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The Distributional Effects of COVID-19 and Optimal Mitigation Policies[1]

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Abstract

This paper develops a quantitative heterogeneous agent–life cycle model with a fully integrated epidemiological model in which economic decisions affect the spread of COVID-19 and, conversely, the virus affects economic decisions. The calibrated model is used to study the effectiveness of two mitigation policies: a stay-at-home subsidy that subsidizes reduced hours worked and a stay-at-home order that imposes a cap on outside hours. First, the stay-at-home subsidy is preferred in that it reduces deaths by more and output by less, leading to not only a larger average welfare gain but also a welfare gain for all individuals. Second, optimal mitigation policies involve a stay-at-home subsidy that is between \$450 and \$900 per week for 16–18 months, depending on the welfare criterion. Finally, it is possible to simultaneously improve public health and economic outcomes, suggesting that debates regarding a supposed tradeoff between economic and health objectives could be misguided.

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1 Introduction

Amidst the deadliest pandemic since the 1918 influenza pandemic and the largest economic contraction since the Great Depression, policymakers and intellectuals continue to debate about a supposed tradeoff between economic and public health outcomes. On one end of the spectrum, US President Trump asked "Will some people be affected badly?" and responded "Yes, but we have to get our country opened and we have to get it open soon" on May 6th, 2020.[2] On the other end, New York Governor Cuomo tweeted "If it's public health versus the economy, the only choice is public health," on March 23rd, 2020.[3] In this paper, however, I show that it is possible to simultaneously improve public health and economic outcomes, suggesting that there is not necessarily a tradeoff between economic and health objectives.

To better understand the economic–health tradeoff, or the lack thereof, I build a quantitative model that I use as a laboratory to investigate the effects of various mitigation policies. Building on the economic-epidemiological model developed by Eichenbaum et al. (2020) that allows for a rich feedback between economic activities and the spread of the virus, I add two important and necessary ingredients: heterogeneity in age and in income and wealth. The former is necessary to take into account the fact that COVID-19 has been particularly dangerous for older individuals, while mitigation policies, such as stay-at-home orders, have more adversely affected working-age individuals. The latter is necessary to consider the heterogeneous effects of mitigation policies such as stay-at-home orders that may disproportionately harm low-wage workers who are less likely to work from home and low-wealth workers who lack the resources to weather prolonged time away from work.

In the first part of the paper, I develop a quantitative heterogeneous agent–life cycle model with a fully integrated epidemiological model in which economic decisions affect the spread of COVID-19, and conversely, the virus affects econonomic decisions. At the time of writing, this is the first paper to develop a quantitative model that integrates economic-epidemiological feedback, heterogeneity across ages, and heterogeneity across income and wealth. For example, Kaplan et al. (2020) feature heterogeneity in income and wealth but not in ages, Glover et al. (2020) include heterogeneity in ages but not in income or wealth, and Bairoliya and Imrohoroglu (2020) model heterogeneity across age, income, and wealth,

[2] See https://www.cnbc.com/2020/05/05/trump-acknowledges-some-coronavirus-deaths-will-result-from-reopening.html.

[3] See https://twitter.com/nygovcuomo/status/1242264009342095361?lang=en.

but do not allow for economic activities to affect the spread of the virus. The model has other important ingredients such as the option to work from home and hospital capacity constraints.

In the second part of the paper, the model's economic parameters are calibrated to match features of the US economy prior to the pandemic and the model's epidemiological parameters are set to match features of COVID-19, such as estimates for the basic reproduction number and age-specific fatality rates. Fully acknowledging that there is quite a bit of uncertainty regarding these and other epidemiological estimates, I conduct a host of sensitivity analyses, which also sheds light on how changes in these estimates affect the optimal responses to the pandemic.

In the third part of the paper, I use the calibrated model to study the effectiveness of various mitigation policies. Specifically, I study a *stay-at-home order* that imposes a cap of 10 outside hours worked per week, meant to resemble the various stay-at-home and shelter-in-place orders implemented by most states in response to the pandemic, and a *stay-at-home subsidy* that provides a weekly subsidy of $600 for individuals that work less than 10 hours per week. Both policies begin March 27, 2020 and begin a gradual phase-out after July 31, 2020. The subsidy policy has similarities to parts of the fiscal response such as the Pandemic Unemployment Assistance program (PUA), which provided an additional $600 in unemployment benefits, and the Paycheck Protection Program (PPP), which provided funds to small business affected by the pandemic to pay furloughed workers. There are also notable differences. The first is that while the PUA subsidy requires involuntary unemployment or underemployment, the subsidy studied in this model is based on voluntary reductions in hours worked. The second is that the model subsidy is funded by a consumption tax, whereas the PUA and PPP program is debt-financed. One reason that I use a consumption tax is that it reduces the incentive to engage in consumption activities, another way in which the virus transmits. Another is that, in contrast to debt-financing, which typically imposes a larger burden on young individuals, the burden of the consumption tax is more widely shared. To the extent that older individuals stand to gain the most from the mitigation policies, this is a desirable feature.

Finally, I investigate the properties of optimal mitigation policies. Specifically, I vary the subsidy amount from $0 to $1800 per week, the subsidy duration from 2 to 22 months, the hours threshold to qualify for the subsidy from 0 to 10 hours per week, with and without a lockdown.

The main findings are summarized below.

1. **Even in the absence of mitigation policies, private mitigation by individuals is substantial.** Individuals voluntarily reduce their consumption and outside hours worked to reduce their probability of infection. While this is a common feature in economic-epidemiological models such as Eichenbaum et al. (2020), the rich heterogeneity in my model allows for additional new insights. All else equal, these reductions are larger for older individuals who face higher death rates if infected, for higher-wage workers who are more likely to work from home, and for wealthier individuals who can afford to sustain prolonged time away from work.

2. **The stay-at-home subsidy is superior to the stay-at-home order (lockdown) along all the relevant dimensions.** Compared to the lockdown alone, the subsidy plan alone delivers a higher average welfare gain and reduces deaths by more and output by less. In the case of the lockdown, older individuals experience a welfare gain because of the reduced infection and death probability, but these gains are mostly canceled by the welfare losses of the younger low-wage workers, who face a large decline in their income. In contrast, the stay-at-home subsidy benefits all individuals.

3. **Optimal policies involve larger and longer duration subsidies compared to current US policy and no lockdown.** I refer to the constrained optimum the policy configuration that delivers the highest average welfare gain, conditional on full support. The constrained optimum involves a larger subsidy ($900 per week), longer duration (18 months), a lower qualifying threshold (zero hours), and no lockdown, compared to the configuration that most resembles US policy. I also study the properties of the output maximizing policy, which involve a somewhat lower subsidy ($450), longer duration (16 months), a zero hour qualifying threshold, and no lockdown, compared to current US policy.

Related literature

The model combines the heterogeneous-agent overlapping-generations model (see, for example, Conesa et al. 2009, Favilukis et al. 2017, Heathcote et al. 2010, and Hur 2018) with an extension of the standard SIR epidemiological model similar to those used in Eichenbaum et al. (2020), Glover et al. (2020), and Jones et al. (2020). Workers face idiosyncratic efficiency shocks and borrowing constraints within an incomplete market setting as in Aiyagari (1994), Bewley (1986), Huggett (1993), and Imrohoroğlu (1989).

The paper is most related to Bairoliya and Imrohoroglu (2020) and Glover et al. (2020). Bairoliya and Imrohoroglu (2020) study quarantine policies in a quantitative life-cycle model with heterogeneity across age, health, income, and wealth. They primarily focus on studying the effects of selective quarantines based on age and health. Relative to my paper, Bairoliya and Imrohoroglu (2020) study the disease progression at a lower frequency (yearly) and do not incorporate the economic-epidemiological feedback channel. Glover et al. (2020) study optimal mitigation policies in a model with three types of agents: retirees, young workers in the essential sector, and young workers in the non-essential sector. Relative to Glover et al. (2020), this paper features heterogeneity across not only age, but also income and wealth, and complements both papers by analyzing mitigation policies that specifically target the behavior of these different groups.

The epidemiological part of the model borrows from the economics literature that builds on the SIR model, originally developed by Kermack and McKendrick (1927). Atkeson (2020) was one of the first papers to use the SIR model in an economics context. Alvarez et al. (2020), Eichenbaum et al. (2020), Farboodi et al. (2020), and Jones et al. (2020) study optimal mitigation in SIR models extended with lockdowns, economic-epidemiological feedback, social distancing, and work from home with learning-by-doing, respectively. Bodenstein et al. (2020) and Krueger et al. (2020) study the SIR model with multiple sectors. Birinci et al. (2020), Garibaldi et al. (2020), and Kapicka and Rupert (2020) incorporate search and matching frictions into the SIR framework, while Berger et al. (2020), Chari et al. (2020), and Piguillem and Shi (2020) extend the SIR model to focus on testing and quarantine. Chudik et al. (2020) extend the SIR model to allow for compulsory and voluntary social distancing and estimate the model using data from Chinese provinces, while Argente et al. (2020) extend the SIR model with city structure, estimated with South Korean mobile phone data. Bognanni et al. (2020) develop a SIR model with multiple regions and estimate it on daily county-level US data. Aum et al. (2020) study the effects of lockdowns in a model with heterogeneous age, skill, and occupation choice, while Kaplan et al. (2020) study the distributional effects of the pandemic in a heterogeneous agent new Keynesian model.

By studying the heterogeneous welfare consequences of COVID-19 and mitigation efforts, this paper complements the empirical literature that has documented the early effects of the pandemic and various mitigation policies on different segments of the population, such as Chetty et al. (2020). Adams-Prassl et al. (2020) and Wozniak (2020) use survey data to document that COVID-19 has disproportionately impacted young and low-wage individuals in the US. Alstadsæter et al. (2020) use register data from Norway to document that pandemic-induced layoffs have disproportionately affected not only young and low-wage, but also low-wealth individuals. Additionally, Bertocchi and Dimico (2020) focus on differential effects of the COVID-19 crisis across race, Alon et al. (2020a,b) study the differences across gender, and Osotimehin and Popov (2020) study the heterogeneous impact by sector of employment.

2 Model

This section presents a model economy used to quantitatively analyze the welfare consequences of COVID-19 and to run policy counterfactuals. The setting combines the heterogeneous-agent overlapping-generations model with an extension of the standard SIR epidemiological model that is similar to those used in Eichenbaum et al. (2020). The economy is inhabited by overlapping generations of stochastically aging individuals. Time is discrete and indexed by $t = 0, ..., \infty$. Workers face idiosyncratic efficiency shocks and borrowing constraints within an incomplete market setting. I now describe the model in more detail.

2.1 Individuals

Individuals of age $j \in J \equiv \{1, 2, .., \overline{J}\}$ face conditional aging probabilities given by $\{\psi_j\}$.[4] Mandatory retirement occurs at age $j = J_R$. The period utility function is given by

$$u(c, \ell, h) = \frac{c^{1-\sigma}}{1-\sigma} - \varphi \frac{\ell^{1+\nu}}{1+\nu} + \bar{u} + \hat{u}_h \tag{1}$$

where c is consumption, ℓ is labor supply, and $\bar{u}$ and $\hat{u}_h$ govern the flow value of being alive and being in health state h, respectively.

[4] Given that the model will be used to analyze disease progression at a high frequency, the assumption of stochastic aging greatly reduces the state space and computational burden.

