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ABSTRACT

We analyze the effects of an epidemic in three standard macroeconomic models. We find that the neoclassical model does not rationalize the positive comovement of consumption and investment observed in recessions associated with an epidemic. Introducing monopolistic competition into the neoclassical model remedies this shortcoming even when prices are completely flexible. Finally, sticky prices lead to a larger recession but do not fundamentally alter the predictions of the monopolistic competition model.

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1 Introduction

A central feature of recessions is the positive comovement between output, hours worked, consumption, and investment. In this respect, the COVID-19 recession is not unique. At least since Barro and King (1984), it has been recognized that, absent aggregate productivity shocks, it is difficult for many models to generate comovement in macroeconomic aggregates. So, a natural question is: what class of models generates comovement in a recession caused by an epidemic?

To address this question, we extend the framework developed in Eichenbaum, Rebelo, and Trabandt (2020a) to include investment. A key feature of that framework is that an epidemic naturally generates negative shifts in both the demand for consumption and the supply of labor. These shifts arise because consumption and working increase the risks of infection for people who are not immune to the virus.

We consider three canonical macroeconomic models: the neoclassical model, a flexible-price model with monopolistic competition, and a New Keynesian model with sticky prices. Calibrated versions of all three models generate recessions in response to an epidemic. However, the neoclassical model fails to generate positive comovement between investment and consumption. In contrast, both the model with monopolistic competition and flexible prices, and the New Keynesian model succeed in doing so. In addition, both models imply that the epidemic is accompanied by a moderate decline in the inflation rate.

The intuition for our results is as follows. Consider first the neoclassical model. Suppose that people can become infected through consumption activities but not by working. Then, an epidemic leads to a large drop in consumption and a boom in investment. The latter boom reflects two forces: the household wants to consume more once the infection wanes and it wants to smooth hours worked over time. By building up the capital stock, it can accomplish both objectives.

Now suppose that people can become infected by working but not through consumption activities. Then, an epidemic leads to a small decline in consumption but a large fall in hours worked and output. There is also a large fall in investment because households smooth consumption in the face of a transitory fall in income.

In the calibrated version of the model, people can become infected through both consumption and working activities. We find that the shift in consumption demand dominates the shift in labor supply. So consumption falls but investment remains above its steady-state value throughout most of the epidemic.

In contrast, in the monopolistic competition model the shift in labor supply dominates the shift in consumption demand. So an epidemic generates a steep recession along with sharp declines in both consumption and investment. The shift in labor supply becomes more important because monopolistic competition reduces the real wage relative to the case of perfect competition. A lower wage means that the compensation to a worker for being exposed to the virus is lower. The household responds by reducing hours worked of non-immune people by more than it does under perfect competition. As a result, consumption and investment comove positively.

Sticky prices increase the depth of the recession relative to the model with monopolistic competition and flexible prices. But the effect of sticky prices is relatively small. The intuition for this result is as follows. It is well known that nominal price rigidities exacerbate the effects of negative demand shifts. But they alleviate the impact of negative supply shifts.[1] Since both shifts are operative during an epidemic, sticky prices do not, on net, have a strong effect on the response of output to an epidemic.

The remainder of this paper is organized as follows. In Sections 2 and 3 we study the effects of an epidemic in the neoclassical model. Sections 4 and 5 discuss the effects of an epidemic in a monopolistically competitive model and a New Keynesian model, respectively. Section 6 reviews the related literature and Section 7 concludes.

2 An epidemic in the neoclassical model

In this section, we describe the effects of an epidemic in two versions of the neoclassical growth model: with competitive producers and with monopolistic competition. The economy is initially in a steady state where all people are identical. The population is then divided into four groups: susceptible (people who have not yet been exposed to the virus), infected (people who have been infected by the virus), recovered (people who survived the infection and acquired immunity), and deceased (people who died from the infection). We denote the fraction of the initial population in each group by S_t, I_t, R_t and D_t, respectively. The variable T_t denotes the number of newly infected people.

[1] See Woodford (2011) and Gali (2015) for classic discussions of the effect of demand and supply shocks in New Keynesian models.

At time zero, a fraction ε of the population is infected by a virus:

$$I_0 = \varepsilon.$$

The rest of the population is susceptible to the virus:

$$S_0 = 1 - \varepsilon.$$

Social interactions occur at the beginning of the period (infected and susceptible people meet). Then, changes in health status unrelated to social interactions (recovery or death) occur. At the end of the period, the consequences of social interactions materialize and T_t susceptible people become infected.

As in Eichenbaum, Rebelo and Trabandt (2020a,b), we assume that susceptible people can become infected in three ways: purchasing consumer goods, working, and through random interactions unrelated to economic activity. The number of newly infected people is given by the transmission function:

$$T_t = \pi_1 \left(S_t C_t^s\right) \left(I_t C_t^i\right) + \pi_2 \left(S_t N_t^s\right) \left(I_t N_t^i\right) + \pi_3 S_t I_t. \tag{1}$$

The variables C_t^s and C_t^i represent the consumption of a susceptible and infected person, respectively. The variables N_t^s and N_t^i represent hours worked of a susceptible and infected person, respectively. The number of newly infected people that results from consumption-related interactions is given by $\pi_1 \left(S_t C_t^s\right) \left(I_t C_t^i\right)$. The terms $S_t C_t^S$ and $I_t C_t^I$ represent total consumption of susceptible and infected people, respectively. The parameter π_1 reflects both the amount of time spent in consumption activities and the probability of becoming infected as a result of those activities.

The number of newly infected people that results from interactions at work is given by $\pi_2(S_t N_t^S) \left(I_t N_t^I\right)$. The terms $S_t N_t^S$ and $I_t N_t^I$ represent total hours worked by susceptible and infected people, respectively. The parameter π_2 reflects the probability of becoming infected as a result of work interactions.

Susceptible and infected people can meet in ways unrelated to consuming or working. The number of random meetings between infected and susceptible people is $S_t I_t$. These meetings result in $\pi_3 S_t I_t$ newly infected people. The number of susceptible people at time $t+1$ is given by:

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

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 people (T_t) minus the number of infected people who recovered ($\pi_r I_t$) and the number of infected people who died ($\pi_d I_t$):

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

Here, π_r is the rate at which infected people recover from the infection and π_d is the probability that an infected person dies.

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 ($\pi_r I_t$):

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

Finally, the number of deceased people at time $t+1$ is the number of deceased people at time t plus the number of new deaths ($\pi_d I_t$):

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

People have rational expectations so that they are aware of the initial infection and understand the laws of motion governing population health dynamics.

Final good producers Final output, Y_t, is produced by a representative, competitive firm using the technology:

$$Y_t = \left(\int_0^1 Y_{i,t}^{\frac{1}{\gamma}} di \right)^{\gamma}, \gamma > 1. \tag{6}$$

The variable $Y_{i,t}$ denotes the quantity of intermediate input i used by the firm. We use units of the final good as the numeraire.

Profit maximization implies the following demand schedule for intermediate products:

$$Y_{i,t} = P_{i,t}^{-\frac{\gamma}{\gamma-1}} Y_t. \tag{7}$$

Here, $P_{i,t}$ denotes the price of intermediate input i in units of the final good.

Intermediate goods producers Intermediate good i is produced by a single monopolist using labor, $N_{i,t}$, and capital, $K_{i,t}$, according to the technology:

$$Y_{i,t} = AK_{i,t}^{1-\alpha} N_{i,t}^{\alpha}.$$

Intermediate good firms maximize profits:

$$\pi_{i,t} = P_{i,t}Y_{i,t} - mc_t Y_{i,t}$$

subject to the demand equation (7).

Optimal pricing implies that all firms set their price as a fixed markup over marginal cost:

$$P_{i,t} = \gamma mc_t.$$

Here, mc_t denotes the real marginal cost at time t:

$$mc_t = \frac{w_t^{\alpha}\left(r_t^k\right)^{1-\alpha}}{A\alpha^{\alpha}(1-\alpha)^{1-\alpha}}. \tag{8}$$

Here, w_t and r_t^k denote the real wage and the rental rate of capital, respectively. The standard neoclassical model corresponds to the special case where $\gamma = 1$.

Households At time zero, a household has a continuum of measure one of family members. The household maximizes its lifetime utility:

$$U = \sum_{t=0}^{\infty} \beta^t \left\{ s_t \left[\log(c_t^s) - \frac{\theta}{2}\left(n_t^s\right)^2\right] + i_t \left[\log(c_t^i) - \frac{\theta}{2}\left(n_t^i\right)^2\right] + r_t \left[\log(c_t^r) - \frac{\theta}{2}\left(n_t^r\right)^2\right]\right\}, \tag{9}$$

subject to the budget constraint:

$$s_t c_t^s + i_t c_t^i + r_t c_t^r + x_t + \psi = w_t(s_t n_t^s + i_t n_t^i + r_t n_t^r) + r_t^k k_t + \phi_t.$$

Here, s_t, i_t, and r_t denote the measure of family members who are susceptible, infected and recovered. The variables (c_t^s, c_t^i, c_t^r) and (n_t^s, n_t^i, n_t^r) denote the consumption and hours worked of susceptible, infected and recovered family members, respectively. The variables ϕ_t and ψ denote profits from the monopolistically competitive firms and lump-sum taxes, respectively. The variable x_t denotes household investment.

The law of motion for the stock of capital is:

$$k_{t+1} = x_t + (1-\delta)k_t. \tag{10}$$

The number of newly infected people is given by:

$$\tau_t = \pi_1 s_t c_t^s \left(I_t C_t^I\right) + \pi_2 s_t n_t^s \left(I_t N_t^I\right) + \pi_3 s_t I_t. \tag{11}$$

The household can affect this probability through its choice of c_t^s and n_t^s. However, the household takes economy-wide aggregates $I_t C_t^I$, and $I_t N_t^I$ as given, i.e. it does not internalize the impact of its choices on economy-wide infection rates.

