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 and analyze the role of monetary policy as a virus spreads and triggers a sizable recession. In our framework, consumption is less sensitive to real interest changes in a pandemic than in normal times because individuals have to balance the benefits of taking advantage of intertemporal substitution opportunities with the risk of becoming sick. Accommodative monetary policies such as forward guidance result in large increases in inflation but have only limited effects on real economic activity as long as the risk of infection is large. The optimal design of monetary policy hinges on how other tools used to limit virus spread, such as lockdowns, are deployed. If the lockdown policy is conducted optimally, monetary policy should focus on keeping inflation on target. However, if the lockdown policy is not optimal, the central bank faces a trade-off between its objective of stabilizing inflation and the necessity to minimize the inefficiencies associated with virus spread.

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1. Introduction

The COVID-19 pandemic has been a shock of unprecedented size and nature, which has translated into new challenges for policymakers. A key feature of the crisis was the interdependency between virus dynamics and economic outcomes. As the virus spread, governments enacted restrictive measures and individuals drastically cut back on social activities. While necessary to keep the pandemic under control, these measures caused tremendous economic damage. For example, in the United States, the unemployment rate reached a post-World War II high of 14.8 percent in April 2020. In the face of the contraction in economic activity, central banks around the world acted swiftly and forcefully by deploying a wide array of tools. In addition to interest-rate cuts, central bankers relied on forward guidance and asset purchases — staples of the monetary policy toolkit since the Great Financial Crisis —, and introduced ambitious new programs aimed at stabilizing financial markets and avoiding the disruption of the flow of credit to households and businesses (English, Forbes and Ubide, 2021).

In this paper, we develop a framework where economic decisions and virus dynamics are interlinked and analyze the role played during a pandemic by two monetary policy tools: conventional interest rate policy and forward guidance. In particular, we ask two interrelated questions. First, given the particular environment brought about by the COVID-19 pandemic, should we expect the transmission mechanism of monetary policy to be the same as in normal times? Second, how should monetary policy be optimally conducted in this environment?

To address these questions, we embed an extension of the classic SIR (Susceptible, Infected, Recovered) epidemiology model in a standard New Keynesian model. On the firm side, monopolistic firms face price adjustment costs, which gives rise to a Phillips curve relating firms' markups to inflation and gives monetary policy some leverage over real activity. The novelty lies in the interaction between household decisions and virus dynamics. Notably, the transition probability from being healthy (susceptible) to sick (infected) depends on households' consumption and labor supply decisions. Therefore, susceptible individuals cut back voluntarily on consumption and hours worked when the risk of infection becomes too large. This feature implies that, even in the absence of government interventions, the economy experiences a large drop in output as the epidemic progresses. The model economy converges to the standard New Keynesian model à la Galí (2008) in the long run when the effects of the virus dissipate.

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 savings decrease and households want to consume more today. In our model, increasing one's consumption increases the probability of becoming infected and individuals therefore have to strike a balance between the willingness to consume and the desire to avoid infection, an effect we call the *consumption-versus-health-risk* motive. By that logic, in response to a decline in the real interest rate, households weigh the benefits of taking advantage of intertemporal substitution opportunities against the heightened risk of infection. As a result, the intertemporal substitution channel is partly impaired and households' consumption is less sensitive to real interest rate changes than in normal times. The importance of the consumption-versus-health-risk motive and, therefore, the extent to which monetary policy is less powerful than in normal times depends on the state of the pandemic. At the onset of the pandemic, 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 pandemic, when the risk of infection is maximal, monetary policy has more limited effects on real economic activity.

The feedback between economic activity and infection dynamics also generates persistence in the effects of monetary policy. Initially, an easing of monetary policy provides a boost to economic activity. However, the increase in economic activity necessarily requires an increase in social interactions, which in turn leads to a rise in infections. In subsequent periods, the economy is left with a larger stock of infected individuals, which depresses demand through the consumption-versus-health-risk motive: with the perceived risk of infection being now higher, susceptible individuals decide to postpone consumption until the epidemiological situation improves. Thus, the monetary authority faces a dynamic trade-off: any attempt to support aggregate demand today results in lower 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 two or four quarters in a calibrated version of our model. Under perfect foresight, the more accommodative stance of monetary policy cushions the initial decline in economic activity in the early stages of the pandemic. However, at the height of the pandemic, forward guidance is unsuccessful at softening the magnitude of the trough in output. 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.

The preceding analysis suggests that the very nature of the COVID-19 shock implies that the problem faced by the monetary authority is non trivial. On the one hand, the central bank can intervene to limit the extent of the economic damage, although with decreased efficacy. On the other hand, doing so results in additional infections, which is costly from a human standpoint. A comparison of the decentralized equilibrium with the allocation that a planner would achieve reveals that the main inefficiency arising in the decentralized equilibrium stems from the fact that infected individuals do not internalize the effects of their actions on the dynamics of the epidemic. In other words, infected individuals consume and work too much. This has two implications for monetary policy. First, since it affects the consumption of all individuals in a similar way, monetary policy is not particularly effective at addressing the infection externality. Second, absent any policy intervention, the overall level of economic activity in the decentralized equilibrium is too high. If measures targeted directly at infected individuals are not available, a planner would rather engineer a decrease in consumption and hours worked for all individuals in order to limit virus spread.

With this in mind, we draw some implications for the optimal conduct of monetary policy. We proceed in two stages. In the first stage, we assume that the planner chooses both lockdown and monetary policies optimally. In the second stage, we relax the assumption that the lockdown policy is optimal and analyze optimal monetary policy conditional on a potentially sub-optimal lockdown path. With two instruments available, we find that the government should deploy each instrument to achieve a different objective: the lockdown policy is used to minimize the distortions arising from the infection externality while monetary policy focuses on minimizing the distortions arising from monopolistic competition and price stickiness, which implies keeping inflation on target at all times. However, when the lockdown policy is not set optimally, monetary policy faces a trade-off between its objective of price stability and the necessity to minimize the distortions due to the infection externality. In this case, it is optimal for the central bank to tighten monetary policy the more sub-optimal the lockdown policy is. This comes at the cost of a deviation from the inflation target, but limits the adverse effects of sub-optimal lockdown policies on health outcomes.

Our paper is related to the literature on the macroeconomic implications of the COVID-19 health crisis, which draws on earlier literature integrating behavioral choice into epidemiological models of the HIV/AIDS epidemic, such as Kremer (1996) and Greenwood et al. (2019). Given the vast literature on the COVID-19 pandemic, we limited our references in this section to studies that are close to ours in terms of focus and modeling choices. In particular, we follow the approach in Eichenbaum, Rebelo and Trabandt (2021) to introduce a feedback between individuals' economic decisions and epidemic dynamics in an otherwise standard macroeconomic model. Eichenbaum, Rebelo and Trabandt (2021) and Jones, Philippon and Venkateswaran (2021) 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 (2022) 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.

Several papers have examined the role of monetary policy in the face of the COVID-19 shock. Levin and Sinha (2020) stress that several issues such as the myopia of economic agents or limited commitment by the central bank may have been especially relevant in the early stage of the COVID-19 pandemic, thereby weakening the power of forward guidance. While we share their conclusion that monetary policy may be less effective in a pandemic than in normal times, our argument rests instead on the observation that households' consumption behavior changes as the virus spreads. Woodford (2022) argues that monetary policy is ineffective at restoring the first-best allocation when the effects of a shock are sectorally concentrated. In his framework, the disruption of the circular flow of payments brought about by the initial shock leads to cascading effects across sectors. In that case, an interest-rate cut is not desirable since, although it can stimulate aggregate demand, it fails to stimulate demand of the right sorts. We reach similar conclusions for different reasons. In our model, monetary policy is also poorly equipped to address the inefficiencies arising in the decentralized equilibrium since it cannot target infected individuals directly. Moreover, if health policies are not successful at containing virus spread, additional monetary policy stimulus is not desirable. Lastly, Brzoza-Brzezina, Kolasa and Makarski (2022) develop a framework similar to ours and also find that the optimal conduct of monetary policy hinges on the behavior of the lockdown policy. An important difference between this paper and ours lies in the implementation of optimal policy: while these authors rely on simple rules for lockdown and monetary policies, we derive the fully optimal Ramsey plans[1].

Our paper is also related to the literature on the "forward guidance puzzle" (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, 2019, Gabaix, 2020), sticky information (Chung, Herbst and Kiley, 2015, Kiley, 2016), incomplete markets (McKay, Nakamura and Steinsson, 2016, Werning, 2015, Bilbiie, 2019, Bilbiie, 2020, Hagedorn et al., 2019, Ferrante and Paustian, 2019), wealth in the utility function (Michaillat and Saez, 2019), or the presence of durable goods (McKay and Wieland, 2022) have been proposed in the literature. For the reasons outlined above, in our model, forward guidance is less powerful in a pandemic.

Finally, several recent studies have argued that the effects of monetary policy may be state-dependent. In Berger et al. (2021) and Eichenbaum, Rebelo and Wong (2022), the state dependency stems from the presence of fixed-rate mortgages. In McKay and Wieland (2022), the state dependency is related to the distribution of durable expenditures relative to adjustment thresholds. In our paper, the state dependency is linked to individuals' behavioral response to the diffusion of the virus and depends on the stock of infected individuals in the population.

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 analyzes optimal policy. Section 6 examines the sensitivity of our results to reasonable parameter variations. Section 7 concludes.

2. Model

Our model economy is populated by: *(i)* households who are subject to the evolution of a pandemic; *(ii)* monopolistically competitive firms facing price adjustment costs; and *(iii)* a central bank conducting monetary policy subject to the effective lower bound on nominal interest rates. The frequency of our model economy is weekly. In this section, we first describe the epidemiological model and then overview the macroeconomic side of the model[2].

[1] We should also note the contribution of Ascari, Colciago and Silvestrini (2021), who find that a persistent decline in the real rate is essential to capture the sectoral reallocation effects observed during the COVID-19 pandemic.

[2] Our model is similar to the New Keynesian model developed by Eichenbaum, Rebelo and Trabandt (2020). Unlike these authors, we do not include physical capital and government spending, but we enforce the effective lower bound on nominal interest rates.

2.1. Epidemics: The extended SIR model

We consider a SIR (Susceptible, Infected, Recovered) model with the possibility of death. In the standard SIR model (Kermarck and McKendrick, 1927), 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. Thus, following Eichenbaum, Rebelo and Trabandt (2021), we extend the SIR model by assuming that the transition probability from being healthy (susceptible) to sick (infected) depends on people's economic decisions.

Once the epidemic starts, individuals are divided in three groups: *(i)* susceptible individuals, S_t, who have not yet been exposed to the disease; *(ii)* infected individuals, I_t, who have contracted the disease; and *(iii)* recovered individuals, R_t, who have survived and acquired immunity. We assume that individuals know their health status, that both symptomatic and asymptomatic individuals are equally infectious, that everyone is equally susceptible to contagion, and that recovered individuals have long-lasting immunity[3]. A susceptible person can contract the virus only through contact with an already infected person and infected people remain infectious until they recover or die. Moreover, we assume that a vaccine arrives stochastically at rate δ_v.[4] As in Makris and Toxvaerd (2020), the vaccine is costless and provides immediate and perfect protection against infection. We also assume there is no vaccine hesitancy in the population so that all susceptible individuals get vaccinated as soon as the vaccine arrives. Therefore, there are no new infections after the vaccine arrives and the number of infected individuals gradually declines as people eventually recover or die.

We now describe population dynamics before the arrival of the vaccine at an unknown date $t^\star$. The number of newly infected people T_t is given by

$$T_t = \pi_{s1} S_t C_{s,t} I_t C_{i,t} + \pi_{s2} S_t N_{s,t} I_t N_{i,t} + \pi_{s3} S_t I_t, \tag{1}$$

where S_t is the number of susceptible individuals, I_t is the number of infected individuals, R_t is the number of recovered individuals, and $C_{k,t}$ and $N_{k,t}$ are the consumption and hours worked by individuals of type k, where $k = S, I, R$. The technological parameters π_{s1} and π_{s2} denote the probability of contracting the virus while purchasing consumption goods and supplying hours of work, respectively. The parameter π_{s3} captures both how likely one is to become infected in random interactions and the intensity of these interactions[5].

The number of susceptible people at time $t + 1$ is the number of susceptible people at time t minus the number of newly infected people at time t, T_t,

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

[3]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.

[4]While Eichenbaum, Rebelo and Trabandt (2021) also consider the stochastic arrival of a vaccine, Makris and Toxvaerd (2020) explore the deterministic arrival of a vaccine and Farboodi, Jarosch and Shimer (2021) explore both stochastic and deterministic arrivals.

[5]Note that in the standard SIR model $\pi_{s1} = \pi_{s2} = 0$.

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, $\pi_d I_t$,

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

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 deaths at time $t+1$ is the number of deaths at time t plus the number of infected individuals who just died, $\pi_d I_t$,

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

The basic reproduction number, $\mathcal{R}_0$, is a useful statistic to summarize the transmissibility of a virus and, hence, quantify the potential intensity of an outbreak. $\mathcal{R}_0$ 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. In our model, however, individuals can reduce the probability of becoming infected by cutting down on consumption and hours worked, which implies a time-varying $\mathcal{R}_{0,t}$. The basic reproduction number in our model is given by

$$\mathcal{R}_{0,t} = \frac{\pi_{s1} C_{s,t} C_{i,t} + \pi_{s2} N_{s,t} N_{i,t} + \pi_{s3}}{\pi_r + \pi_d}, \tag{6}$$

where the numerator captures the transmission rate and the denominator summarizes the recovery and fatality rates.

Once the vaccine arrives at time $t^\star$, all susceptible individuals who have not been infected yet are transferred to the recovered state. Therefore, for $t = t^\star - 1$, the epidemiological dynamics are given by equations 1, 3, 5, and

$$S_{t+1} = 0, \tag{7}$$

$$R_{t+1} = R_t + \pi_r I_t + S_t - T_t. \tag{8}$$

For any $t \geq t^\star$, the SIR dynamics are given by

$$T_t = 0, \tag{9}$$

$$S_{t+1} = 0, \tag{10}$$

$$I_{t+1} = (1 - \pi_r - \pi_d) I_t, \tag{11}$$

$$R_{t+1} = R_t + \pi_r I_t. \tag{12}$$

2.2. Households

The economy is populated by a continuum of households of measure one. Households are of size one and the momentary utility function of household members is given by

$$u(c_t, n_t) = \frac{c_t^{1-\sigma}}{1-\sigma} - \chi \frac{n_t^{1+1/\varphi}}{1+1/\varphi} + \bar{u}, \tag{13}$$

where $1/\sigma$ is the elasticity of intertemporal substitution, φ is the Frisch elasticity of labor supply, and $\bar{u}$ is a flow value of being alive. 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.

