The Distributional Effects of COVID-19 and Optimal Mitigation Policies

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Motivation

"Will some people['s *health*] be affected badly? Yes ... but we have to get our country['s *economy*] opened and we have to get it open soon"

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- Is there a tradeoff between public health and economic outcomes?

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- Is there a tradeoff between public health and economic outcomes? Not necessarily

Introduction

- To better understand the economic-health tradeoff (or lack thereof), I build a quantitative model to use as a laboratory for policy counterfactuals
- Key ingredients:
  - heterogeneity in age
    - old individuals face higher fatality risk
    - young individuals face worse labor market outcomes
  - heterogeneity in income and wealth
  - two-way feedback between economic activity and virus transmission

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- Key ingredients:
  - heterogeneity in age
  - heterogeneity in income and wealth
    - most low-wage workers cannot work from home
    - many low-wealth workers lack the resources to weather prolonged time away from work
  - two-way feedback between economic activity and virus transmission

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  - heterogeneity in age
  - heterogeneity in income and wealth
  - two-way feedback between economic activity and virus transmission
- Other ingredients:
  - endogenous labor with option to work from home
  - optimal outside/home consumption and saving decisions
  - hospital capacity constraints

Preview of findings

- Without mitigation, young workers engage in too much economic activity, relative to the social optimum
  - especially true for young low-wage/wealth workers
  - leading to higher infection rates and deaths in the aggregate
- Mitigation policies
- Stay-at-home subsidy reduces deaths by more and output by less
- Welfare maximizing Pareto improvement
- Output maximizing policy

Preview of findings

- Without mitigation, young workers engage in too much economic activity, relative to the social optimum
- Mitigation policies
  - *stay-at-home subsidy* (e.g. FPUC)
  - *stay-at-home order* (lockdown) that imposes a cap on outside work hours
    (e.g. stay-at-home, shelter-at-home, safe-at-home orders)
- Stay-at-home subsidy reduces deaths by more and output by less
- Welfare maximizing Pareto improvement
- Output maximizing policy

Preview of findings

- Without mitigation, young workers engage in too much economic activity, relative to the social optimum
- Mitigation policies
- Stay-at-home subsidy reduces deaths by more and output by less
  - lockdown benefits older individuals at the expense of low-wage workers
  - stay-at-home subsidy benefits all
- Welfare maximizing Pareto improvement
- Output maximizing policy

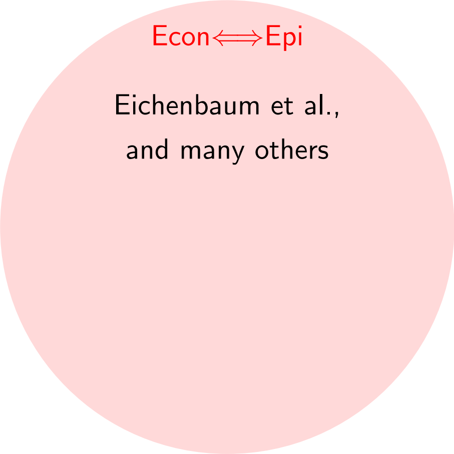
Preview of findings

- Without mitigation, young workers engage in too much economic activity, relative to the social optimum
- Mitigation policies
- Stay-at-home subsidy reduces deaths by more and output by less
- Welfare-maximizing Pareto improvement
  - weekly subsidy of $1050 (gradually phased out after 7 months)
  - no lockdown
  - reduces deaths by 60 percent and output by 2 percent, compared to no mitigation