The fraction of the initial family that is susceptible, infected and recovered at time $t+1$ is given by:

$$s_{t+1} = s_t - \tau_t, \tag{12}$$

$$i_{t+1} = i_t + \tau_t - (\pi_r + \pi_d) i_t, \tag{13}$$

$$r_{t+1} = r_t + \pi_r i_t. \tag{14}$$

The first-order conditions for c_t^s, c_t^i and c_t^r are:

$$\begin{aligned} \frac{1}{c_t^s} &= \lambda_t^b - \lambda_t^\tau \pi_1 \left(I_t C_t^I\right), \\ \frac{1}{c_t^i} &= \lambda_t^b, \\ \frac{1}{c_t^r} &= \lambda_t^b. \end{aligned}$$

Here, λ_t^b is the Lagrange multiplier on the household budget constraint. The first-order conditions for n_t^s, n_t^i and n_t^r are:

$$\begin{aligned} \theta n_t^s &= \lambda_t^b w_t + \lambda_t^\tau \pi_2 \left(I_t N_t^I\right), \\ \theta n_t^i &= \lambda_t^b w_t, \\ \theta n_t^r &= \lambda_t^b w_t. \end{aligned}$$

The first-order condition for k_{t+1} is:

$$\lambda_t^b = (r_{t+1}^k + 1 - \delta)\beta \lambda_{t+1}^b. \tag{15}$$

The first-order conditions for s_{t+1}, i_{t+1}, r_{t+1}, and τ_t are:

$$\log(c_{t+1}^s) - \frac{\theta}{2}\left(n_{t+1}^s\right)^2 + \lambda_{t+1}^\tau \left[\pi_1 c_{t+1}^s \left(I_{t+1} C_{t+1}^I\right) + \pi_2 n_{t+1}^s \left(I_{t+1} N_{t+1}^I\right) + \pi_3 I_{t+1}\right] \\ + \lambda_{t+1}^b \left[w_{t+1} n_{t+1}^s - c_{t+1}^s\right] - \lambda_t^s/\beta + \lambda_{t+1}^s = 0,$$

$$\log(c_{t+1}^i) - \frac{\theta}{2}\left(n_{t+1}^i\right)^2 + \\ + \lambda_{t+1}^b \left[w_{t+1} n_{t+1}^i - c_{t+1}^i\right] - \lambda_t^i/\beta + \lambda_{t+1}^i (1 - \pi_r - \pi_d) \\ + \lambda_{t+1}^r \pi_r = 0,$$

$$\log(c^r_{t+1}) - \frac{\theta}{2}\left(n^r_{t+1}\right)^2 +$$
$$+\lambda^b_{t+1}(w_{t+1}n^r_{t+1} - c^r_{t+1}) - \lambda^r_t/\beta + \lambda^r_{t+1} = 0,$$
$$-\lambda^\tau_t - \lambda^s_t + \lambda^i_t = 0.$$

Government budget constraint We assume that the government finances a constant stream of government spending, G with lump-sum taxes, ψ:

$$\psi = G. \tag{16}$$

Equilibrium conditions In equilibrium, the market for goods and hours worked clear, households and firms solve their maximization problems, and agents have rational expectations.

The fraction of people in the family who are susceptible, infected and recovered is the same as the corresponding fraction in the population:

$$s_t = S_t,\ i_t = I_t, \text{ and } r_t = R_t.$$

The labor demand is equal to labor supply:

$$s_t n^s_t + i_t n^i_t + r_t n^r_t = N_t.$$

The demand for goods equals goods supply:

$$AK_t^{1-\alpha}N_t^\alpha = C_t + X_t + G,$$

where K_t is the aggregate supply of capital, k_t,

$$K_t = k_t,$$

and C_t and X_t are aggregate consumption and investment, respectively. These variables are given by:

$$C_t = s_t c^s_t + i_t c^i_t + r_t c^r_t,$$

$$X_t = x_t.$$

The law of motion for the aggregate capital stock is:

$$K_{t+1} = X_t + (1-\delta)K_t.$$

The appendix contains the list of model equilibrium conditions. The case of perfect competition in those equations corresponds to the special case of $\gamma = 1$.

2.1 Parameter values

We choose the same parameter values used in Eichenbaum, Rebelo and Trabandt (2020b). Each time period corresponds to a week. We assume that it takes on average 14 days to either recover or die from the infection. Since our model is weekly, we set $\pi_r + \pi_d = 7/14$. Based on data for South Korea for people younger than 65 years, we choose the mortality rate to be 0.2 percent which implies $\pi_d = 7 \times 0.002/14$.

We set π_1, π_2, and π_3 to 3.1949×10^{-7}, 1.5936×10^{-4}, and 0.4997, respectively. These values imply that in the beginning of the epidemic 1/6 of the virus transmissions come from consumption, 1/6 come from work and 2/3 come from non-economic activities:

$$\frac{\pi_1 C^2}{\pi_1 C^2 + \pi_2 N^2 + \pi_3} = 1/6, \tag{17}$$

$$\frac{\pi_2 N^2}{\pi_1 C^2 + \pi_2 N^2 + \pi_3} = 1/6. \tag{18}$$

Here, C and N denote consumption and hours worked in the pre-epidemic steady state, respectively.

The initial population is normalized to one. The number of people who are initially infected, ε, is 0.001. We choose $A = 1.9437$ and $\theta = 0.001517$ so that in the pre-epidemic steady state the representative person works 28 hours per week and earns a weekly income of $\$58,000/52$. We set the weekly discount factor, β, to $0.98^{1/52}$ so that the value of a life is 9.3 million 2019 dollars in the pre-epidemic steady state. This value is consistent with the economic value of life used by U.S. government agencies (see Viscusi and Aldy (2003) for a discussion). We set the weekly depreciation rate, $\delta = 0.06/52$ and the labor share, $\alpha = 2/3$. In the competitive model there is no markup, i.e. $\gamma = 1$. In the monopolistic competition model, we set the parameter that determines the markup, γ, to 1.35. This value is consistent with the range of estimates reported in Christiano, Eichenbaum and Trabandt (2016).

The steady-state share of government spending to GDP is set to 19 percent, a value that corresponds to the average share of government expenditures in the U.S. economy. These parameter values imply that the share of investment as a fraction of GDP is 25 percent. This share corresponds roughly to the average share of investment in GDP in the U.S. economy when we include purchases of consumer durables as part of investment.

Tables 1 and 2 summarize the parameters and implied steady-state values, respectively.

Table 1: Parameters and Steady-State Calibration Targets

Parameter	Value	Description
π_d	0.001	Probability of dying (weekly)
π_r	0.499	Probability of recovering (weekly)
ε_0	0.001	Initial infection
δ	0.06/52	Capital depreciation rate (weekly)
α	2/3	Marginal product of labor
υ	$\{0, 0.259\}$	Steady state wage tax
γ	$\{1, 1.35\}$	Gross price markup
ξ	$\{0, 0.98\}$	Calvo price stickiness (weekly)
r_π	1.5	Taylor rule coefficient inflation
r_x	0.5/52	Taylor rule coefficient output gap
η	0.19	Gov. consumption share of output
n	28	Hours worked (weekly)
y	58000/52	Income (weekly)

Table 2: Steady States and Model-Specific Parameters Across Models

	Model with Perfect Competition	Model with Imperfect Competition
π_1	3.194×10^{-7}	2.568×10^{-7}
π_2	1.593×10^{-4}	1.593×10^{-4}
π_3	0.499	0.499
A	1.943	2.148
θ	0.0015	0.0010
c/y	0.561	0.625
x/y	0.249	0.184
g/y	0.190	0.190
VoL	9.4×10^6	1.1×10^6
k/y	4.15	3.07
y	1115.3	1115.3
c	625.3	697.4
x	278.1	206.0
g	211.9	211.9
w	26.55	19.67
k	241042	178551
r^k	0.00154	0.00154
λ^b	0.00159	0.00143
λ^τ	-31.02	-30.56
R^b	1.00039	1.00039
π	1	1
mc	1	0.74

Notes: VoL denotes value of life. k/y expressed in annual terms. Perfect competition model with 26 percent steady state wage tax has identical steady states as in column two except for $\theta = 0.0011, VoL = 9.6 \times 10^6$ and $\lambda^\tau = -30.23$.

3 The impact of an epidemic in the neoclassical model

In this section, we discuss the impact of an epidemic in the neoclassical model. This model corresponds to the case where $\gamma = 1.$ so that intermediate goods are perfect substitutes and the net markup is zero.

Our parameterization of the transmission function (1) implies that an epidemic can be thought of as giving rise to negative aggregate demand and aggregate supply shocks. The aggregate demand shock arises because susceptible people reduce their consumption to lower their probability of being infected. A simple way to see this effect is to consider the first-order condition for c_t^s:

$$\frac{1}{c_t^s} = \lambda_t^b - \lambda_t^\tau \pi_1 \left(I_t C_t^I \right). \tag{19}$$

Recall that $\lambda_t^b > 0$ is the Lagrange multiplier on the household budget constraint and $\lambda_t^\tau < 0$ is the Lagrange multiplier on τ_t. In equation (19), we used the fact that output is the numeraire so $P_t = 1$. Other things equal, the larger is $\pi_1 \left(I_t C_t^I \right)$ the lower is c_t^s.

The negative aggregate supply shock arises because susceptible people reduce their hours worked to lower their probability of becoming infected. To see this effect, recall the first-order condition for n_t^s:

$$\theta n_t^s = \lambda_t^b w_t + \lambda_t^\tau \pi_2 \left(I_t N_t^I \right). \tag{20}$$

Other things equal, the larger is $\pi_2 \left(I_t N_t^I \right)$ the smaller is n_t^s.

Working in tandem, aggregate demand and supply shocks generate a prolonged recession. However, the qualitative and quantitative responses of consumption, hours worked and investment depend very much on which shock dominates.

The previous intuition about demand and supply shocks is suggestive about the first-order effects of the epidemic. There are other general equilibrium effects that must be considered. As it turns out, those effects do not overturn the intuition based on demand and supply shocks.

Subsections 3.1 and 3.2 focus on the effect of the shock to consumption demand and labor supply, respectively. In subsection 3.3, we combine the two shocks to assess the full impact of the epidemic.

3.1 Epidemics as a shock to the demand for consumption

To isolate the effect of the epidemic on consumption demand, we set π_2 to zero so that hours worked do not affect the probability of a susceptible person becoming infected. We calibrate π_1 to 6.3897×10^{-7}, so that $1/3$ of the infections at the beginning of the epidemic are driven by consumption (see equation (17)).

Figure 1 displays the impact of the epidemic on key macro variables. The main results can be summarized as follows. First, there is a relatively small recession, with output and hours worked falling from peak to trough by 0.4 and 0.6 percent, respectively. Second, there is a very large drop in consumption (15 percent from peak to trough) and an enormous rise in investment (33 percent from trough to peak).

Figure 2 shows consumption and hours worked for susceptible, infected and recovered people. There is a large drop in the consumption of susceptible people (23 percent from peak to trough). In contrast, consumption of infected and recovered people rise by a small amount. Hours worked by susceptible, infected and recovered people are relatively stable, exhibiting some dynamics that we discuss below.

The intuition for the results in Figures 1 and 2 is that the infection acts like a negative shock to the demand for consumption by susceptible people. The household reduces c_t^s to lower the probability of susceptible people becoming infected. Consistent with this intuition, the path for c_t^s is the mirror image of the path for I_t.

The health status of infected and recovered people is not affected by being exposed to the virus. So, their consumption demand does not shift down in response to movements in I_t. As a result, the household does not reduce c_t^i and c_t^r. In fact, they rise by a modest amount. To understand this response, note that the income of the household does not fall by very much. But c_t^s falls by a very large amount. The household uses a small part of the savings from the earnings of susceptible people to fund a small rise in c_t^i and c_t^r.

Figure 1 shows that the household uses most of those savings to finance a massive increase in investment. By building up the capital stock, the household makes it possible for c_t^s to rise once infections start to decline without large increases in n_t^s, n_t^i or n_t^r. In effect, investment allows the household to smooth the response of consumption and hours worked to a transitory shock in susceptible people's consumption demand.

Since a large part of the household wants to lower their consumption, the overall return to working declines. So, there is a small initial fall in hours worked. After a delay, hours worked then rise, reflecting the increase in the marginal product of labor associated with the build up of capital.