We proceed by describing the household's problem before the vaccine arrives at an unknown date $t^\star$. After the vaccine arrives, the infection risk disappears and the problem is standard. Initially, all household members are susceptible to the disease. Once the epidemic starts and before the vaccine arrives, household members can be either susceptible, infected, or recovered. The head of the household makes decisions on behalf of all household members. She maximizes the intertemporal welfare of household members using a utilitarian welfare criterion (identical weights for all members). At the beginning of the period, the head of the household pools resources and determines the consumption/saving and labor supply choices for each type of member, implementing symmetric choices for all individuals of a given type. This setup implies that individuals are insured against the income risk associated with transitioning between health states. Moreover, the head of the household is aware of the infection technology described by equation 1, but does not internalize the impact of her choices on economy-wide infection rates. Thus, from the household perspective, the per-period probability of infection of its susceptible members is given by

$$\tau_t\left(c_{s,t}, n_{s,t}\right) = \pi_{s1} c_{s,t} I_t C_{i,t} + \pi_{s2} n_{s,t} I_t N_{i,t} + \pi_{s3} I_t, \tag{14}$$

where we denote household-level variables with lower-case letters and economy-wide variables with upper-case letters. Households have access to one-period nominal government bonds that promise a given nominal return tomorrow, R_t^{mp}. They receive firm dividends, Υ_t, and government transfers, Γ_t, in the form of lump-sum payments.

The optimization program of the head of the household is given by:

$$\begin{aligned} V\left(s_t, i_t, r_t, b_t\right) = \max_{c_{s,t}, c_{i,t}, c_{r,t}, n_{s,t}, n_{i,t}, n_{r,t}, b_{t+1}} \quad & \left\{ s_t u\left(c_{s,t}, n_{s,t}\right) + i_t u\left(c_{i,t}, n_{i,t}\right) + r_t u\left(c_{r,t}, n_{r,t}\right) \right. \\ & \left. + \beta V\left(s_{t+1}, i_{t+1}, r_{t+1}, b_{t+1}\right) \right\}, \end{aligned} \tag{15}$$

subject to

$$
\begin{aligned}
(1+\mu_t)\left(s_t c_{s,t}+i_t c_{i,t}+r_t c_{r,t}\right)+b_{t+1} &= \frac{1+R_{t-1}^{mp}}{\Pi_t} b_t + w_t\left(s_t \phi_s n_{s,t}+i_t \phi_i n_{i,t}+r_t \phi_r n_{r,t}\right) \\
&\quad +\Upsilon_t+\Gamma_t, \qquad (16)\\
s_{t+1} &= (1-\delta_v)\left(1-\tau_t\left(c_{s,t}, n_{s,t}\right)\right) s_t, \qquad (17)\\
i_{t+1} &= (1-\pi_r-\pi_d)\, i_t+\tau_t\left(c_{s,t}, n_{s,t}\right) s_t, \qquad (18)\\
r_{t+1} &= r_t+\pi_r i_t+\delta_v\left(1-\tau_t\left(c_{s,t}, n_{t,s}\right)\right) s_t, \qquad (19)
\end{aligned}
$$

where b_t is the real value of bonds, μ_t is the tax rate on consumption, R_t^{mp} is the nominal interest rate, Π_t is the current gross inflation rate, ϕ_k is the labor productivity of type k households, and w_t is the wage per efficient hour. The notation $\tau_t\left(c_{s,t}, n_{s,t}\right)$ makes it explicit that, from the household's perspective, the probability of infection only depends on the consumption and hours choices of susceptible individuals. Eichenbaum, Rebelo and Trabandt (2021) 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.

Let λ_t be the Lagrange multiplier associated with the budget constraint of the household. The marginal utility of consumption for susceptible members, infected members, and recovered members is given, respectively, by

$$
\begin{aligned}
u_c\left(c_{s,t}, n_{s,t}\right)+\beta \frac{\partial \tau_t\left(c_{s,t}, n_{s,t}\right)}{\partial c_{s,t}}\left(V_{i,t+1}-(1-\delta_v) V_{s,t+1}-\delta_v V_{r,t+1}\right) &= \lambda_t\left(1+\mu_t\right), \qquad (20)\\
u_c\left(c_{i,t}, n_{i,t}\right) &= \lambda_t\left(1+\mu_t\right), \qquad (21)\\
u_c\left(c_{r,t}, n_{r,t}\right) &= \lambda_t\left(1+\mu_t\right). \qquad (22)
\end{aligned}
$$

Similarly, the labor supply condition for each type of household member is

$$
\begin{aligned}
u_n\left(c_{s,t}, n_{s,t}\right)+\beta \frac{\partial \tau_t\left(c_{s,t}, n_{s,t}\right)}{\partial n_{s,t}}\left(V_{i,t+1}-(1-\delta_v) V_{s,t+1}-\delta_v V_{r,t+1}\right) &= -\lambda_t w_t \phi_s, \qquad (23)\\
u_n\left(c_{i,t}, n_{i,t}\right) &= -\lambda_t w_t \phi_i, \qquad (24)\\
u_n\left(c_{r,t}, n_{r,t}\right) &= -\lambda_t w_t \phi_r. \qquad (25)
\end{aligned}
$$

The Euler equation for bond holdings is given by

$$
\lambda_t=\beta \lambda_{t+1} \frac{1+R_t^{mp}}{\Pi_{t+1}}. \qquad (26)
$$

The envelope conditions with respect to health status are

$$\begin{aligned}
V_{s,t} &= u\left(c_{s,t}, n_{s,t}\right) + \lambda_t \left(w_t \phi_s n_{s,t} - \left(1+\mu_t\right) c_{s,t}\right) + \left(1-\delta_v\right)\left(1-\tau_t\left(c_{s,t}, n_{s,t}\right)\right) \beta V_{s,t+1} \\
&\quad + \tau_t\left(c_{s,t}, n_{s,t}\right) \beta V_{i,t+1} + \delta_v \left(1-\tau_t\left(c_{s,t}, n_{s,t}\right)\right) \beta V_{r,t+1}, \qquad (27) \\
V_{i,t} &= u\left(c_{i,t}, n_{i,t}\right) + \lambda_t \left(w_t \phi_i n_{i,t} - \left(1+\mu_t\right) c_{i,t}\right) \\
&\quad + \left(1-\pi_r-\pi_d\right) \beta V_{i,t+1} + \pi_r \beta V_{r,t+1}, \qquad (28) \\
V_{r,t} &= u\left(c_{r,t}, n_{r,t}\right) + \lambda_t \left(w_t \phi_r n_{r,t} - \left(1+\mu_t\right) c_{r,t}\right) + \beta V_{r,t+1}. \qquad (29)
\end{aligned}$$

We explore next the role played by the virus in the labor supply and consumption decisions of susceptible household members. We first combine equations 20 and 23 to obtain the following expression for their labor supply

$$\frac{w_t \phi_s}{1+\mu_t} = \frac{\chi n_{s,t}^{1/\varphi} - \beta \frac{\partial \tau_t(c_{s,t}, n_{s,t})}{\partial n_{s,t}} \left[V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1}\right]}{c_{s,t}^{-\sigma} + \beta \frac{\partial \tau_t(c_{s,t}, n_{s,t})}{\partial c_{s,t}} \left[V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1}\right]}. \qquad (30)$$

Equation 30 equates the hourly wage with the marginal rate of substitution between hours worked and consumption. The marginal disutility of labor, the numerator in equation 30, includes an additional term compared to the case without a pandemic: $-\beta \frac{\partial \tau_t(c_{s,t}, n_{s,t})}{\partial n_{s,t}} \left[V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1}\right]$. By working longer hours, individuals have higher chances of becoming infected, that is, $\partial \tau_t\left(c_{s,t}, n_{s,t}\right)/\partial n_{s,t} > 0$, and, in case of infection, they suffer a loss in lifetime utility since $V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1} < 0$. Thus, as the pandemic progresses through the population, susceptible household members willingly cut back on hours worked. Similarly, the marginal utility of consumption, the denominator in equation 30, depends on the probability that individuals will become infected through consumption activities: $\beta \frac{\partial \tau_t(c_{s,t}, n_{s,t})}{\partial c_{s,t}} \left[V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1}\right]$.

Second, we combine equations 20 and 26 to obtain the following Euler equation for susceptible household members:

$$\begin{aligned}
c_{s,t}^{-\sigma} + &\overbrace{\beta \frac{\partial \tau_t\left(c_{s,t}, n_{s,t}\right)}{\partial c_{s,t}} \left[V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1}\right]}^{\text{consumption vs. health risk}} \qquad (31) \\
&= \beta \frac{1+R_t^{mp}}{\Pi_{t+1}} \frac{1+\mu_t}{1+\mu_{t+1}} \left(c_{s,t+1}^{-\sigma} + \overbrace{\beta \frac{\partial \tau_{t+1}\left(c_{s,t+1}, n_{s,t+1}\right)}{\partial c_{s,t+1}} \left[V_{i,t+2} - \left(1-\delta_v\right) V_{s,t+2} - \delta_v V_{r,t+2}\right]}^{\text{consumption vs. health risk}} \right).
\end{aligned}$$

Equation 31 includes a new motive that we label as the *consumption-versus-health-risk* motive. As in the case of the labor supply choice, consuming more exposes susceptible individuals to a greater risk of infection, that is, $\partial \tau_t\left(c_{s,t}, n_{s,t}\right)/\partial c_{s,t} > 0$, which in turn may result in a loss in lifetime utility since $V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1} < 0$. Thus, susceptible individuals factor in the risk of infection when deciding on their intertemporal consumption allocation. In particular, they prefer to consume more when the risk of infection is low. The optimal consumption pattern is a function of the state of the pandemic: if the outlook for the virus is about to improve (worsen), susceptible household members prefer to delay (increase) consumption.

In contrast, since infected and recovered individuals are no longer exposed to the risk of infection, the consumption-versus-health-risk motive is not present in their respective Euler equations:

$$u_c\left(c_{i,t}, n_{i,t}\right) = \beta \frac{1+R_t^{mp}}{\Pi_{t+1}} \frac{1+\mu_t}{1+\mu_{t+1}} u_c\left(c_{i,t+1}, n_{i,t+1}\right), \tag{32}$$

$$u_c\left(c_{r,t}, n_{r,t}\right) = \beta \frac{1+R_t^{mp}}{\Pi_{t+1}} \frac{1+\mu_t}{1+\mu_{t+1}} u_c\left(c_{r,t+1}, n_{r,t+1}\right). \tag{33}$$

2.3. Firms

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

$$Y_t(j) = A\left[S_t \phi_s N_{s,t}(j) + I_t \phi_i N_{i,t}(j) + R_t \phi_r N_{r,t}(j)\right], \tag{34}$$

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

$$\Phi_t(j) = \frac{\phi^p}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \Pi^*\right)^2 Y_t, \tag{35}$$

where Π^* is the inflation target of the monetary authority. These costs have the same composition as the aggregate consumption basket and are proportional to aggregate output. Firms are controlled by a risk-neutral manager who discounts future profits at rate β and their revenues are subsidized at the constant rate ζ[6]. Firms choose the price $P_t(j)$ to maximize the expected discounted sum of future profits

$$V_t^p\left(P_{t-1}(j)\right) = max_{P_t(j)}\left\{(1+\zeta)\frac{P_t(j)}{P_t}Y_t(j) - \frac{w_t}{A}Y_t(j) - \frac{\phi^p}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \Pi^*\right)^2 Y_t + \beta V_{t+1}^p\left(P_t(j)\right)\right\}, \tag{36}$$

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. 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

$$(1+\zeta)(1-\theta) + \theta\frac{w_t}{A} - \phi^p \Pi_t\left(\Pi_t - \Pi^*\right) + \beta\phi^p \Pi_{t+1}\left(\Pi_{t+1} - \Pi^*\right)\frac{Y_{t+1}}{Y_t} = 0. \tag{37}$$

2.4. Government and monetary policy

The government finances the subsidy to firms' revenues by taxing households in a lump-sum fashion. Similarly, the proceeds of the consumption tax are redistributed to households in a lump-sum fashion. Therefore,

[6]We make this assumption for practical reasons, but it does not affect our results. In steady state (but not in response to shocks), this subsidy neutralizes the distortions arising from monopolistic competition and implies that the optimal consumption tax is equal to zero. In the absence of the subsidy, the optimal consumption tax would be negative in steady state. Given our interpretation of the consumption tax as a containment rate, we find it preferable that it converges to zero once the pandemic is over.

$$\mu_t \left(S_t C_{s,t} + I_t C_{i,t} + R_t C_{r,t}\right) - \zeta Y_t = \Gamma_t. \quad (38)$$

The monetary authority sets the short-term nominal interest rate using the following rule

$$1 + R_t^{mp} = max\left\{(1 + R^{mp}) \left[\left(\frac{\Pi_t}{\Pi^*}\right)^{\delta_\pi} \left(\frac{Y_t}{Y}\right)^{\delta_y}\right], 1 + R_{min}^{mp}\right\}, \quad (39)$$

where the absence of time subscript denotes steady-state values and the max operator captures the presence of the effective lower bound, fixed at R_{min}^{mp}. We introduce a policy response to the deviation of output from its steady-state value, and not to the deviation of output from its flexible-price level, in order to provide a more realistic account of the dynamics of the policy rate over the course of the pandemic. Indeed, given that the pandemic induces a substantial endogenous shift in supply, our model's flexible-price output gap is small or even, in some periods, positive. Thus, a monetary policy response to the flexible-price output gap would imply a counter-factually muted response of the nominal interest rate. Notably, under that specification, the nominal interest rate would not reach the effective lower bound in our baseline simulation below.

