevent unrealistic price movements. To this end, we target a slope of the Phillips curve of 0.002 at a quarterly frequency, which implies a value of $\phi^p = 25000$ for the price adjustment cost parameter[3]. Finally, we normalize output, hours worked, and population in the pre-pandemic steady state to one. Through steady-state relationships, this pins down the parameters A and χ.

Next, we choose parameters for the SIR side of the model. Following evidence in Bar-On et al. (2020) and Fernández-Villaverde and Jones (2020), we set the basic reproduction number in the absence of containment measures to 2, the infection fatality rate to 0.8%, and the average duration in the "infected" state to 15 days. Since our calibration is weekly, this implies that $\pi_d = 0.008 * \frac{7}{15}$ and $\pi_r = \frac{7}{15} - \pi_d$. Citing evidence in Ferguson et al. (2020), Jones, Philippon and Venkateswaran (2020) assume that work and consumption activites account each for 1/3 of transmissions in the beginning of the epidemic. Instead, based on Ferguson, Cummings and Fraser (2006) and their own calculations, Eichenbaum, Rebelo and Trabandt (2020) hypothesize that work and consumption activies should account each for 1/6 of transmissions. We choose a middle value of 1/4. This implies $\pi_{s1} = 0.2456$, $\pi_{s2} = 0.2456$, $\pi_{s3} = 0.4912$. The psychological cost of death U_d is chosen to be consistent with estimates of the value of a statistical life used by government entities such as the Environmental Protection Agency (EPA). Greenstone and Nigam (2020) report that the EPA uses a 2020 value of a statistical life of \$9.9 million 2011 dollars. After accounting for income growth to 2020, they find a value of statistical life of \$11.5 million 2020 dollars. For an annual rate of return of 2%, this translates in a weekly flow value of \$4600 dollars, or about 4 times average per capita GDP. Thus, we calibrate U_d such that the flow disutility from death in our model $-\left(log(c) - \chi \frac{n^{1+1/\varphi}}{1+1/\varphi}\right) + (1-\beta)\, U_d$ is equal to 4 times average per capita GDP.

We solve the nonlinear model under the assumption of perfect foresight using

[3] To obtain this value, we conduct the following experiment. Assume that marginal cost is permanently 1% higher. In a quarterly (linearized) version of the model, this would result in a permanent $\frac{0.002}{1-\beta^{13}}$ percent increase in inflation. We want to obtain a similar answer in our weekly model. Given that the slope of the (linearized) Phillips curve is $\frac{\theta-1}{\phi^p}$, this implies that $\frac{\theta-1}{\phi^p(1-\beta)} = \frac{0.002}{1-\beta^{13}}$.

Dynare's (Adjemian et al., 2011) perfect foresight solver.

3.2 The economic effects of a pandemic

In this section, we simulate a pandemic of moderate size and overview the equilibrium population and economic dynamics. In our model economy, economic agents have perfect foresight and, hence, they know about the new virus and how it propagates through the population.

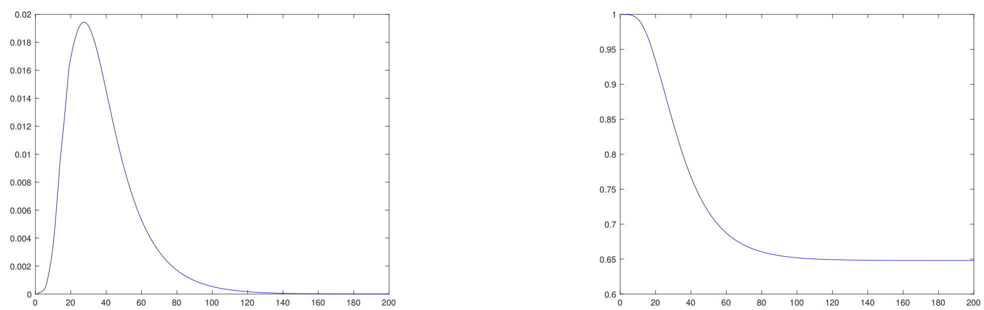
The pandemic is such that, at time zero, a small fraction of susceptible individuals is infected through zoonotic exposure, so that $I_0 = 0.0001$. We assume that there are no public health measures in place at the onset of the pandemic and thereafter, that is, the containment rate, μ_t, is set to zero at all times. Figure 1a shows that the share of population that is infected by the virus peaks at 1.94 percent in week 27, after which the disease prevalence falls. As shown in Figure 1b, the share of susceptible households progressively declines and remains steady around 64.8 percent from week 120 until the end of the simulation. We argue that the pandemic is of moderate size because only 35.2 percent of households ever become infected[4], which, for a U.S. population of 330 million people, amounts to about 116.2 million Americans.[5]

The pandemic triggers a sizable recession in the model economy: weekly real GDP output is about 18 percent lower at the trough as shown in Figure 2a. Several factors are behind the relatively large slowdown in economic activity: *(i)* households know they can effectively reduce the probability of becoming infected by consuming and working less, *(ii)* households are aware of the income risk associated with the virus and, hence, via precautionary savings reduce their consumption, and *(iii)* as households become infected, their productivity temporarily declines so that aggregate productivity is lower during the pandemic. The economy steadily recovers reaching output levels close to its post-epidemic steady state around 100 weeks after the start

[4] Eichenbaum, Rebelo and Trabandt (2020) simulate a pandemic in which 54 percent of the population gets infected.