In sum, when $\pi_2 = 0$, the epidemic generates a mild recession. But, with this parameterization the model cannot rationalize two key features of the COVID-19 recession: the large drop in output and the positive comovement between investment and consumption.[2]

[2] These declines in measures of economic activity occurred before lockdowns were imposed, as well as in countries like Sweden and South Korea, and U.S. states that did not impose lockdowns (see Andersen et al. (2020), Aum et al. (2020.) and Gupta et al. (2020)).

3.2 Epidemics as a shock to the supply of labor

To isolate the effect of the epidemic on the supply of labor, we set π_1 to zero. With this assumption, consumption does not affect the probability of a susceptible person becoming infected. We calibrate π_2 to 3.1871×10^{-4} so that 1/3 of the infections in the beginning of the epidemic (equation (18)) are driven by hours worked.

Figure 3 displays the impact of an epidemic on key macro variables. The epidemic causes a very large recession, with output and hours worked falling from peak to trough by 9 and 13 percent, respectively. Consumption declines modestly (0.7 percent from peak to trough) and there is a large drop in investment (36 percent from trough to peak).

Figure 4 shows that c_t^s, c_t^i, and c_t^r all decline by the same small amount. In contrast, hours worked by different types of people respond very differently: n_t^s falls by 23 percent from peak to trough, while both n_t^i and n_t^r rise by 5 percent from trough to peak.

As discussed above, when $\pi_1 = 0$, the infection acts like a negative shock to susceptible people's supply of labor. The household cuts back on n_t^s to reduce the probability of susceptible people becoming infected. Consistent with this logic, the reduction in n_t^s mirrors the path for I_t.

The household has an incentive to smooth consumption over time because consuming does not increase anyone's probability of becoming infected. Infected and recovered people are not affected by exposure to the virus. So, to smooth consumption over time and across people, the household increases n_t^i and n_t^r.

The income of susceptible people falls dramatically. But their consumption does not, so their savings turn sharply negative. The household finances that dissaving by a massive decline in investment. In effect, investment allows the household to smooth consumption and hours worked in response to a transitory fall in n_t^s.

In sum, when $\pi_1 = 0$, the epidemic causes a large recession. But, with this parameterization the model cannot rationalize a key feature of the COVID-19 recession: the large observed decline in consumption.

3.3 Epidemics as a shock to the demand for consumption *and* the supply of labor

In our benchmark calibration, both π_1 and π_2 are positive. So an epidemic acts like a negative shock to both consumption demand and labor supply.[3]

Figure 5 displays the total impact of the epidemic on key macro variables. With one important caveat, the model captures the salient features of the epidemic recession. There is a very large drop in output, consumption, and hours worked with peak to trough declines of 5, 9 and 7 percent, respectively. Investment drops on impact by a modest 1 percent. It then rebounds, peaking at 2 percent above its pre-epidemic steady state level. The caveat is that, after an initial fall, investment rebounds and is above its steady-state level throughout most of the epidemic.

Figure 6 displays consumption and hours worked for susceptible, infected and recovered people, respectively. Again, these responses reflect the combined effects of a negative shock to consumption demand and labor supply. Note that c_t^s drops dramatically, reflecting the importance of the negative shock to consumption demand. Also, n_t^s drops dramatically, reflecting the importance of the negative shock to susceptible people's labor supply.

The behavior of investment reflects the combined effect of the household's desire to smooth c_t^i and c_t^r, and the negative shock to the demand for c_t^s. These two effects work in opposite directions, with investment initially falling but then rising in a hump-shaped pattern. Compared to the single shock scenarios, the movements in investment are relatively small.

Finally, Figure 6 shows that, after the epidemic runs its course, the economy converges to a steady state where the real interest rate, per-capita output, consumption, investment, and hours worked return to their respective pre-epidemic values. Since the population declines, aggregate output, consumption, investment, and hours worked also decline, i.e. they do not return to their pre-epidemic steady state values.

4 Monopolistic competition and flexible prices

In this section, we discuss the impact of an epidemic in the version of our model with monopolistic competition ($\gamma = 1.35$) and flexible prices. We recalibrate the value of θ so

[3] While this decomposition is useful for intuition, the quantitative impact is not the simple sum of the two shocks given the nonlinear nature of the model.

that hours worked in the steady state are 28. Tables 1 and 2 display our parameter values as well as the values of key aggregate steady-state variables.

In the steady state, the marginal cost is equal to $1/\gamma$. Equation (15) implies that the real rental rate of capital is independent of the markup. Since the marginal cost is a decreasing function of γ, equation (8) implies that the real wage rate also falls for higher values of γ. The steady-state real wage is 26.5 and 19.6 in the competitive and monopolistically competitive model, respectively. It turns out that this difference in the real wage has important implications for the response of the economy to an epidemic.

Figures 7 and 8 show results for the case where the epidemic corresponds to a consumption demand shock ($\pi_2 = 0$) and a labor-supply shock ($\pi_1 = 0$), respectively.

Figures 1 and 7 show that that the effects of the demand shock are very similar under perfect and monopolistic competition. The main difference is that investment is more volatile under monopolistic competition with a trough to peak increase of 50 percent as opposed to 33 percent under perfect competition.

Comparing Figures 3 and 8, we see that the qualitative effects of the supply shock are very similar under perfect and monopolistic competition. But the quantitative differences are larger than those pertaining to the demand shock. The drop in hours worked is much larger under monopolistic competition with a peak to trough fall of 20 percent compared to 13 percent under perfect competition. The intuition is as follows. The steady-state real wage is lower under monopolistic competition. So, equation (20) implies that, other things equal, the impact of the infection term, $\lambda_t^\tau \pi_2 \left(I_t N_t^I \right)$, on labor supply is larger under monopolistic competition than under perfect competition. Basically, a lower real wage means that the return to incurring infection risk from working is lower. So, the household reduces by more the hours worked by susceptible people.

The larger fall in hours in the monopolistically competitive model translates into a larger output fall. Since it is optimal for the household to smooth consumption, there is a large fall in investment. Figures 3 and 8 show that the peak to trough fall in investment is 35 and 70 percent under perfect competition and monopolistic competition, respectively.

Figure 9 displays the total impact of the epidemic on key macro variables. This figure shows that the model captures the salient features of the epidemic recession. There is a large drop in output, consumption, investment, and hours worked with peak to trough declines of $7, 9, 7$ and 10 percent, respectively. The drop in consumption reflects the fall in consumption demand by susceptible people. The large fall in investment reflects the magnified importance of the labor supply shock under monopolistic competition relative to perfect competition.

We conclude this section by corroborating our intuition about the way in which monopolistic competition magnifies the effect of the labor-supply shock on investment. The key to that intuition is the lower value of the real wages under monopolistic competition.

To corroborate our intuition, we introduce a tax on labor income into the model with perfect competition. Proceeds from this tax are rebated lump sum to the household. The modified household budget constraint is given by

$$s_t c_t^s + i_t c_t^i + r_t c_t^r + x_t + \Psi_t = w_t(s_t n_t^s + i_t n_t^i + r_t n_t^r)(1-v) + R_t^k k_t + \Phi_t,$$

where the new element is the tax rate on labor income, v. The modified government budget constraint is given by:

$$\Psi_t + v w_t N_t = G.$$

Suppose that we set $v = 0.259$. Then, the steady-state wage rate is the same in the competitive and monopolistic competition models. As it turns out, the dynamic response of the wage-tax perfect-competition model is very similar to the one that obtains under monopolistic competition.

5 New Keynesian model

We now consider the effects of an epidemic in a simple New Keynesian model with sticky prices. This model differs from the version of the neoclassical model with monopolistic competition by assuming that intermediate goods producers are subject to nominal price rigidities.

Households The only change to the household problem pertains to the budget constraint. We write this constraint in nominal terms and include a one-period riskless bond:

$$B_{t+1} + P_t\left(s_t c_t^s + i_t c_t^i + r_t c_t^r + x_t\right) + \Psi = R_{t-1}^b B_t + W_t\left(s_t n_t^s + i_t n_t^i + r_t n_t^r\right) + R_t^k k_t + \Phi_t. \quad (21)$$

Here, B_t nominal bond holdings, R_t^b the interest rate on nominal bonds, W_t is the nominal wage rate, R_t^k is the nominal rental price, and P_t is the consumer price index.

The household maximizes lifetime utility, (9), subject to the budget constraint, (21), the law of motion for capital, (10), and the equations that govern the health status of the household's members, (11), (12), (13), and (14). The first-order conditions for consumption, hours worked, k_{t+1} s_{t+1}, i_{t+1}, r_{t+1}, and τ_t are described in the appendix.

Final goods producers Profit maximization implies the following demand schedule for intermediate products:

$$Y_{i,t} = \left(\frac{P_{i,t}}{P_t}\right)^{-\frac{\gamma}{\gamma-1}} Y_t.$$

The price of output is given by:

$$P_t = \left(\int_0^1 P_{i,t}^{-\frac{1}{\gamma-1}} di\right)^{-(\gamma-1)}.$$

Intermediate goods producers Intermediate goods firms maximize profits:

$$\pi_{i,t} = P_{i,t}Y_{i,t} - P_t mc_t Y_{i,t},$$

subject to the demand equation (7).

Monopolist i chooses its price subject to Calvo (1983) style price-setting frictions. With probability $1-\xi$ the firm reoptimizes $P_{i,t}$. With probability ξ, $P_{i,t} = P_{i,t-1}$. The firm chooses its optimal time-t price, $\tilde{P}_t$, to maximize:

$$\max_{\tilde{P}_t} \sum_{j=0}^{\infty} (\xi\beta)^j \lambda_{t+j}^b \left(\tilde{P}_t Y_{i,t+j} - P_{t+j} mc_{t+j} Y_{i,t+j}\right),$$

subject to the demand curve (7).

Here, mc_t denotes the real marginal cost at time t:

$$mc_t = \frac{W_t^\alpha \left(R_t^k\right)^{1-\alpha}}{P_t A \alpha^\alpha (1-\alpha)^{1-\alpha}}.$$

Monetary and fiscal policy The monetary authority controls the nominal interest rate. It chooses this rate according to the following Taylor-type rule:

$$\log \frac{R_t^b}{R^b} = \theta_\pi \log \frac{\pi_t}{\pi} + \theta_x \log(Y_t/Y_t^f),$$

where Y_t^f is output in a flexible-price version of the economy. The government budget constraint is given by:

$$\Psi_t = P_t G.$$

Equilibrium The equilibrium conditions are the same as in the flexible price model with one addition. Since nominal bonds are in zero net supply, in equilibrium:

$$B_t = 0.$$

We summarize the model's equilibrium conditions in the appendix.

5.1 The impact of an epidemic in the New Keynesian model

We assume that $\xi = 0.98$ so that prices change on average once a year. The coefficients in the Taylor rule are $\theta_\pi = 1.5$ and $\theta_x = 0.5/52$.

Figure 10 displays the dynamics of key macro aggregates in the New Keynesian model (blue-solid line). For ease of comparison, the figure also displays the dynamics of the monopolistically competitive economy with flexible prices (red-dashed line). The latter is a special case of the new Keynesian model where $\xi = 0$.