2.5. Equilibrium

In equilibrium, the fraction of household members who are susceptible, infected, and recovered is the same as the corresponding fraction in the population. Therefore, $s_t = S_t$, $i_t = I_t$, and $r_t = R_t$. Moreover, all households implement symmetric consumption and labor choices for individuals of the same type. Therefore, $c_{s,t} = C_{s,t}$, $c_{i,t} = C_{i,t}$, $c_{r,t} = C_{r,t}$, $n_{s,t} = N_{s,t}$, $n_{i,t} = N_{i,t}$, and $n_{r,t} = N_{r,t}$. Aggregate consumption is a weighted average of the consumption of each type

$$C_t = S_t C_{s,t} + I_t C_{i,t} + R_t C_{r,t}. \quad (40)$$

Firm dividends are given by

$$\Upsilon_t = \left((1 + \zeta) A - w_t\right) \left(\phi S_t N_{s,t} + \phi_i I_t N_{i,t} + \phi_r R_t N_{r,t}\right) - \frac{\phi^p}{2} \left(\Pi_t - \Pi^*\right)^2 Y_t. \quad (41)$$

In the absence of government-provided liquidity, bonds are in zero net supply. The economy-wide resource constraint is obtained by aggregating the budget constraints of households

$$C_t = A \left(1 - \frac{\phi^p}{2} \left(\Pi_t - \Pi^*\right)^2\right) \left(\phi S_t N_{s,t} + \phi_i I_t N_{i,t} + \phi_r R_t N_{r,t}\right). \quad (42)$$

3. The baseline economy

3.1. Calibration

The model is calibrated at a weekly frequency. We first discuss the calibration of the parameters of the New Keynesian side of the model. The elasticity of substitution between goods is set to $\theta = 6$

and the subsidy ζ is fixed to ensure that the steady-state markup is equal to one. The inflation target and the steady-state real interest rate are equal to 2% at an annual frequency, which correspond to a weekly gross rate of $1.02^{\frac{1}{52}}$. The monetary authority responds to deviations of inflation and output from target with coefficients $\delta_\pi = 1.5$ and $\delta_y = 0.5/52$, respectively. Both the intertemporal elasticity of substitution $1/\sigma$ and the Frisch elasticity of labor supply φ are set to $1/2$, which are standard values in the literature. The discount factor is set to an annual value of 0.98 or, equivalently, a weekly value of $0.98^{1/52}$. The productivity levels of each type of household are fixed as in Eichenbaum, Rebelo and Trabandt (2021): $\phi_s = \phi_r = 1$ and $\phi_i = 0.8$. We calibrate the price adjustment cost parameter ϕ^p according to the following logic. While the current COVID-19 pandemic was an unprecedented shock to the economy, inflation remained relatively stable. Thus, we need to have a flat Phillips curve in order to prevent unrealistic price movements. In particular, we target a slope of the Phillips curve of 0.0019 at a quarterly frequency, as in the Federal Reserve Board's FRB/US model of the U.S. economy (Brayton, Laubach and Reifschneider, 2014), which implies a value for the price cost parameter, ϕ^p, of 40926[7]. Finally, we normalize output, hours worked, and population in the pre-pandemic steady state to one. Through steady-state relationships, these assumptions allow us to pin down the parameters A and χ.

Next, we choose the parameters characterizing the SIR side of the model. Following the evidence presented in Bar-On et al. (2020), we set the infection fatality rate to 0.5% and the average duration in the infected state to 15 days. Since our calibration is weekly, this implies that the per period probability of dying if infected is equal to $\pi_d = 0.005 * 7/15$ and that the recovery probability is equal to $\pi_r = 7/15 - \pi_d$. Following Eichenbaum, Rebelo and Trabandt (2021), we calibrate the basic reproduction number to $\mathcal{R}_0 = 1.45$. This value is at the low end of available estimates but is consistent with evidence that takes sampling uncertainty into account[8]. As in Jones, Philippon and Venkateswaran (2021), and consistent with the evidence presented in Ferguson et al. (2020), we assume that work and consumption activities account each for 1/4 of transmissions. The flow value of life $\bar{u}$ is chosen so that the cost of death is 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[9], which corresponds to 10,310 times per capita weekly income in the United States in 2019. For simplicity, we define the value of a statistical life, VSL, based on the situation of an infinitely-lived representative individual in the pre-pandemic steady state. We have

$$VSL = \frac{\frac{\frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{n^{1+1/\varphi}}{1+1/\varphi} + \bar{u}}{1-\beta}}{c^{-\sigma}} = 10310 * c, \tag{43}$$

[7]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 $\frac{0.0019}{1-\beta^{13}}$ 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 $\frac{\theta}{\phi^p (\Pi^*)^2}$, this implies that $\frac{\theta}{\phi^p (1-\beta)(\Pi^*)^2} = \frac{0.0019}{1-\beta^{13}}$.

[8]We explore the robustness of our results to alternative values of $\mathcal{R}_0$ in Section 6.

[9]The U.S. Department of Transportation provides an estimate for the valuation of a statistical life using a 2020 base year equal to \$11.6 million.

which implies that $\bar{u}$ is equal to

$$\bar{u} = (1-\beta) * c^{1-\sigma} * 10310 - \frac{c^{1-\sigma}}{1-\sigma} + \chi \frac{n^{1+1/\varphi}}{1+1/\varphi} = 5.4. \tag{44}$$

Our baseline economy incorporates active containment policies, but we also explore the laissez-faire policy in which $\mu_t = 0$ at all times. For simplicity, in the baseline economy, we assume that the severity of the containment policy is a linear function of the stock of infected individuals

$$\mu_t = \beta_\mu I_t. \tag{45}$$

We calibrate the parameter β_μ to match the excess deaths rate as of March 2021, approximately a year after the onset of the epidemic in the United States. The excess mortality data is provided by The Economist and the COVID-19 mortality data is provided by COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University. Both sources of data are compiled by Ritchie et al. (2020). At the end of March 2021, the median estimate of excess deaths in the United States was $631,432$, or 0.19% of the population, while total confirmed deaths for COVID-19 were equal to $551,457$, or 0.17% of the population. We therefore set $\beta_\mu = 15$ in order to match a cumulative death rate of 0.19% 52 weeks after the onset of the pandemic.

We acknowledge that considerable uncertainty remains about the values of certain epidemiological parameters, even many months after the onset of the pandemic. For this reason, we check that our results are robust to sensible parameter variations in Section 6.

We solve the nonlinear model under the assumption of perfect foresight using Dynare's (Adjemian et al., 2011) perfect foresight solver.

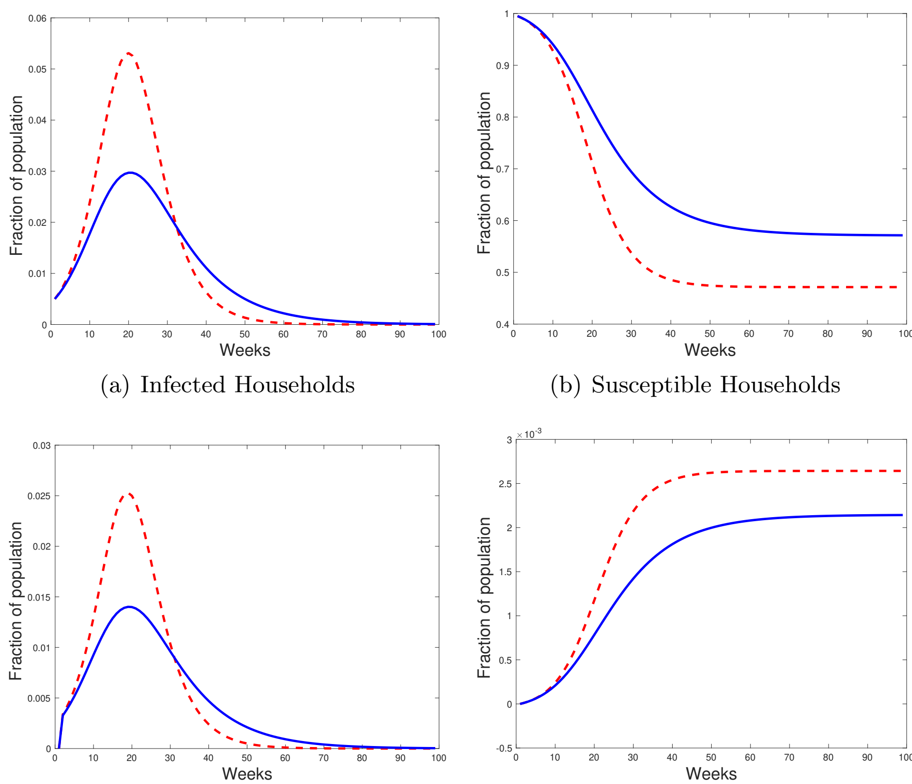
3.2. The economic effects of a pandemic

In this section, we simulate a pandemic and overview the equilibrium population and economic dynamics. In our model economy, agents have perfect foresight and, hence, know about the new virus and how it propagates through the population. We start the simulation with an initial infection rate of $I_0 = 0.5\%$. This corresponds to a situation where agents do not become immediately aware of the extent to which the virus has propagated within the population. Once they do and adapt their behavior accordingly, the virus has already taken hold. For simplicity, we simulate a pandemic with only one wave but, depending on the containment measures put in place, the model can accommodate for more complex scenarios, such as multiple waves.

We report the simulation results for epidemiological variables in Figure 1 and for macroeconomic variables in Figure 2. We consider two scenarios: *(i)* our baseline simulation, which includes containment policies according to equation 45; and *(ii)* a laissez-faire case, which is characterized by the absence of containment policies, that is, $\mu_t = 0 \; \forall t$. We start by describing the results for the laissez-faire policy and then explore the role of containment policies by comparing the outcomes in the laissez-faire case with the outcomes in the baseline economy.

The simulation results for the laissez-faire case are given by the dashed lines in Figure 1 and Figure 2. As shown in Figure 1 (a), in the economy with the laissez-faire policy, the virus rapidly spreads from the start of the simulation until week 21, when the share of infected individuals in the population reaches a peak of 5.3 percent. Epidemiological outcomes improve gradually thereafter. As reported in Figure 1 (b), the share of susceptible individuals progressively declines and remains steady around 47 percent from week 50 until the end of the simulation. Therefore, only 53 percent of the population ever becomes infected in the laissez-faire economy, which, for a U.S. population of 330 million people, amounts to about 175 million Americans.

Figure 1. Epidemiological Effects (weekly)



(a) Infected Households

(b) Susceptible Households

(c) New Infections

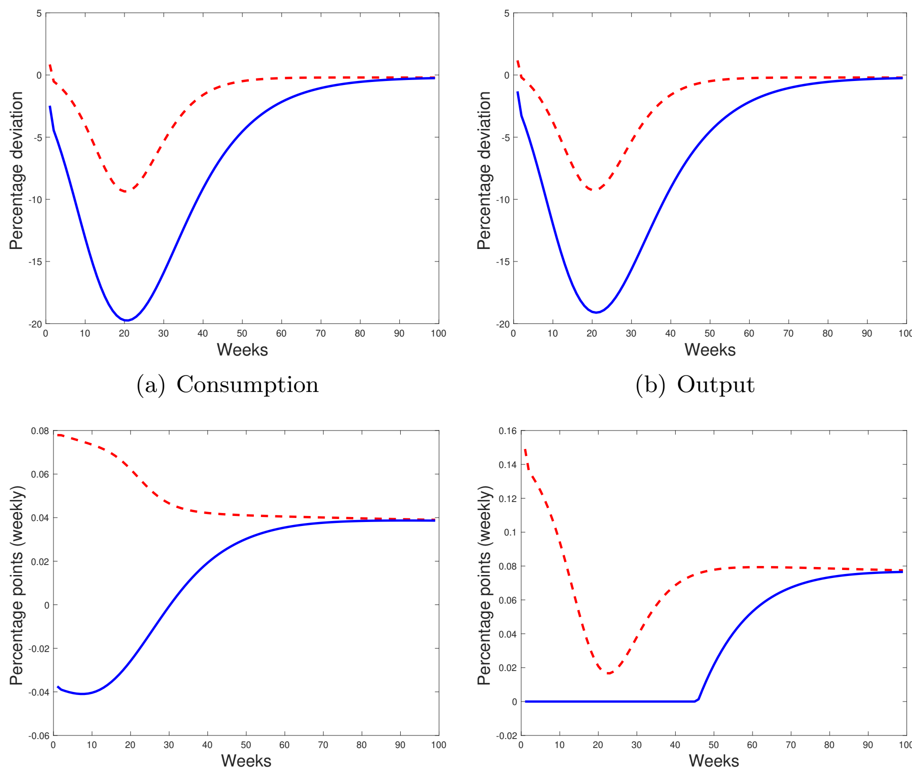
(d) Deaths

Note: The solid line represents the outcomes for an active containment policy ($\mu_t = 15I_t$). The dashed line represents the outcomes for the laissez-faire policy ($\mu_t = 0, \forall t$).

The pandemic triggers a sizable recession in the laissez-faire economy: as shown in Figure 2 (b), weekly output falls by about 9 percent from peak to trough. Several factors are behind the drop in economic activity: *(i)* households know they can effectively reduce the probability of becoming infected by consuming and working less, and *(ii)* as household become infected, their productivity temporarily declines so that aggregate productivity is lower during the pandemic. Once the epidemiological situation starts improving, the economy steadily recovers reaching output levels close to its post-pandemic steady state 60 weeks after the start of the pandemic (about 40 weeks after the trough). In our model, the pandemic shows up both as a shock to aggregate demand through the

Euler equation of susceptible individuals (equation 31) and as a shock to labor supply through the labor supply condition of susceptible individuals (equation 30). While the drop in demand and the associated decrease in labor demand put downward pressure on wages, the shock to labor supply puts upward pressure on wages. As shown in Figure 2 (c), the labor supply effect dominates: inflation initially increases as forward-looking firms anticipate future rises in costs and start adjusting prices accordingly. With the large initial increase in inflation, the Taylor rule prescribes that the policy rate should rise on impact. The policy rate then declines and undershoots its steady-state value at the peak of the pandemic, when the trough in output is reached, before slowly converging back to steady state thereafter.

Figure 2. Economic Effects (weekly)



(a) Consumption

(b) Output

(c) Inflation

(d) Policy rate

Note: The solid line represents the outcomes for an active containment policy ($\mu_t = 15I_t$). The dashed line represents the outcomes for the laissez-faire policy ($\mu_t = 0, \forall t$).

We analyze the epidemiological and economic effects of introducing containment policies by comparing the outcomes under the laissez-faire policy – the dashed lines – with the outcomes in the baseline economy – the solid lines. As expected, the overall size of the pandemic is smaller when containment policies are in place: *(i)* the peak fraction of infected individuals is 3 percent in our baseline economy, while it stands at 5.3 percent in the laissez-faire case; *(ii)* 43 percent of the population ever becomes infected with containment policies, while 53 percent of the population gets infected in the absence of containment policies; and *(iii)* cumulative deaths in the baseline economy are about 20 percent smaller than in the economy without containment. However, the pandemic is more persistent when containment measures are in place: while the fraction of newly infected individuals is zero by week 60 under the laissez-faire policy, it takes about 30 more weeks to reach that level in the baseline economy.

Containment measures successfully reduce the risk of infection by reducing the incentives to engage in consumption and work during a pandemic. Better epidemiological outcomes come at the expense of a more severe economic downturn. As shown in Figure 2, weekly output drops by about 19 percent from peak to trough in the baseline economy, compared to just 9 percent in the laissez-faire case. When containment measures are in place, the downward pressure on wages linked to the drop in demand dominates the upward pressure coming from the shock to labor supply so that inflation declines at the beginning of the pandemic and converges to its steady state from below. Given the large and immediate drop in inflation, and although output declines only gradually, the policy rate reaches its effective lower bound (ELB thereafter) at the onset of the pandemic and remains there for 45 weeks. Overall, containment measures are successful at reducing the epidemiological cost of a pandemic, but at the expense of a more dire economic contraction.