An individual's health status is given by $h \in \{S, I, R, D\}$: *susceptible* agents are healthy but may contract the virus, *infected* agents have contracted the virus and may pass it onto others, and agents that exit the infection can either *recover* or *die*. Recovered agents are assumed to be immune from further infection.[5] The transition between health states builds on the widely used SIR model, originally developed by Kermack and McKendrick (1927). Susceptible individuals get infected with probability π_{It}, which depends on individual consumption and outside labor (c, ℓ^o) and the aggregate measure of infected individuals (μ_{It}) and their consumption and outside labor (C_{It}, L^o_{It}). Formally,

$$\pi_{It}(c, \ell^o; Z_t) = \beta_c c C_{It} + \beta_\ell \ell^o L^o_{It} + \beta_e \mu_{It}, \tag{2}$$

where $Z_t \equiv \{\mu_{It}, C_{It}, L^o_{It}\}$. This framework allows the virus to be contracted from consumption-related activities, labor-related activities, and from other settings. It also allows a feedback between disease progression and economic activities as in Eichenbaum et al. (2020), Glover et al. (2020), and Jones et al. (2020).

Infected individuals exit the infection with probability π_{Xt} and upon exit, they recover with probability $1 - \delta_{jt}(\mu_{It})$ and die with probability $\delta_{jt}(\mu_{It})$. The fatality rate depends on the individual's age and on the aggregate measure of infected individuals, reflecting hospital capacity constraints. If we assume that a vaccine and cure are developed and implemented in period $\hat{t}$, then the transition matrix between health states, for $t < \hat{t}$, is given by

$$\Pi_{jhh't}(c, \ell^o; Z_t) = \begin{array}{c|cccc} & S & I & R & D \\ \hline S & 1 - \pi_{It}(c, \ell^o; Z_t) & \pi_{It}(c, \ell^o; Z_t) & 0 & 0 \\ I & 0 & 1 - \pi_{Xt} & \pi_{Xt}(1 - \delta_{jt}(Z_t)) & \pi_{Xt}\delta_{jt}(Z_t) \\ R & 0 & 0 & 1 & 0 \\ D & 0 & 0 & 0 & 1 \end{array} \tag{3}$$

and for $t \geq \hat{t}$,

$$\Pi_{jhh't}(c, \ell^o; Z_t) = \begin{array}{c|cccc} & S & I & R & D \\ \hline S & 0 & 0 & 1 & 0 \\ I & 0 & 0 & 1 & 0 \\ R & 0 & 0 & 1 & 0 \\ D & 0 & 0 & 0 & 1 \end{array} \tag{4}$$

[5] At this point, it is not clear whether individuals that have recovered from COVID-19 have lasting immunity. One could easily extend the model to have shorter durations of immunity.

Each period, workers receive idiosyncratic efficiency shocks $\varepsilon \in E$, which follows a Markov process, with transition matrix Γ. Their labor income is given by $w_t \eta_{jh} \varepsilon \ell$, where w_t is the efficiency wage, η_{jh} is the health- and age-profile of efficiency units, and ℓ is total hours worked. Workers may choose to work up to a fraction $\bar{\theta}_j(\varepsilon)$ of their labor hours from home, where $\bar{\theta}_j(\varepsilon)$ is allowed to vary by age and efficiency. Retirees are assumed to receive a fixed income of s each period.[6] Individuals can accumulate non-contingent assets k, which delivers a net return of r_t.

Given the sequence of prices $\{w_t, r_t\}$, consumption taxes $\{\tau_{ct}\}$, and aggregate states $\{Z_t\}$, a retiree with age $j \geq J_R$, wealth k, and health h in period t chooses consumption c and savings k' to solve:

$$\begin{aligned} v^R_{jt}(k,h) = \max_{c,k' \geq 0} \; & u(c,0,h) + \beta\psi_j \sum_{h' \in H} \Pi_{hh't}(c,0) v^R_{j+1,t+1}(k',h') \\ & + \beta(1-\psi_j) \sum_{h' \in H} \Pi_{hh't}(c,0) v^R_{j,t+1}(k',h') \\ \text{s.t.} \; & (1+\tau_{ct})c + k' \leq s + k(1+r_t) \end{aligned} \tag{5}$$

where β is the time discount factor. Solving this yields retiree policy functions $\{c^R_j(k,h), k^{R\prime}_j(k,h)\}_{j \geq J_R}$ for consumption and savings, respectively. I assume that the value of death is zero and that $v^R_{\bar{J}+1,t} = 0$, which implies that agents in the last stage of life ($j = \bar{J}$) may die due to stochastic aging and, if infected, due to the virus.

Given the sequence of prices $\{w_t, r_t\}$, consumption and labor income taxes $\{\tau_{ct}, \tau_{\ell t}\}$, and aggregate states $\{Z_t\}$, a worker with age $j < J_R$, wealth k, efficiency ε, and health h in period t chooses consumption c, total labor ℓ, outside labor ℓ^o and savings k' to solve:

$$\begin{aligned} v_{jt}(k,\varepsilon,h) = \max_{c,\ell,\ell^o,k' \geq 0} \; & u(c,\ell,h) + \beta\psi_j \sum_{\varepsilon' \in E} \sum_{h' \in H} \Gamma_{\varepsilon\varepsilon'} \Pi_{hh't}(c,\ell^o) v_{j+1,t+1}(k',\varepsilon',h') \\ & + \beta(1-\psi_j) \sum_{\varepsilon' \in E} \sum_{h' \in H} \Gamma_{\varepsilon\varepsilon'} \Pi_{hh't}(c,\ell^o) v_{j,t+1}(k',\varepsilon',h') \\ \text{s.t.} \; & (1+\tau_{ct})c + k' \leq w_t \eta^h_j (1-\tau_{\ell t})\varepsilon\ell + k(1+r_t) \\ & (1-\bar{\theta}_j(\varepsilon))\ell \leq \ell^o \leq \ell \end{aligned} \tag{6}$$

where $v_{jt}(k,\varepsilon,h) = v^R_{jt}(k,h)$ for $j \geq J_R$ and $\varepsilon \in E$. Solving this yields worker policy functions $\{c_j(k,\varepsilon,h),\ \ell_j(k,\varepsilon,h), \ell^o_j(k,\varepsilon,h), k'_j(k,\varepsilon,h)\}_{j<J_R}$ for consumption, labor, outside labor, and

[6] This can readily be extended to depend on lifetime earnings as in Hur (2018).

savings, respectively. Additionally, let $c_j(k,\varepsilon,h) = c_j^R(k,h)$ and $k_j'(k,\varepsilon,h) = k_j^{R\prime}(k,h)$ for $j \geq J_R$ and $\varepsilon \in E$.

2.2 Production

A representative firm hires labor (L_{ft}) and capital (K_{ft}) to produce according to

$$Y_{ft} = K_{ft}^{\alpha} L_{ft}^{1-\alpha} \tag{7}$$

Taking prices as given, the firm solves

$$\max_{L_{ft},K_{ft}} Y_{ft} - w_t L_{ft} - (r_t + \delta) K_{ft}, \tag{8}$$

where δ is the deprecation rate of capital. Optimality conditions are given by

$$w_t = (1-\alpha) K_{ft}^{\alpha} L_{ft}^{-\alpha}, \tag{9}$$

$$r_t = \alpha K_{ft}^{\alpha-1} L_{ft}^{1-\alpha} - \delta. \tag{10}$$

2.3 Law of motion for aggregate states

Let C_{jht} and L_{jht}^o denote aggregate consumption and outside labor, respectively, of individuals with age j and health h in period t. Then, by the law of large numbers, equation (2) implies that new infections within an age-j cohort are given by

$$T_{jt} = \beta_c C_{jSt} C_{It} + \beta_\ell L_{jSt}^o L_{It}^o + \beta_e \mu_{jSt} \mu_{It} \tag{11}$$

where μ_{jSt} is the measure of susceptible age-j individuals in period t. The measure of infected agents is then given by $\mu_{I,t+1} = \sum_{j \in J} \mu_{jI,t+1}$ where, for $j > 1$,

$$\begin{aligned} \mu_{jI,t+1} = {} & \psi_j(\mu_{j-1,It}(1-\pi_{Xt}) + T_{j-1,t}) \\ & + (1-\psi_j)(\mu_{jIt}(1-\pi_{Xt}) + T_{jt}), \end{aligned} \tag{12}$$

and

$$\mu_{1I,t+1} = (1-\psi_1)(\mu_{1It}(1-\pi_{Xt}) + T_{1t}).$$

2.4 Equilibrium

We are ultimately interested in studying disease dynamics along a transition path. However, because most of the model parameters are calibrated to an initial pre-pandemic steady state, let's first define a stationary equilibrium in which $\mu_I = 0$. In this case, aggregate consumption and labor of infected individuals is trivially zero. Thus $Z = (0, 0, 0)$ and Π is the identity matrix. Define the state space over wealth, efficiency, and health as $X = K \times E \times H$ and let a σ-algebra over X be defined by the Borel sets, $\mathcal{B}$, on X.

Definition. A *steady-state recursive equilibrium*, given fiscal policies $\{\tau_c, \tau_\ell, s\}$, is a set of value functions $\{v_j\}_{j\in J}$, policy functions $\{c_j, \ell_j, \ell_j^o, k_j'\}_{j\in J}$, prices $\{w, r\}$, producer plans $\{Y_f, L_f, K_f\}$, the distribution of newborns ω, and invariant measures $\{\mu_j\}_{j\in J}$ such that:

1. Given prices, retirees and workers solve (5) and (6), respectively.

2. Given prices, firms solve (8).

3. Markets clear:

   (a) $Y_f = \int_X \sum_{j\in J} (c_j(k, \varepsilon, h) + \delta k)\, d\mu_j(k, \varepsilon, h)$

   (b) $L_f = \int_X \sum_{j<J_R} l_j(k, \varepsilon, h) d\mu_j(k, \varepsilon, h)$

   (c) $K_f = \int_X \sum_{j\in J} k d\mu_j(k, \varepsilon, h)$

4. The government budget constraint holds:

$$\int_X \left[\tau_\ell w \sum_{j<J_R} \eta_{jh} \varepsilon \ell_j(k, \varepsilon, h) + \tau_c \sum_{j\in J} c_j(k, \varepsilon, h)\right] d\mu_j(k, \varepsilon, h) = s \int_X \sum_{j\geq J_R} d\mu_j(k, \varepsilon, h)$$

5. For any subset $(\mathcal{K}, \mathcal{E}, \mathcal{H}) \in \mathcal{B}$, the invariant measure μ_j satisfies, for $j > 1$,

$$\begin{aligned} \mu_j(\mathcal{K}, \mathcal{E}, \mathcal{H}) = & \int_X \psi_{j-1} \mathbb{1}_{\left\{k'_{j-1}(k,\varepsilon,h)\in\mathcal{K}\right\}} \sum_{\varepsilon'\in\mathcal{E}} \sum_{h'\in\mathcal{H}} \Gamma_{\varepsilon\varepsilon'} \Pi_{hh'} d\mu_{j-1}(k, \varepsilon, h) \\ & + \int_X (1-\psi_j) \mathbb{1}_{\left\{k'_j(k,\varepsilon,h)\in\mathcal{K}\right\}} \sum_{\varepsilon'\in\mathcal{E}} \sum_{h'\in\mathcal{H}} \Gamma_{\varepsilon\varepsilon'} \Pi_{hh'} d\mu_j(k, \varepsilon, h) \end{aligned} \tag{13}$$

   and

$$\mu_1(\mathcal{K}, \mathcal{E}, \mathcal{H}) = \int_X (1-\psi_1) \mathbb{1}_{\left\{k'_1(k,\varepsilon,h)\in\mathcal{K}\right\}} \sum_{\varepsilon'\in\mathcal{E}} \sum_{h'\in\mathcal{H}} \Gamma_{\varepsilon\varepsilon'} \Pi_{hh'} d\mu_1(k, \varepsilon, h) + \omega(\mathcal{K}, \mathcal{E}, \mathcal{H}) \tag{14}$$

6. The newborn distribution satisfies:

$$\int_X k d\omega(k,\varepsilon,h) = \int_X \psi_{\bar{J}} k'_{\bar{J}}(k,\varepsilon,h) d\mu_{\bar{J}}(k,\varepsilon,h) \tag{15}$$

3 Calibration

In this section, I begin by calibrating some of the model's parameters to the pre-pandemic steady state and discuss how other parameters are set. I will then use the calibrated model to analyze the distributional effects of the pandemic and mitigation policies. The parameters are summarized in Tables 1 and 2.