The main results can be summarized as follows. First, sticky prices increase the depth of the recession but only marginally so. This result is not entirely surprising given that an epidemic is both a demand and a supply shock. In New Keynesian models, sticky prices generally exacerbate the effects of a negative demand shock and alleviate the impact of negative supply shocks. Putting these two effects together, we would not expect sticky prices to have a strong impact on the response of output to an epidemic. Second, in contrast to the flexible price model, investment falls by more than consumption. Third, regardless of whether prices are sticky or flexible, the epidemic reduces the inflation rate relative to the steady state. But inflation drops by about half as much in the new Keynesian model.

On net, sticky prices amplify the severity of the recession while leading to a muted response of the inflation rate.

6 Related literature

There is by now a very large literature on the macroeconomic impact of epidemics. A large strand of this literature studies the impact of lockdowns and other mitigation policies. See e.g., Alvarez, Argente, and Lippi (2020), Buera, Fattal-Jaef, Neumeyer, and Shin (2020), Eichenbaum, Rebelo and Trabandt (2020a,b), Farboodi, Jarosch, and Shimer (2020), Glover, Gonzalez-Eiras and Niepelt (2020), Heathcote, Krueger, and Rios-Rull (2020), Krueger, Uhlig, and Xie (2020), Piguillem and Shi (2020), and Toxvaerd (2020).

In contrast to this body of work, this paper focuses on the endogenous business cycle dynamics associated with an epidemic in models with capital accumulation and monopolist competition with and without sticky prices. In this section, we discuss the papers that are most closely related to our work.

Guerrieri, Lorenzoni, Straub, and Werning (2020) study how, in the presence of sticky prices, supply shocks can trigger changes in aggregate demand that are larger than the initial supply shocks. In contrast with Guerrieri et al. (2020), we incorporate investment and an explicit model of epidemics into our analysis.

Faria-e-Castro (2020) studies the impact of a negative demand shock on consumption modeled as a negative shock to the utility of consumption. In our model, the negative demand shock arises from the nature of the epidemic. In addition, the focus of our analysis is on the relative importance of negative shifts in aggregate demand and supply for the behavior of macroeconomic aggregates during an epidemic.

Bodenstein, Corsetti, and Guerrieri (2020) study a multi-sector model of epidemics with capital accumulation. In their model, the supply of labor is exogenous but an infection reduces the number of people who go to work. This decline in employment can compromise essential linkages in production, thus exacerbating the social costs of an epidemic. In contrast with Bodenstein et al. (2020), in our analysis labor supply is endogenous and the transmission of the virus depends on people's decisions about labor supply and consumption.

Jones, Philippon, and Venkateswaran (2020) study optimal mitigation policies in a model where economic activity and epidemic dynamics interact. In contrast to those authors, we allow for capital accumulation as well as sticky prices. Also, our analysis focuses on understanding the comovement between output, consumption and investment during an epidemic.

7 Conclusion

We analyze the effects of an epidemic in three standard macroeconomic models. Our main conclusions are as follows. The neoclassical model does not rationalize the positive comovement of consumption and investment observed in recessions associated with an epidemic. Introducing monopolistic competition into the neoclassical model remedies this shortcoming even when prices are completely flexible. Finally, sticky prices lead to a larger recession but do not fundamentally alter the predictions of the monopolistic competition model.

In our analysis, we abstract from financial frictions and the zero lower bound constraint on interest rates. Allowing for these considerations is a natural next step which would allow us to evaluate the myriad of policy interventions implemented during the COVID-19 epidemic.

References

[1] Alvarez, Fernando, David Argente and Francesco Lippi "A Simple Planning Problem for COVID-19 Lockdown," manuscript, University of Chicago, 2020.

[2] Andersen, A.L., Hansen, E.T., Johannesen, N. and Sheridan, A. "Consumer Responses to the COVID-19 crisis: Evidence from Bank Account Transaction Data," manuscript, University of Copenhagen, 2020.

[3] Atkeson, Andrew "What Will Be The Economic Impact of COVID-19 in the US? Rough Estimates of Disease Scenarios," National Bureau of Economic Research, Working Paper No. 26867, 2020.

[4] Aum, S., Lee, S.Y.T. and Shin, Y., "COVID-19 Doesn't Need Lockdowns to Destroy Jobs: The Effect of Local Outbreaks in Korea," NBER Working Paper No. w27264, National Bureau of Economic Research, 2020.

[5] Barro, Robert J., and Robert G. King "Time-separable Preferences and Intertemporal-substitution Models of Business Cycles." *The Quarterly Journal of Economics* 99, no. 4 (1984): 817-839.

[6] Bartik, Alexander W., Marianne Bertrand, Feng Li, Jesse Rothstein, and Matt Unrath. 2020."Labor market impacts of COVID-19 on hourly workers in small- and medium-sized businesses: Four facts from Homebase data" (April).

[7] Berger, David Kyle Herkenhoff, and Simon Mongey "An SEIR Infectious Disease Model with Testing and Conditional Quarantine," manuscript, Duke University, 2020.

[8] Bodenstein, Martin, Giancarlo Corsetti, and Luca Guerrieri "Social distancing and supply disruptions in a pandemic." Manuscript, 2020.

[9] Buera, Francisco, Roberto Fattal-Jaef, Pablo Andres Neumeyer, and Yongseok Shin "The Economic Ripple Effects of COVID-10," manuscript, World Bank, 2020.

[10] Calvo, G.A., "Staggered Prices in a Utility-maximizing Framework," *Journal of Monetary Economics*, 12(3), pp.383-398, 1983.

[11] Chetty, Raj, John N. Friedman, Nathaniel Hendren, and Michael Stepner. Real-Time Economics: A New Platform to Track the Impacts of COVID-19 on People, Businesses, and Communities Using Private Sector Data. Mimeo, 2020.

[12] Christiano, Lawrence, Martin Eichenbaum, and Mathias Trabandt "Unemployment and Business Cycles," *Econometrica*, 84(4), pp.1523-1569, 2016.

[13] Eichenbaum, Martin, Sergio Rebelo, and Mathias Trabandt "The Macroeconomics of Epidemics," NBER Working Paper No. w26882, National Bureau of Economic Research, 2020a.

[14] Eichenbaum, Martin, Sergio Rebelo, and Mathias Trabandt "The Macroeconomics of Testing and Quarantining," NBER Working Paper No. w27104, National Bureau of Economic Research, 2020b.

[15] Farboodi, M., Jarosch, G. and Shimer, R., 2020. "Internal and External Effects of Social Distancing in a Pandemic," University of Chicago, Becker Friedman Institute for Economics Working Paper, (2020-47).

[16] Faria-e-Castro, Miguel "Fiscal Policy During a Pandemic," manuscript, Federal Reserve Bank of St. Louis, 2020.

[17] Galí, Jordi. Monetary Policy, Inflation, and the Business Cycle: an Introduction to the New Keynesian Framework and its Applications. Princeton University Press, 2015.

[18] Glover, Andrew, Jonathan Heathcote, Dirk Krueger, and José-Victor Ríos-Rull "Health versus Wealth: On the Distribution Effects of Controlling a Pandemic," manuscript, University of Pennsylvania, 2020.

[19] Gonzalez-Eiras, Martín and Dirk Niepelt "On the Optimal "Lockdown" During an Epidemic," manuscript, Study Center Gerzensee, 2020.

[20] Guerrieri, Veronica, Guido Lorenzoni, Ludwig Straub, and Ivan Werning "Macroeconomic Implications of COVID-19: Can Negative Supply Shocks Cause Demand Shortages?" manuscript, Northwestern University, 2020.

[21] Gupta, S., Montenovo, L., Nguyen, T.D., Rojas, F.L., Schmutte, I.M., Simon, K.I., Weinberg, B.A. and Wing, C. "Effects of Social Distancing Policy on Labor Market

Outcomes," NBER Working paper No. w27280, National Bureau of Economic Research, 2020.

[22] Hornstein, Andreas, 1993 "Monopolistic Competition, Increasing Returns to Scale, and the Importance of Productivity Shocks," *Journal of Monetary Economics*, 31(3), pp.299-316.

[23] Jones, Callum J., Thomas Philippon, and Venky Venkateswaran. "Optimal mitigation policies in a pandemic: Social distancing and working from home," NBER Working Paper. No. w26984. National Bureau of Economic Research, 2020.

[24] Kermack, William Ogilvy, and Anderson G. McKendrick "A Contribution to the Mathematical Theory of Epidemics," *Proceedings of the Royal Society of London*, series A 115, no. 772: 700-721, 1927.

[25] Krueger, Dirk, Harald Uhlig, and Taojun Xie "Macroeconomic dynamics and reallocation in an epidemic,". NBER Working Paper w27047. National Bureau of Economic Research, 2020.

[26] Piguillem, Facundo and Liyan Shi "The Optimal covid-19 Quarantine and Testing Policies," Einaudi Institute for Economics and Finance, Working Paper No. 2004, 2020.

[27] Toxvaerd, Flavio "Equilibrium Social Distancing," manuscript, Cambridge University, 2020.

[28] Villas-Boas, Sofia B, James Sears, Miguel Villas-Boas, and Vasco Villas-Boas. 2020. "Are We #StayingHome to Flatten the Curve?" UC Berkeley: Department of Agricultural and Resource Eco- nomics CUDARE Working Papers (April).

[29] Viscusi, W.K. and Aldy, J.E. "The Value of a Statistical Life: a Critical Review of Market Estimates Throughout the World," *Journal of Risk and Uncertainty*, 27(1), pp.5-76, 2003.

[30] Woodford, Michael Interest and Prices: Foundations of a Theory of Monetary Policy. Princeton University Press, 2011.

Appendix A Equilibrium equations

We have the following 31 endogenous variables:

$$
\begin{aligned}
& y_t, k_t, n_t, w_t, r_t^k, x_t, c_t, s_t, i_t, r_t, n_t^s, n_t^i, n_t^r, \\
& c_t^s, c_t^i, c_t^r, \tau_t, \tilde{\lambda}_t^b, \lambda_t^\tau, \lambda_t^i, \lambda_t^s, \lambda_t^r, d_t, pop_t \\
& \breve{p}_t, mc_t, rr_t, R_t^b, \pi_t, K_t^f, F_t.
\end{aligned}
$$