4. The transmission of monetary policy in a pandemic

In this section, we study how monetary policy transmits to real activity in our baseline economy. First, we outline some mechanisms suggesting that monetary policy is weaker in a pandemic than in normal times. Second, we analyze the response of macroeconomic and epidemiological variables to one-time changes in the real interest rate at different horizons and at different stages of the pandemic. Third, we explore the consequences of delaying lift-off from the effective lower bound by two or four quarters in our baseline economy[10].

4.1. What should we expect?

In our model, monetary policy transmits through the Euler equations of the different types of household members. While the Euler equations of infected and recovered individuals are standard, a new consumption-versus-health-risk motive appears in the Euler equation of susceptible individuals. Therefore, understanding how aggregate consumption reacts to changes in real interest rates during a pandemic requires: 1) tracking the fraction of individuals in each health state; and 2) understanding how the presence of the consumption-versus-health-risk motive shapes the response of consumption to real interest changes for susceptible individuals.

To tackle the second issue, we consider the Euler equation of susceptible individuals, equation 31. To lighten notation, we denote the consumption-versus-health-risk motive by Ω_t

$$\Omega_t = \beta \frac{\partial \tau_t \left(C_{s,t}, N_{s,t}\right)}{\partial C_{s,t}} \left[V_{i,t+1} - (1-\delta_v)V_{s,t+1} - \delta_v V_{r,t+1}\right]. \tag{46}$$

[10] 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 shocks to the monetary policy rule at different stages of the pandemic. The results from this experiment support our finding that monetary policy is weaker when the stock of infected individuals is large.

Solving forward the Euler equation of susceptible individuals, we obtain

$$C_{s,t}^{-\sigma} + \Omega_t = \beta^n \frac{1+\mu_t}{1+\mu_{t+n}} \left(C_{s,t+n}^{-\sigma} + \Omega_{t+n}\right) \prod_{j=0}^{n-1} RR_{t+j}, \tag{47}$$

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

We first study the time t effect of a decline in the real interest rate at time $t+h$, with $0 < h < n-1$, under the assumption that n is large enough so that, by time $t+n$, the pandemic has died out and economic outcomes are independent of real interest rate changes happening before $t+n$. Since μ_t is predetermined within the period (because of its dependence on the stock of infected individuals), the elasticity of time t consumption to a change in the real interest rate at time $t+h$ is given by

$$\frac{\partial C_{s,t}}{\partial RR_{t+h}} \frac{RR_{t+h}}{C_{s,t}} = -\frac{1}{\sigma} \frac{C_{s,t}^{-\sigma} + \Omega_t}{C_{s,t}^{-\sigma}} + \frac{1}{\sigma} \frac{\partial \Omega_t}{\partial RR_{t+h}} \frac{RR_{t+h}}{C_{s,t}^{-\sigma}}. \tag{48}$$

In normal times, $\Omega_t = 0$ for all t so the elasticity is simply equal to $-1/\sigma$, regardless of the horizon of the shock. In a pandemic, the elasticity depends both on the value of Ω_t at the time of the shock, as captured by the first term on the right hand side of equation 48, and its responsiveness to interest rate changes, as captured by the second term on the right hand side of equation 48.

We start by considering the first term on the right hand side of equation 48. We note that $\Omega_t < 0$ since increasing one's consumption leads to a greater probability of being exposed to the virus, that is $\partial \tau_t \left(C_{s,t}, N_{s,t}\right) / \partial C_{s,t} > 0$, and individuals would rather avoid being infected, that is $V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1} < 0$. This implies that $\left(C_{s,t}^{-\sigma} + \Omega_t\right) / C_{s,t}^{-\sigma} < 1$ and, hence, that the first term in equation 48 is larger (smaller in absolute value) than $-1/\sigma$: a decline in the real interest rate is less stimulative when the risk of infection is positive. To understand this result from a different perspective, let us consider equation 47. In this equation, a decline in the real interest rate results in a decrease in the term on the right hand side of the equation. In order to restore the equality, consumption $C_{s,t}$ needs to increase but, since utility is concave in consumption, the required increase is smaller the more negative Ω_t is. In turn, the higher the probability of being infected through consumption activities, the more negative Ω_t is and, hence, the smaller the required expansion in consumption. Intuitively, individuals are much less willing to take advantage of intertemporal substitution opportunities when doing so involves a non-negligible risk of becoming sick. Thus, according to this channel, we expect: *(i)* the effects of monetary policy on consumption to be smaller during a pandemic than in normal times; and *(ii)* the effects of monetary policy to be the weakest at the peak of the pandemic, when the probability of getting infected is the highest.

Next, we assess how the response of Ω_t to the shock contributes to shaping the interest rate elasticity of consumption for susceptible individuals by analyzing the second term in equation 48. We have that

$$\frac{\partial \Omega_t}{\partial RR_{t+h}} = \beta \pi_{s1} I_t \left[\frac{\partial C_{i,t}}{\partial RR_{t+h}} \left[V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1} \right] \right. \\ \left. + C_{i,t} \frac{\partial \left[V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1} \right]}{\partial RR_{t+h}} \right], \tag{49}$$

where I_t is predetermined within the period. The response of Ω_t to a change in the real interest rate depends on both the responses of $C_{i,t}$ and $V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1}$. From the Euler equation of infected individuals, equation 32, we know that $\partial C_{i,t} / \partial RR_{t+h}$ is negative. Therefore, given that $V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1} < 0$, the first term of the partial derivative is positive. Also, $\partial \left(V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1} \right) / \partial RR_{t+h}$ is generally negative, as susceptible individuals benefit less (more) from a monetary policy easing (tightening) than infected and recovered individuals (because of a smaller increase in consumption and hours worked and a rise in the probability of infection). Therefore, the sign of $\partial \Omega_t / \partial RR_{t+h}$ is ambiguous. On the one hand, through an increase in $C_{i,t}$, a monetary easing triggers a rise in the probability of infection. On the other hand, it leads to a decrease in the utility loss of infection. If the first effect dominates, susceptible individuals are incentivized to consume less, which further blunts the positive effects of the interest rate shock. If the second effect dominates, the reverse happens. In general, we find in our simulations that the impact response of Ω_t does not contribute meaningfully to the initial response of consumption to the shock. That is, the impact response of consumption is best characterized by ignoring the second term in equation 48.

While we have so far focused on the effects of a real interest rate change in the period agents learn about this change, monetary policy influences economic activity beyond this initial period through its effect on the dynamics of the epidemic. Notably, although movements in μ_t and Ω_t are inconsequential for the response of consumption *on impact*, this is no longer the case in subsequent periods once infections I_t start responding to the shock. Consider for example the effects of a one-time decline in RR_t announced in period t. Initially, the easing of monetary policy provides a boost to economic activity. However, since the increase in economic activity necessarily requires an increase in social interactions, this inevitably leads to a rise in infections. In subsequent periods, once policy accommodation is removed, the economy is left with a larger stock of infected individuals, which depresses demand through both mandatory (an increased severity of lockdowns μ_t) and voluntary social distancing (an increased desire to postpone consumption through the consumption-versus-health-risk motive Ω_t). Thus, because of the feedback between economic activity and infection dynamics, the monetary authority faces a dynamic trade-off. Any attempt to support aggregate demand in the present may result in lower aggregate demand tomorrow.

4.2. Monetary policy experiments

To illustrate the relevance of the mechanisms described above, we conduct several experiments. For simplicity, suppose that monetary policy by the central bank is given by an exogenous rule for the real interest rate as follows

$$RR_t = RR + \epsilon_{t,t+j},$$

where $\epsilon_{t,t+j}$ denotes the shock to the real rate in period $t + j$ that becomes known in period t. Under this specification for the policy rule, in the absence of monetary policy shocks, the real interest rate is constant and equal to its steady-state value in all periods. The dynamics of real and epidemiological variables in this economy with a real interest rate peg are qualitatively similar to those in the baseline economy of Section 3, where monetary policy was instead conducted according to a Taylor rule and subject to the effective lower bound on nominal interest rates. In Section 4.2, we characterize the effects of one-time anticipated changes in the real interest rate $\epsilon_{t,t+j}$ announced in different periods t and with different horizons j. Figures 3 to 5 report impulse response functions (IRFs): they show deviations from the economy with a real interest rate peg in response to the one-time real rate shocks $\epsilon_{t,t+j}$[11]. In describing the results, we first analyze the response of consumption and output and then overview the responses of epidemiological variables[12].

In our first experiment, we set $t = 1, ..., 80$ and $j = 0$ — that is, we examine the 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. Figure 3 reports the IRFs for consumption, output, the stock of infected and susceptible individuals, and cumulative deaths. As shown in Figure 3 (a), the effects of the real interest change on consumption are the smallest at the peak of the pandemic, around week 20. The effects are also smaller throughout the course of the pandemic than in normal times, thereby confirming the relevance of the consumption-versus-health-risk motive[13]. The negative effects of consumption are persistent even after policy accommodation is removed since the initial increase in activity leads to new infections, which, in turn, depress consumption through the mechanisms described in Section 4.1.

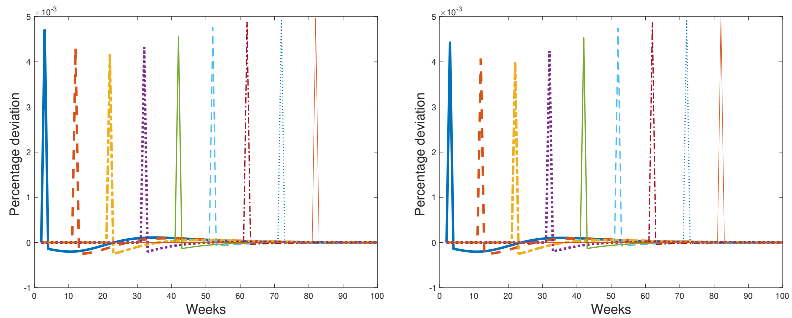
In our second experiment, we set $t = 1$ and let the horizon j vary between 0 and 80 — that is, we examine the effect on consumption of a one basis point drop in the weekly real interest rate *announced* at time 1 and with a horizon comprised between 0 and 80 weeks. Figure 4 presents the results. Let us focus our discussion on the IRFs to an anticipated decline in the real interest rate at a horizon of 20 weeks — the dashed orange line. As shown in Figure 4 (a), the response of consumption is initially quite strong but declines abruptly as the epidemic progresses. As the number of infections rises households become less willing to take advantage of intertemporal substitution opportunities.

[11]Here, we consider the case of an active lockdown policy. Results under the laissez-faire policy are presented in Appendix C.

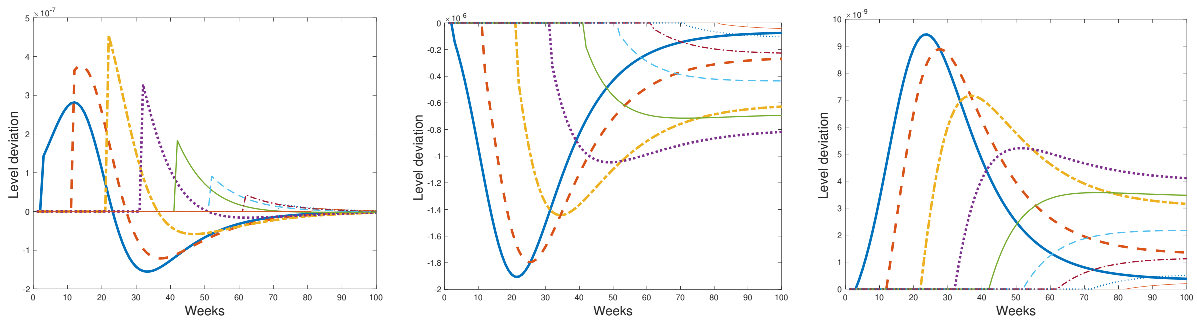
[12]The responses of output and consumption are qualitatively similar. Any difference in the responses is driven by the presence of price adjustment costs. As shown in Figure 3, after an unanticipated change in the real interest rate, the responses of consumption and output are virtually identical. Figure 4 and Figure 5 report the IRFs to anticipated changes in the real interest rate. In these cases, the shocks translate into meaningful inflationary pressures that increase price adjustment costs, thereby driving a wedge between the consumption and output responses.

[13]For comparison, in a similarly calibrated standard New Keynesian model, the consumption response would be equal to $5 * 10^{-3}$ at the time of shock and zero in all other periods.

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



(a) Consumption (b) Output



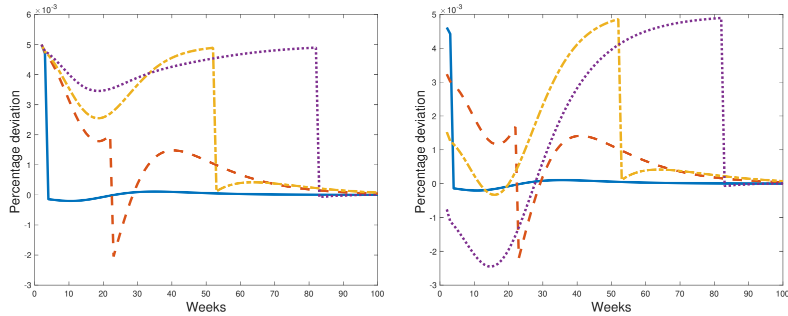
(c) Infected (d) Susceptible (e) Cumulative deaths

Note: The left dark blue line shows the response to a 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.

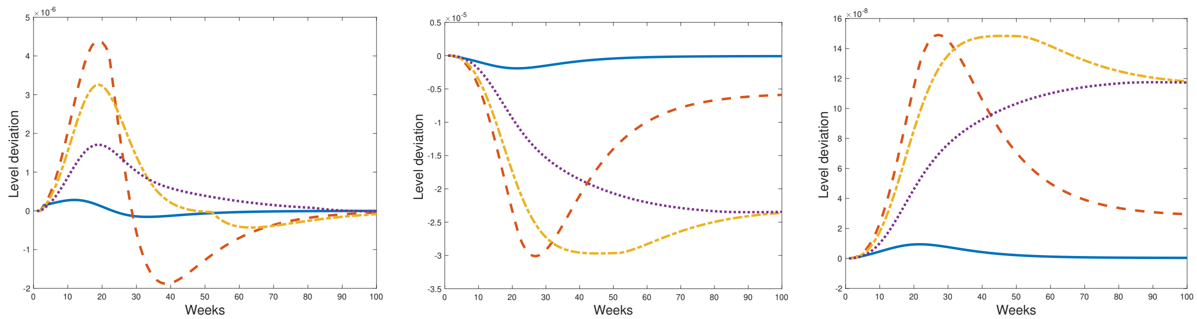
Policy accommodation is removed in period 21, which brings the response of consumption to negative territory. Indeed, the prolonged boost to economic activity between periods 1 and 20 increases the number of new infections, leading to tighter lockdown measures and leaving households with a greater desire to postpone consumption compared to a case without monetary policy stimulus. After period 30, the consumption response bounces back above zero. Since infections have been brought forward in time, the 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 consumption to anticipated decreases in the real interest rate at longer horizons — the dash-dotted yellow line and the dotted purple line —, with the noticeable exception that the drop in consumption at the peak of the pandemic is smaller, reflecting the fact that monetary policy accommodation is removed later in those simulations, once the pandemic is already under control[14].