3.1 Economic parameters

A period in the model is two weeks. The aggregate measure of individuals in the steady state economy is normalized to one. The number of age cohorts, J, is set to 3, so that $j = 1$ corresponds to ages 25–44 (young), $j = 2$ corresponds to ages 45–64 (middle), and $j = J_R = \bar{J} = 3$ corresponds to ages 65–84 (old). The aging probability $\psi_j = \psi$ is set so that agents spend, on average, 20 years in each age cohort. The wealth of deceased individuals are rebated to a fraction of newborn individuals each period. Specifically, 85 percent of individuals are born with zero wealth, whereas 15 percent of individuals are endowed with 28 times annual per capita consumption.[7]

The age-profile of efficiency units, η_{jS}, is normalized to one for healthy young workers and healthy middle-age workers are assumed to be 35 percent more efficient, to match the wage ratio in the data (2014, *Panel Survey of Income Dynamics*). I assume that the efficiencies of recovered individuals are the same as that of susceptible individuals, $\eta_{jR} = \eta_{jS}$.[8] The fraction of labor that can be done from home, $\bar{\theta}_j(\varepsilon)$ is set to match the average share of jobs that can be done from home by occupations grouped into five wage bins, computed based on Dingel and Neiman (2020). The average share of jobs that can be done from home ranges

[7]This is based on the fact that 85 percent of households whose heads are between the ages of 21 and 25 had a cumulative net worth of zero in 2016 (*Survey of Consumer Finances*). The calibrated value of the endowment is rather large. One way to address this issue would be to increase the number of age cohorts so that retired individuals draw down more wealth before dying.

[8]It is too early to conclude about the potentially long-lasting consequences of COVID-19. That said, these assumptions can easily be modified if evidence dictates.

from 0.03 for the occupations in the bottom 20 percent of the wage distribution to 0.66 for those in the top 20 percent.

The time discount factor β is chosen so that the model replicates the US net-worth-to-GDP ratio (2014, *US Financial Accounts*). The parameter that governs the disutility from labor, φ, is set so that the model generates a share of disposable time spent working of 0.3, equivalent to 30 hours per week. I set risk aversion, σ, to be 2 and the Frisch elasticity, $1/\nu$, to be 0.5 (for example, see Chetty et al. (2011), which are both standard values in the literature.

To set the flow value of life, I follow Glover et al. (2020) and Greenstone and Nigam (2020) who use a value of statistical life (VSL) of \$11.5 million, which corresponds to 7,475 times biweekly consumption per capita in the United States.[9] For simplicity, I assume that the VSL is computed based on the consumption of a healthy infinitely-lived representative agent that discounts time at the rate of $\beta(1-\psi)$ in the pre-pandemic steady state, whose present discounted utility is given by

$$v = \frac{(\bar{c}+\Delta_c)^{1-\sigma}}{1-\sigma} + \bar{u} + \frac{\beta(1-\psi+\Delta_\psi)}{1-\beta(1-\psi)}\left(\frac{\bar{c}^{1-\sigma}}{1-\sigma}+\bar{u}\right) \tag{16}$$

where $\bar{c}$ denotes steady state consumption per capita and Δ_c and Δ_ψ denote small one-time deviations to consumption and survival probability. Then, the VSL—defined as the marginal rate of substitution between survival and consumption—can be expressed as

$$VSL = \left.\frac{\frac{\partial v}{\partial \Delta_\psi}}{\frac{\partial v}{\partial \Delta_c}}\right|_{\Delta_c=0} = \frac{\beta}{1-\beta(1-\psi)}\frac{\frac{\bar{c}^{1-\sigma}}{1-\sigma}+\bar{u}}{\bar{c}^{-\sigma}}. \tag{17}$$

Then, by substituting $VSL = 7475 \times \bar{c}$, we obtain

$$\bar{u} = 7475 \times \bar{c}^{1-\sigma}\frac{1-\beta(1-\psi)}{\beta} - \frac{\bar{c}^{1-\sigma}}{1-\sigma}. \tag{18}$$

The capital elasticity in the production function, α, is set to match the aggregate capital income share of 0.36. The consumption tax τ_c is set to zero, while the income tax τ_ℓ and retirement income s are chosen so that retirement income is 30 percent of average labor

[9] To arrive at \$11.5 million, Greenstone and Nigam (2020) use the \$9.9 million in 2011 dollars used in U.S. Environmental Protection Agency (2015), and adjust for inflation. As a robustness check, I use a lower VSL recommended in U.S. Environmental Protection Agency (2020), which is 7.4 million 2006 dollars, or 6,208 times biweekly consumption per capita in 2006. The main results of the paper are robust to this lower value.

Table 1: Calibration of economic parameters

Parameters	Values	Targets / Source
Discount factor, annualized, β	0.97	Wealth-to-GDP: 4.81 (2014)
Risk aversion, σ	2	Standard value
Disutility from labor, φ	114	Average hours: 30 hours per week
Frisch elasticity, $1/\nu$	0.50	Standard value
Flow value of life, $\bar{u}$	9.51	Value of statistical life: \$11.5 million
Aging probability, annualized, ψ	0.05	Expected duration: 20 years
Efficiency units, $\eta_{jS} = \eta_{jR}$	$\{1, 1.35\}_{j=1,2}$	Wage ratio of age 45-64 workers to age 25-44 workers (PSID)
Factor elasticity, α	0.36	Capital share
Capital depreciation, annualized, δ	0.05	Standard value
Retirement income, s	1.00	30% of average earnings per worker
Labor income tax, τ_ℓ	0.15	Government budget constraint
Consumption tax, τ_c	0.00	
Persistence, annual, ρ_ε	0.94	Author estimates (PSID)
Standard deviation, annual, σ_υ	0.19	Author estimates (PSID)

earnings in the model and the government budget constraint is satisfied. The depreciation rate of capital, δ, is set at an annualized rate of 5 percent per year.

The labor efficiency shocks ε are assumed to follow an order-one autoregressive process as follows:

$$\log \varepsilon_t = \rho_\varepsilon \log \varepsilon_{t-1} + \upsilon_t,\ \upsilon_t \sim N\left(0, \sigma_\upsilon^2\right). \tag{19}$$

This process is estimated using annual wages constructed from the PSID to find a persistence of $\rho_\varepsilon = 0.94$ and a standard deviation of $\sigma_\upsilon = 0.19$.[10] These parameters are then converted to a higher frequency, following Krueger et al. (2016). The process is approximated with a seven-state Markov process using the Rouwenhurst procedure described in Kopecky and Suen (2010).

[10] The wages are constructed similarly to Floden and Lindé (2001) and the sample selection and estimation procedures closely follow Krueger et al. (2016) and Carroll and Hur (2020). See Appendix A for details.

3.2 Parameters related to COVID-19

The exit rate, π_X is set to 14/18 so that the expected duration of the infection is 18 days, as in Atkeson (2020) and Eichenbaum et al. (2020). For the unconstrained case fatality rates, I use data from South Korea's Ministry of Health and Welfare to compute a fatality rate of 8.47 percent for ages 65–84, 0.94 percent for ages 45–64, and 0.09 percent for ages 25–44. I use South Korean data because testing has been abundant since the outbreak began[11], the peak in infections was early enough that case fatality rates are not biased due to lags in deaths, and hospitals were not overwhelmed, as the number of active cases never exceeded 0.015 percent of the population.[12]

Next, I discuss the hospital capacity constraints and how they affect death rates. Following Piguillem and Shi (2020), I use the functional form

$$\delta_j(\mu_I) = \delta_j^u \min\left\{1, \frac{\kappa}{\mu_I}\right\} + \delta_j^c \max\left\{0, 1 - \frac{\kappa}{\mu_I}\right\} \tag{20}$$

where δ_j^u and δ_j^c denote the unconstrained and untreated death rates and κ denotes the measure of infected individuals that can be treated without the constraint binding. According to the American Hospital Association, there are roughly 924,000 hospital beds in the US, corresponding to 0.28 percent of the population.[13] Since not all infected cases require hospitalization, I use a generous capacity constraint, κ, of 1 percent. The unconstrained death rates, δ_j^u, are set to match those documented for South Korea, and the untreated death rates are set as $\delta_j^c = 2\delta_j^u$, following Piguillem and Shi (2020).

There is quite a bit of uncertainty regarding the basic reproduction number (R_0), which corresponds to the number of people to whom the average infected person passes the disease absent mitigation efforts, though most estimates range between 2.2 and 3.1 (see for example, Wang et al. 2020 and Fauci et al. 2020). Using equation (11), total new infections in a given period is given by

$$T = \beta_c C_S C_I + \beta_\ell L_S^o L_I^o + \beta_e \mu_S \mu_I, \tag{21}$$

[11]For example, see https://www.bloomberg.com/news/articles/2020-04-18/seoul-s-full-cafes-apple-store-lines-show-mass-testing-success. Aum et al. (2020) also discuss the success of early testing and tracing efforts in South Korea.

[12]Active infection cases in South Korea peaked at 7,362 on March 11, 2020, according to Worldometer. See https://www.worldometers.info/coronavirus/country/south-korea/

[13]See https://www.aha.org/statistics/fast-facts-us-hospitals.

where C_h and L_h^o are the aggregate steady state consumption and outside labor of individuals with health status $h \in H$. In the pre-pandemic steady state, workers are indifferent between working outside or working from home. Thus, I assume that all steady state work is done outside, which can be obtained by introducing an arbitrarily small difference in either efficiency or preference in favor of working outside. If we assume that when the virus is first introduced into the model, we have that $L_S/\mu_S = L_I/\mu_I$ and $C_S/\mu_S = C_I/\mu_I$, then by taking $\mu_S \to 1$, the basic reproduction number is given by[14]

$$R_0 = \frac{\beta_c C_S^2 + \beta_\ell L_S^2 + \beta_e}{\pi_X}. \tag{22}$$

Thus given values for the basic reproduction number, R_0, the exit rate, π_X, the steady state values for aggregate consumption and labor, C_S and L_S, we need to assign values to the fractions of new infections occurring through consumption activities, work activities, and other channels to pin down the values for β_c, β_ℓ, and β_e. Evidence on how COVID-19 is transmitted is limited, but in the case of other infectious diseases, Ferguson et al. (2006) report that 70 percent of transmissions occur outside of the household. In another study that investigates the transmission channels of infectious diseases, Mossong et al. (2008) find that 35 percent of high-intensity contacts occur in workplaces and schools. Based on these studies, I assume that one-third of initial transmission occurs through consumption activities, one-third through labor activities, and one-third through other channels.

For the value of being infected, Glover et al. (2020) assume a 30 percent reduction in the flow value of life for an average infected agent with mild symptoms and a 100 percent reduction in the flow value of life for an average infected agent with severe symptoms. I take an intermediate value of 50 percent by setting $\hat{u}_I = -0.5(\bar{c}^{1-\sigma}/(1-\sigma) + \bar{u})$ and set $\hat{u}_S = \hat{u}_R = 0$.[15]

Next, I discuss how the efficiency units change when an individual gets infected. It is reasonable to expect that those with no symptoms would suffer little, if any, efficiency loss, whereas those that experience very severe symptoms would suffer something close to a 100 percent efficiency loss. Without sufficient evidence regarding how COVID-19 affects labor efficiency and the fraction of infected individuals suffering severe symptoms, I assume that

[14]These assumptions allow the calibration of these epidemiological parameters using steady state values. These may also be reasonable assumptions, given that the very first infected individuals may not change their behavior given the lack of testing and information regarding the pandemic in the early stages.