The following 31 equilibrium conditions nest the models with perfect competition ($\gamma \to 1$, $\xi = 0$), imperfect competition ($\gamma = 1.35$, $\xi = 0$), and sticky prices ($\gamma = 1.35$, $\xi = 0.98$):

$$
\begin{aligned}
1)\ y_t &= \breve{p}_t A k_t^{1-\alpha} n_t^\alpha \\
2)\ mc_t &= \frac{w_t^\alpha \left(r_t^k\right)^{1-\alpha}}{A\alpha^\alpha (1-\alpha)^{1-\alpha}} \\
3)\ w_t &= mc_t \alpha A n_t^{\alpha-1} k_t^{1-\alpha} \\
4)\ k_{t+1} &= x_t + (1-\delta) k_t \\
5)\ y_t &= c_t + x_t + g \\
6)\ n_t &= s_t n_t^s + i_t n_t^i + r_t n_t^r \\
7)\ c_t &= s_t c_t^s + i_t c_t^i + r_t c_t^r \\
8)\ \tau_t &= \pi_1 s_t c_t^s \left(i_t c_t^i\right) + \pi_2 s_t n_t^s \left(i_t n_t^i\right) + \pi_3 s_t i_t \\
9)\ s_{t+1} &= s_t - \tau_t \\
10)\ i_{t+1} &= i_t + \tau_t - (\pi_r + \pi_d)\, i_t \\
11)\ r_{t+1} &= r_t + \pi_r i_t \\
12)\ d_{t+1} &= d_t + \pi_d i_t, \\
13)\ pop_{t+1} &= pop_t - \pi_d i_t, \\
14)\ \frac{1}{c_t^s} &= \tilde{\lambda}_t^b - \lambda_t^\tau \pi_1 \left(i_t c_t^i\right) \\
15)\ \frac{1}{c_t^i} &= \tilde{\lambda}_t^b \\
16)\ \frac{1}{c_t^r} &= \tilde{\lambda}_t^b \\
17)\ \theta n_t^s &= \tilde{\lambda}_t^b w_t + \lambda_t^\tau \pi_2 \left(i_t n_t^i\right) \\
18)\ \theta n_t^i &= \tilde{\lambda}_t^b w_t \\
19)\ \theta n_t^r &= \tilde{\lambda}_t^b w_t
\end{aligned}
$$

$$
\begin{aligned}
20)\ \tilde{\lambda}_t^b &= \beta(r_{t+1}^k + 1 - \delta)\tilde{\lambda}_{t+1}^b \\
21)\ \lambda_t^i &= \lambda_t^\tau + \lambda_t^s \\
22)\ 0 &= \log(c_{t+1}^s) - \frac{\theta}{2}\left(n_{t+1}^s\right)^2 + \lambda_{t+1}^\tau \begin{bmatrix} \pi_1 c_{t+1}^s \left(i_{t+1} c_{t+1}^i\right) \\ +\pi_2 n_{t+1}^s \left(i_{t+1} n_{t+1}^i\right) + \pi_3 i_{t+1} \end{bmatrix} \\
&\quad + \tilde{\lambda}_{t+1}^b \left[w_{t+1} n_{t+1}^s - c_{t+1}^s\right] - \lambda_t^s/\beta + \lambda_{t+1}^s \\
23)\ 0 &= \log(c_{t+1}^i) - \frac{\theta}{2}\left(n_{t+1}^i\right)^2 + \tilde{\lambda}_{t+1}^b \left[w_{t+1} n_{t+1}^i - c_{t+1}^i\right] \\
&\quad - \lambda_t^i/\beta + \lambda_{t+1}^i (1 - \pi_r - \pi_d) + \lambda_{t+1}^r \pi_r \\
24)\ 0 &= \log(c_{t+1}^r) - \frac{\theta}{2}\left(n_{t+1}^r\right)^2 + \tilde{\lambda}_{t+1}^b \left[w_{t+1} n_{t+1}^r - c_{t+1}^r\right] - \lambda_t^r/\beta + \lambda_{t+1}^r \\
25)\ \tilde{\lambda}_t^b &= \beta r r_t \tilde{\lambda}_{t+1}^b \\
26)\ r r_t &= \frac{R_t^b}{\pi_{t+1}}.
\end{aligned}
$$

The optimality conditions for optimal price setting are:

$$
\begin{aligned}
27)\ K_t^f &= \gamma m c_t \tilde{\lambda}_t^b y_t + \beta \xi \pi_{t+1}^{\frac{\gamma}{\gamma-1}} K_{t+1}^f \\
28)\ F_t &= \tilde{\lambda}_t^b y_t + \beta \xi \pi_{t+1}^{\frac{1}{\gamma-1}} F_{t+1} \\
29)\ K_t^f &= F_t \left(\frac{1 - \xi \pi_t^{\frac{1}{\gamma-1}}}{1-\xi}\right)^{-(\gamma-1)}.
\end{aligned}
$$

The price dispersion term is given by:

$$
30)\ \breve{p}_t = \left[(1-\xi)\left(\frac{1 - \xi \pi_t^{\frac{1}{\gamma-1}}}{1-\xi}\right)^{\gamma} + \xi \frac{\pi_t^{\frac{\gamma}{\gamma-1}}}{\breve{p}_{t-1}}\right]^{-1}.
$$

Finally, the Taylor rule is given by:

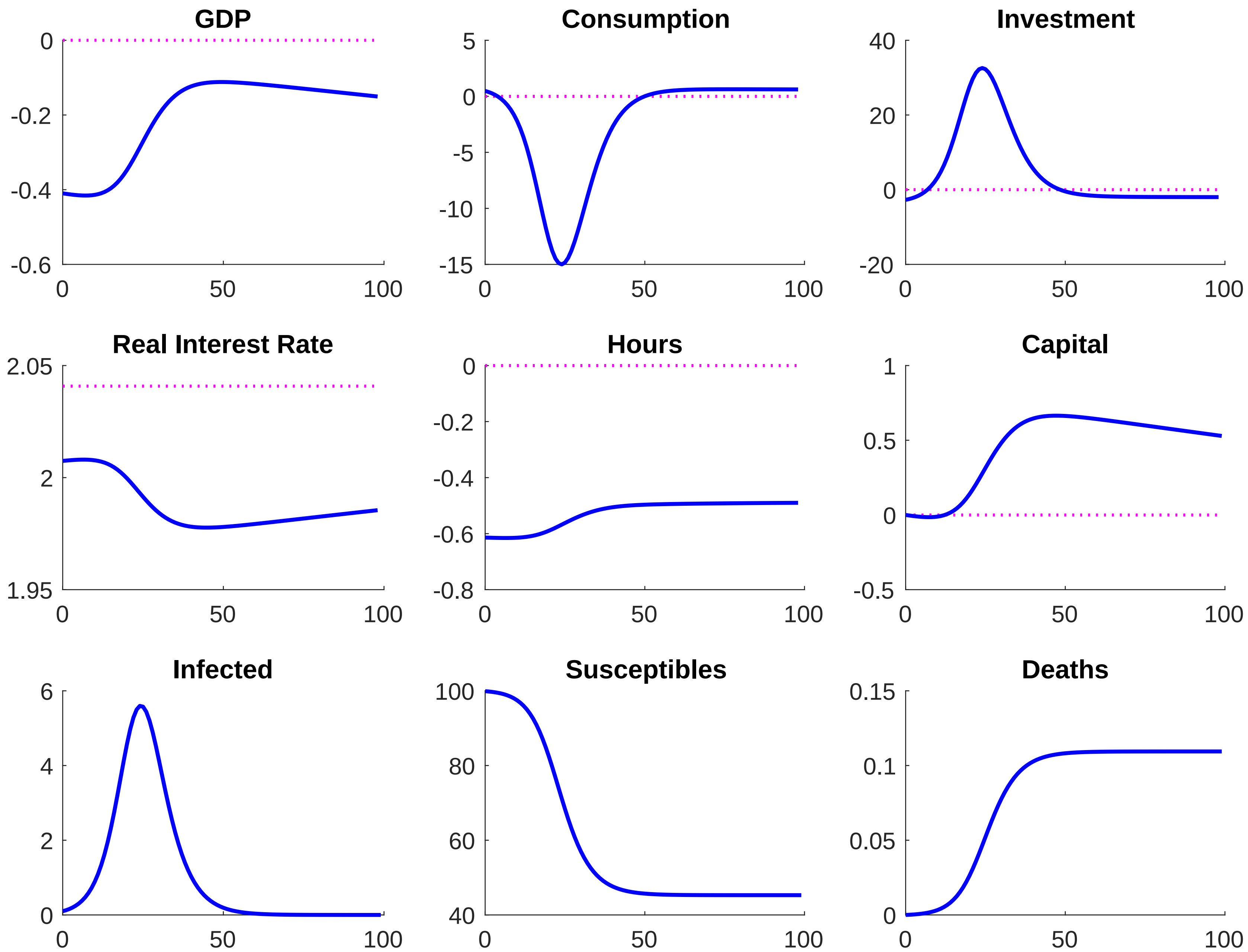
$$
31)\ \log \frac{R_t^b}{R^b} = r_\pi \log \frac{\pi_t}{\pi} + r_x \log(y_t / y_t^f).
$$

Here, y_t^f is flexible price output which can be computed using equations $1) - 31)$ setting $\xi = 0$.

In equations $1) - 31)$ $\tilde{\lambda}_t^b$ is the scaled Lagrange multiplier, i.e. $\tilde{\lambda}_t^b = \lambda_t^b P_t$. For the perfect and imperfect competition models with flexible prices, note that $P_t = 1$ and $\tilde{\lambda}_t^b = \lambda_t^b$.

We solve the nonlinear equilibrium equations $1) - 31)$ as well as their flexible price version using a gradient-based two-point boundary-value algorithm.

Figure 1: Perfect Competition -- Epidemic as a Shock to Consumption Demand (1/2)



Notes: GDP, consumption, investment, hours and capital in percent deviations from initial steady state.
Real interest rate in percent. Infected, susceptibles and deaths in percent of initial population. x-axis in weeks.

Figure 2: Perfect Competition -- Epidemic as a Shock to Consumption Demand (2/2)