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

Figure 4. IRFs to anticipated changes in the real interest rate. Anticipated at date 1, horizon 1 (solid blue), 20 (dashed orange), 50 (dash-dotted yellow), 80 (dotted purple).



(a) Consumption (b) Output

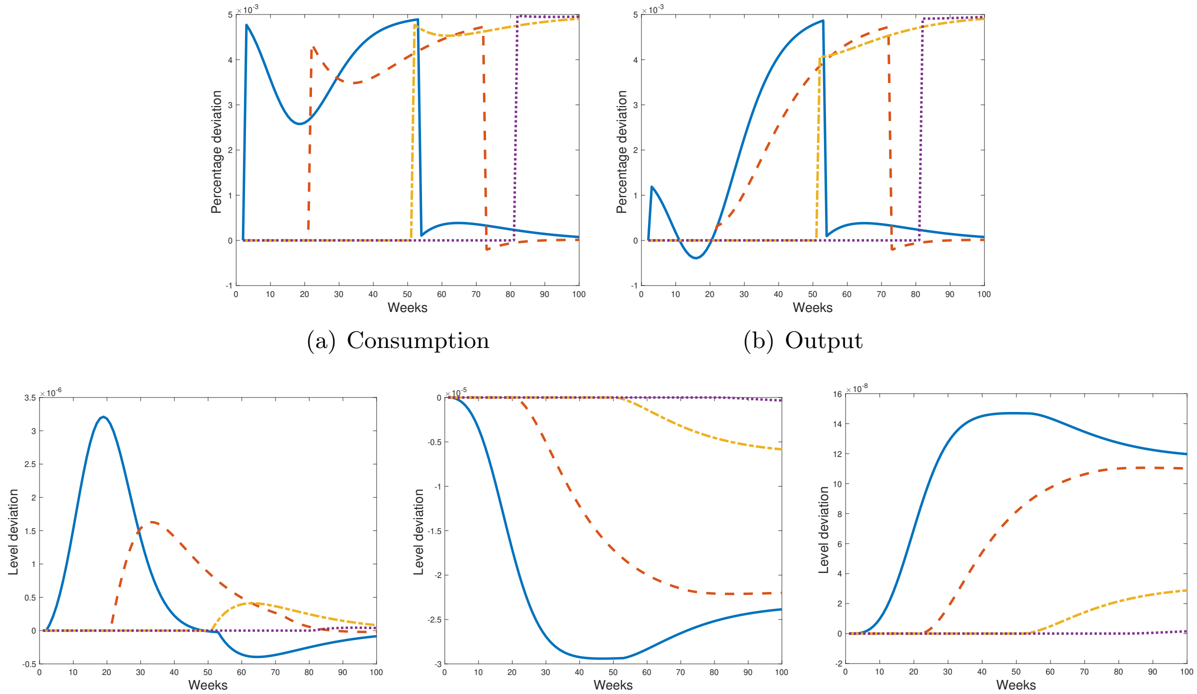


(c) Infected (d) Susceptible (e) Cumulative deaths

In the third experiment, we set $j = 50$ and let time t vary between 1 and 80 – that is, we examine the consumption 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 horizon of 50 weeks. Figure 5 presents the results. The response of consumption 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 consumption 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 consumption is less pronounced. See, for example, the dashed orange line versus the dashed-dotted yellow line in Figure 5.

In all three of the experiments, we observe that a temporary easing of monetary policy conditions leads to an increase in deaths and in a decrease in the stock of susceptible individuals in the long run. In SIR models, the final size of the epidemic overshoots the threshold of herd immunity and policies

Figure 5. IRFs to anticipated changes in the real interest rate. Horizon 50, revealed at time 1 (solid blue), 20 (dashed orange), 50 (dash-dotted yellow), 80 (dotted purple).



(a) Consumption (b) Output

(c) Infected (d) Susceptible (e) Cumulative deaths

that are successful at temporarily reducing the basic reproduction number $\mathcal{R}_0$, such as lockdowns, can reduce the final size of the epidemic and save lives[15]. As shown in Figure 1, the final number of deaths is larger in the absence of a lockdown policy than in our baseline economy. A similar logic operates in response to a change in monetary policy conditions. By fostering social interactions and temporarily raising the basic reproduction number, expansionary demand policies accentuate the epidemic overshoot and result in a higher overall number of deaths in the long run[16].

From these experiments, we conclude that monetary policy is likely to be less effective at the height of the pandemic. It could, however, help sustain the recovery in economic activity once the virus starts dissipating. However, such a support to economic activity will necessarily come at the expense of a deterioration in health outcomes.

[15] The threshold of herd immunity is given by $S^* = \frac{1}{\mathcal{R}_0}$. With $\mathcal{R}_0 = 1.45$, we have that $S^* \approx 0.69$. For a discussion of the epidemic overshoot beyond the threshold of herd immunity in SIR models, see for example Moll (2020).

[16] In all our simulations, we assume that the vaccine never arrives. Instead, if we were to assume that the vaccine does arrive, say after one year, then an easing of monetary policy conditions in the first year of the pandemic would be even more deadly. Indeed, as seen in Figures 3 and 4, cumulative deaths tend to peak a few weeks after the shock and decline slowly thereafter.

4.3. A delayed lift-off

Thus far, we have 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 funds rate stayed at the effective lower bound from weeks 1 to 45. We now consider two alternative scenarios in which the central bank delays lift-off by either 26 weeks (2 quarters) or 52 weeks (4 quarters).

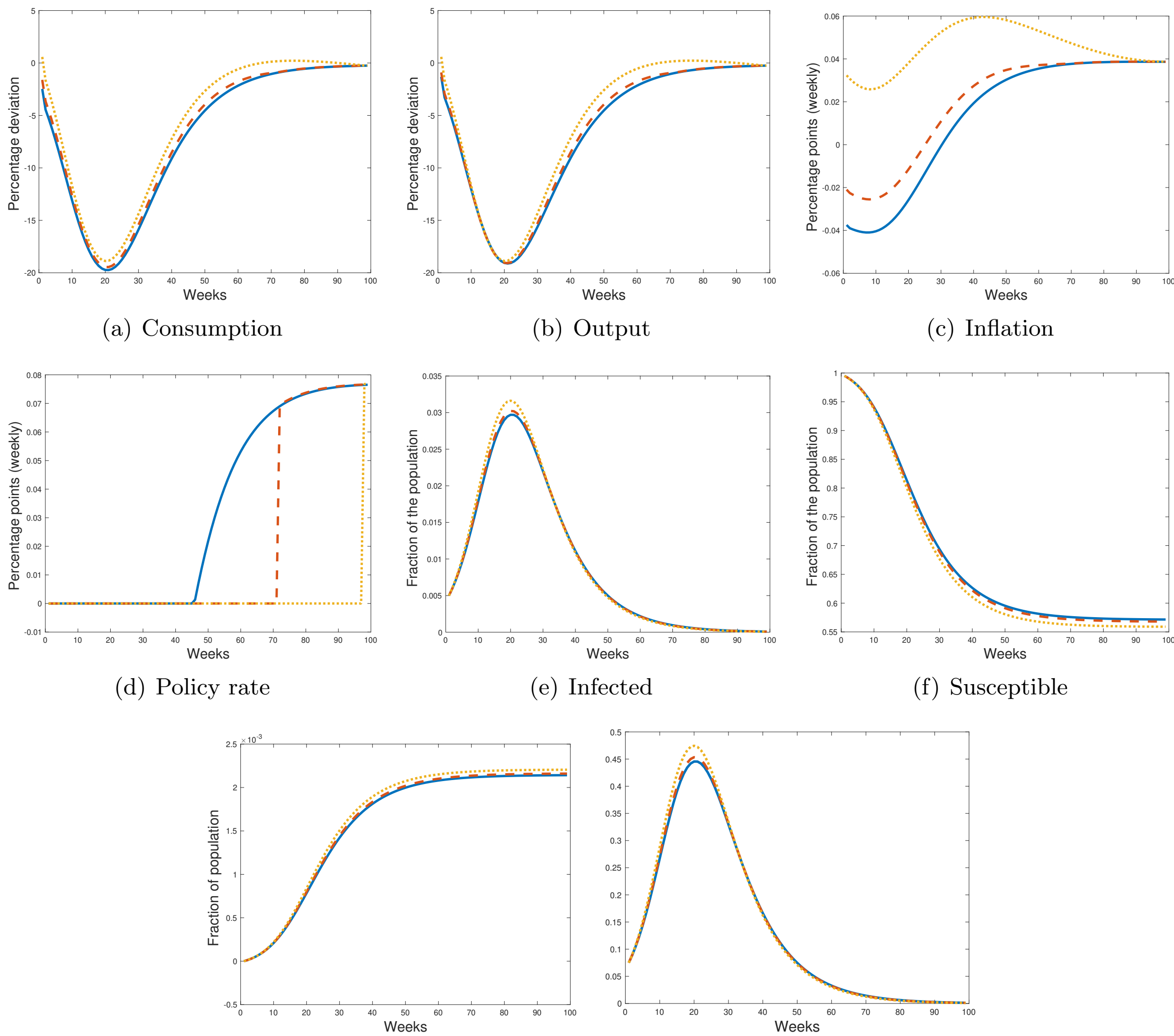
Figure 6 shows the simulated paths for economic and epidemiological variables after the same initial zoonotic exposure under different monetary policy rules. In particular, we report the results for our baseline economy (the solid lines), for an economy identical to the baseline but with a two-quarter delayed lift-off policy (the dashed lines), and for an economy with a four-quarter delayed lift-off policy (the dotted lines).

The main message from Figure 6 is that delayed lift-off policies lead to a significant increase in inflation but have only limited effects on real variables. Delaying lift-off from the effective lower bound brings about higher demand. To accommodate the expansion in demand, firms increase hours worked, which puts upward pressure on wages and, ultimately, prices as susceptible individuals are still reluctant to participate in the labor market. With the federal funds rate at its effective lower bound, the rise in inflation leads to a large decline in the real interest rate, which further stimulates economic activity. Initially, the delayed lift-off policies cushion the decline in economic activity, although the effects are small. However, as the epidemic progresses, the effects of forward guidance become less stimulative. In particular, forward guidance is not effective at softening the magnitude of the peak decline in output as shown in Figure 6 (b). Note that the trough in output is reached at the height of the pandemic, when the interest-sensitivity of consumption is the lowest. Furthermore, the higher initial path of economic activity under the delayed lift-off policy leads to an increase in infections, which, in turn, leads to more severe lockdowns and reinforces households' incentives to postpone consumption until the risk of infection wanes. Once the situation on the epidemiological front starts improving, the economy recovers at a faster pace under the delayed lift-off policies. 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. What should monetary policy do in a pandemic?

While we have so far shown that the effectiveness of monetary policy during a pandemic can be weaker, we have not analyzed how monetary policy should *optimally* be conducted in this context. Notably, a benevolent planner would likely weigh the limited gains in the stabilization of real activity against the human costs of additional infections when setting a path for the nominal interest rate. To identify which inefficiencies arise in the decentralized equilibrium and how monetary policy can

Figure 6. Economic and Epidemiological Effects (weekly). Baseline (solid), 2-quarter lift-off delay (dashed), 4-quarter lift-off delay (dotted)



(a) Consumption (b) Output (c) Inflation

(d) Policy rate (e) Infected (f) Susceptible

(g) Deaths (h) Containment rate

attempt to correct for them, we first compare the decentralized equilibrium with the allocation that a planner would achieve in section 5.1. We then study optimal policy in section 5.2, where we proceed in two steps: first, we compute the allocation under the joint optimal lockdown and monetary policies; and second, we study optimal monetary policy conditional on a given (and potentially sub-optimal) lockdown path.

5.1. The optimal allocation

The planner seeks to maximize the intertemporal utility of households subject to the epidemiological population dynamics equations and the economy-wide resource constraint. Formally:

$$V(S_t, I_t, R_t) = \max_{C_{s,t}, C_{i,t}, C_{r,t}, N_{s,t}, N_{i,t}, N_{r,t}} \{S_t u(C_{s,t}, N_{s,t}) + I_t u(C_{i,t}, N_{i,t}) + R_t u(C_{r,t}, N_{r,t}) + \beta V(S_{t+1}, I_{t+1}, R_{t+1})\} \quad (50)$$

subject to

$$S_t C_{s,t} + I_t C_{i,t} + R_t C_{r,t} = A(S_t \phi_s N_{s,t} + I_t \phi_i N_{i,t} + R_t \phi_r N_{r,t}) \quad (51)$$

$$S_{t+1} = (1-\delta_v)(S_t - \pi_{s1} S_t C_{s,t} I_t C_{i,t} - \pi_{s2} S_t N_{s,t} I_t N_{i,t} - \pi_{s3} S_t I_t) \quad (52)$$

$$I_{t+1} = (1 - \pi_r - \pi_d) I_t + \pi_{s1} S_t C_{s,t} I_t C_{i,t} + \pi_{s2} S_t N_{s,t} I_t N_{i,t} + \pi_{s3} S_t I_t \quad (53)$$

$$R_{t+1} = R_t + \pi_r I_t + \delta_v (S_t - \pi_{s1} S_t C_{s,t} I_t C_{i,t} - \pi_{s2} S_t N_{s,t} I_t N_{i,t} - \pi_{s3} S_t I_t) \quad (54)$$

The first-order conditions are:

$$u_c(C_{s,t}, N_{s,t}) + \beta \pi_{s1} I_t C_{i,t} (V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1}) = \lambda_t \quad (55)$$

$$u_c(C_{i,t}, N_{i,t}) + \overbrace{\beta \pi_{s1} S_t C_{s,t} (V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1})}^{\text{infection externality}} = \lambda_t \quad (56)$$

$$u_c(C_{r,t}, N_{r,t}) = \lambda_t \quad (57)$$

$$u_n(C_{s,t}, N_{s,t}) + \beta \pi_{s2} I_t N_{i,t} (V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1}) = -\lambda_t \phi_s \overbrace{A}^{\text{imperfect competition}}$$

$$u_n(C_{i,t}, N_{i,t}) + \overbrace{\beta \pi_{s2} S_t N_{s,t} (V_{i,t+1} - (1-\delta_v) V_{s,t+1} - \delta_v V_{r,t+1})}^{\text{infection externality}} = -\lambda_t \phi_i \overbrace{A}^{\text{imperfect competition}} \quad (58)$$

$$u_n(C_{r,t}, R_{r,t}) = -\lambda_t \phi_r \overbrace{A}^{\text{imperfect competition}} \quad (59)$$

where λ_t is the Lagrange multiplier associated with the budget constraint.