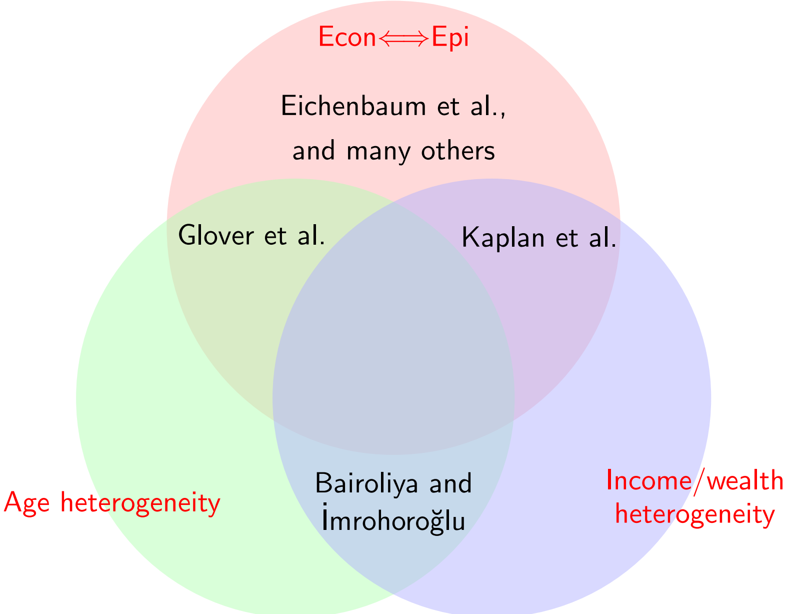
Preview of findings

- Without mitigation, young workers engage in too much economic activity, relative to the social optimum
- Mitigation policies
- Stay-at-home subsidy reduces deaths by more and output by less
- Welfare maximizing Pareto improvement
- Output maximizing policy
  - weekly subsidy of $350 (gradually phased out after 13 months)
  - no lockdown
  - reduces deaths by 20 percent and *increases* output by 2 percent, compared to no mitigation

Relation to literature



Relation to literature



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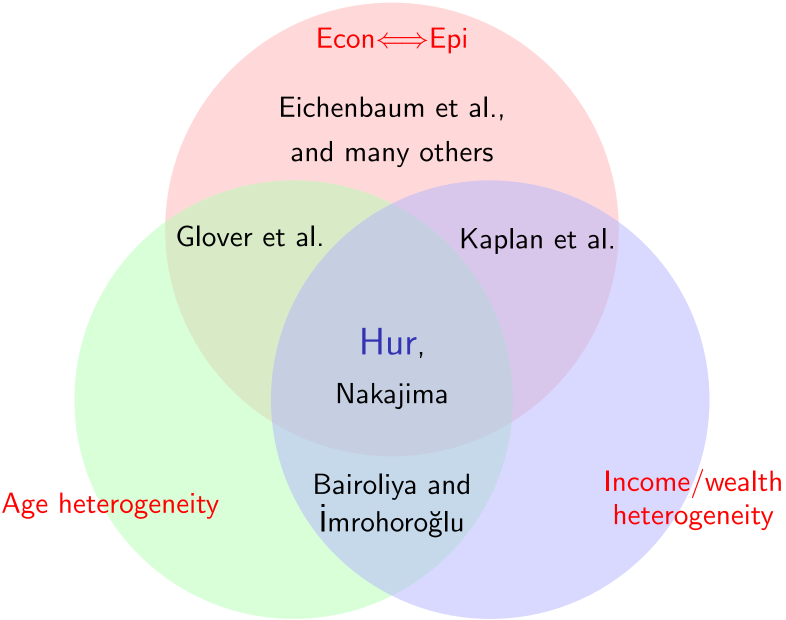

Model

Features of model

- Stochastic aging
- Income fluctuations + borrowing constraints + incomplete markets $\longrightarrow$ precautionary savings
- Outside versus home consumption
- Endogenous labor supply with option to work from home
- Economic-Epidemiology model
  (economic activities $\longleftrightarrow$ virus transmission)
- Hospital capacity constraints

Demographics

- Individuals of age denoted by $j \in J \equiv \{1, 2, .., \overline{J}\}$
- Stochastic aging
  - ψ_j: probability of transitioning from age j to $j + 1$
- Retirement at $j = J^R$
- Health status $h \in \{S, I, R, D\}$

Demographics

- Individuals of age denoted by $j \in J \equiv \{1, 2, .., \overline{J}\}$
- Stochastic aging
- Retirement at $j = J^R$
- Health status $h \in \{S, I, R, D\}$ for Susceptible, Infected, Recovered, and Dead

Epidemiological block

- Build on widely used SIR model
- Susceptible individuals get infected with probability π_{It}, which depends on individual outside consumption and labor (c_o, ℓ_o) and the measure of infected individuals (μ_{It}) and their outside consumption and labor (C^o_{It}, L^o_{It})

$$\pi_{It}(c_o, \ell_o) = \beta_c c_o C^o_{It} + \beta_\ell \ell_o L^o_{It} + (\beta_e + \epsilon_t)\mu_{It}$$

  where ϵ_t captures time-varying transmissibility (e.g. seasonal factors)
- Infected individuals exit infection with probability π_X
- Recovered individuals are assumed to be immune
- Let $\Pi_{jhh't}(c_o, \ell_o)$ denote the transition matrix