[5] Toxvaerd (2020) and Eichenbaum, Rebelo and Trabandt (2020) show that a standard SIR model tends to overstate the severity of the pandemic in health outcomes relative to a model in which individuals' behavior affects the transition rates between different health status.

Figure 1: Epidemiological Effects (weekly)



(a) Infected households (b) Susceptible households

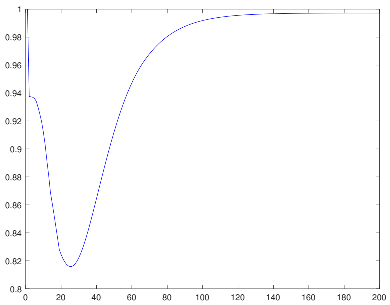
of the pandemic (about 70 weeks after the through). The post-epidemic steady state level of output is lower than the pre-epidemic one because during the pandemic some people die, in fact, the pandemic reduces population in the economy by 0.3 percent. The slowdown in economic activity and the significant decline in inflation reported in Figure 2b bring the policy rate to its effective lower bound (ELB thereafter) the week after the start of the pandemic and remains there for about 66 weeks.

4 The transmission of monetary policy in a pandemic

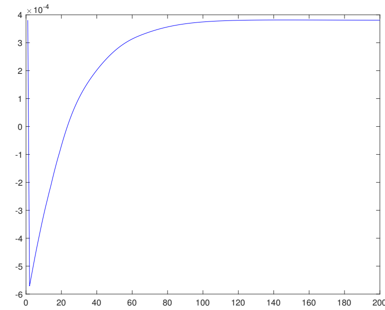
We now study how monetary policy transmits to the economy in our framework. First, we outline some mechanisms suggesting that monetary policy is weaker in a pandemic than in normal times. Second, we confirm the relevance of these mechanisms by analyzing the response of output to changes in the real interest rate at different horizons and at different stages of the pandemic[6]. Third, we examine the inflation and output effects of delaying lift-off by another 50 weeks compared to the baseline economy described above.

[6]In Appendix A, we conduct an alternative and complementary exercise. We assume that the effective lower bound on nominal interest rates does not bind and simulate the effects of persistent monetary policy shocks at different stages of the pandemic.

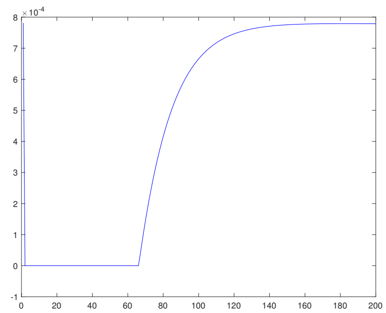
Figure 2: Economic Effects (weekly)



(a) Output



(b) Inflation



(c) Policy rate

4.1 What should we expect?

In our model, monetary policy transmits through the Euler equation of the marginal savers who, in most cases, are the susceptible households. As discussed earlier, two new motives appear in the Euler equation of susceptible households in a pandemic: a "consumption vs risk" motive and a precautionary savings motive, as shown below

$$
\begin{aligned}
\frac{1}{c_{s,t}} + \overbrace{\beta \tau_{c_{s,t}} \left[U_{i,t+1} - U_{s,t+1} \right]}^{\text{consumption vs. risk}} \quad = \quad & \beta \left(1 + rr_t\right) \frac{1+\mu_t}{1+\mu_{t+1}} \left(\frac{1}{c_{s,t+1}} + \overbrace{\beta \tau_{c_{s,t+1}} \left[U_{i,t+2} - U_{s,t+2} \right]}^{\text{consumption vs. risk}} \right) \\
& \cdot \underbrace{\left[1 - \tau_t + \tau_t \frac{1/c_{i,t+1}}{1/c_{s,t+1} + \beta \tau_{c_{s,t+1}} \left[U_{i,t+2} - U_{i,t+1} \right]} \right]}_{\text{precautionary savings}},
\end{aligned}
$$

where $1 + rr_t = \frac{1+R_t}{\Pi_{t+1}}$ is the real interest rate in period t.

We analyze how each of these motives affects the response of consumption to real interest rate changes. Let us start with the "consumption vs risk" motive using a simple heuristic approach: we set $\mu_t = 0$ in all periods and assume that the precautionary savings motive is absent from the Euler equation of susceptible households. Under these assumptions, solving the above Euler equation forward gives

$$\frac{1}{c_{s,t}} + \Omega_t = \beta^n \prod_{j=0}^{n-1} (1 + rr_{t+j}) \left(\frac{1}{c_{s,t+n}} + \Omega_{t+n} \right), \tag{36}$$