The envelope conditions are:

$$
\begin{aligned}
V_{s,t} &= u\left(C_{s,t}, N_{s,t}\right) + \lambda_t \left(\overbrace{A}^{\text{imperfect competition}} \phi_s N_{s,t} - C_{s,t} \right) + \left(1-\delta_v\right)\left(1-\tau_t\right)\beta V_{s,t+1} + \tau_t \beta V_{i,t+1} \\
&\quad + \delta_v \left(1-\tau_t\right)\beta V_{r,t+1} \qquad (60) \\
V_{i,t} &= u\left(C_{i,t}, N_{i,t}\right) + \lambda_t \left(\overbrace{A}^{\text{imperfect competition}} \phi_i N_{i,t} - C_{i,t} \right) \\
&\quad + \left(1-\pi_r-\pi_d\right)\beta V_{i,t+1} + \pi_r \beta V_{r,t+1} + \overbrace{\beta \tau_t \frac{S_t}{I_t}\left(V_{i,t+1} - \left(1-\delta_v\right)V_{s,t+1} - \delta_v V_{r,t+1}\right)}^{\text{infection externality}} \qquad (61) \\
V_{r,t} &= u\left(C_{r,t}, N_{r,t}\right) + \lambda_t \left(\overbrace{A}^{\text{imperfect competition}} \phi_r N_{r,t} - C_{r,t} \right) + \beta V_{r,t+1} \qquad (62)
\end{aligned}
$$

In the equations above, we highlight the differences with the decentralized equilibrium in red and blue as well as with the tags "imperfect competition" and "infection externality". Three types of distortions arise in the decentralized equilibrium: *(i)* for a given level of output, the presence of price adjustment costs reduces the amount of resources available for consumption, as can be seen by comparing equations 42 and 51 ; *(ii)* monopolistic competition drives a wedge between the marginal rate of substitution between consumption and hours worked and the marginal product of labor (terms in blue, also indicated by the tag "imperfect competition"); *(iii)* households do not internalize the effects of the consumption and labor supply decisions of infected individuals on the dynamics of the epidemic (terms in red, also indicated by the tag "infection externality").

While the first two distortions are standard in New Keynesian models and imply that the monetary authority should focus on stabilizing inflation, the infection externality is specific to the context of a pandemic. Infected individuals consume and work too much and, in doing so, contribute to the spread of the virus. This has two potential implications for monetary policy. First, monetary policy is a blunt tool: it affects consumption and hours worked of all individuals in a similar way. However, the infection externality is best addressed by policies that target only infected individuals. The same shortcoming is shared by other policies that affect individuals equally despite their health status, such as lockdowns. Second, absent any policy intervention, the decentralized equilibrium is inefficient with a level of economic activity that is too high. That is, the planner would be willing to engineer a decline in consumption and hours worked for *all* individuals in order to limit the spread of the virus within the population (see, for example, Eichenbaum, Rebelo and Trabandt, 2021, Jones, Philippon and Venkateswaran, 2021, and Farboodi, Jarosch and Shimer, 2021, among others).

5.2. Ramsey optimal policy

We now turn to the study of optimal policy. To build intuition, we proceed in two steps. First, we equip the planner with the ability to choose optimally the lockdown policy. In doing so, we want to give the chance for another tool than monetary policy to address the infection externality. We presume that the lockdown policy may be more effective in this task than monetary policy. Thus, in that first step, we study the joint optimal lockdown and monetary policies. Second, we relax the assumption that the lockdown policy is chosen optimally and we analyze how monetary policy should be conducted when the lockdown policy is sub-optimal to varying degrees.

The joint Ramsey optimal lockdown and monetary policies entail the government choosing paths for the containment rate $\{\mu_t\}_{t=0}^{\infty}$ and the nominal interest rate $\{R_t^{mp}\}_{t=0}^{\infty}$ to maximize social welfare, equation 50, subject to the constraints of the competitive economy. The formal optimal policy problem is presented in Appendix B. We assume that the policies are conducted with commitment; the government announces the paths for $\{\mu_t\}_{t=0}^{\infty}$ and $\{R_t^{mp}\}_{t=0}^{\infty}$ and sticks with them although the plan is time-inconsistent. We also assume that the government fully re-optimizes at time zero without incurring a loss in credibility, an assumption that we believe to be realistic given the unprecedented nature of the COVID-19 shock and the extraordinary policy measures that were put in place to address the crisis[17]. Lastly, for the sake of simplicity, and to make the intuition for our results as transparent as possible, we do not enforce the zero lower bound on nominal interest rates, which would constitute an additional constraint on the conduct of monetary policy.

The paths of μ_t, R_t^{mp}, and several economic and epidemiological variables under the joint optimal lockdown and monetary policies are presented in Figure 7. For comparison, we also plot economic and epidemiological outcomes in our baseline. Most variables exhibit considerable persistence under the optimal policies and we report only the first 500 periods of the simulation, when most of the action takes place. We see that the consumption tax μ_t is increased immediately in the first period of the simulation to a level close to 200 percent and declines only persistently thereafter. Output and consumption drop by about 25 percent on impact and inherit the persistent behavior of the consumption tax throughout the simulation. The forced decline in economic activity is successful at reducing the peak number of infections to about 1 percent of the population against 3 percent in our baseline. Thereafter, infections are maintained at a low level until the threshold of herd immunity is reached at very long horizons (beyond what is shown in the figures). Crucially, the persistent behavior of the lockdown policy helps reach the threshold of herd immunity without ever overshooting it, thereby minimizing the cumulative number of infections and deaths. As for monetary policy, the nominal interest rate is decreased substantially so as to keep inflation equal to its target in every period of the simulation. Thus, the government uses the two tools at its disposal to achieve two different objectives. The lockdown policy is used to achieve the level of economic activity that strikes the right balance between economic and health outcomes. Monetary policy is used to offset the distortions arising from monopolistic competition and price adjustment costs, which implies keeping the inflation rate on target.

What happens if one of those two tools is not set optimally? For example, assume that the lockdown policy is not optimal: should monetary policy be used to achieve a level of economic activity that minimizes the inefficiencies arising from the infection externality? To address this

[17]This assumption is immaterial for our findings — the results are unchanged if we instead assume that the lockdown and monetary policies are conducted according to a timeless perspective.

issue, we now derive the Ramsey optimal monetary policy conditional on a given path for the containment rate. That is, we assume that the government chooses a path for the nominal interest rate $\{R_t^{mp}\}_{t=0}^{\infty}$ to maximize social welfare subject to the constraints of the competitive economy and taking the path of the containment rate $\{\mu_t\}_{t=0}^{\infty}$ as given. As in the preceding exercise, we assume that monetary policy is conducted under commitment and we do not enforce the zero lower bound on nominal interest rates.

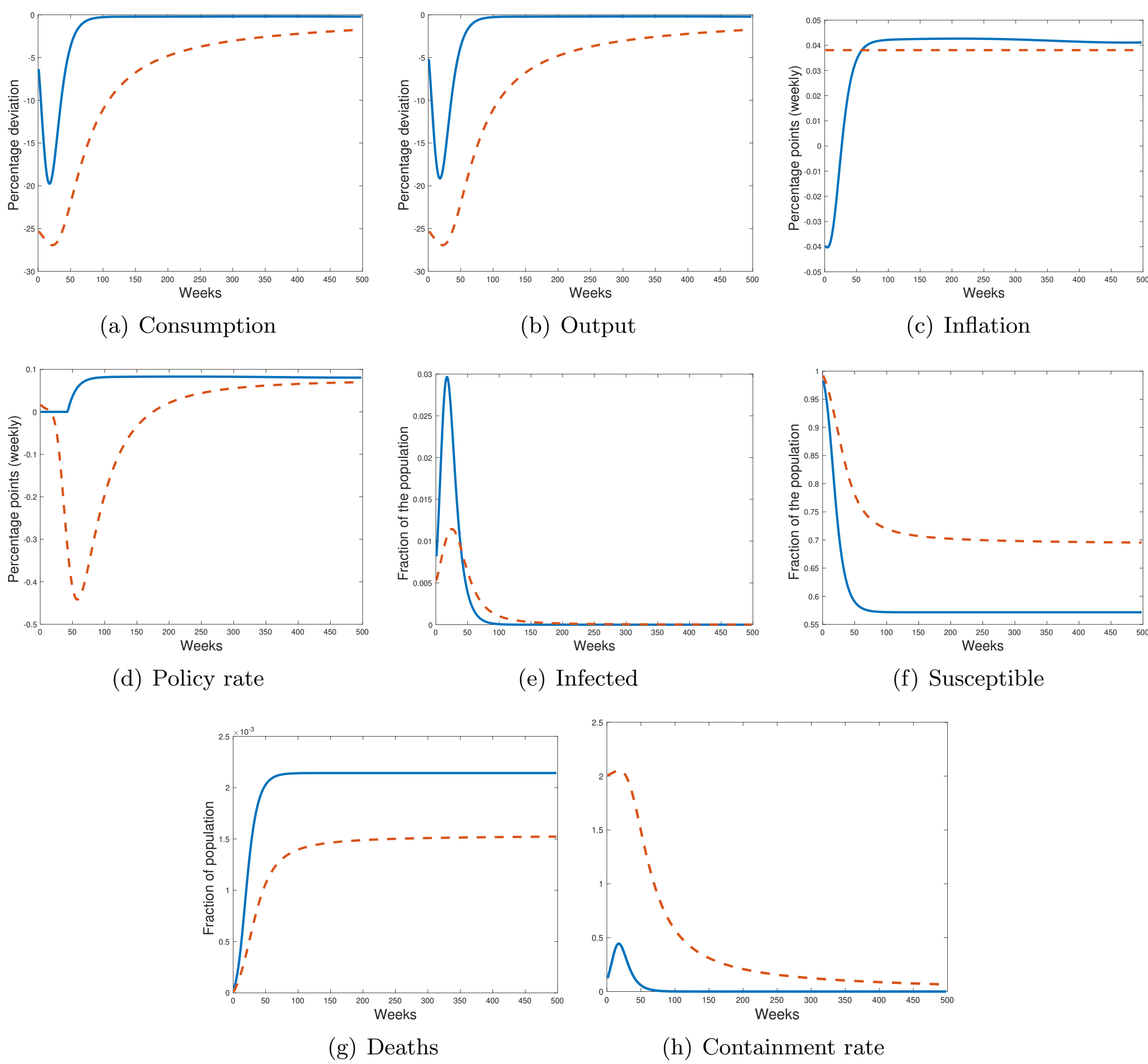
Figure 8 shows the policy rate R_t^{mp} as well as several economic and epidemiological variables in three cases: *(i)* the lockdown policy is optimal (solid blue line); *(ii)* the lockdown policy is at all times 75 percent as stringent as the optimal policy $\mu_t = 0.75 * \mu_t^{opt}$ (dashed orange line); *(iii)* the lockdown policy is at all times 50 percent as stringent as the optimal policy $\mu_t = 0.5 * \mu_t^{opt}$ (dashed-dotted yellow line). The solid blue line replicates the results from the joint optimal lockdown and monetary policies exercise: when the lockdown path is the optimal one, monetary policy is tasked with stabilizing inflation. Focusing on the dashed orange and dashed-dotted yellow lines, we see that monetary policy is tighter — the path for the federal funds rate is above that with an optimal lockdown policy — when the lockdown policy is sub-optimal[18]. Indeed, the monetary authority now faces a trade-off between its objective of inflation stabilization and the necessity to minimize the inefficiencies arising from the infection externality. Since the level of economic activity in the decentralized equilibrium is too high, monetary policy tightens and engineers a fall in economic activity. In our calibration, the central bank faces a meaningful trade-off. Indeed, while inflation deviates significantly from target — it drops to about minus 3 percent on an annual basis on impact when the lockdown policy is half as stringent as the optimal policy —, the output path is still noticeably above that under the optimal lockdown policy. Moreover, health outcomes deteriorate compared to the case with an optimal lockdown policy: with a lockdown policy half as stringent as the optimal policy, infections peak at about 1.5 percent of the population, 34.3 percent of the population ends up contracting the virus, and 0.171 percent of the population ends up dying from the virus. These numbers are 1.15 percent, 31 percent, and 0.152 percent, respectively, under the optimal lockdown policy.

Thus, our analysis of optimal policy reveals two main results: *(i)* with both lockdowns and monetary policy at its disposal, the planner should use lockdowns to address the infection externality and monetary policy to address the distortions arising from monopolistic competition and price stickiness; *(ii)* if the lockdown policy is sub-optimal, monetary policy faces a trade-off between its objective of inflation stabilization and the necessity to minimize the distortions arising from the infection externality and resolves that trade-off by tightening monetary policy the more sub-optimal the lockdown policy is. Interestingly, some leading monetary policymakers, notably Bullard (2020), argued that monetary policy should not be stimulative in the midst of a pandemic. In our framework, whether monetary policy should be accommodative or not depends on the government's ability to control virus spread.

[18] The variable relevant for household's consumption decisions is the real interest rate, not the nominal interest rate. The path of the real interest rate is also higher when the lockdown policy is sub-optimal.

To finish, let us add a word of caution. In this section, we did not attempt to provide a comprehensive quantitative assessment of how monetary policy should behave in a pandemic. Rather, we studied in details how one key feature of the pandemic — the interaction between economic decisions and virus dynamics — affects the optimal design of monetary policy. Using a simple framework and focusing on one key aspect of the pandemic enabled us to cleanly isolate the forces at work and build solid intuition for our results. However, we do not dispute that, in reality, other motives such as a desire to keep otherwise profitable businesses afloat and preserving employment relationships may very well dominate the motive that we emphasize in determining the optimal stance of monetary policy.