Epidemiological block

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- Susceptible individuals get infected with probability π_{It}, which depends on individual outside consumption and labor (c_o, ℓ_o) and the measure of infected individuals (μ_{It}) and their outside consumption and labor (C^o_{It}, L^o_{It})
- Infected individuals exit infection with probability π_X, then
  - recover with prob. $1 - \delta_j(\mu_{It})$
  - die with prob. $\delta_j(\mu_{It})$
- Recovered individuals are assumed to be immune
- Let $\Pi_{jhh't}(c_o, \ell_o)$ denote the transition matrix

Labor income

- Each period, workers receive idiosyncratic productivity shocks $\varepsilon \in E$, which follows a Markov process, with trans. matrix Γ
- Their labor income is given by $w_t \eta_{jh} \varepsilon \ell$, where
  - w_t: efficiency wage
  - η_{jh}: age-health-profile of efficiency units
- A fraction $\bar{\theta}_j(\varepsilon)$ of labor can be done at home
- Retirees receive a fixed income of s each period
  - can easily depend on lifetime earnings as in Hur (2018)

Retiree's problem

- Retirees with age $j \geq J^R$, wealth k, and health h choose inside and outside consumption c_i, c_o and savings k' to solve:

$$v_{jt}^R(k,h) = \max_{c_i, c_o, k' \geq 0} \; u(c_i, c_o) + \bar{u} + \hat{u}^h + \beta \sum_{h' \in H} \Pi_{jhh't}(c_o, 0)$$
$$\times \left[\psi_j v_{j+1,t+1}^R(k', h') + (1-\psi_j) v_{j,t+1}^R(k', h') \right]$$
$$\text{s.t.} \;\; (1+\tau_{ct})c + k' \leq s + k(1+r_t)$$

  - $\bar{u}, \hat{u}_h$: flow value of life, health
  - $c = c_o + c_i$
  - $v_{J+1}^R = 0$
  - τ_{ct}: consumption tax
  - r_t: net return to capital

Worker's problem

- Workers with age $j < J^R$, wealth k, productivity ε, and health h choose consumption c_i, c_o, inside and outside labor ℓ_i, ℓ_o, and savings k' to solve:

$$
\begin{aligned}
v_{jt}(k,\varepsilon,h) = \max_{\substack{c_i,c_o,\ell_i \\ \ell_o,k'\geq 0}} \quad & u(c_i,c_o) - g(\ell) + \bar{u} + \hat{u}^h + \beta \sum_{\varepsilon' \in E} \sum_{h' \in H} \Gamma_{\varepsilon,\varepsilon'} \Pi_{jhh't}(c_o, \ell_o) \\
& \times [\psi_j v_{j+1,t+1}(k',\varepsilon',h') + (1-\psi_j) v_{j,t+1}(k',\varepsilon',h')] \\
\text{s.t.} \quad & (1+\tau_{ct})c + k' \leq w_t \eta_{jh}(1-\tau_{\ell t})\varepsilon\ell + k(1+r_t) + T_t(\ell) \\
& \ell_i \leq \bar{\theta}_j(\varepsilon)\ell, \ \ \ell_o \leq \bar{\ell}_{ot}
\end{aligned}
$$

  - $\ell = \ell_i + \ell_o$
  - Let $v_{jt}(k,\varepsilon,h) = v_{jt}^R(k,h)$ for $j \geq J^R$
  - $\tau_{\ell t}$: labor income tax
  - $g(\ell)$: disutility of labor