[15]The results are robust to a 30 percent reduction in the flow value of life, as shown in Appendix **??**

Table 2: Calibration of Epidemiological parameters

Parameters	Values	Targets / Source
Infection exit rate, π_X	0.78	Expected infection duration: 18 days
Unconstrained death rate,		Fatality rates in South Korea
$\delta_1^u \times 100$	0.09	
$\delta_2^u \times 100$	0.94	
$\delta_3^u \times 100$	8.47	
Untreated death rate, δ_j^c	$2\delta_j^u$	Piguillem and Shi (2020)
Hospital capacity, κ	0.01	See discussion above
Transmission parameters,		Basic reproduction number, $R_0 = 2.2$,
consumption-related, β_c	0.08	and initial transmission equally
labor-related, β_ℓ	14.20	likely through three channels
other, β_e	0.57	
Flow value of infection $\hat{u}_I$	–4.57	50 percent reduction in flow utility value of average agent
Efficiency units η_{jI}	$0.5\eta_{jS}$	See discussion above

infected individuals suffer a 50 percent loss in efficiency.[16]

4 Pandemic

This section uses the model to investigate the distributional consequences of the pandemic and various mitigation measures. First, I will explore how the endogenous transmission model—one in which economic interactions change the spread of the virus—differs from an exogenous transmission model—one in which the spread of the virus only depends on the number of susceptible and infected agents. This can also be thought of as the role of private mitigation. Second, I will explore the effect of various mitigation policies. In particular, I contrast a *lockdown*, implemented in the model by imposing a maximum outside labor supply of 10 hours per week for all agents, with a *subsidy-and-tax* policy that subsidizes working less than 10 hours per week, funded by a tax on consumption. While both policies reduce infections and deaths, the subsidy-and-tax policy delivers a higher welfare gain and

[16] Appendix **??** shows that the main results are robust to assuming a 30 percent loss in efficiency.

is favored by all agents in the economy, whereas the lockdown benefits older individuals at the expense of younger, low-wage workers.

The economy starts in the pre-pandemic steady state in period $t = 0$. Then, in period $t = 1$ (March 27, 2020), the virus is introduced into the model so that 0.75 percent of the population is infected.[17] This implies a total of I assume that a vaccine and cure is developed and fully implemented in $t = \hat{t}$ (March 27, 2022), after which the model transits back toward its original steady state.[18] An important caveat is that, while the steady state analysis was done in general equilibrium, the transition path analysis is done in partial equilibrium, meaning that efficiency wages and capital rental rates are fixed at their steady-state levels.[19] I also do not require the government budgets to be balanced nor do I change the measure of newborns and their wealth distribution throughout the transition. This implies that, as a result of the pandemic, the measure of agents in the economy may be less than 1 during the transition.

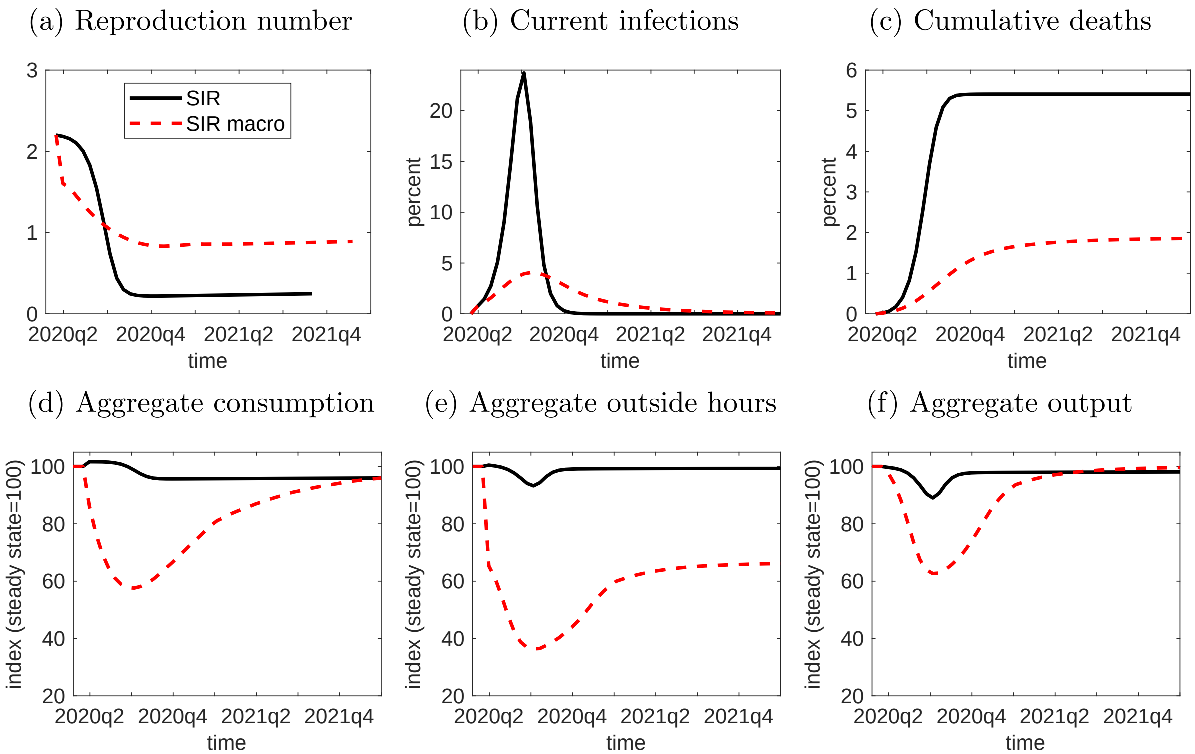
To solve the transition, the economy begins at the steady-state distribution, μ_j, at $t = 0$. Then, the virus is introduced in $t = 1$, and I solve for a sequence of value functions, $\{v_{jt}\}_{t=1}^{\infty}$, policy functions, $\{c_{jt}, \ell_{jt}, \ell^o_{jt}, k'_{jt}\}_{t=1}^{\infty}$, distributions μ_{jt}, fiscal policies, $\{\tau_{ct}, \tau_{\ell t}\}_{t=1}^{\infty}$, for $j \in J$, such that given prices and distributions, households make optimal decisions; given prices, firms optimize; and distributions are consistent with shocks, the invariant distribution of newborns, the law of motion for aggregate states, and household decisions.

[17] Due to the widely documented lack of testing, I use the number of deaths and the case fatality rates from South Korea to infer the number of infections. In the US, there were 17,982 COVID-19 related deaths during the 14-day period from March 27, 2020 to April 9, 2020, according to https://www.worldometers.info/coronavirus/country/us/. Using the unconditional case fatality rate of 0.94 percent implied by the data from South Korea and the average infection duration of 18 days, this implies 2.5 million infections in the US as of March 27, or 0.75 percent of the population.

[18] While there is a lot of uncertainty regarding when a vaccine might be approved and distributed, this approach allows the computational burden to be reduced dramatically. An alternative approach would be to model the arrival of a vaccine and cure probabilistically.

[19] In conjunction with the assumption of a deterministic arrival of a vaccine and cure at $t = \hat{t}$, the partial equilibrium assumption implies that I do not need to solve for value and policy functions for $t \geq \hat{t}$, since even though the capital stock and distribution of agents evolves over a very long transition path, the prices and disease dyanmics that are relevant for the household problem are constant for $t \geq \hat{t}$.

Figure 1: Engodenous vs. exogenous transmission (no mitigation)



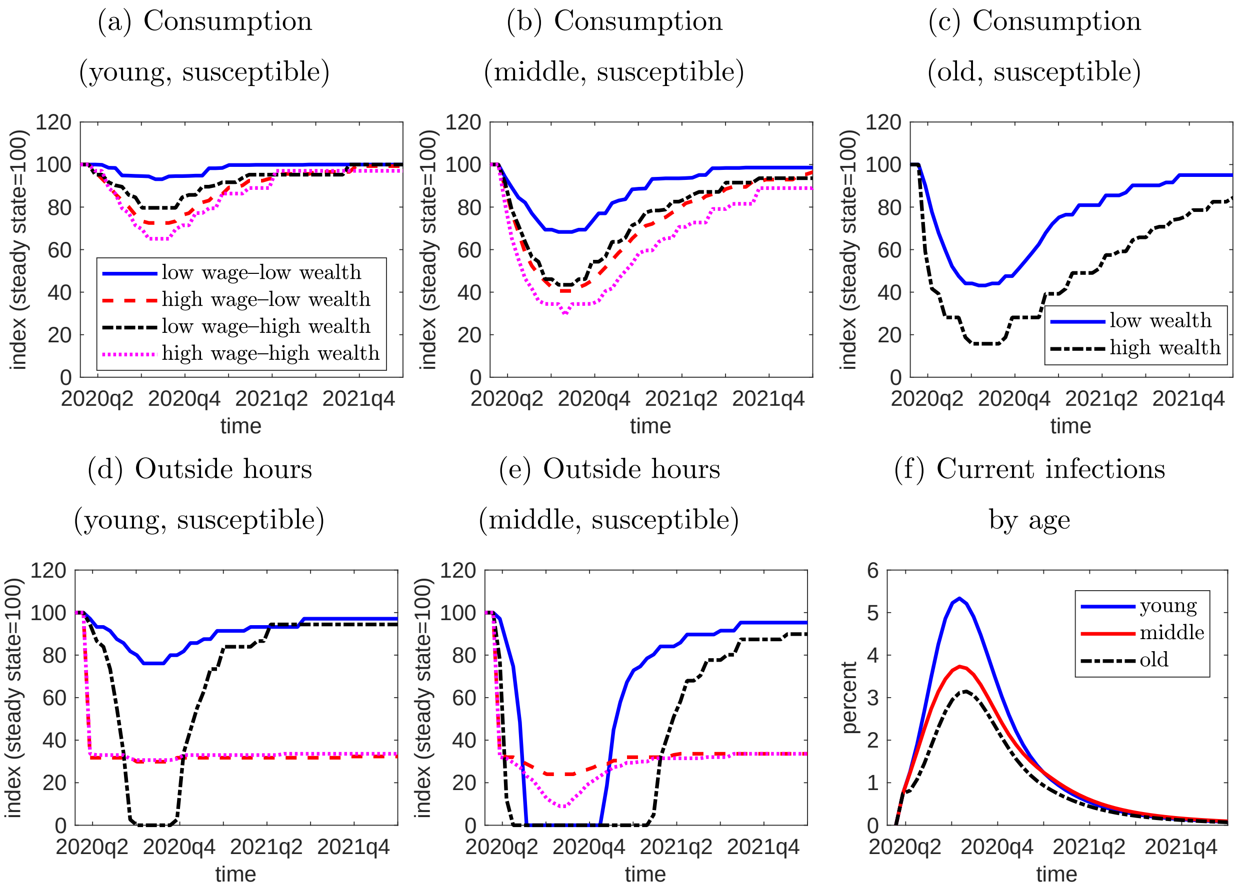
4.1 Endogenous virus transmission

To better understand how the baseline model—the "SIR Macro" model with endogenous transmission—works, I contrast it with the alternative "SIR" model with exogenous transmission, where $\beta_c = \beta_\ell = 0$. In the SIR model, we set $\beta_e = 1.71$ so that the model has the same basic reproduction number, $R_0 = 2.2$, as in the baseline SIR Macro model.

Figure 1 shows that even though the SIR Macro and SIR models begin with the same reproduction number (panel a), the SIR Macro model exhibits a quicker decline in the reproduction number and consequently a lower number of infections (panel b) and deaths (panel c). This is because, in response to the pandemic, agents in the SIR Macro model reduce their consumption and outside hours dramatically, leading to a large decline in output, as can be seen in panels (d)–(f).