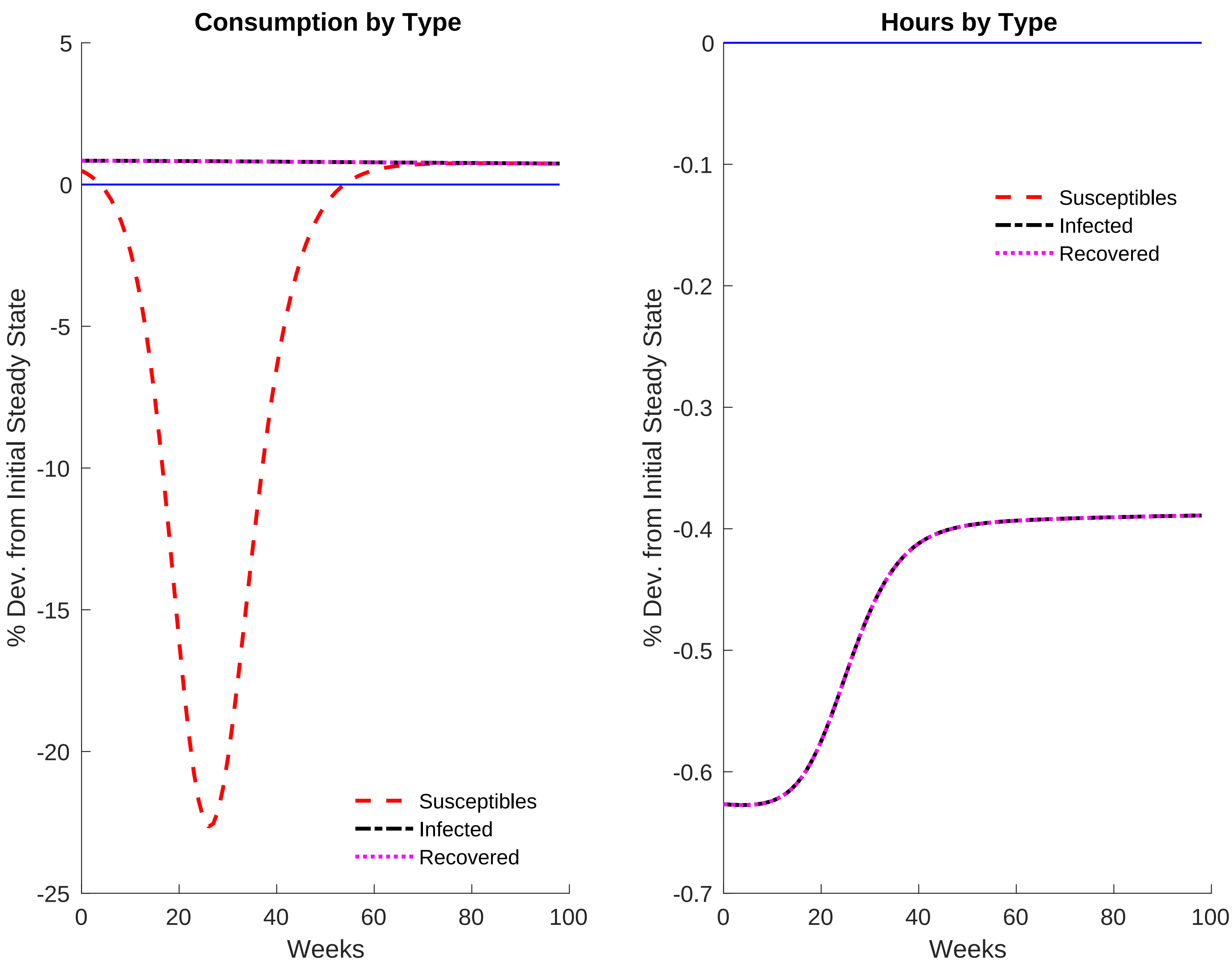
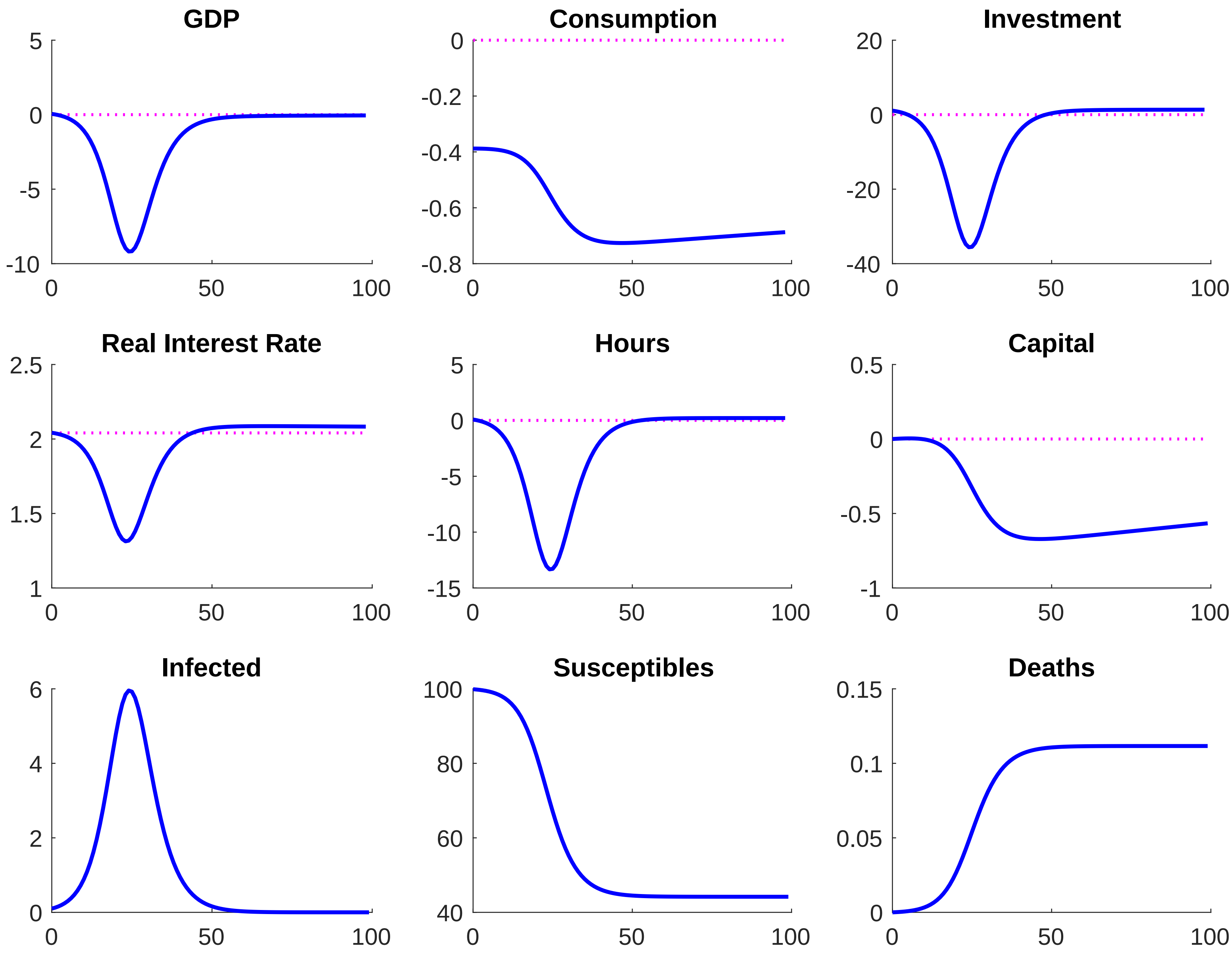


Figure 3: Perfect Competition -- Epidemic as a Shock to Labor Supply (1/2)



Notes: GDP, consumption, investment, hours and capital in percent deviations from initial steady state.
Real interest rate in percent. Infected, susceptibles and deaths in percent of initial population. x-axis in weeks.

Figure 4: Perfect Competition -- Epidemic as a Shock to Labor Supply (2/2)

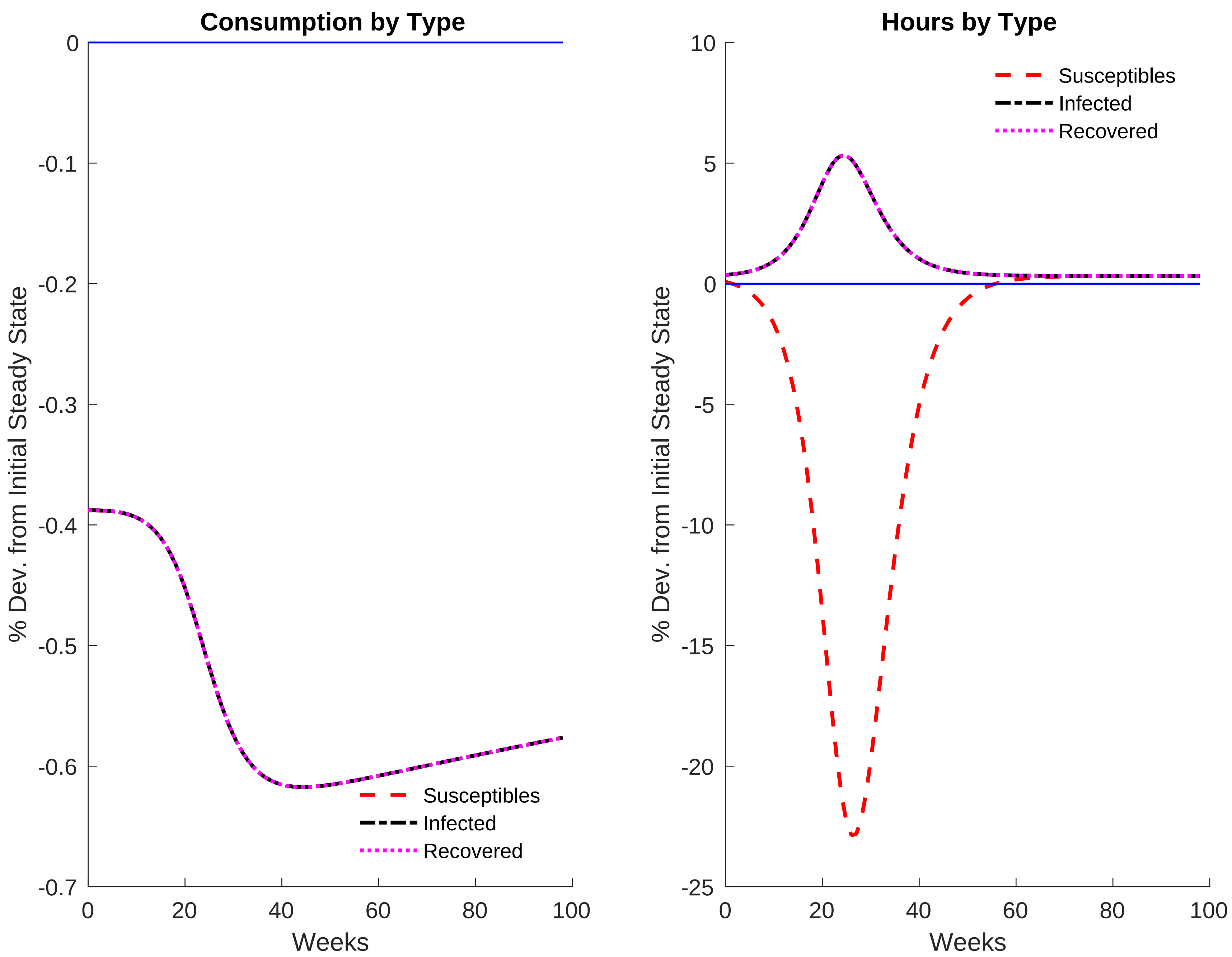
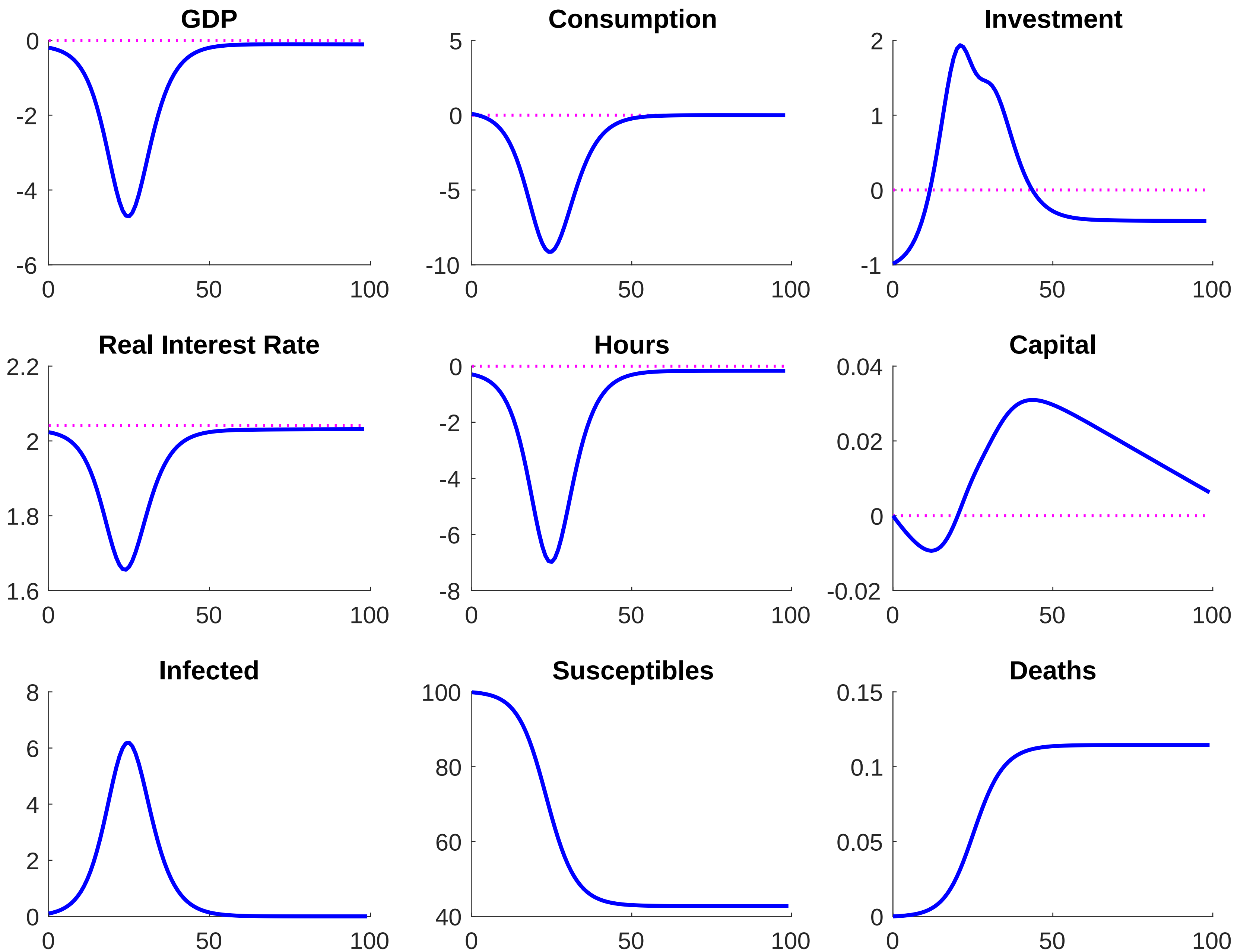