Optimality conditions ($h = S$)

$$\frac{\partial u}{\partial c_i} = \frac{\partial u}{\partial c_o} - \beta_c C^o_{It} \beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon,\varepsilon'} \times \underbrace{\left\{ \begin{array}{l} \psi_j \left[v_{j+1,t+1}(k',\varepsilon',S) - v_{j+1,t+1}(k',\varepsilon',I) \right] \\ +(1-\psi_j) \left[v_{j,t+1}(k',\varepsilon',S) + v_{j,t+1}(k',\varepsilon',I) \right] \end{array} \right\}}_{\text{value of remaining susceptible}}$$

$$w_t \eta_{jS} \varepsilon \frac{\partial u}{\partial c_i} \frac{1-\tau_{\ell t}}{1+\tau_{ct}} = -\frac{\partial g}{\partial \ell} - (1-\bar{\theta}_j(\varepsilon)) \beta_\ell L^o_{It} \beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon,\varepsilon'} \times \underbrace{\left\{ \begin{array}{l} \psi_j \left[v_{j+1,t+1}(k',\varepsilon',S) - v_{j+1,t+1}(k',\varepsilon',I) \right] \\ +(1-\psi_j) \left[v_{j,t+1}(k',\varepsilon',S) + v_{j,t+1}(k',\varepsilon',I) \right] \end{array} \right\}}_{\text{value of remaining susceptible}}$$

Production

- A representative firm solves

$$\max L_f^{1-\alpha} K_f^{\alpha} - w_t L_f - (r_t + \delta) K_f$$

  where L_f are effective units of labor demanded

- Optimality conditions:

$$w_t = (1-\alpha)\left(\frac{K_f}{L_f}\right)^{\alpha}$$
$$r_t = \alpha\left(\frac{K_f}{L_f}\right)^{\alpha-1} - \delta$$

Rest of talk

1. Calibrate the model
   - pre-pandemic steady state ▸ Definition of equilibrium
   - transition path
2. Model fit
3. Welfare consequences of pandemic and U.S. mitigation policies
4. Optimal mitigation policies

Calibration

Envioronment

- Period length: 2 weeks
- Number of age cohorts: 3 (25–44, 45–64, 65+)
- Newborn endowments: 85% begin with zero wealth and 15% receive accidental bequests ($\sim 28\times$ annual per capita cons.)
- Preferences

$$u(c_i, c_o) = \frac{\left(c_i^{\gamma} c_o^{1-\gamma}\right)^{1-\sigma}}{1-\sigma}$$

$$g(\ell) = \varphi \frac{\ell^{1+\nu}}{1+\nu} + \mathbb{1}_{\ell=0}\tilde{u}$$

  - $\tilde{u}$: disutility from not working (e.g. administrative costs, stigma, or any other costs not modeled)

Labor income

- Labor that can be done from home: set to match the Dingel and Neiman (2020) average share of jobs that can be done from home by occupations sorted into wage quintiles: 0.03, 0.21, 0.32, 0.47, 0.66
- Productivity shocks (ε) follow a finite-state Markov process which approximates the continuous process,

$$\log \varepsilon_t = \rho_\varepsilon \log \varepsilon_{t-1} + \nu_t, \; \nu_t \sim N\left(0, \sigma_\nu^2\right)$$

- Estimate using wage residuals constructed from PSID
  - $\rho_\varepsilon = 0.94$ and $\sigma_\nu = 0.19$
  - Convert to higher frequency, following Krueger et al. (2016)

Economic parameters

Parameters	Values	Targets / Source
Discount factor, annualized, β	0.97	Wealth-to-GDP: 4.8 (BOG, 2019)
Risk aversion, σ	2	Standard value
Inside consumption share, γ	0.51	Expenditure share (BEA, 2019)
Disutility from labor, φ	22.64	Average weekly hours: 34.4 (BEA, 2019)
Frisch elasticity, $1/\nu$	0.50	Standard value
Death prob., annualized, ψ_3	0.10	65+ share of population 25+: 0.2
Aging prob., annualized, $\psi_1 = \psi_2$	0.05	Expected duration: 20 years
Efficiency units, $\eta_{1R} = \eta_{1S}$	1.00	Wage ratio of age 45–64 to
$\eta_{2R} = \eta_{2S}$	1.35	age 25–44 workers (PSID, 2014)
Factor elasticity, α	0.36	Capital share
Depreciation, annualized, δ	0.05	Standard value
Retirement income, s	1.00	30% of earnings per worker
Labor income tax, τ_ℓ	0.07	Gov't budget constraint
Consumption tax, τ_c	0.00	
Transfer, T	0.00	

Epidemiological parameters

- Death rates: as in Piguillem and Shi (2020) and other papers, I use the functional form