where $\Omega_t = \beta \tau_{c_{s,t}} [U_{i,t+1} - U_{s,t+1}]$ captures the disutility of becoming infected while consuming. Given that increasing one's consumption leads to a greater probability of being exposed to the virus ($\tau_{c_{s,t}} > 0$) and individuals would rather remain susceptible than being infected ($U_{i,t+1} - U_{s,t+1} < 0$), we have that $\Omega_t < 0$. We further assume that n is large enough such that, by time $t + n$, the pandemic has died out and economic outcomes are independent of real interest rate changes happening before $t + n$. Let us consider that the real interest rate declines at time $t + s$ with $0 < s < n - 1$ and assume, as a rough approximation, that Ω_t does not move initially in response to that real interest rate change – the main determinant of movements in Ω_t, the number of infections, is predetermined in the current period. Then, consumption $c_{s,t}$ needs to increase following the shock but, since utility is concave in consumption, this increase will be smaller the more negative Ω_t is. The higher is the probability of being infected through consumption activities, the more negative Ω_t is and, hence, the smaller will be the expansion of current consumption after a given decline in the real interest rate. Intuitively, individuals are much less willing to take advantage of intertemporal substitution opportunities when doing so involves a non-negligible risk of becoming sick. In normal times, however, $\Omega_t = 0$ and, hence, the increase in consumption brought about by a decline in the real interest rate is larger than in a pandemic. Thus, according to the "consumption vs risk" motive, we conclude that: *(i)* the effects of monetary policy on consumption are smaller during a pandemic than in normal times; and *(ii)* the effects of monetary policy are the weakest at the peak of the pandemic, when the probability of getting infected is the highest.

We proceed with the same heuristic approach to analyze the role of the precautionary savings motive in the response of consumption to a change in the real interest rate. We assume that the "consumption vs risk" motive is absent from the Euler equation of susceptible households and solve the Euler equation forward. We obtain

$$\frac{1}{c_{s,t}} = \beta^n \prod_{j=0}^{n-1} (1 + rr_{t+j}) \left(riskp_{t+j} \right) \frac{1}{c_{s,t+n}}, \tag{37}$$

where the precautionary savings motive is summarized by

$$riskp_t = 1 - \tau_t + \tau_t \frac{1/c_{i,t+1}}{1/c_{s,t+1} + \beta\tau_{c_{s,t+1}} \left[U_{i,t+2} - U_{i,t+1} \right]}, \tag{38}$$

since it enters as an endogenous "risk premium" shock in the Euler equation of susceptible households. The precautionary savings motive depends on both the probability of becoming infected, τ_t, and the ratio of the marginal utilities of consumption in the infected and susceptible states. Consider again that the real interest rate declines at time $t + s$ with $0 < s < n - 1$. This leads to an improvement in economic activity before time $t + s$, and, because this improvement necessarily implies that the intensity of interactions in goods and labor markets increases, to a rise in the probability of becoming infected. As a consequence, $riskp_{t+j}$ increases between time t and time $t + s$ (and possibly beyond), thereby requiring a smaller increase in $c_{s,t}$ to rebalance the equation. In other words, susceptible households start building up precautionary savings, which counteracts the initial stimulative effect of the drop in the real interest rate. In the terminology of Werning (2015), we are in a situation of pro-cyclical income risk. Moreover, note that the cumulative increase in the probability of becoming infected, and the associated build-up in precautionary savings, is likely to be larger the further away in the future the real interest rate drop is. Thus, the precautionary savings motive leads to a mitigation of the effects of monetary policy, which is potentially more pronounced at longer horizons.

Lastly, unlike in normal times, changes in the real interest rates have persistent consequences in a pandemic through their effects on the state variable I_t, that is, the number of infected households. Once policy accommodation is removed, the economy is left with a larger stock of infected individuals, which depresses economy activity in several ways. First, to reduce infection risk, households limit their consumption purchases and hours worked. Second, precautionary savings remain persistently high. Third, aggregate productivity is lower because infected individuals are less productive.

4.2 Monetary policy experiments

To illustrate the relevance of the mechanisms described above, we conduct several experiments. We consider the effects of one-time anticipated changes in the real interest rate announced in different periods t and with different horizons j. The real interest rate is held fixed at its steady-state value in all other periods[7]. The dynamics of output and epidemiological variables in this economy with a real interest rate peg are qualitatively similar to those in the baseline economy of Section 3, which is a first indication that our economy is not very interest rate sensitive.

In our first experiment, we set $t = 1, ..., 80$ and $j = 0$ – that is, we examine the output effects of an *unanticipated* one basis point drop in the weekly real interest rate at any time between week 1 and week 80 of the pandemic. The left blue line in Figure 3 shows the response of output to an *unanticipated* policy rate shock revealed in week 1. The left orange line reports the response of output to an *unanticipated* policy rate shock revealed in week 10 of the simulation. The yellow line shows the response to a shock revealed in week 20, the purple line to a shock revealed in week 30, the green line to a shock revealed in week 40, the light blue line to a shock revealed in week 50, the red line to a shock revealed in week 60, the right blue line to a shock revealed in week 70, and the right orange line to a shock revealed in week 80.