Figure 5: Perfect Competition -- Epidemic as a Shock to Demand and Supply (1/2)



Notes: GDP, consumption, investment, hours and capital in percent deviations from initial steady state.
Real interest rate in percent. Infected, susceptibles and deaths in percent of initial population. x-axis in weeks.

Figure 6: Perfect Competition -- Epidemic as a Shock to Demand and Supply (2/2)

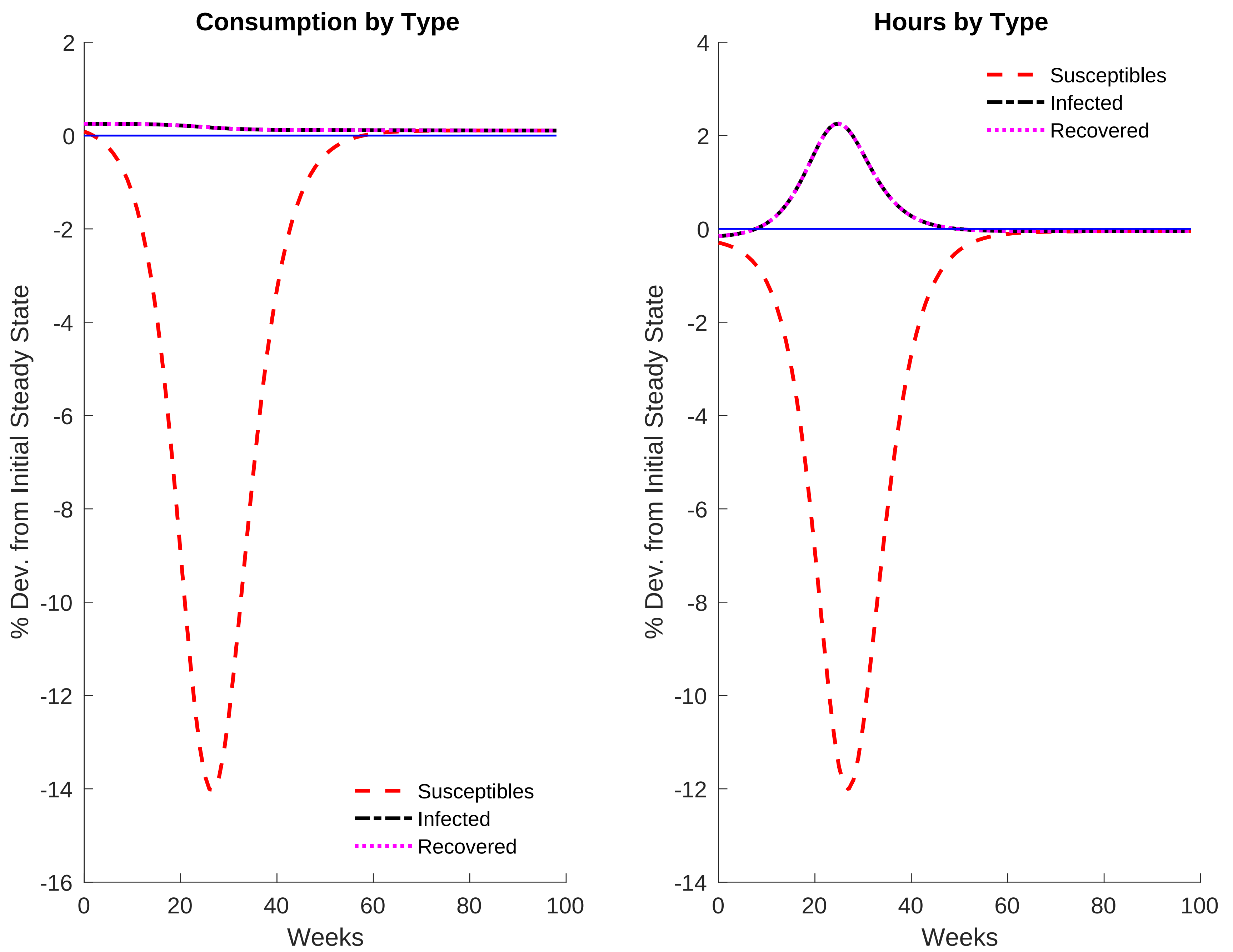
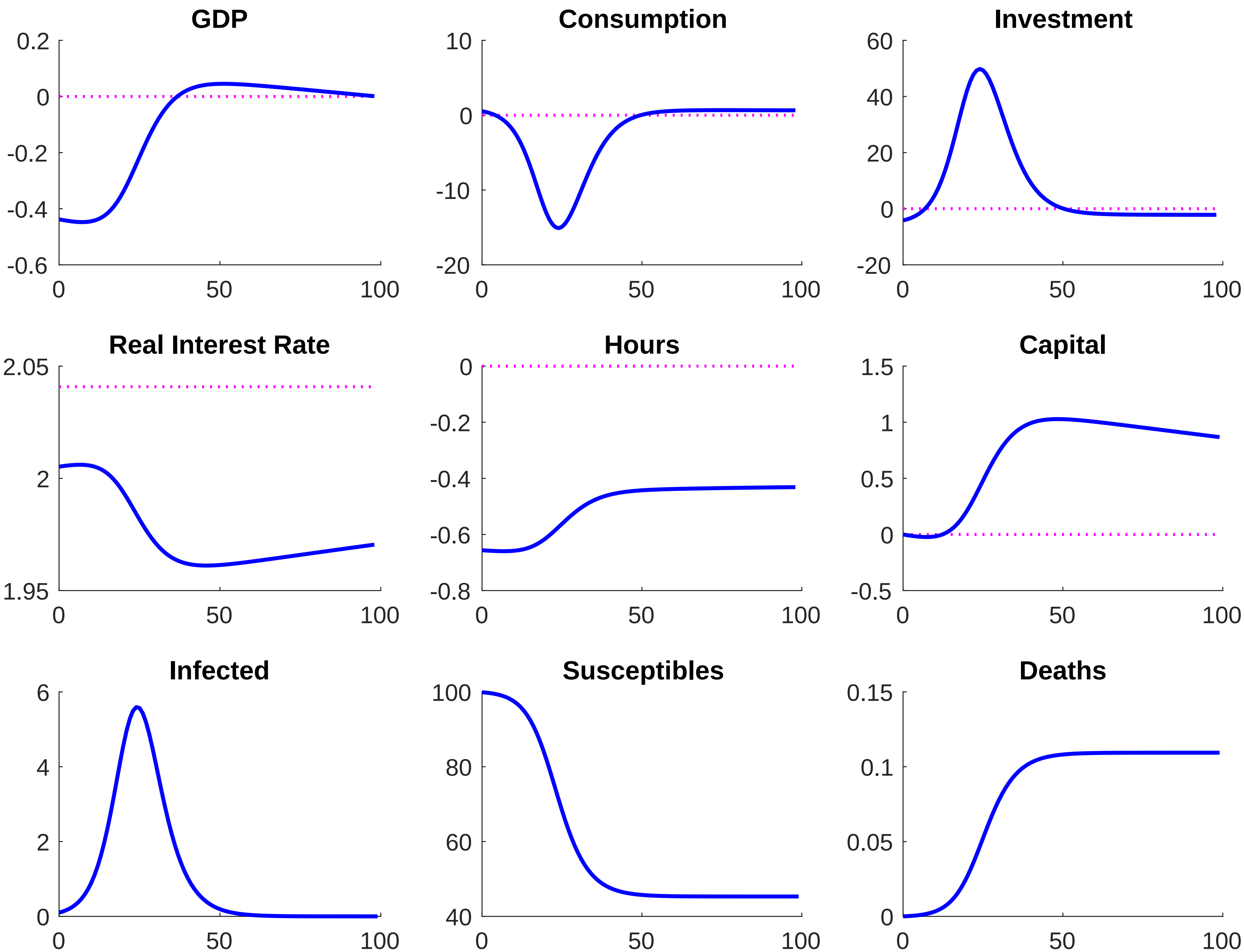
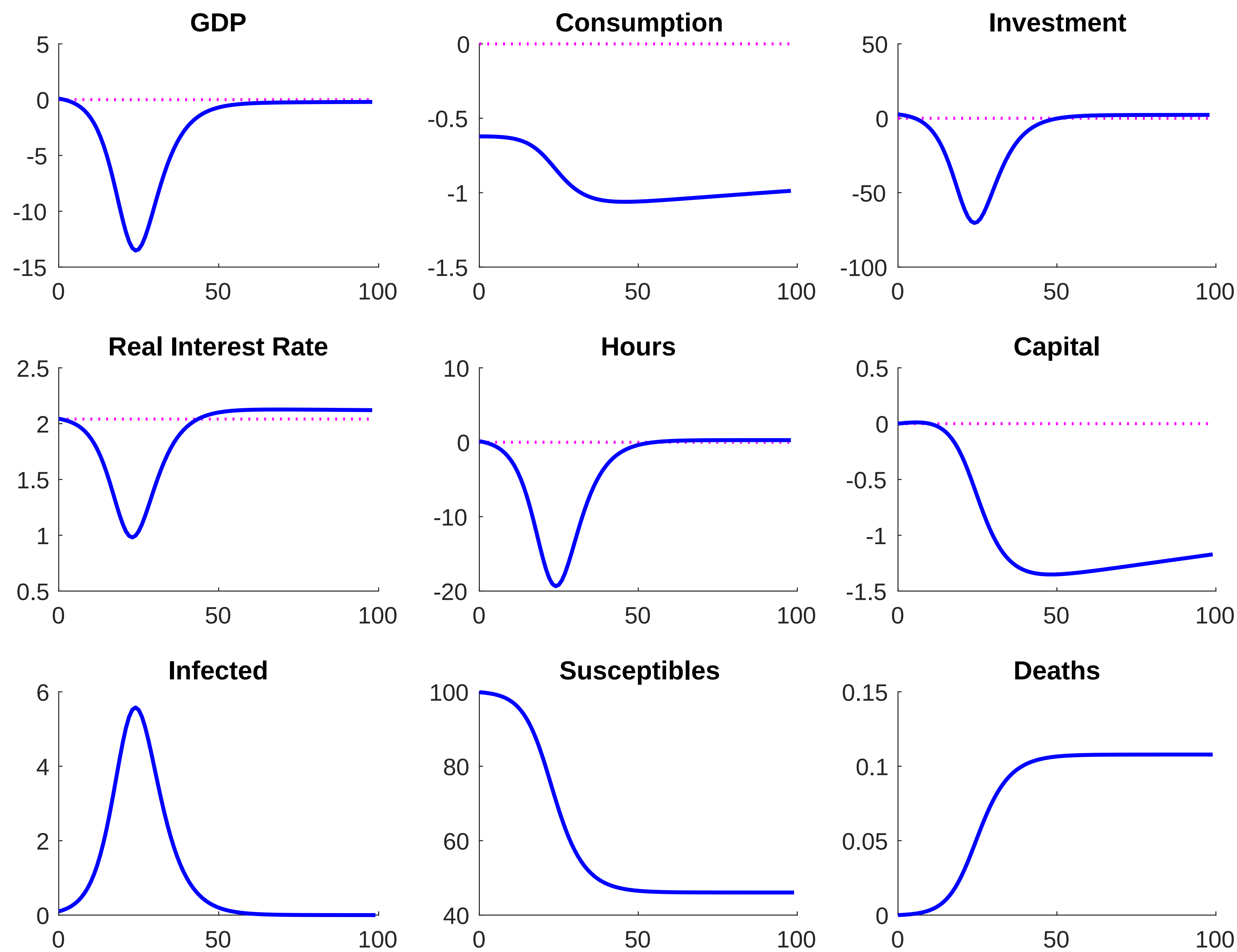