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

  - δ_j^u: unconstrained death rates
  - δ_j^c: untreated death rates
  - κ: measure of infected individuals that can be treated

- 924 thousand hospital beds in the US (0.28% of population)

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  - δ_j^u: unconstrained death rates
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  - κ: measure of infected individuals that can be treated
- 924 thousand hospital beds in the US (0.28% of population)
  - not all infected cases require hospitalization $\rightarrow \kappa = 0.01$

Reproduction number

- Total new infections:

$$T_t = \beta_c C^o_{St} C^o_{It} + \beta_\ell L^o_{St} L^o_{It} + (\beta_e + \epsilon_t)\mu_{St}\mu_{It}$$

- The basic reproduction number, as $\mu_I \to 0$ and $\epsilon_t = 0$, assuming $C^o_I/\mu_I \to C^o_S/\mu_S$ and $L^o_I/\mu_I \to L^o_S/\mu_S$, is given by

$$R_0 = \frac{\beta_c (C^o_S)^2 + \beta_\ell (L^o_S)^2 + \beta_e}{\pi_X}$$

assuming that initially people are not working from home
- Most estimates range between 2.2 and 3.1. I use $R_0 = 2.2$
- I assume that, initially, virus transmission equally likely between 3 channels (evidence from other infectious diseases: Ferguson et al., 2006, Mossong et al., 2008)

Reproduction number

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Epidemiological parameters (2)

Parameters	Values	Targets / Source
Infection exit rate, π_X	0.78	Expected infection duration: 18 days
Unconstrained death rate,		Fatality rates in South Korea
$\delta_1^u \times 100$	0.08	
$\delta_2^u \times 100$	0.85	
$\delta_3^u \times 100$	8.47	
Untreated death rate, δ_j^c	$2\delta_j^u$	Piguillem and Shi (2020)
Flow value of life, $\bar{u}$	25.91	VSL: \$7.4 mil. (EPA, 2006) Derivation
Flow value of infection, $\hat{u}^I$	–12.48	50 percent reduction in flow utility value of average agent
Disutility of not working, $\tilde{u}$	0.62	19 percent reduction in employment
Efficiency units, η_{jI}	$0.5\eta_{jS}$	

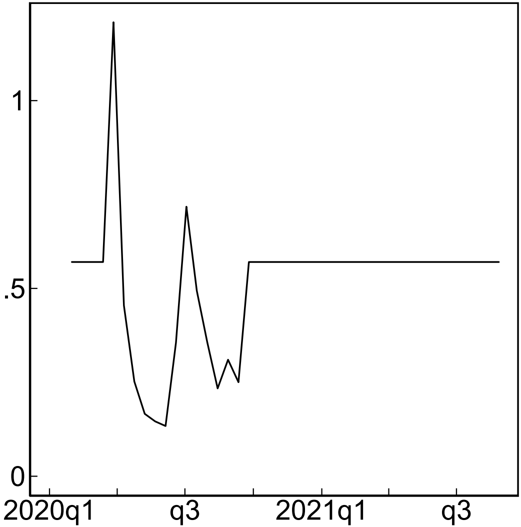
Transition path with pandemic

- COVID-19 introduced as an unanticipated MIT-shock
  - initial infections are set to 0.5 percent to match 17,982 deaths in the US during 3/27–4/9 ($t = 1$)
- Use first six months of the pandemic to fit $\beta_e + \epsilon_t$ to biweekly deaths (capturing seasonal factors, etc.)
- Fiscal policies that are relevant for virus mitigation
- Transition path solved in partial equilibrium

Transition path with pandemic

- COVID-19 introduced as an unanticipated MIT-shock
- Use first six months of the pandemic to fit $\beta_e + \epsilon_t$ to biweekly deaths (capturing seasonal factors, etc.)
  - set $\epsilon_t = 0$ after first six months
- Policies that are relevant for virus mitigation
- transition path solved in partial equilibrium

Time-varying transmissibility $(\beta_e + \epsilon_t)$



Transition path with pandemic

- COVID-19 introduced as an unanticipated MIT-shock
- Use first six months of the pandemic to fit $\beta_e + \epsilon_t$ to biweekly deaths (capturing seasonal factors, etc.)
- Policies that are relevant for virus mitigation
  1. *stay-at-home subsidy (subsidy)*: \$600 subsidy to individuals working 0 hours per week (e.g. FPUC)
  2. *stay-at-home order (lockdown)*: impose a cap of 15 outside work hours per week
- Transition path solved in partial equilibrium