As shown in Figure 3, the effects of the real interest change on output are the

[7] McKay, Nakamura and Steinsson (2016) and Ferrante and Paustian (2019) conduct similar experiments

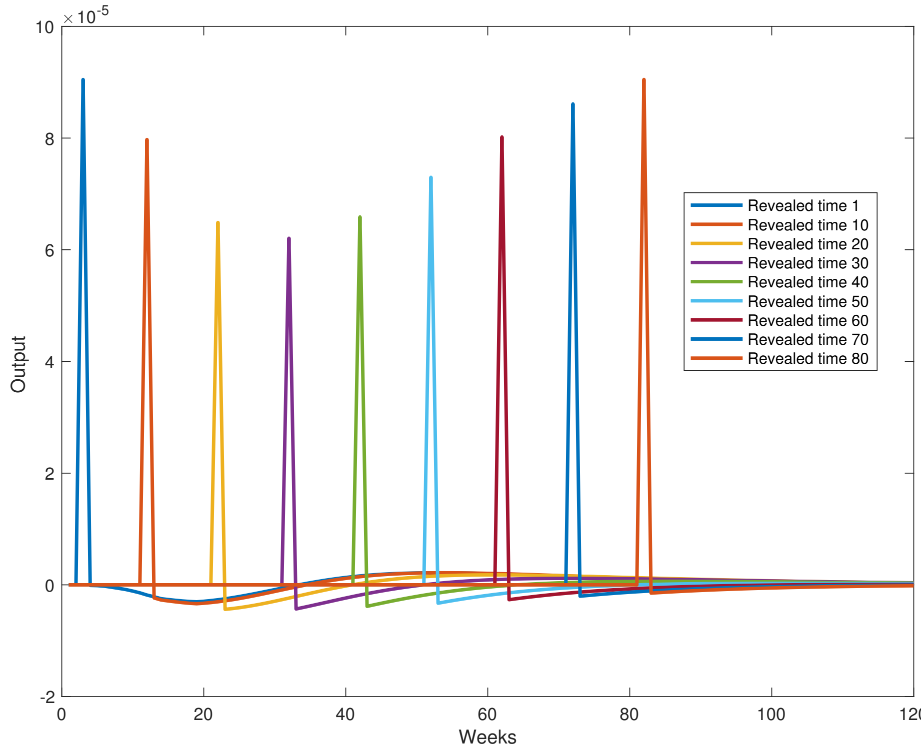
smallest at the peak of the pandemic, around week 30. The effects are also smaller throughout the course of the pandemic than in normal times, thereby confirming the relevance of the consumption vs risk motive[8]. The negative effects on output are persistent even after policy accommodation is removed since the initial increase in output leads to new infections, which, in turn, depress output through the mechanisms described in Section 4.1.

In our second experiment, we set $t = 1$ and let the horizon j vary between 0 and 80 – that is, we examine the effect on output of a one basis point drop in the weekly real interest *announced* at time 1 and with a horizon comprised between 0 and 80 weeks. In Figure 4, we report in solid blue the response of output to an anticipated monetary policy shock in period 1. The dashed orange line shows the response of output to an anticipated monetary policy shock in period 20, while the two-dashed yellow line shows the response of output to an anticipated monetary policy shock in period 50 and the dotted purple line to an anticipated monetary policy shock in period 80. Since a horizon of 0 corresponds to an unanticipated shock, the solid blue line in Figure 4 is the same as the first solid blue line in Figure 3.

Let us focus our discussion on the response of output to an anticipated decline in the real interest rate at an horizon of 20 weeks. The response of output is initially quite strong but declines abruptly as the epidemic progresses. As the probability of becoming infected while consuming increases, households become less willing to take advantage of intertemporal substitution opportunities. Policy accommodation is removed in period 21, which brings the response of output to negative territory because the prolonged boost to economic activity between periods 1 and 20 increases the number of new infections, leaving the economy with lower aggregate productivity, larger precautionary savings, and a greater desire to postpone consumption compared to a case without monetary policy stimulus. After period 40, the output response bounces back above zero. Since infections have been brought forward in time, the

[8]In a standard New Keynesian model linearized around a zero-inflation deterministic steady state, the output response would be equal to $10 * 10^{-5}$ at the time of shock and zero in all other periods. In a nonlinear New Keynesian model without COVID-19 effects but with a similar path for output than in our simulation, the output response to the shock would be weaker than $10 * 10^{-5}$ but larger than that shown in Figure 3.

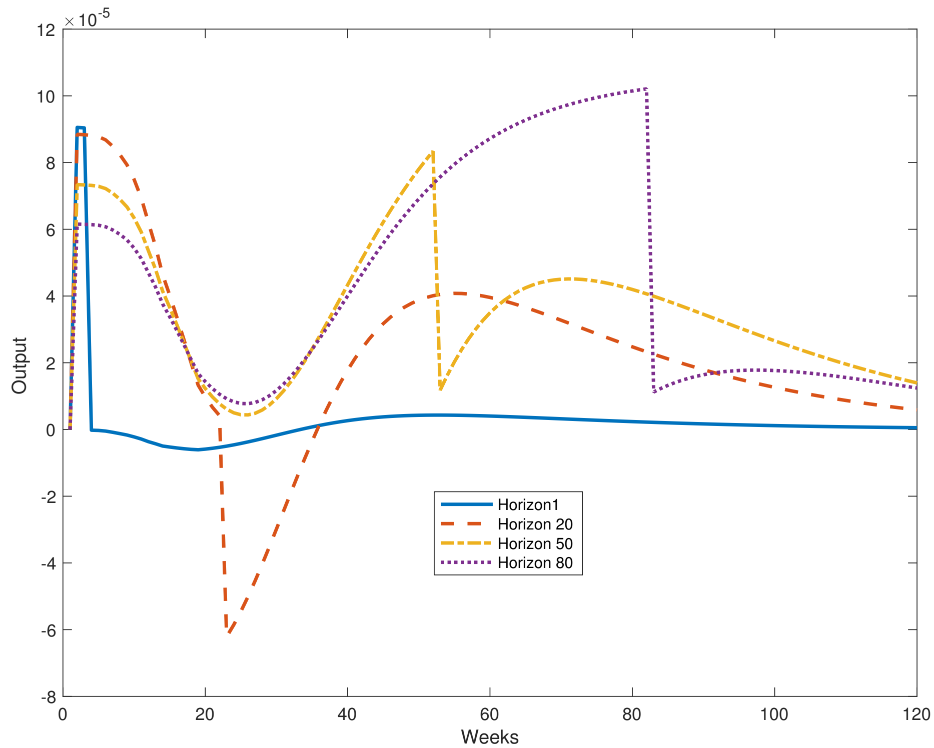
Figure 3: IRFs to unanticipated changes in the real interest rate at different dates (week 1 to week 80)