Taking a closer look at the baseline model, consider the policy functions for consumption and outside labor of susceptible agents across the age, income, and wealth distribution (Figure 2). The decline in hours and consumption is broad based. However, the decline in consumption is much greater for middle-aged and old agents than for young agents (panels

Figure 2: Response to pandemic (no mitigation)



Notes: Low income and high income correspond to 10th and 90th percentiles of the steady state wage distribution, respectively. Low wealth and high wealth correspond to the 25th and 75th percentiles of the steady state wealth distribution, respectively.

a–c), and the declines in outside hours are much larger and more sustained for middle-aged workers than for young workers (panels d–e). This reflects the lower fatality risk for young agents. Moreover, among young workers, the declines in consumption and outside hours are the smallest for low-wage, low-wealth workers. Low-wage, high-wealth workers sit out the labor market altogether during the infection peak, suggesting that the lack of precautionary savings to draw from prevents low-wealth individuals from reducing their labor supply by more. Overall, young workers experience a much larger increase in infections, as shown in panel (f).

4.2 Mitigation policies

The previous subsection highlighted the externalities at work: Young workers do not reduce their consumption and labor as much as their older counterparts and incur higher infections. These responses are individually rational in the sense that young workers do not face high fatality risk. However, higher rates of infection among young agents also lead to higher infections among older individuals, who face higher fatality rates.

In this subsection, I compare and contrast two different mitigation policies that reduce infection and death rates. The first is a *lockdown*, implemented in the model by restricting outside labor supply to less than $\bar{\ell}^o = 0.1$, equivalent to 10 hours per week, beginning $t = 1$ (March 27, 2020), with a phase-out after $t = \bar{t}$ (July 31, 2020). Specifically, the outside hours cap follows

$$\bar{\ell}^o_t = \begin{cases} \bar{\ell}^o & \text{if } t < \bar{t} \\ \bar{\ell}^o \left(\frac{\hat{t} - t}{\hat{t} - \bar{t}}\right)^2 + 1 - \left(\frac{\hat{t} - t}{\hat{t} - \bar{t}}\right)^2 & \text{if } \bar{t} \leq t \leq \hat{t} \\ 1 & \text{otherwise} \end{cases}$$

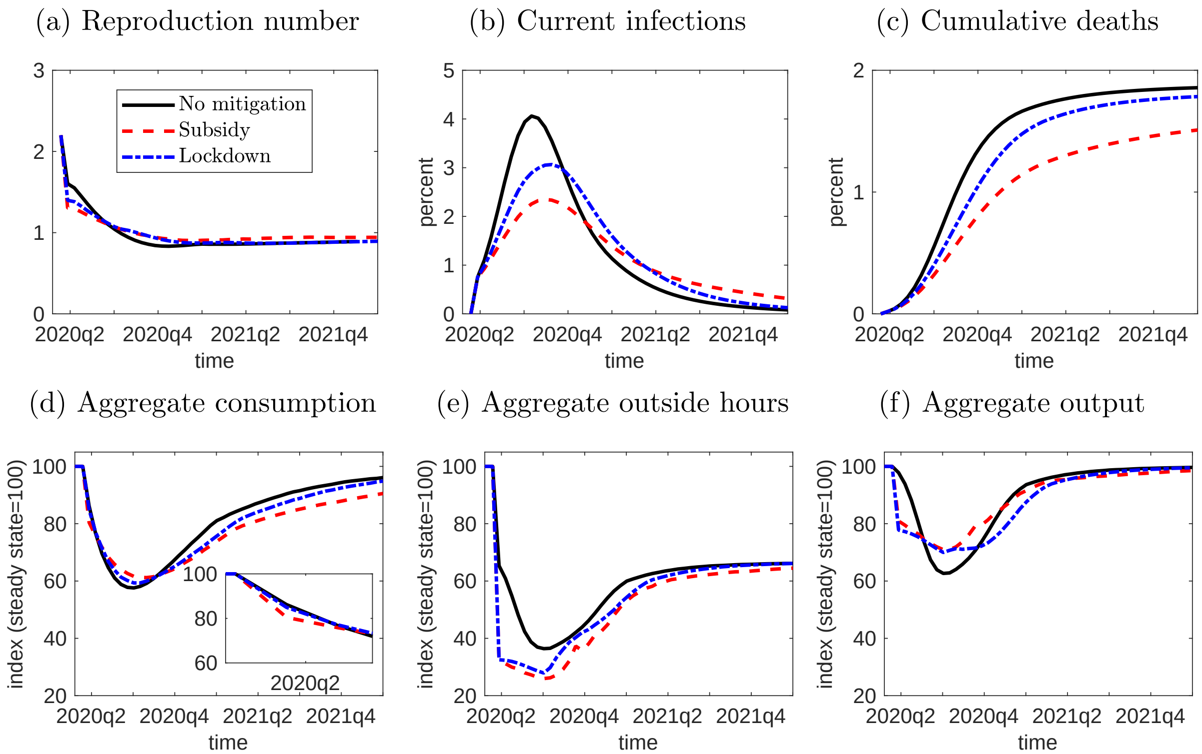
where $t = \hat{t}$ (March 27, 2022) is the date at which a vaccine and cure is developed and fully implemented. In equilibrium, the cap is no longer binding for any individual after October 9, 2020.

The second is a *subsidy-and-tax* policy, which incentivizes reduced work by providing a subsidy amount of $x = \$600$ per week for any working-age individual working less than $\bar{l} = 0.1$, equivalent to 10 hours per week.[20] The subsidy begins at $t = 1$ (March 27, 2020), with a gradual reduction after $t = \bar{t}$ (July 31, 2020). The time-varying subsidy amount follows

$$x_t = \begin{cases} x & \text{if } t < \bar{t} \\ x \left(\frac{\hat{t} - t}{\hat{t} - \bar{t}}\right)^2 & \text{if } \bar{t} \leq t \leq \hat{t} \\ 0 & \text{otherwise} \end{cases}$$

[20]Here, I assume that, for administrative purposes, the criteria to qualify for the subsidy is for total hours worked as it may be difficult for the administrator to ascertain what fraction of hours were outside versus at home. This is in contrast to the lockdown policy, where I assume that the hours cap is for outside labor. The idea is that the lockdown is administered at the firm-level whereas the subsidy is administered at the individual-level.

Figure 3: Disease transmission (with and without mitigation)



The subsidy declines to \$300 by January 15, 2021, and to zero by $t = \hat{t}$ (March 27, 2022). The subsidy is funded by a 18 percent consumption tax, beginning at $t = 1$ (March 27, 2020), with a gradual phase-out after $t = \bar{t}$ (July 31, 2020), following a similar path to the subsidy amount. The tax and subsidy do not clear period-by-period, but rather they clear in net present value. Thus, both mitigation policies are budget neutral from the government's perspective.

Figure 3 panels (a)–(c) plot the evolution of the disease under the laissez-faire scenario as well as the two mitigation scenarios. Relative to the case with no mitigation, both mitigation policies reduce the reproduction number faster, leading to a lower peak in infection rates and less deaths. However, the subsidy-and-tax policy is more effective in reducing the number of deaths than the lockdown policy. This is because, as shown in panels (d)–(e), the subsidy-and-tax policy generates a sharper initial decline in consumption and a more sustained decline in outside hours. Finally, as can be seen in panel (f), both mitigation policies induce a sharp reduction in output initially but avoid the larger reductions in output that occur during the peak in infections in the no-mitigation scenario.

Figure 4 panels (a)–(c) and (d)–(e) show the policy functions for consumption and outside hours, respectively, for susceptible individuals under the subsidy-and-tax policy.[21] Relative to the case with no mitigation, the reduction in consumption and outside hours is more broad-based, including declines in consumption and hours for young low-wage, low-wealth workers. As a result, the peak infection rate for young agents declines from 5.3 percent to 2.7 percent (panel f). Notice that, relative to the case with no mitigation, the decline in outside hours for young low-wage, low-wealth workers is entirely due to the subsidy, whereas the decline in outside hours for young high-wage workers is hardly unchanged, and if anything, a little bit smaller due to the lower infection risk under the subsidy-and-tax policy. Furthermore, the decline in outside hours for high-wage workers reflects a shift to larger share of work being done at home, and does not qualify them for the subsidy.

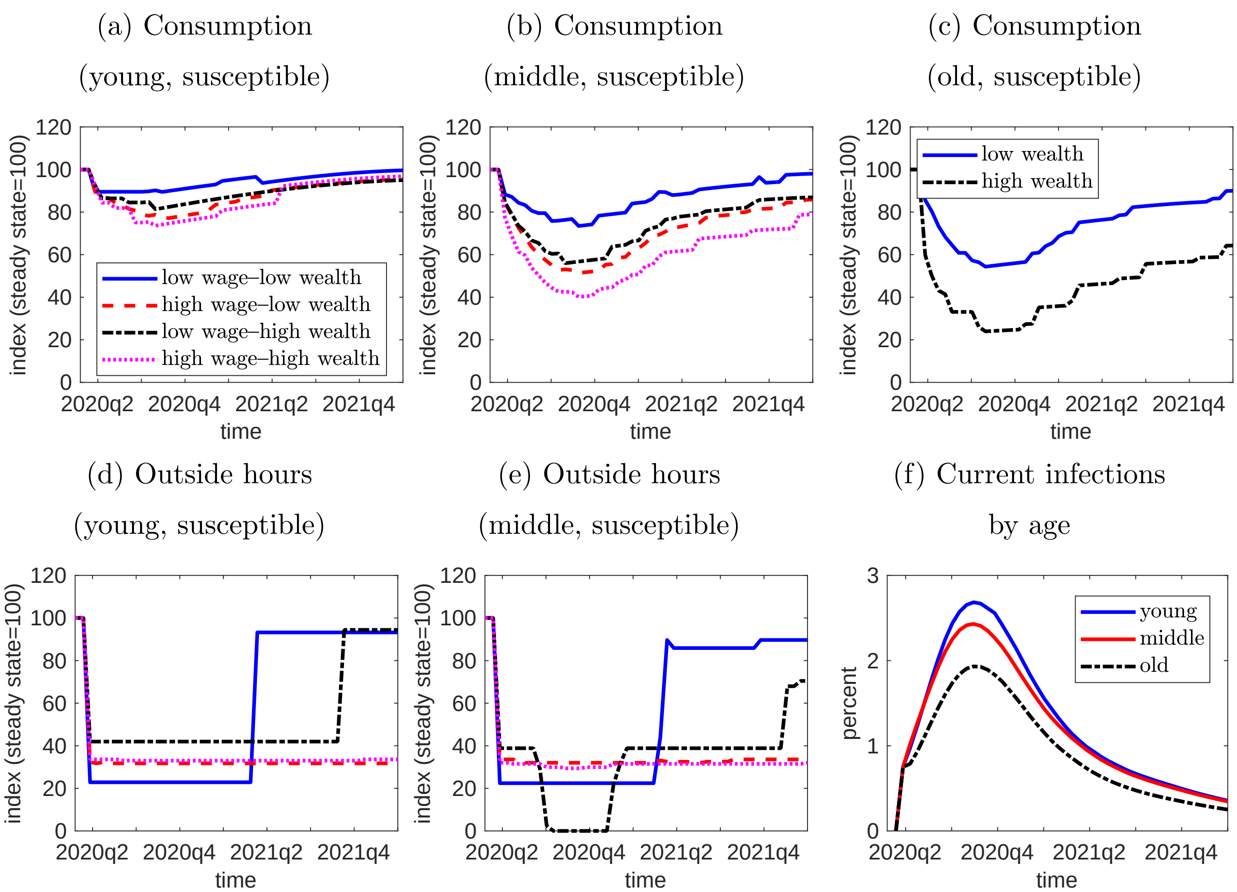
Qualitatively, the lockdown policy has similar properties as the subsidy-and-tax policy in the sense that they both reduce consumption and outside labor, infection, and death rates. However, in terms of welfare, measured in consumption equivalents, the lockdown policy is vastly inferior.[22] The subsidy-and-tax policy reduces the average welfare loss from the pandemic by 2.4 percentage points, whereas the lockdown policy reduces the average welfare loss by only 0.2 percentage points, as can be seen in Table 3. This is because the lockdown policy is mainly favored by older agents who most value the lower risk of death induced by the policy and is opposed by younger low-wage, low-wealth workers for whom the lockdown policy is most binding. Overall, the lockdown policy is favored by only 73.6 percent of the initial population. In contrast, the subsidy-and-tax policy is favored by all agents in the economy, making it a Pareto improvement relative to no mitigation.