Transition path with pandemic

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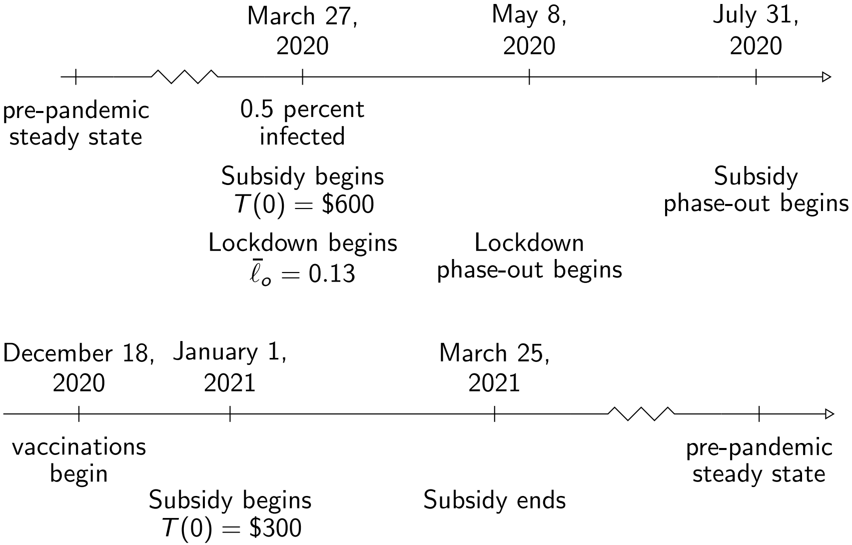
- Use first six months of the pandemic to fit $\beta_e + \epsilon_t$ to biweekly deaths (capturing seasonal factors, etc.)
- Policies that are relevant for virus mitigation
- Transition path solved in partial equilibrium
  - prices fixed
  - retirement benefits and contributions fixed
  - newborn distribution fixed

Timeline



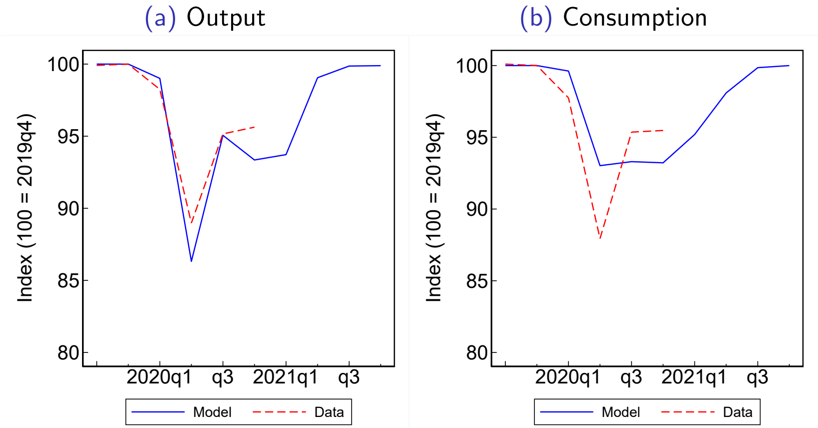
March 27, 2020
May 8, 2020
July 31, 2020
pre-pandemic steady state
0.5 percent infected
Subsidy begins $T(0) = \$600$
Lockdown begins $\bar{\ell}_o = 0.13$
Lockdown phase-out begins
Subsidy phase-out begins
December 18, 2020
January 1, 2021
March 25, 2021
vaccinations begin
Subsidy begins $T(0) = \$300$
Subsidy ends
pre-pandemic steady state