Note: The left dark blue line shows the response of output to an unanticipated monetary policy shock revealed in week 1. The left orange line shows the response to a shock revealed in week 10. The yellow line shows the response to a shock revealed in week 20. The purple line shows the response to a shock revealed in week 30. The green line shows the response to a shock revealed in week 40. The light blue line shows the response to a shock revealed in week 50. The red line shows the response to a shock revealed in week 60. The right blue line shows the response to a shock revealed in week 70. The right orange line shows the response to a shock revealed in week 80.

economy is left with less susceptible individuals and the spread of the virus slows down, thereby accelerating the recovery from the pandemic. A similar pattern can be observed for the responses of output to anticipated drops in the real interest rate at longer horizons, with the noticeable exception that the initial increase in output is smaller, reflecting the importance of the precautionary savings motive. In turn, this smaller initial increase in output leads to a smaller increase in the number of new infections, which implies that the trough in the output effects of real interest rate changes around period 30 is less pronounced for shocks at longer horizons[9].

Figure 4: IRFs to anticipated changes in the real interest rate. Anticipated at date 1, horizon 1, 20, 50, 80.



Note: The solid blue line shows the response of output at time 1 to an anticipated monetary policy shock in period 1. The dashed orange line shows the response of output at time 1 to an anticipated monetary policy shock in period 20. The two-dashed yellow line shows the response of output at time 1 to an anticipated monetary policy shock in period 50. The dotted purple line shows the response of output at time 1 to an anticipated monetary policy shock in period 80.

In the third experiment, we set $j = 50$ and let time t vary between 1 and 80 – that is, we examine the output effects of a one basis point drop in the weekly real interest rate *announced* at any time between week 1 and week 80 and with a fixed

[9]For comparison, in a standard New Keynesian model linearized around a zero-inflation deterministic steady state, such an anticipated decline in the real interest rate at horizon j would lead to an output response equal to $10 * 10^{-5}$ from periods 1 to j and zero afterwards.

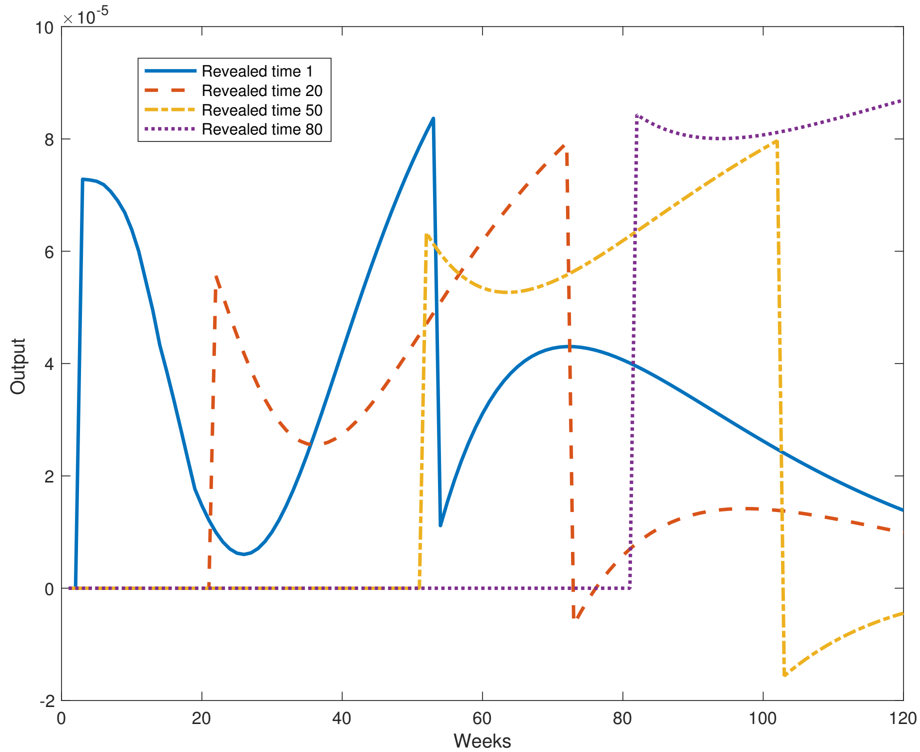
horizon of 50 weeks. In Figure 5, the solid blue line shows the response of output to an anticipated monetary policy shock announced in period 1, the dashed orange line shows the response of output to an anticipated shock announced in period 20, the two-dashed yellow line shows the response to an anticipated shock announced in period 50, and the dotted purple line shows the response of output to an anticipated shock announced in period 80. As shown in Figure 5, the response of output is U-shaped and qualitatively similar regardless of the timing of the announcement. In the downward-sloping part of the U, the number of new infections brought about by the shock builds up before reaching a peak. In the upward-sloping part of the U, new infections gradually decline. However, the quantitative effects of these anticipated shocks are state-dependent. If the announcement takes place early in the pandemic, when a large fraction of individuals are susceptible to the virus, the build-up in infections is large and the U-shaped response of output is very pronounced. See, for example, the blue solid line versus the dashed orange line in Figure 5. If the announcement takes place later during the pandemic, when a significant fraction of the population has already been infected and recovered, the build-up in infections is much smaller and the U-shaped response of output is less pronounced. See, for example, the dashed orange line versus the two-dashed yellow line in Figure 5.