The lockdown and subsidy-and-tax policies are meant to resemble, in part, the state-level stay-at-home orders and the Federal Pandemic Unemployment Compensation (FPUC) under the Coronavirus Aid, Relief, and Economic Security (CARES) act, which provided an additional $600 per week for unemployed individuals. However, there are some notable differences. First, while the timing of the subsidy-and-tax plan is fairly consistent with the FPUC, which became effective March 27, 2020 and expired July 31, 2020, it is less so for the lockdown. The stay-at-home orders began in most states between March 23rd and

[21] The analogous figure for the lockdown can be found in Appendix B.

[22] Specifically, the consumption equivalent is defined as what percentage change of remaining lifetime consumption in the steady state would make the individual indifferent to the pandemic and, if applicable, mitigation policies.

Figure 4: Response to pandemic (subsidy-and-tax)



Notes: Low wage and high wage correspond to 10th and 90th percentiles of the steady state wage distribution, respectively. Low wealth and high wealth correspond to the 25th and 75th percentiles of the steady state wealth distribution, respectively.

Table 3: Welfare consequences of pandemic and mitigation policies

	consumption equivalents (percent)					policy	2-year	
wealth	low		high		average	support	output	deaths
wage	low	high	low	high		(percent)	(index)	(percent)
no mitigation					–19.6		90.2	1.9
young	–2.6	–3.6	–3.8	–4.7				
middle	–11.4	–14.7	–15.2	–20.4				
old	–30.3		–46.0					
stay-at-home subsidy					–17.2	100.0	89.8	1.5
young	–2.2	–3.5	–3.2	–4.4				
middle	–9.1	–12.5	–13.0	–18.0				
old	–26.3		-41.5					
stay-at-home order					–19.4	73.6	88.6	1.8
young	–4.3	–3.7	–3.8	–4.6				
middle	–11.8	–14.5	–15.0	–20.1				
old	–29.3		–45.0					

Notes: Low and high wage correspond to below and above the median wage, respectively. Low and high wealth corresponds to below and above the median wealth, respectively. Blue and red colors denote groups with welfare gains and losses from the mitigation policies, respectively. Policy support refers to the percent of the initial population that benefits from the mitigation policy. Output refers to output from $t = 1$ (March 27, 2020) to $t = 52$ (March 24, 2022), compared to the analogous 52-period output in the steady state, indexed at 100.

April 1st, but the duration and intensity vary substantially across states and many began the reopening process in early May.[23] Second, while the FPUC subsidy requires involuntary unemployment or underemployment, the subsidy studied in this model is based on voluntary reductions in hours worked. Third, the stay-at-home orders affected workers differently based on whether or not their place of work was essential such as grocery stores or social-intensive such as restaurants and bars. By abstracting from sectors and occupations, the model cannot speak directly to these differences; however, to the extent that social-intensive occupations tend to have lower wages as documented by Kaplan et al. (2020), the model indirectly captures these differences since the lockdown disproportionately affects lower-wage individuals. Finally, the model subsidy is funded by a consumption tax, whereas the FPUC subsidy is debt-financed. I chose the consumption tax for two reasons. First, it increases the incentive to reduce consumption, another way in which the virus transmits. Second, in contrast to debt-financing, which typically imposes a disproportionately larger burden on young individuals, the burden of the consumption tax is more widely shared. To the extent that older individuals stand to gain the most from the mitigation policies, this is a desirable feature.

At the time of writing, Congress is yet to agree on an appropriate extension of the CARES act, which expired on July 31, 2020. While the policies studied in this subsection were designed to resemble some of the policies that were previously implemented, I now discuss the properties of optimal mitigation policies in the next section.

5 Optimal mitigation policies

I investigate the properties of optimal mitigation policies over a limited set of policy instruments. In particular, I solve for many transition paths for various policy parameters, in which the weekly subsidy amount, x, varies from \$0 to \$1800, the duration varies from 2 months to 2 years, and the hours threshold to qualify for the subsidy, $\bar{\ell}$, varies from 0 to 10 weekly hours, with and without a lockdown. In all cases with a positive subsidy, I solve for a consumption tax that clears the government budget constraint in present value, making all configurations budget-neutral. All other parameters are kept the same as in the previous subsection.

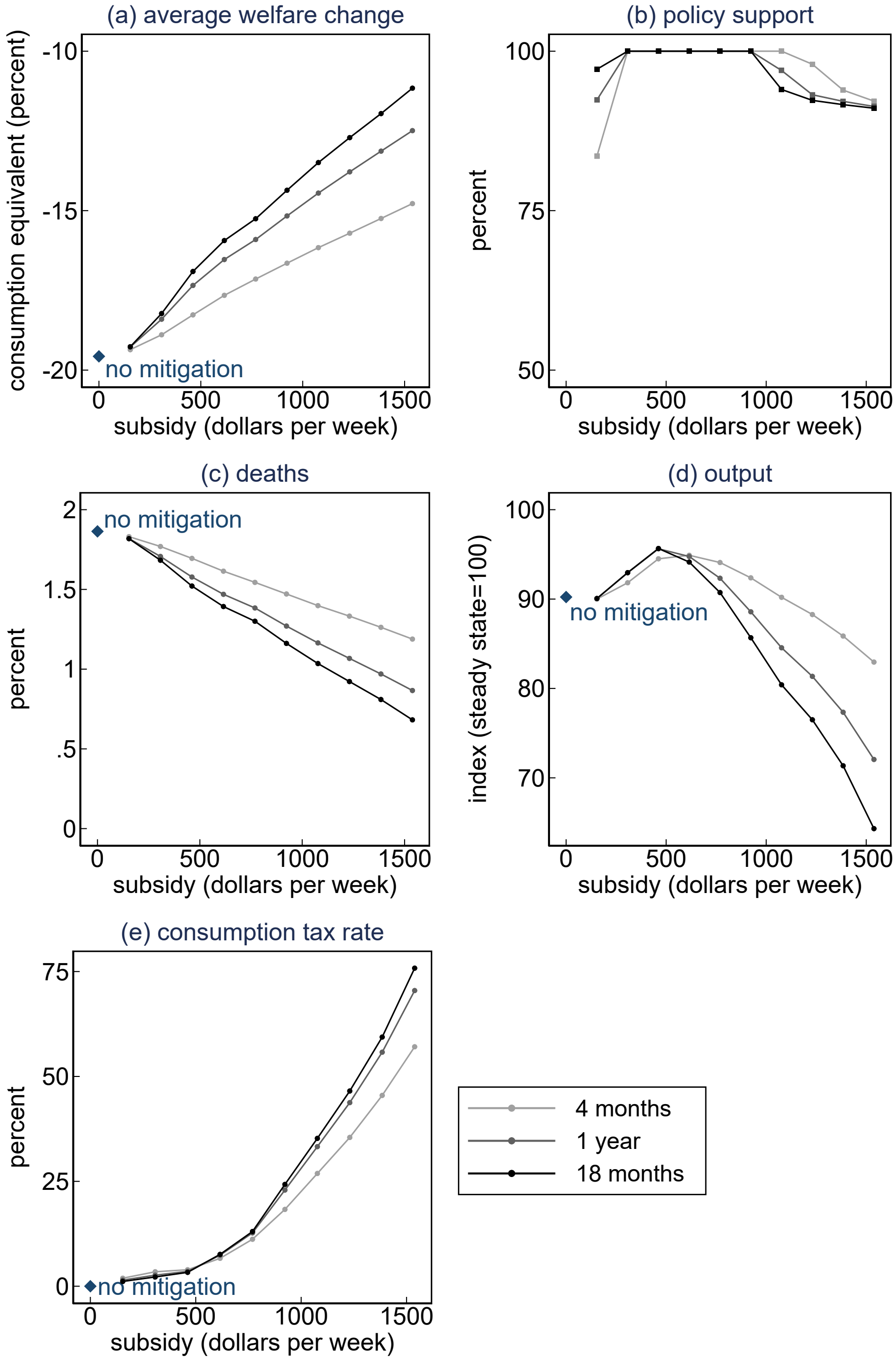
[23] See Moreland (2020) for an analysis of stay-at-home orders across states.

Figure 5 plots the effects of varying subsidy amounts and duration, where the hours threshold, $\bar{\ell}$, is fixed at 0 and no lockdown. Panel (a) shows that average welfare is increasing in both the subsidy amount and duration, and panel (b) shows that for moderate subsidy amounts, support for the mitigation policy is unanimous. Falling support for the policy is due to the higher consumption tax rate associated with larger subsidy amounts and longer durations (panel e). Panel (c) demonstrates that deaths are decreasing in both the subsidy amount and duration. Interestingly, the effects of the subsidy amount on output are nonmonotonic (panel d). In particular, for moderate subsidy amounts, the mitigation policy actually increases output relative to the case with no mitigation. This is due to two opposing effects. On the one hand, larger subsidies induce increasingly productive workers to reduce their hours, reducing aggregate productivity and output. This is the *selection* effect. On the other hand, larger subsidies induce lower economic activities, causing a decline in the severity of the infection peak. This reduces the fatality risk, and thus makes it safer to engage in more economic activities. This is the *public health* effect. At moderate subsidy amounts, the public health effects dominate the selection effect, leading to an increase in output relative to the no-mitigation scenario.

Next, I investigate the effects of changing the hours threshold that determines the eligibility for receiving a subsidy and the effects of implementing a lockdown, where the subsidy amount and duration are fixed at \$900 and 18 months, respectively (Figure 6). Panel (a) shows that average welfare is slightly higher with a lockdown and is relatively unchanged with respect to the hours threshold. Lockdowns and positive hours thresholds, however, are not supported unanimously, as can be seen in panel (b). This is because lockdowns and positive hours thresholds increase the consumption tax rate (panel e) and reduce output (panel d), while only slightly reducing deaths (panel c). Lockdowns reduce output because they induce a large selection effect: they reduce the labor supply of medium-to-high wage workers by more than the low wage workers who have already reduced their labor supply to qualify for the subsidy. Larger hours thresholds also reduce output through a negative selection effect: they increase the labor supply of low-wage workers but reduce the labor supply of increasingly more productive workers. The net effect on outside hours worked is ambiguous, leading to very little changes in deaths.