Model validity

Pre-pandemic steady state

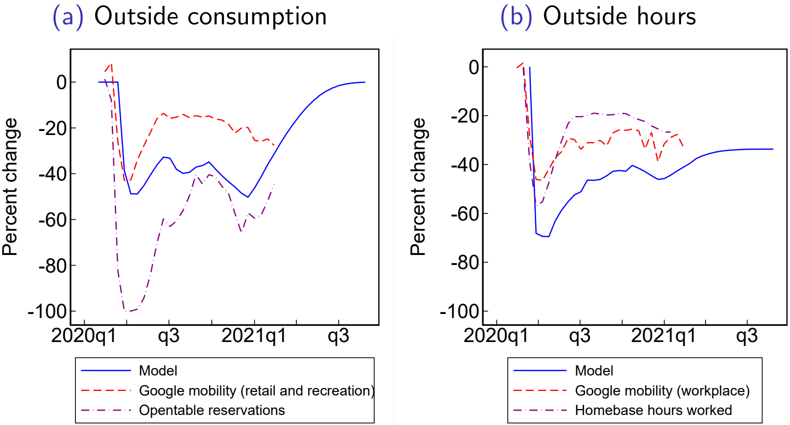
	Data	Model
Targeted moments		
wealth/GDP	4.8	4.8
average weekly hours	34.4	34.4
average VSL (annual cons. per capita)	238.8	238.8
Nontargeted moments		
disposable earnings gini	0.37	0.36
consumption gini	0.33	0.25
wealth gini	0.74	0.59
wealth p75/p25	11.9	13.2

Aggregates during the pandemic



Notes: Both consumption and output in the data are linearly detrended at 2 percent per year.

Aggregates during the pandemic (2)

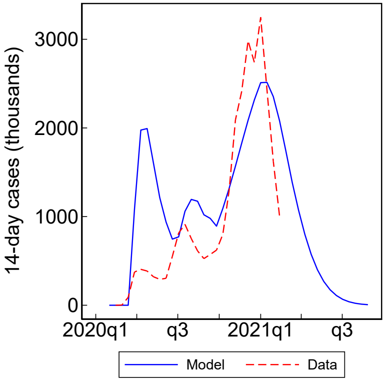


Notes: Outside consumption and hours in the model is relative to the pre-pandemic steady state. Google mobility and Opentable reservations are year over year percent changes. Homebase hours are relative to the median for each day of the week during January 4–31, 2020.

Aggregates during the pandemic (3)

(a) Cases

(b) Deaths



Quantitative exercises

Quantitative exercises

- Use the calibrated model to investigate the aggregate and distributional effects of the pandemic and mitigation policies
- First, explore how the economic-epi model of virus transmission differs from an exogenous one ($\beta_c = \beta_\ell = 0$)
  - private mitigation is very heterogeneous across age, income, and wealth
- Second, explore optimal mitigation policies

Quantitative exercises

- Use the calibrated model to investigate the aggregate and distributional effects of the pandemic and mitigation policies
- First, explore how the economic-epi model of virus transmission differs from an exogenous one ($\beta_c = \beta_\ell = 0$)
- Second, evaluate US mitigation policies
  - stay-at-home subsidies (e.g. FPUC)
  - stay-at-home orders
- Third, explore optimal mitigation policies

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- Second, evaluate US mitigation policies
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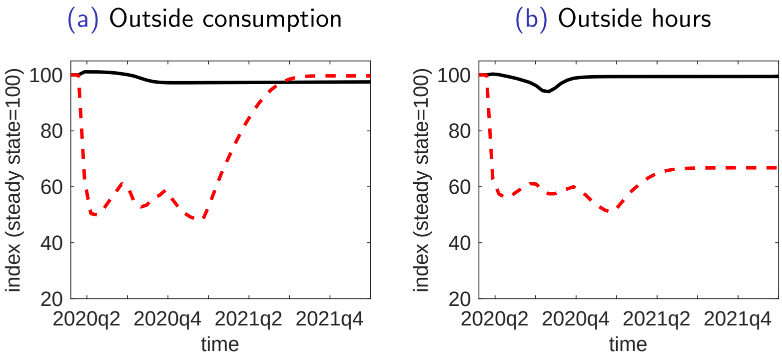
Private mitigation

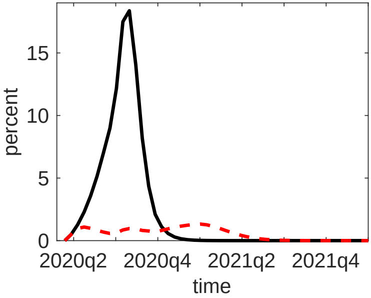
- To understand the magnitude and properties of private mitigation, compare
  - calibrated model without mitigation policy (i.e. $T(0) = 0, \bar{\ell}_o >> 0$)
  - exogenous SIR model ($\beta_c = \beta_\ell = 0$)

Private mitigation is large ...