From these experiments, we conclude that monetary policy is likely to be ineffective at the height of the pandemic. It should, however, help sustain the recovery in economic activity once the virus starts dissipating.

4.3 A delayed lift-off

To build intuition, we have thus far assumed that there is no feedback from changes in output and inflation back onto real interest rates. However, in practice, when the policy rate is constrained by the effective lower bound, as is the case in our baseline economy, forward guidance about lower nominal interest rates reduces real interest rates both at the time of the announcement and before the announcement through endogenous movements in inflation. In this section, we examine the effects of such forward guidance policies. In our baseline economy, described in Section 3, the federal

Figure 5: IRFs to anticipated changes in the real interest rate. Horizon 50, revealed at time 1, 20, 50, 80.



Note: The solid blue line shows the response of output at time 1 to an anticipated monetary policy shock announced in period 1 and with a fixed horizon of 50 weeks. The dashed orange line shows the response of output at time 1 to an anticipated monetary policy shock announced in period 20 and with a fixed horizon of 50 weeks. The two-dashed yellow line shows the response of output at time 1 to an anticipated monetary policy shock announced in period 50 and with a fixed horizon of 50 weeks. The dotted purple line shows the response of output at time 1 to an anticipated monetary policy shock announced in period 80 and with a fixed horizon of 50 weeks.

funds rate stayed at the effective lower bound for 66 weeks. We now assume that the central bank delays lift-off by another 50 weeks, or about one year, as shown by the red line in Figure 6c. Figure 6 shows the economic effects of a pandemic under the baseline policy rule subject to the effective lower bound in blue, and under the delayed lift-off policy in red. Given that agents have perfect foresight, a delayed lift-off policy brings about an initial expansion in economic activity. However, as the epidemic progresses, the effects of forward guidance become less stimulative. The peak decline in output brought about by the pandemic is even larger under the delayed lift-off policy than under the baseline rule as the initial expansion in economic activity leads to a surge in new infections, which in turn reinforces households' incentives to engage in precautionary savings and postpone consumption until the risk of infection wanes. Once the situation on the epidemiological front starts improving, around week 30, the economy recovers at a faster pace under the delayed lift-off policy. Output even overshoots its steady-state value from week 50 onwards. Indeed, as the effects of the virus dissipate, the behavior of households returns to normalcy and forward guidance regains its effectiveness. Such a policy is, however, ineffective at sustaining economic activity at the height of the pandemic.

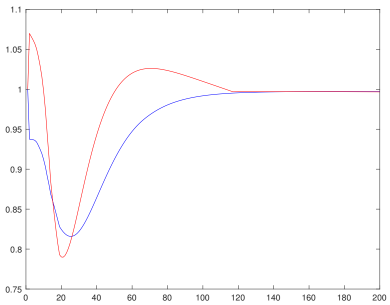
5 Two extensions

Our analysis of the effectiveness of forward guidance in Section 4 abstracts from non-pharmaceutical interventions (NPIs). However, NPIs could mitigate the adverse epidemiological effects linked to forward guidance as described in Section 4.3 and, hence, potentially improve the effectiveness of forward guidance even in the midst of the pandemic. In this section, we analyze the effectiveness of forward guidance under two NPIs: *(i)* better public health policies and *(ii)* mandatory social distancing measures (lockdowns).

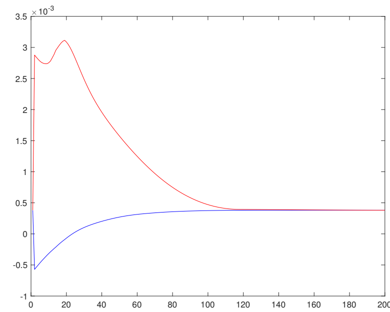
5.1 Better health policies

In the calibration of the baseline economy, we introduced shocks to the parameter π_{s3}, which accounts for the likelihood of infection through random interactions, in order to generate a reasonable path for the epidemic. In our model, individuals can choose to reduce consumption and hours worked to mitigate the probability of becoming infected. By introducing exogenous variations in π_{s3}, we wanted to capture social distancing in interactions not involving consumption or work, a behavior that likely happens in reality but does not arise endogenously in our framework. However,