Figure 7: Imperfect Competition -- Epidemic as a Shock to Consumption Demand



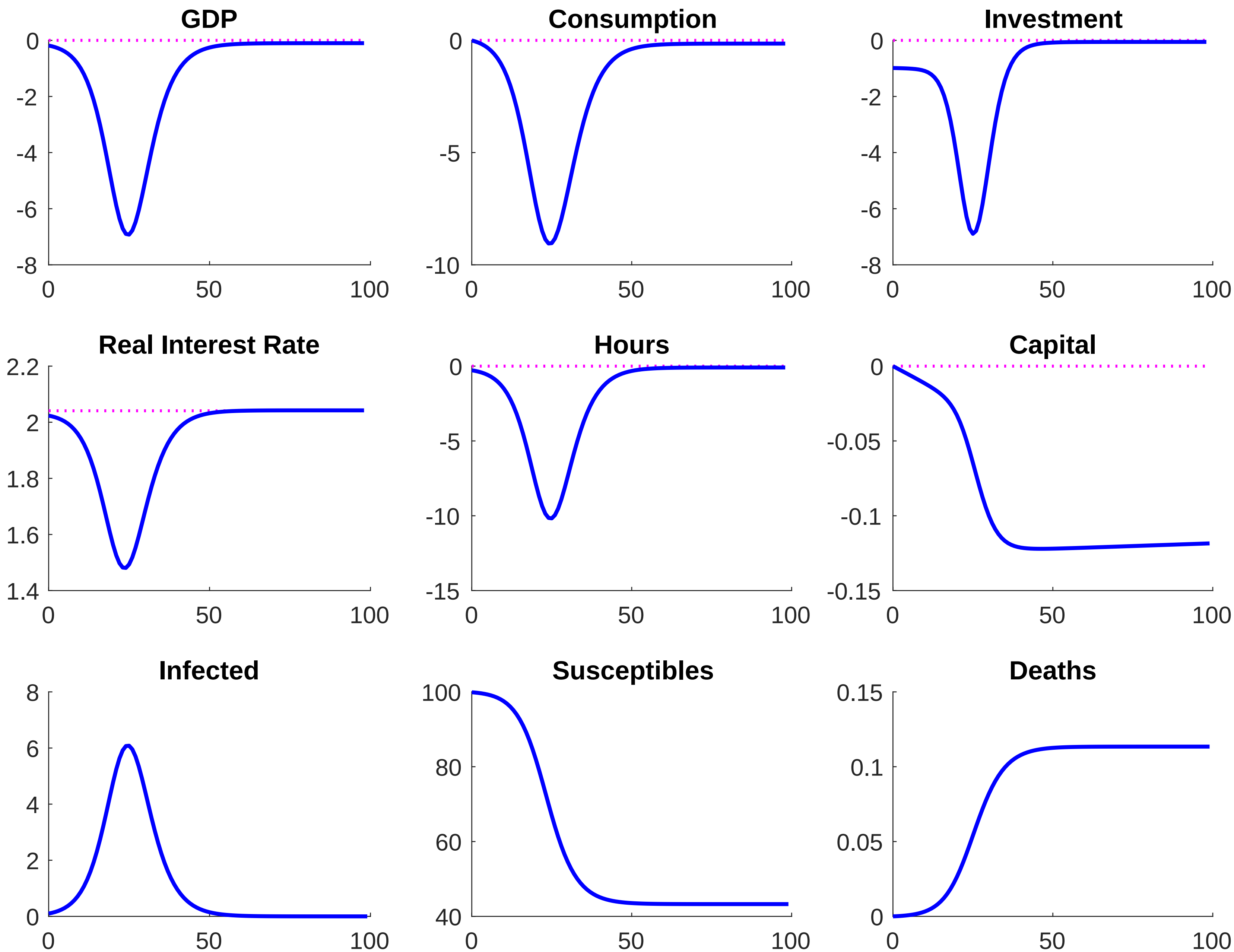
Notes: GDP, consumption, investment, hours and capital in percent deviations from initial steady state.
Real interest rate in percent. Infected, susceptibles and deaths in percent of initial population. x-axis in weeks.

Figure 8: Imperfect Competition -- Epidemic as a Shock to Labor Supply



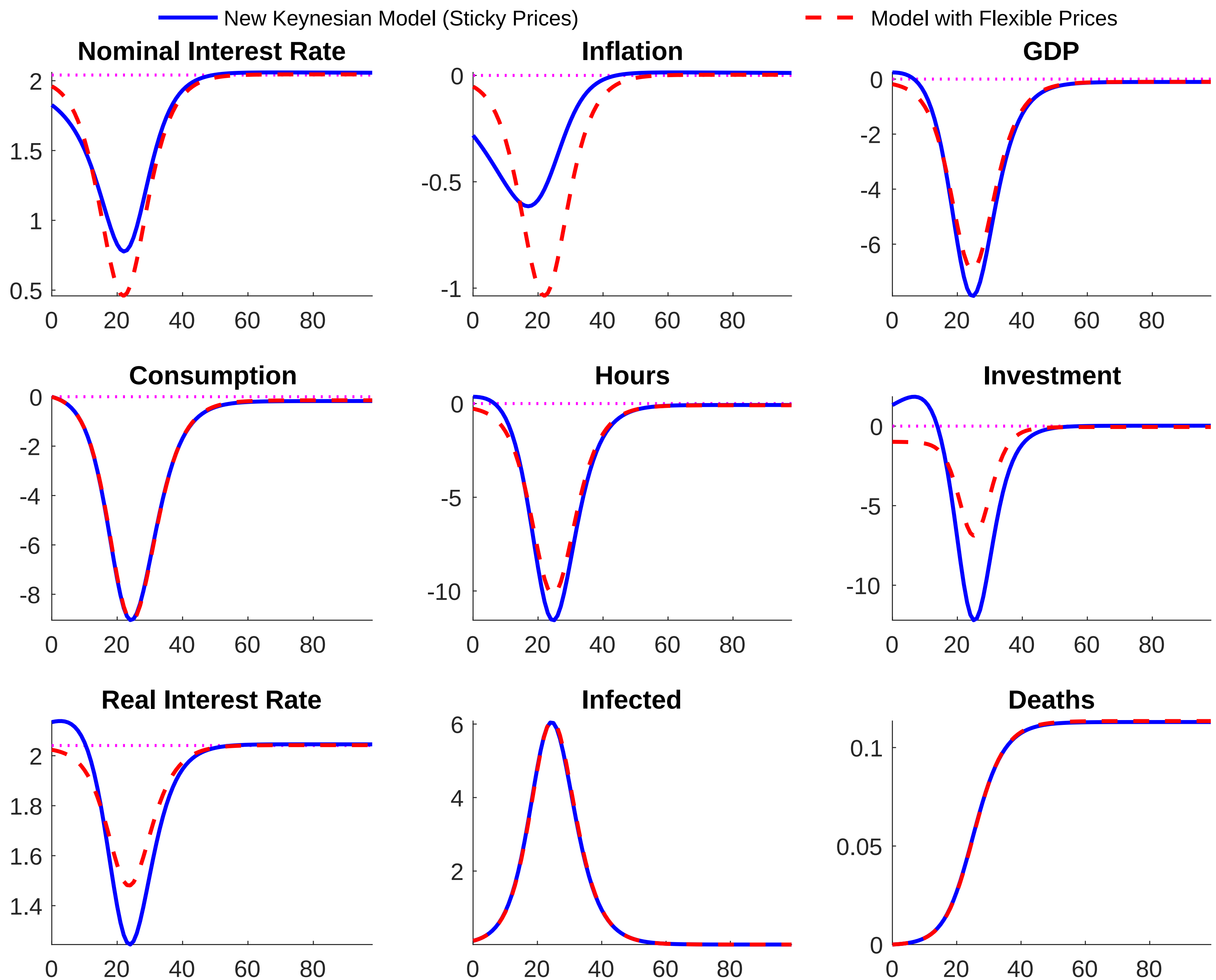
Notes: GDP, consumption, investment, hours and capital in percent deviations from initial steady state.
Real interest rate in percent. Infected, susceptibles and deaths in percent of initial population. x-axis in weeks.

Figure 9: Imperfect Competition -- Epidemic as a Shock to Demand and Supply



Notes: GDP, consumption, investment, hours and capital in percent deviations from initial steady state.
Real interest rate in percent. Infected, susceptibles and deaths in percent of initial population. x-axis in weeks.

Figure 10: Epidemic in a New Keynesian Model



Notes: x-axis in weeks. GDP, consumption, hours and investment in percent deviations from initial steady state. Inflation, nominal and real interest rates in percent. Infected and deaths in percent of initial population.