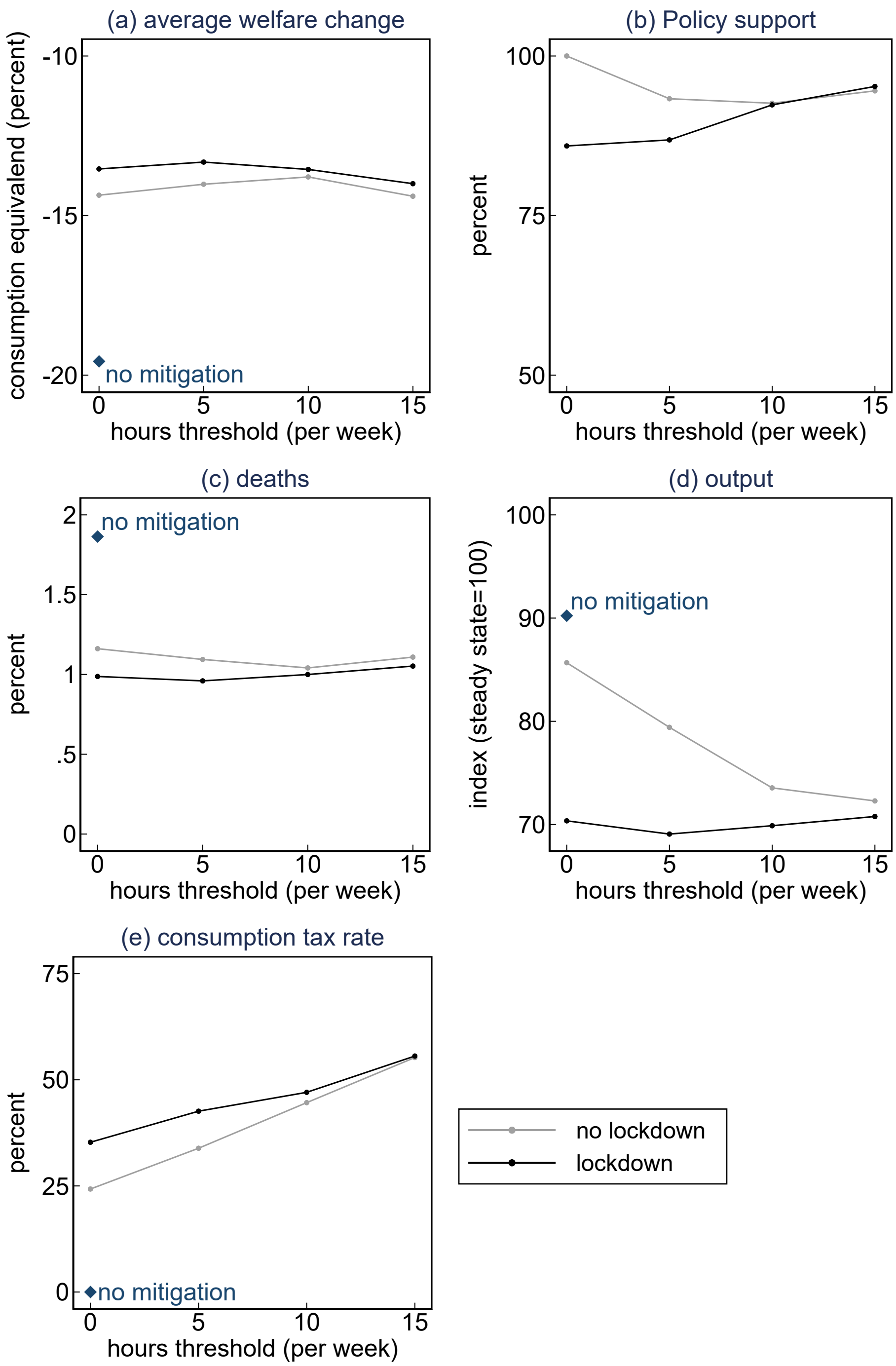
Mitigation policies have often been portrayed in the context of a tradeoff between output and health. Figure 7 provides a scatter plot of the two-year output and COVID-19 related

Figure 5: Effects of subsidy amount and duration



Notes: The graphs show the effects of varying subsidy amounts and duration, with the hours threshold, $\bar{\ell}$, equal to 0 and no lockdown. Average welfare change reports the population-weighted average of individual consumption equivalents. Policy support refers to the percent of the initial population that gains from the mitigation policy. Output refers to output from $t = 1$ (March 27, 2020) to $t = 52$ (March 24, 2022), compared to the analogous 52-period output in the steady state, indexed at 100.

Figure 6: Effects of hours threshold and lockdown



Notes: The graphs show the effects of varying hours thresholds with and without lockdown, where the subsidy amount and duration is fixed at \$900 and 18 months, respectively. Average welfare change reports the population-weighted average of individual consumption equivalents. Policy support refers to the percent of the initial population that gains from the mitigation policy. Output refers to output from $t = 1$ (March 27, 2020) to $t = 52$ (March 24, 2022), compared to the analogous 52-period output in the steady state, indexed at 100.

Table 4: Policy configurations

	subsidy amount ($/week)	duration (months)	threshold (hours /week)	lock-down	average welfare change (percent)	2-year output (index)	deaths (percent)
constrained optimum*	900	18	0	no	–14.4	85.7	1.2
output maximizing*	450	16	0	no	–17.0	95.7	1.5
US policy	600	4	10	yes	–17.2	87.9	1.5
no mitigation	0	0	none	no	–19.6	90.2	1.9

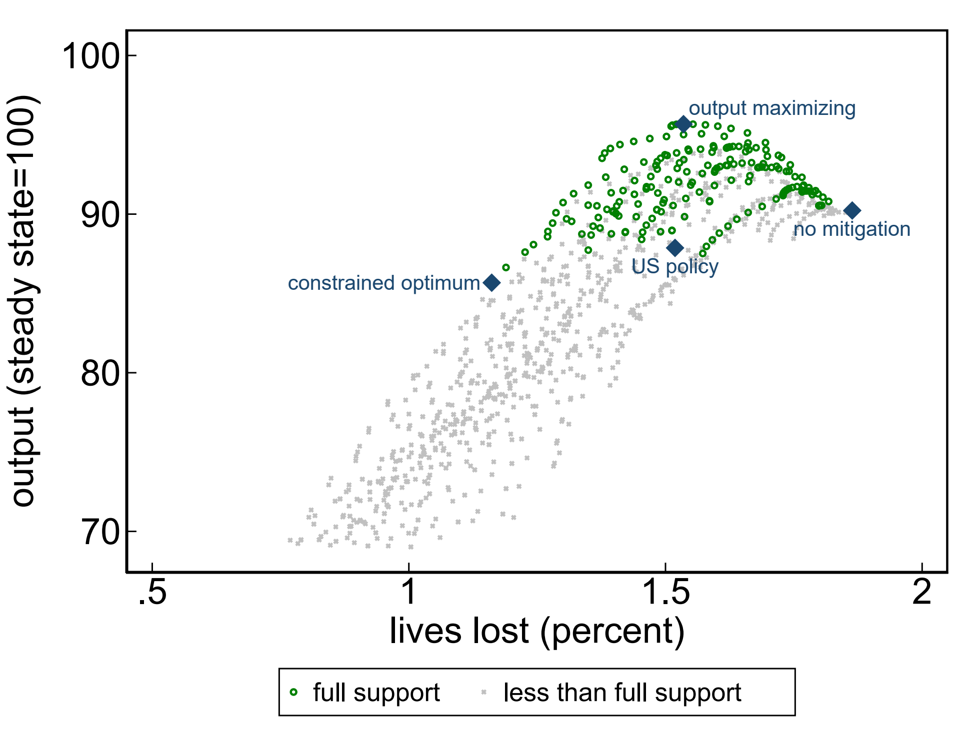
Notes: Average welfare change reports the population-weighted average of individual consumption equivalents. Output refers to output from $t = 1$ (March 27, 2020) to $t = 52$ (March 24, 2022), compared to the analogous 52-period output in the steady state, indexed at 100. * denotes Pareto improvements relative to the no mitigation case.

deaths for all of the policy parameter configurations. We can see that for large reductions in deaths, it is indeed the case that there is a tradeoff between output and saving lives. However, we can also see that there are plenty of policy configurations that simultaneously increase output and save more lives relative to the no mitigation case. As reference points, I include the constrained optimum, which maximizes welfare conditional on full support, the output maximizing configuration, and the configuration which most closely resembles US policy. The policy parameters of each configuration is summarized in Table 4. Relative to the configuration that most resembles current US policy, figure 7 shows that extending the duration of the subsidy (from 4 to 18 months) and increasing the subsidy amount (from $600 to $900 per week) can lead to a substantially larger reduction in deaths without significantly changing the level of output. Similarly, extending the duration of the subsidy (from 4 to 16 months) and decreasing the subsidy amount (from $600 to $450 per week) can substantially increase output without a large change in deaths. Neither policy features a lockdown or a positive hours threshold.

5.1 Robustness

In this subsection, I explore the robustness of the results to alternative parameter and modeling choices. I find that although the level of average welfare, deaths, and output can vary substantially, the main policy implications are extremely robust. Under all alternative

Figure 7: Output and lives



Notes: Output refers to output from $t = 1$ (March 27, 2020) to $t = 52$ (March 24, 2022), compared to the analogous 52-period output in the steady state.

configurations, the constrained optimal policies involve weakly larger subsidies and longer durations than US policy and the output maximizing policies involve weakly smaller subsidies and longer durations than US policy. Furthermore, the result that both constrained optimal and output maximizing policies involve no lockdown and a zero hour threshold is robust to most alternative configurations. The policy parameters of the constrained optimal and output maximizing policies under alternative parameter values and modeling choices are summarized in Tables 5–6.

Lower value of statiscal life. In the baseline calibration, I use a VSL of \$11.5 million, which corresponds to 7,475 biweekly consumption per capita. As a robustness check, I use an alternative VSL recommended by the U.S. Environmental Protection Agency (2020), which is 7.4 million 2006 dollars, or 6,208 times biweekly consumption per capita in 2006. By comparing the no mitigation results in Tables 4 and 5, I find that assigning a lower value of statistical life leads to slightly higher deaths and output and a smaller welfare loss. The main policy implications, however, remain the same: the constrained optimal policy involves a larger and longer duration subsidy than US policy and the output maximizing policy also involves a slightly lower but long duration subsidy than US policy. Both configurations feature no lockdowns and a zero hour threshold for qualifying for the subsidy.

Smaller utility loss during infection. I also consider a 30 percent reduction in the flow value of life during infection and compare the results to the 50 percent reduction studied in the baseline. The no mitigation scenarios are nearly identical and the main policy implications are also unchanged. I conclude that the utility loss is not a main driver of the economic or epidemiological dynamics.

Smaller efficiency loss during infection. Next, I consider a 30 percent reduction labor efficiency during infection, compared to the baseline calibration of a 50 percent reduction. Interestingly, comparing the no mitigation scenarios under a 30 percent versus a 50 percent efficiency reduction during infection reveal that welfare and output is actually lower under the 30 percent reduction. This is because the smaller efficiency loss for infected individuals induce these individuals to work more, increasing the infection risk of susceptible agents, leading to a decline in hours worked among susceptible agents. The main policy implications are also unchanged, except that the output maximizing policy involves the same size subsidy as US policy but for a longer duration.

Larger hospital capacity. I also investigate the implications of a larger hospital capacity of 1.5 percent. As expected, this leads to less deaths and a smaller welfare loss under the no mitigation scenario, compared to the baseline calibration. Nevertheless, the policy prescriptions remain nearly identical.

Earlier vaccine. In the baseline calibration, I assume that a vaccine and cure is developed and implemented two years after the introduction of the virus. As can be seen in the fifth panel of Table 5, assuming an earlier arrival of a vaccine and cure arrives leads to a lower deaths and a smaller welfare loss. The main policy prescriptions are robust to this alternative assumption. However, we can see that the constrained optimal response is much stronger, prescribing a much larger subsidy ($1800), leading to a dramatic decline in both output and deaths.

Transmission only through economic activities. In the baseline calibration, I assigned an equal likelihood of transmitting the virus through consumption, labor, and other channels during the initial stages of the pandemic. I also study the case in which the virus transmits through consumption and labor channels only, by setting $\beta_e = 0$ and adjusting $\beta_c = 0.12$ and $\beta_\ell = 21.30$ so that the basic reproduction number remains unchanged at 2.2. In this case, private mitigation alone causes the death rate to fall to 0.5 percent, as can be seen in the first panel of Table 6. Even so, the main policy implications are robust to this alternative setting, with a notably larger subsidy amount in the constrained optimal policy configuration that brings the death rate to nearly zero.