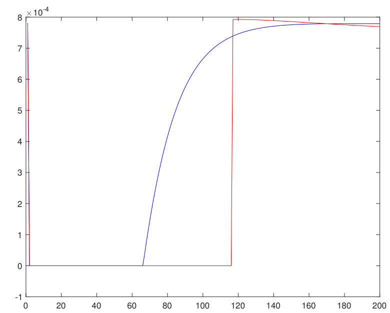
Figure 6: Economic Effects (weekly)



(a) Output



(b) Inflation



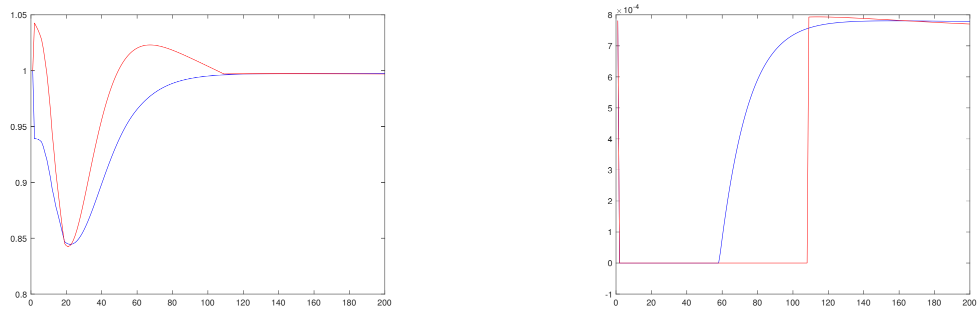
(c) Policy rate

Note: The blue line represents the outcomes in the baseline economy. The red line represents the outcomes in the economy with a delayed lift-off policy.

other factors such as widespread mask wearing, changes in consumption patterns (ordering take-out instead of eating at restaurants), or teleworking can also contribute to shaping the dynamics of the epidemic and are not captured in our baseline calibration. These improvements in the infection technology can be modeled through decreases in π_{s1} and π_{s2}. We refer to them as "better health policies", although they may not necessarily arise from government interventions.

With a lower risk of being infected through consumption and work, individuals might become more responsive to real interest rate changes and forward guidance policies could become more effective at stabilizing real activity. To evaluate this conjecture, we assume that both π_{s1} and π_{s2} decline by 25 percent starting in week

Figure 7: Better health policies



(a) Output (b) Policy rate

Note: The blue line represents the outcomes in the economy with better health policies and the baseline monetary policy rule. The red line represents the outcomes in the economy with better health policies and a delayed lift-off policy.

5 and until the end of the simulation and recalibrate π_{s3} to obtain a similar path for infections than in our baseline economy. Figure 7 reports the paths of output and the nominal interest rate under this new calibration for two different specifications of monetary policy: the blue lines show outcomes when monetary policy follows the baseline rule and the red lines report outcomes when the monetary authority delays lift-off by an 50 additional weeks.

Better health policies mitigate the economic effects of the pandemic: output declines at most by 15 percent in the economy with better health policies, versus 18 percent in the baseline economy. With better health policies, engaging in economic activities is safer and households cut on consumption and hours worked by less after the onset of the pandemic. Consequently, the policy rate remains at the effective lower bound for a shorter period of time. The lift-off in the policy rate occurs after 58 weeks, against 66 weeks in the baseline economy.

As seen in Figure 7, forward guidance is slightly more effective at stabilizing real activity when better health practices enable individuals to participate more safely in goods and labor markets. Notably, the introduction of forward guidance no longer worsens the trough in output, as was the case in the baseline economy. However, forward guidance on its own is still not sufficient to prevent a sizable decline in output.

5.2 Endogenous lockdowns

In the U.S., and around the world, the initial response to the spread of the virus was characterized by the widespread imposition of lockdown measures. At the time of this writing, some of these measures are still in this place. Following Eichenbaum, Rebelo and Trabandt (2020), in our model, mandatory social distancing measures or lockdowns are modeled through a tax on consumption. In the baseline economy, we assumed that such a tax was equal to zero at all times. We now assume that the consumption tax responds endogenously to the spread of the virus according to

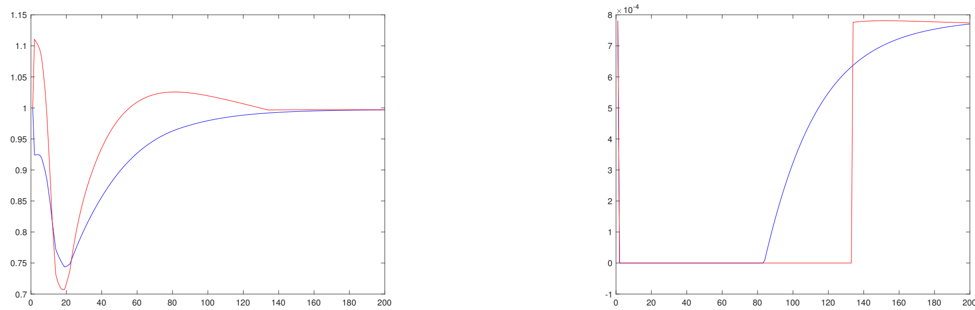
$$\mu_t = \alpha \left(1 - exp(-I_t)\right). \tag{39}$$

The specification above captures the idea that governments have ramped up lockdown measures in a nonlinear fashion: once a certain threshold for infections was reached, the severity of lockdown measures increased drastically. As in Section 5.1, we recalibrate π_{s3} to obtain a similar path for infections as in our baseline economy[10]. Figure 8 reports the paths of output and the nominal interest rate under this new calibration for two different specifications of monetary policy: the blue lines show outcomes when monetary policy follows the baseline rule and the red lines report outcomes when the monetary authority delays lift-off by an 50 additional weeks.