Figure 7. Economic and Epidemiological Variables (weekly). Baseline (solid), Optimal policy (dashed)

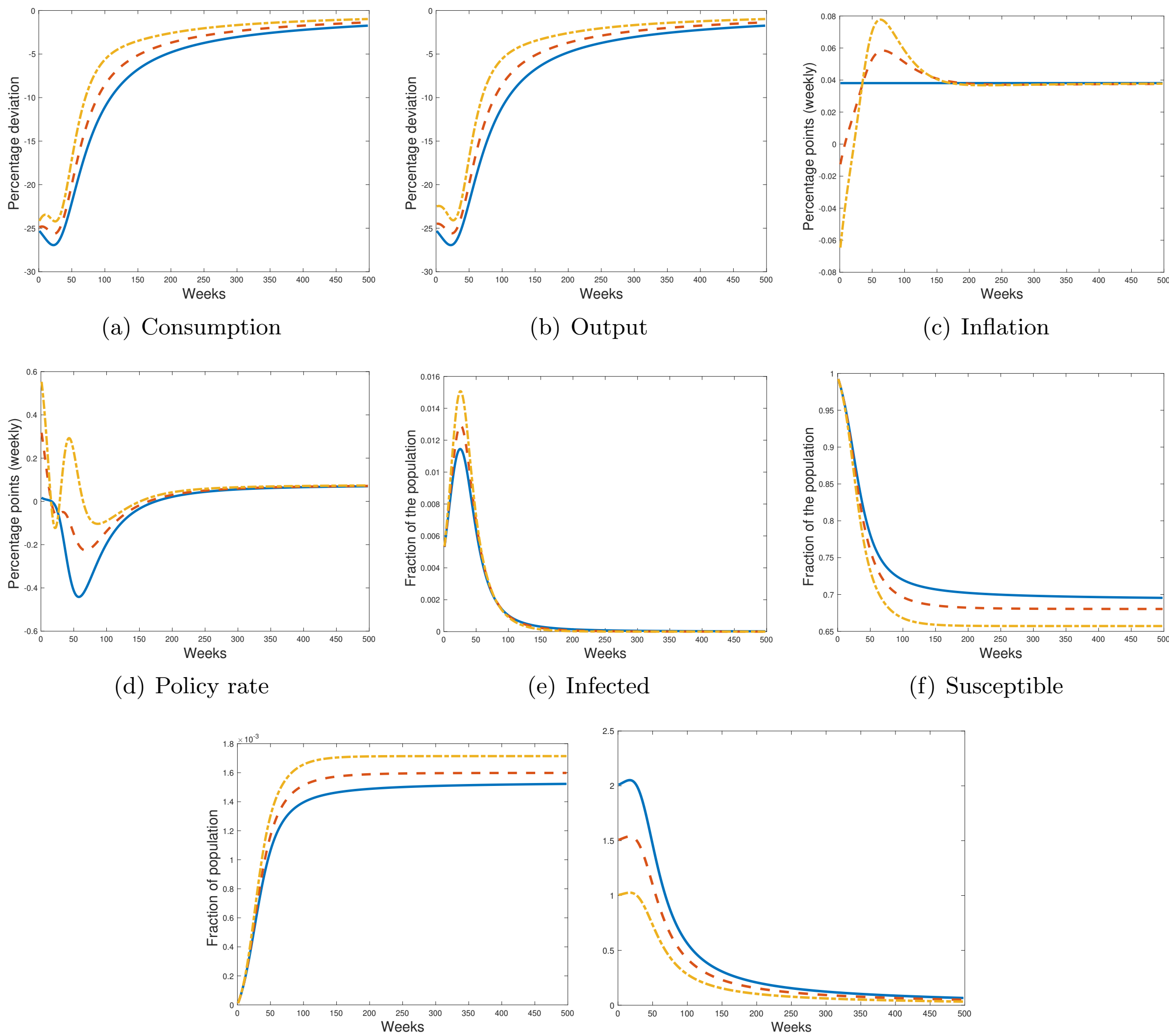


(a) Consumption (b) Output (c) Inflation

(d) Policy rate (e) Infected (f) Susceptible

(g) Deaths (h) Containment rate

Figure 8. ECONOMIC AND EPIDEMIOLOGICAL VARIABLES (WEEKLY). OPTIMAL LOCKDOWN POLICY (SOLID), $\mu_t = 0.75 * \mu_t^{opt}$ (DASHED), $\mu_t = 0.5 * \mu_t^{opt}$ (DASHED-DOTTED)



(a) Consumption (b) Output (c) Inflation

(d) Policy rate (e) Infected (f) Susceptible

(g) Deaths (h) Containment rate

6. Robustness

There is a great deal of uncertainty about the parameters governing epidemiological dynamics during the still on-going COVID-19 pandemic. In this section, we study the sensitivity of our results to variations in the basic reproduction number, $\mathcal{R}_0$, the per-period probability of dying when infected or mortality rate, π_d, and the flow value of being alive, $\bar{u}$. We focus our analysis on the following statistics: the peak infection rate, the timing of the peak, the overall size of the pandemic measured by the percentage of susceptible individuals at the end of it, the maximum drop in output, and a measure of the effectiveness of monetary policy. This last statistic is computed as the increase in output generated by an unanticipated one basis point drop in the weekly real interest rate at the peak of the pandemic (the first experiment in Section 4.2) divided by the increase in response to the same shock in the absence of a pandemic. As should be clear from the exercises conducted in Section 4, the dynamic interaction between virus dynamics and economic decisions is critical in shaping the transmission of monetary policy in our framework. In the interest of space, we have decided to report only one measure of monetary policy effectiveness, but one should keep in mind that it does not provide an account of those dynamic considerations and is therefore an imperfect indicator of monetary policy effectiveness. We divide Table 1 in three sections, one for each variation we are analyzing. The first row for each section in Table 1 corresponds to the baseline described in Section 3.2.

Table 1: Robustness

	Infection rate	Timing	Susceptibles	Output	MP effectiveness
Basic reproductive number					
$\mathcal{R}_0 = 1.45$	2.97	21	57	-19	80%
$\mathcal{R}_0 = 2$	8.14	16	35	-35	78%
$\mathcal{R}_0 = 2.5$	13.26	13	25	-44	79%
Mortality rate					
$\pi_d = 0.005 * 7/15$	2.97	21	57	-19	80%
$\pi_d = 0.0025 * 7/15$	3.04	21	57	-17	84%
$\pi_d = 0.010 * 7/15$	2.87	21	58	-22	73%
Flow value of being alive					
$\bar{u} = 5.4$	2.97	21	57	-19	80%
$\bar{u} = 2.9$	3.06	21	56	-17	86%
$\bar{u} = 4.3$	3.01	21	57	-18	82%

The first section in Table 1 reports the results for alternative basic reproduction numbers, $\mathcal{R}_0$. In our baseline, $\mathcal{R}_0 = 1.45$, which is at the lower end of estimates in the literature. For example, Bar-On et al. (2020) provide a range of estimates for $\mathcal{R}_0$ between 2 and 6, while Chudik, Pesaran and Rebucci (2021) suggest that $\mathcal{R}_0$ is comprised between 2.4 and 3.9. We explore two alternative values for the basic reproduction number: $\mathcal{R}_0 = 2$ and $\mathcal{R}_0 = 2.5$. As shown in Table 1, as the basic reproduction number increases, the pandemic gets larger — the peak infection rate increases and a lower fraction of susceptible individuals is left at the end of the pandemic. Consequently, the size of the economic downturn brought about by the pandemic increases with $\mathcal{R}_0$. As shown in the last column of Table 1, monetary policy effectiveness is stable across values of $\mathcal{R}_0$. This is due to two factors. First, when $\mathcal{R}_0$ is high, the interest sensitivity of the consumption of susceptible individuals at the peak of the pandemic is low, but so is the population share of susceptible individuals. Through a compositional effect, the interest sensitivity of aggregate consumption is therefore little affected when $\mathcal{R}_0$ varies. Second, when $\mathcal{R}_0$ is high, the economic experiences a much deeper recession. In that case, the marginal utility of consumption shoots up and, although the risk of infection is extremely high, its importance in consumption decisions is reduced.

In our baseline, we assume an infection fatality rate of 0.5 percent, which implies a weekly mortality rate, π_d, of 0.23 percent. We consider two alternatives: first, an infection fatality rate of 0.25 percent, which implies a weekly mortality rate of 0.12 percent, and an infection fatality rate of 1 percent, which implies a weekly mortality rate of 0.47 percent. As shown in the second panel in Table 1, variations in the mortality rate have smaller effects on epidemiological outcomes than variations in the basic reproduction number. In particular, the timing of the peak and the size of the pandemic are the same across alternative values for the infection fatality rate, while the infection rate at the peak changes slightly: it decreases as the infection fatality rate increases. The economic effects implied by changes in the mortality rate are larger than the epidemiological ones. For example, if the mortality rate is half that in the baseline, the drop in output is about 11 percent smaller than in the baseline. Similarly, when the mortality rate doubles, the drop in output at the peak of the pandemic is about 16 percent larger than in the baseline. Indeed, when the probability of death increases, individuals have more to lose from becoming infected and they cut back more drastically on consumption and hours worked. They also become more reluctant to adjust consumption in response to real interest changes: as shown in the last column in Table 1, the effectiveness of monetary policy is a decreasing function of the infection fatality rate.

The third panel in Table 1 explores the sensitivity of our results to the valuation of a statistical life (VSL). The VSL in our baseline does not adjust by life expectancy at the age of death. Robinson, Sullivan and Shogren (2021) use three approaches to adjust for age: an invariant population-average VSL, a constant value per statistical life-year, and a VSL that follows an inverse-U pattern peaking around middle age. When applying these approaches to the U.S. age distribution of COVID-19 deaths, they obtain average VSL estimates of \$10.6 million, \$4.5 million, and \$8.5 million, respectively. In our framework, those VSL estimates imply the following values for the flow value of life: 5.1, 2.9, and 4.3, respectively. We report in Table 1 the results for $\bar{u} = 2.9$ and $\bar{u} = 4.3$. As shown in Table 1, variations in the VSL have limited effects on epidemiological and economic outcomes. The last column shows that monetary policy regains its effectiveness as the VSL decreases. The intuition for this result is similar to the one outlined above in the case of the mortality rate: with a smaller VSL, individuals are less concerned about the risk of infection and become more willing to engage in economic activities.

To finish, let us note that we have also explored the robustness of our optimal policy results. In the interest of conciseness, we do not report additional results here since our two main findings are unchanged. Regardless of parameter combinations, we still find that: *(i)* with both lockdowns and monetary policy at its disposal, the planner uses lockdowns to address the infection externality and monetary policy to stabilize inflation; *(ii)* in case the lockdown policy is sub-optimal, monetary policy should be tighter the more sub-optimal the lockdown policy is.

7. Conclusion

In response to the COVID-19 shock, central banks around the world acted swiftly and forcefully by cutting short-term interest rates, extending forward guidance and asset purchases, and providing liquidity and credit support (English, Forbes and Ubide, 2021). In this paper, we develop a framework where economic decisions and virus dynamics are interlinked and analyze the role played during a pandemic by two monetary policy tools: conventional interest rate policy and forward guidance.

Our first main result pertains to the effectiveness of monetary policy. We find that monetary policy is generally less effective in a pandemic than in normal times. In the model, the transition probability from being healthy (susceptible) to sick (infected) depends on households' consumption and labor supply decisions. In a pandemic, individuals have to balance the benefits of taking advantage of intertemporal substitution opportunities with the risk of becoming sick. As a result, decreases in real interest rates are less effective at propping up economic activity than in normal times. The strength of this channel is strongly state-dependent: individuals are the most reluctant to engage in intertemporal substitution when the stock of infected individuals — and, thus, the probability of infection — is the largest.

Our second main result pertains to the optimal conduct of monetary policy. We find that monetary policy is poorly equipped to address the main inefficiency arising in the decentralized equilibrium, namely the fact that infected individuals do not internalize the effects of their actions on the dynamics of the epidemic. The optimal behavior of monetary policy depends on how other tools used to limit virus spread, such as lockdowns, are deployed. If the lockdown policy is set optimally, monetary policy should focus on minimizing the distortions arising from price stickiness and monopolistic competition, which implies stabilizing inflation. However, if the lockdown policy is sub-optimal, monetary policy faces a trade-off between ensuring price stability and minimizing the distortions arising from the infection externality. The trade-off is resolved by tightening monetary policy the more sub-optimal the lockdown policy is.

Our paper is a first step to understanding whether monetary policy transmits, and should be conducted, differently in a pandemic than in normal times. We have deliberately considered a simple framework and focused on one key aspect of the pandemic — the interaction between economic decisions and virus dynamics. This strategy has allowed us to trace the inner workings of the transmission of monetary policy and cleanly isolate the forces at work in the optimal policy exercises. However, our model abstracts from many important features of the pandemic recession such as, for example, sectoral and occupational heterogeneity (Kaplan, Moll and Violante, 2020), credit constraints, the heterogeneity in the exposure to the virus by age (Hur, 2020), or unconventional measures implemented by central banks (asset purchases programs, measures to facilitate the flow of credit, etc). Thus, our results should not be taken as a quantitative guide to optimal policy. Undertaking such a quantitative evaluation of monetary policy is an interesting avenue for future research, but is outside the scope of this paper.

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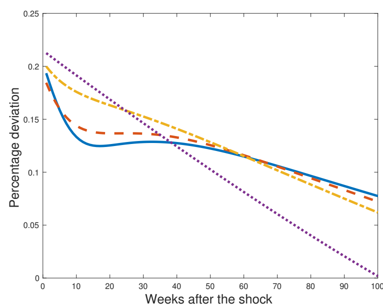
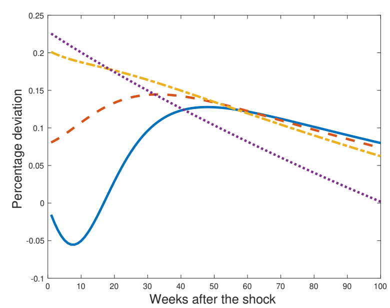
Appendix A. Additional monetary policy experiment

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 re-simulate our baseline pandemic scenario of 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, 100). 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 short-run effects of monetary policy shocks on output and consumption are weaker at the height of the pandemic (shocks happening in weeks 10 and 30) than in normal times (shock happening in week 100). All expansionary monetary policy shocks lead to more deaths and less susceptible individuals in the long run, but the effect is stronger for shocks happening earlier in the pandemic.

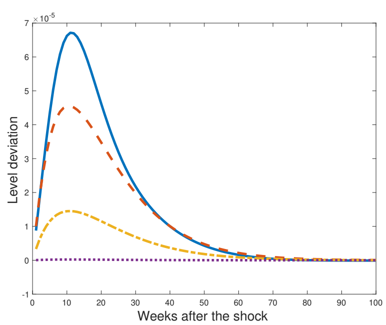
Figure 9. IRFs to Monetary Policy Shocks at time 10 (solid blue), 30 (dashed orange), 50 (dash-dotted yellow), 100 (dotted purple).