Option to consume from home. I also study an extension of the model in which individuals have the option to consume from home. Specifically, I assume that

$$u(c^o, c^h, \ell, h) = \frac{(c^o + \phi c^h)^{1-\sigma}}{1-\sigma} - \varphi \frac{\ell^{1+\nu}}{1+\nu} + \bar{u} + \hat{u}_h \tag{23}$$

where $0 < \phi \leq 1$ and that

$$\pi_{It}(c^o, \ell^o; Z_t) = \beta_c c^o C^o_{It} + \beta_\ell \ell^o L^o_{It} + \beta_e \mu_{It}, \tag{24}$$

Table 5: Sensitivity analysis

	subsidy amount ($/week)	duration (months)	threshold (hours /week)	lock-down	average welfare change (percent)	2-year output (index)	deaths (percent)
lower value of statistical life ($VSL = 6208\bar{c}$)							
constrained optimum*	750	22	0	no	–13.7	89.5	1.4
output maximizing*	450	14	0	no	–15.5	96.1	1.6
US policy	600	4	10	yes	–15.6	88.5	1.6
no mitigation	0	0	none	no	–17.7	91.4	2.0
smaller utility loss during infection ($\hat{u} = -2.74$)							
constrained optimum*	750	22	0	no	–15.0	89.5	1.3
output maximizing*	450	14	0	no	–17.0	95.8	1.6
US policy	600	4	10	yes	–17.1	88.1	1.5
no mitigation	0	0	none	no	–19.4	90.6	1.9
smaller efficiency loss during infection ($\eta_{jI} = 0.7\eta_{jS}$)							
constrained optimum*	750	22	0	no	–15.6	86.8	1.3
output maximizing*	600	10	0	no	–17.6	91.4	1.6
US policy	600	4	10	yes	–17.8	86.1	1.6
no mitigation	0	0	none	no	–19.8	89.5	1.9
larger hospital capacity ($\kappa = 0.015$)							
constrained optimum*	900	18	0	no	–13.3	85.7	1.0
output maximizing*	450	14	0	no	–16.1	96.0	1.4
US policy	600	4	10	yes	–16.0	88.4	1.4
no mitigation	0	0	none	no	–18.6	90.1	1.7
earlier vaccine (March 27, 2021)							
constrained optimum*	1800	10	0	no	–7.5	76.9	0.4
output maximizing*	525	12	0	no	–14.4	96.7	1.2
US policy	600	4	10	yes	–15.3	88.5	1.3
no mitigation	0	0	none	no	–18.5	90.4	1.7

Notes: Average welfare change reports the population-weighted average of individual consumption equivalents. Output refers to output from $t = 1$ (March 27, 2020) to $t = 52$ (March 24, 2022), compared to the analogous 52-period output in the steady state, indexed at 100. * denotes Pareto improvements relative to the no mitigation case.

where C^o_{It} denotes aggregate outside consumption of infected individuals. This functional form implies that, for any $\phi < 1$, all consumption is outside in the pre-pandemic steady state. Thus the calibration of the model parameters is unaffected by this model extension. In this robustness exercise, I assume that there is a 50 percent utility loss for home consumption relative to outside consumption by setting $\phi = 0.5$. For reference, this implies that two months into the pandemic (May 22, 2020), old individuals reduce their outside consumption by 87 percent and young individuals reduce their outside consumption by 10 percent in the no mitigation scenario. As one can expect, allowing for home consumption dramatically reduces the death rate from 1.9 to 1.2 percent, as can be seen in the second panel of Table 6. The main policy implications are mostly unchanged, except that the durations of the mitigation policies of both the constrained optimal and output maximizing configurations are even longer (22 months) compared to the baseline model.

Subsidy funded by taxes on consumption and labor income. In the baseline calibration, I assumed that the stay-at-home subsidy is funded by a tax on consumption. I also study the robustness of the results to assuming that the subsidy is funded by an equal increase in the tax rates on consumption and labor income. The main policy implications are nearly unchanged to the baseline, except that the subsidy is now equal to that of US policy but for much longer duration. In the constrained optimum, output and deaths are higher than in the baseline, but average welfare is lower, as can be seen in panel 3 of Table 6, compared to Table 4.

No Pandemic. Given the relatively large and broad support of the mitigation policies, one might wonder whether such policies would be beneficial in normal times. I find that this is not the case. In fact, when there is no pandemic, there is no policy configuration that delivers an average welfare gain, let alone one with unanimous support.

6 Conclusion

In this paper, I developed a quantitative life-cycle economic-epidemiology model that was used to measure the heterogeneous welfare consequences of COVID-19, with and without mitigation efforts. The paper also shows that, with well-designed policies, there is no trade-

Table 6: Sensitivity analysis (2)

	subsidy amount ($/week)	duration (months)	threshold (hours /week)	lock-down	average welfare change (percent)	2-year output (index)	deaths (percent)
transmission only through economic activities ($\beta_e = 0$)							
constrained optimum*	1050	18	0	no	–2.9	81.2	0.1
output maximizing*	450	22	0	no	–5.1	97.1	0.3
US policy	600	4	10	yes	–6.7	87.5	0.4
no mitigation	0	0	none	no	–8.7	91.0	0.5
option to consume from home							
constrained optimum*	900	22	0	no	–10.3	83.2	0.7
output maximizing*	450	22	0	no	–11.2	95.9	0.8
US policy	600	4	10	yes	–12.6	88.1	1.0
no mitigation	0	0	none	no	–14.8	90.1	1.2
subsidy funded by taxes on consumption and labor income							
constrained optimum*	675	22	0	no	–15.5	91.4	1.3
output maximizing*	525	10	0	no	–17.1	95.6	1.5
US policy	600	4	10	yes	–17.3	85.3	1.5
no mitigation	0	0	none	no	–19.6	90.2	1.9
no pandemic							
constrained optimum	0	0	none	no	0.0	100.0	0.0
output maximizing	0	0	none	no	0.0	100.0	0.0
US policy	600	4	10	yes	-0.4	92.4	0.0
no mitigation	0	0	none	no	0.0	100.0	0.0

Notes: Average welfare change reports the population-weighted average of individual consumption equivalents. Output refers to output from $t = 1$ (March 27, 2020) to $t = 52$ (March 24, 2022), compared to the analogous 52-period output in the steady state, indexed at 100.

off between economic well-being and saving lives. In particular, the optimal mitigation policy, which involves a stay-at-home subsidy that is funded by a consumption tax, saves saves millions of lives and is favored by all individuals, regardless of age, income, or wealth.

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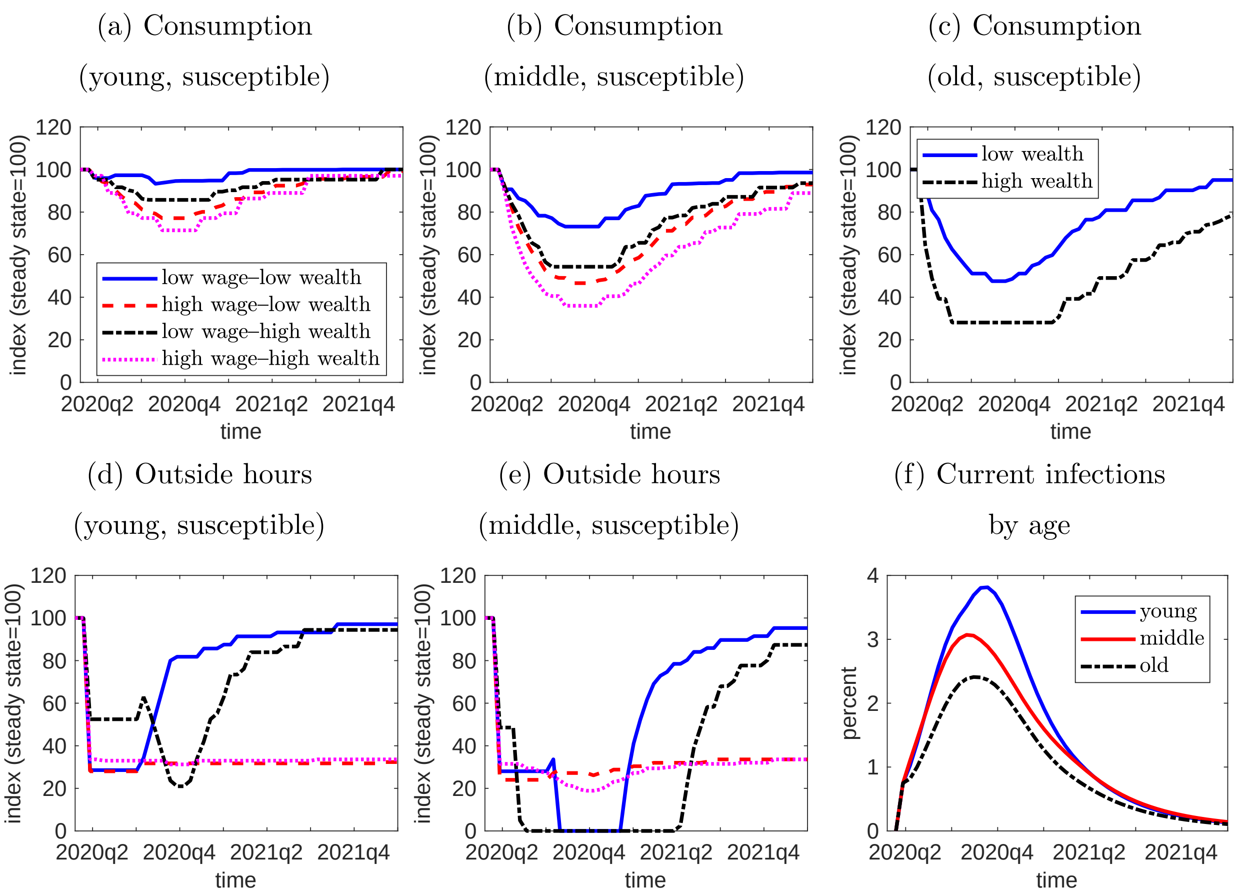
A Estimation of Wage Processes

The sample selection and estimation procedure closely follows the procedure described in Krueger et al. (2016) and Hur (2018). I use annual income data from the PSID core sample (1970–1997), selecting all household heads, ages 23 to 64. For waves before 1993, I use the variable Total Labor Income of Head, which is the sum of wages, tips, labor part of farm and business income, and other items. For waves after 1993, I compute total head labor income as the sum of the head's labor income (excluding farm and business income), head's labor part of business income, and 50 percent of household farm income, divided by two if married. Next, I construct wages by dividing head's total labor income by hours, where hours is the sum of hours worked, hours unemployed, and sick hours. I drop observations with missing education, with wages that are less than half of the minimum wage, with top-coded income, and with fewer than 1,000 hours per year. On this sample, I regress the log wage on age and education dummies, their interaction, and year dummies. I then exclude all individual wage sequences shorter than 5 years, leaving final samples of 4,524 individuals, with an average length of 9 years. On these samples, I compute the autocovariance matrix of the residuals. The stochastic process in equation (19) is estimated using GMM, targeting the covariance matrix, where the weighting matrix is the identity matrix. I thank Chris Tonetti for providing the Matlab routines that perform the estimation.

B Additional figures and tables

Figure 8: Response to pandemic (lockdown)



Notes: Low income and high income correspond to 10th and 90th percentiles of the steady state wage distribution, respectively. Low wealth and high wealth correspond to the 25th and 75th percentiles of the steady state wealth distribution, respectively.