With a similar path for the virus but mandatory lockdown measures, the drop in output under the standard rule is larger than in the baseline economy. Moreover, the federal funds rate also stays at the effective lower bound for a longer period of time: 83 weeks against 66 weeks in the baseline economy. Forward guidance is, overall, weaker. Notably, it significantly worsens the trough in output as accommodative monetary policy in the early stages of the pandemic generates new infections which, in turn, lead to renewed lockdown measures and lower output.

[10]In the baseline economy, $\alpha = 0$ in Equation 39. In this scenario, we set $\alpha = 8$. We have also experimented with other values of α. While the results are quantitatively different, qualitatively, the conclusions are the same.

Figure 8: Lockdowns



(a) Output (b) Policy rate

Note: The blue line represents the outcomes in the economy with lockdown measures and the baseline monetary policy rule. The red line represents the outcomes in the economy with lockdown measures and a delayed lift-off policy.

6 Conclusion

We embed an extension of the classic SIR epidemiological model in a New Keynesian model with uninsurable income risk and evaluate whether monetary policy is likely to be less effective in a pandemic than in normal times. Two main features govern model dynamics. First, the transition probability from being healthy (susceptible) to sick (infected) depends on households' consumption and labor supply decisions. Second, households face the prospect of a drop in income, against which they cannot insure, if they become seriously ill and cannot work. During an epidemic, individuals are less willing to take advantage of intertemporal substitution opportunities since doing so involves a risk of becoming sick. Moreover, the stimulative effects of monetary policy are partially offset by the presence of pro-cyclical income risk: in an attempt to prop up activity, interest rate cuts lead to a build up in the number of new infections that reinforces the precautionary savings motive ands end up depressing output. These effects are strongly state-dependent; their importance rises with the number of individuals infected with the virus. In this environment, we find that accomodative monetary policy in the form of interest rate cuts and forward guidance has only limited effects on real economic activity at the height of a pandemic. It can, however, help sustain the recovery in economic activity once the virus starts dissipating, whether because health interventions keep the number of new infections in check or because the virus has simply run its course.

While we show that monetary policy is potentially less effective during a pandemic, we do not analyze how monetary policy should *optimally* be conducted in this context. A benevolent planner would likely weight the limited gains in the stabilization of real activity obtained in the early stages of the pandemic against the human costs of additional infections when setting a path for the nominal interest rate. Our setup is amenable to studying this issue and we plan to address it in future research.

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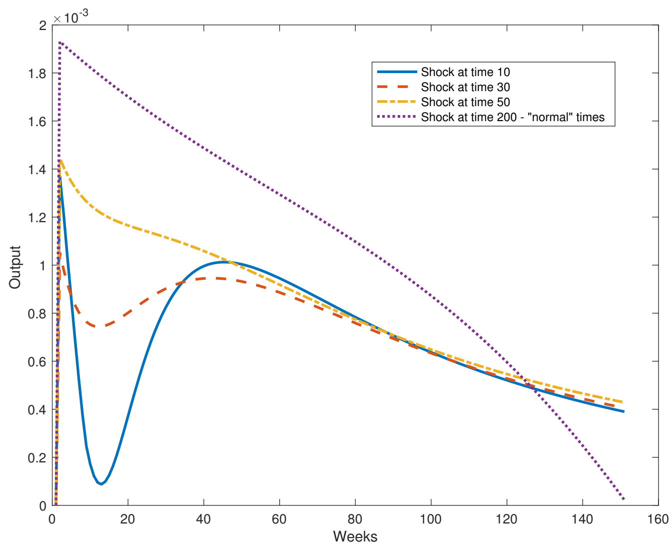
A Experiment

In this appendix, we propose an alternative experiment to illustrate the state-dependent nature of the effects of monetary policy in our framework. In a first stage, we simulate a pandemic of moderate size, as in section 3.2, but we now assume that the monetary authority is not subject to the effective lower bound on nominal interest rates. In a second stage, we compute impulse response functions to shocks to the monetary policy rule at different points in the pandemic (weeks 10, 30, 50, 200). The initial impulse (before the policy rate adjusts endogenously with movements in output and inflation) is a one basis point shock to the weekly interest rate with a persistence of 0.99, also at a weekly frequency. Figure 9 reports the results. We see that the effects of monetary policy are significantly weaker at the height of the pandemic (weeks 10 and 30) than in normal times (week 200).

Figure 9: IRFs to Monetary Policy Shocks at time 10, 30, 50, 200.



Note: The solid blue line shows the response of output to a monetary policy shock at time 10. The dashed orange line shows the response of output to a monetary policy shock at time 30. The two-dashed yellow line shows the response of output to a monetary policy shock at time 50. The dotted purple line shows the response of output to a monetary policy shock at time 200.