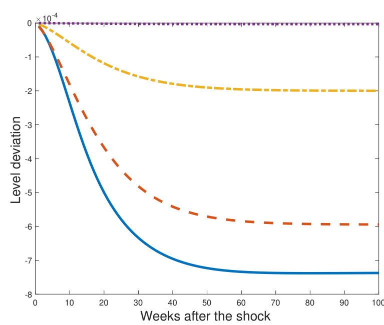
(a) Consumption



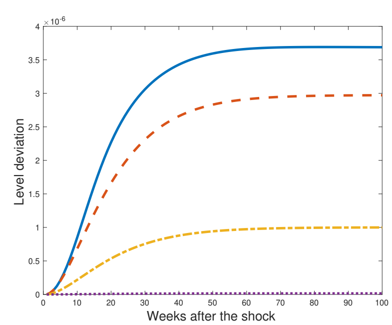
(b) Output



(c) Infected



(d) Susceptible



(e) Cumulative deaths

Appendix B. Optimal policy problem

Joint optimal lockdown and monetary policies. The planner chooses paths for the containment rate $\{\mu_t\}_{t=0}^{\infty}$ and the nominal interest rate $\{R_t^{mp}\}_{t=0}^{\infty}$ to maximize social welfare subject to the constraints of the competitive economy: equations 17 to 19 describing SIR dynamics, the marginal utilities of consumption for susceptible, infected, and recovered individuals, equations 20 to 22], the labor supply conditions for susceptible, infected, and recovered individuals, equations 23 to 25, the value functions for susceptible, infected, and recovered individuals, equations 27 to 29, the Phillips curve, equation 37, the aggregate Euler equation, equation 26, the aggregate resource constraint, equation 42, and the production function, equation 34. The problem can be seen as one in which the planner chooses directly the allocation. Once the paths for the marginal utility of consumption λ_t and inflation are known, the path of nominal interest rates consistent with this allocation can be backed out using the aggregate Euler equation. In the end, the Ramsey planner chooses the sequence $\{S_{t+1}, I_{t+1}, R_{t+1}, \tau_t, C_{s,t}, C_{i,t}, C_{r,t}, N_{s,t}, N_{i,t}, N_{r,t}, V_{s,t}, V_{i,t}, V_{r,t}, \lambda_t, w_t, \Pi_t, Y_t, \mu_t\}_{t=0}^{\infty}$ to maximize the following Lagrangian, where the $\omega_{i,t}$ are the Lagrange multipliers associated with the constraints:

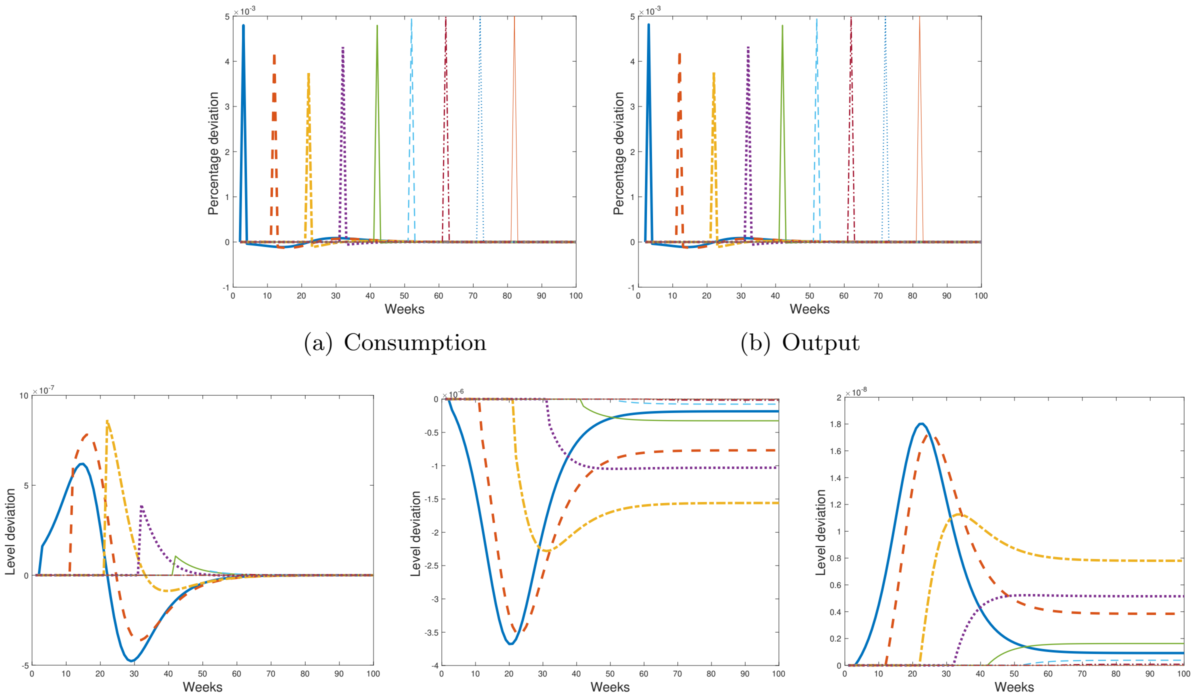
$$
\begin{aligned}
\mathcal{L} \quad = \quad & \sum_{t=0}^{\infty} \beta^t (S_t u\left(C_{s,t}, N_{s,t}\right) + I_t u\left(C_{i,t}, N_{i,t}\right) + R_t u\left(C_{r,t}, N_{r,t}\right) + \omega_{1,t}\left[\left(1-\delta_v\right) S_t\left(1-\tau_t\right) - S_{t+1}\right] \\
& + \omega_{2,t}\left[\left(1-\pi_r-\pi_d\right) I_t + \tau_t S_t - I_{t+1}\right] + \omega_{3,t}\left[R_t + \pi_r I_t + \delta_v S_t\left(1-\tau_t\right) - R_{t+1}\right] \\
& + \omega_{4,t}\left[\pi_{s1} C_{s,t} I_t C_{i,t} + \pi_{s2} N_{s,t} I_t N_{i,t} + \pi_{s3} I_t - \tau_t\right] \\
& + \omega_{5,t}\left[C_{s,t}^{-\sigma} + \beta \pi_{s1} I_t C_{i,t}\left(V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1}\right) - \lambda_t\left(1+\mu_t\right)\right] \\
& + \omega_{6,t}\left[C_{i,t}^{-\sigma} - \lambda_t\left(1+\mu_t\right)\right] + \omega_{7,t}\left[C_{r,t}^{-\sigma} - \lambda_t\left(1+\mu_t\right)\right] \\
& + \omega_{8,t}\left[-\chi N_{s,t}^{1/\varphi} + \beta \pi_{s2} I_t N_{i,t}\left(V_{i,t+1} - \left(1-\delta_v\right) V_{s,t+1} - \delta_v V_{r,t+1}\right) + \lambda_t w_t \phi_s\right] \\
& + \omega_{9,t}\left[-\chi N_{i,t}^{1/\varphi} + \lambda_t w_t \phi_i\right] + \omega_{10,t}\left[-\chi N_{r,t}^{1/\varphi} + \lambda_t w_t \phi_r\right] \\
& + \omega_{11,t}\left[\frac{C_{s,t}^{1-\sigma}}{1-\sigma} - \chi \frac{N_{s,t}^{1+1/\varphi}}{1+1/\varphi} + \bar{u} + \lambda_t\left(w_t \phi_s N_{s,t} - \left(1+\mu_t\right) C_{s,t}\right) + \left(1-\tau_t\right)\left(1-\delta_v\right) \beta V_{s,t+1}\right. \\
& \left. + \tau_t \beta V_{i,t+1} + \left(1-\tau_t\right) \delta_v \beta V_{r,t+1} - V_{s,t}\right] \\
& + \omega_{12,t}\left[\frac{C_{i,t}^{1-\sigma}}{1-\sigma} - \chi \frac{N_{i,t}^{1+1/\varphi}}{1+1/\varphi} + \bar{u} + \lambda_t\left(w_t \phi_i N_{i,t} - \left(1+\mu_t\right) C_{i,t}\right) + \left(1-\pi_r-\pi_d\right) \beta V_{i,t+1} + \pi_r \beta V_{r,t+1} - V_{i,t}\right] \\
& + \omega_{13,t}\left[\frac{C_{r,t}^{1-\sigma}}{1-\sigma} - \chi \frac{N_{r,t}^{1+1/\varphi}}{1+1/\varphi} + \bar{u} + \lambda_t\left(w_t \phi_r N_{r,t} - \left(1+\mu_t\right) C_{r,t}\right) + \beta V_{r,t+1} - V_{r,t}\right] \\
& + \omega_{14,t}\left[\left(1+\zeta\right)\left(1-\theta\right) + \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}\right] \\
& + \omega_{15,t}\left[S_t C_{s,t} + I_t C_{i,t} + R_t C_{r,t} - Y_t\left(1 - \frac{\phi^p}{2}\left(\Pi_t - \Pi^*\right)^2\right)\right] \\
& + \omega_{16,t}\left[A\left(\phi_s S_t N_{s,t} + \phi_i I_t N_{i,t} + \phi_r R_t N_{r,t}\right) - Y_t\right])
\end{aligned}
$$

We derive the first-order conditions associated with this problem and solve analytically for the steady-state values of the Lagrange multipliers $\omega_{i,t}$. We solve for the system of equations comprised of the constraints to the maximization problem and the first-order conditions using Dynare's perfect foresight solver.

Optimal monetary policy. The Ramsey problem for the optimal monetary policy conditional on a given path for the lockdown path $\{\mu_t\}_{t=0}^{\infty}$ is exactly the same except the planner does not maximize with respect to μ_t.

Appendix C. Figures

Figure 10. IRFs to unanticipated changes in the real interest rate at different dates (week 1 to week 80). Laissez-faire policy.

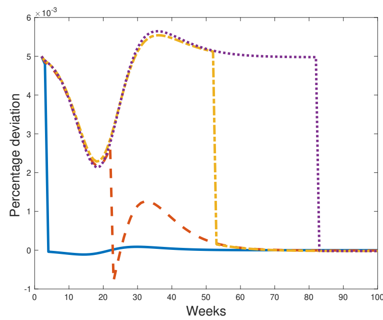


(a) Consumption (b) Output

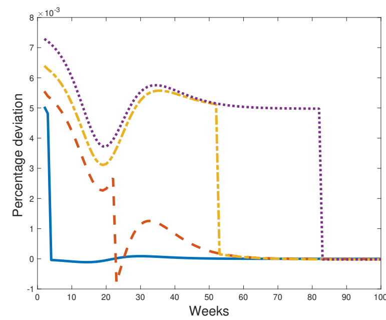
(c) Infected (d) Susceptible (e) Cumulative deaths

Note: The left dark blue line shows the response to a 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.

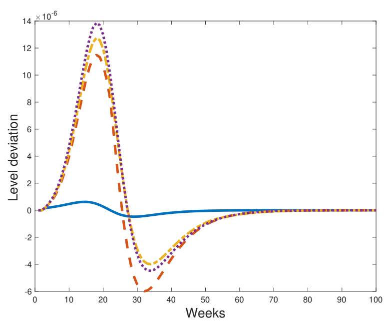
Figure 11. IRFs to anticipated changes in the real interest rate. Anticipated at date 1, horizon 1 (solid blue), 20 (dashed orange), 50 (dash-dotted yellow), 80 (dotted purple). Laissez-faire policy.



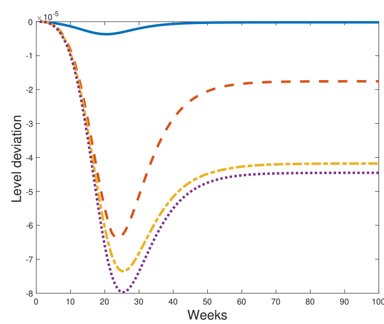
(a) Consumption



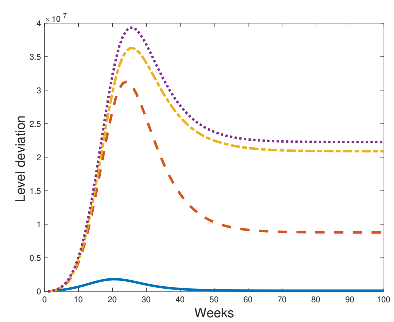
(b) Output



(c) Infected

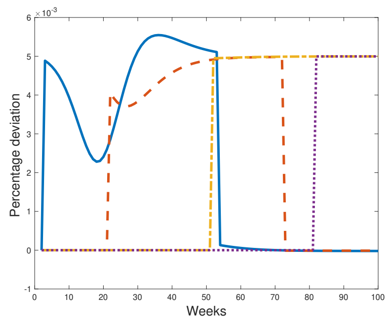


(d) Susceptible

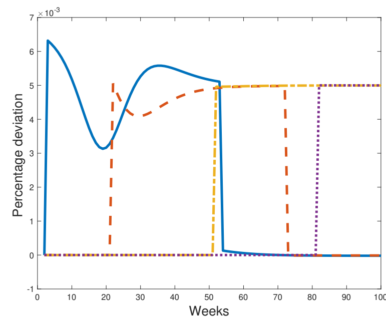


(e) Cumulative deaths

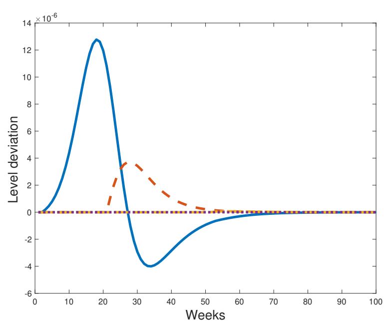
Figure 12. IRFs to anticipated changes in the real interest rate. Horizon 50, revealed at time 1 (solid blue), 20 (dashed orange), 50 (dash-dotted yellow), 80 (dotted purple). Laissez-faire policy.



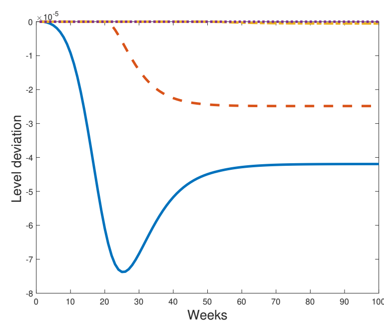
(a) Consumption



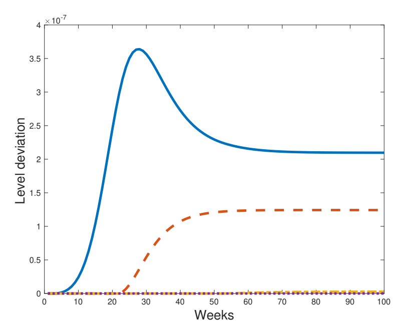
(b) Output



(c) Infected



(d) Susceptible



(e) Cumulative deaths