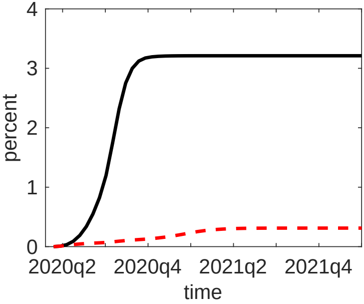


.. leading to less deaths

(a) Current infections



(b) Cumulative deaths



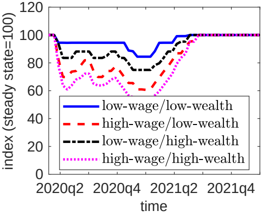
Notes: Percent of population 25+

Private mitigation is heterogeneous

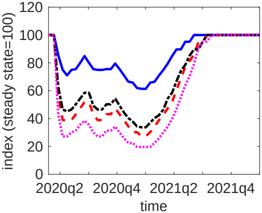
- Private mitigation is increasing in
  - age
  - income
  - wealth

Policy functions of susceptible individuals

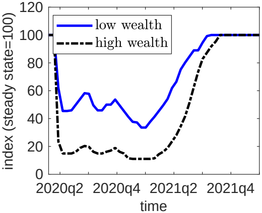
(a) Outside cons. (young)



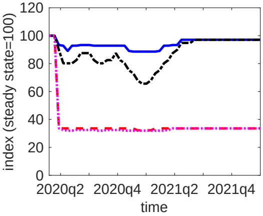
(b) Outside cons. (middle)



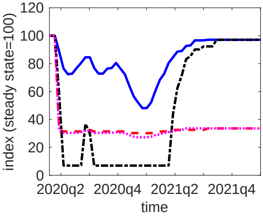
(c) Outside cons. (old)



(d) Outside hours (young)



(e) Outside hours (middle)



US Mitigation Policies

COVID-19 and US mitigation policies

	no mitigation	US mitigation	subsidy only	lockdown only
welfare	–8.0	–6.4	–6.4	–7.8
working-age	–4.9	–3.8	–3.8	–4.9
retired	–20.4	–16.8	–16.9	–19.8
low-wage	–3.1	–2.2	–2.2	–3.2
high-wage	–6.8	–5.4	–5.4	–6.5
low-wealth	–6.0	–4.6	–4.6	–6.0
high-wealth	–10.0	–8.2	–9.2	–9.7
policy support		100.0	100.0	81.4
2-year output	95.6	95.8	96.6	95.0
deaths per 10k	20.6	16.0	16.2	19.8

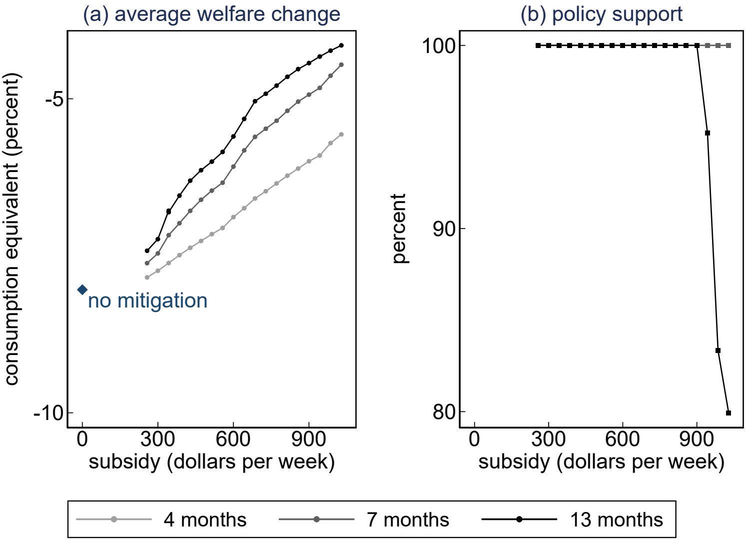
Notes: Low- and high-wage (wealth) correspond to below and above the median wage (wealth), respectively. Welfare reports consumption equivalents (percent). 2-year output is indexed to 2-year output in the pre-pandemic steady state

Optimal Policies

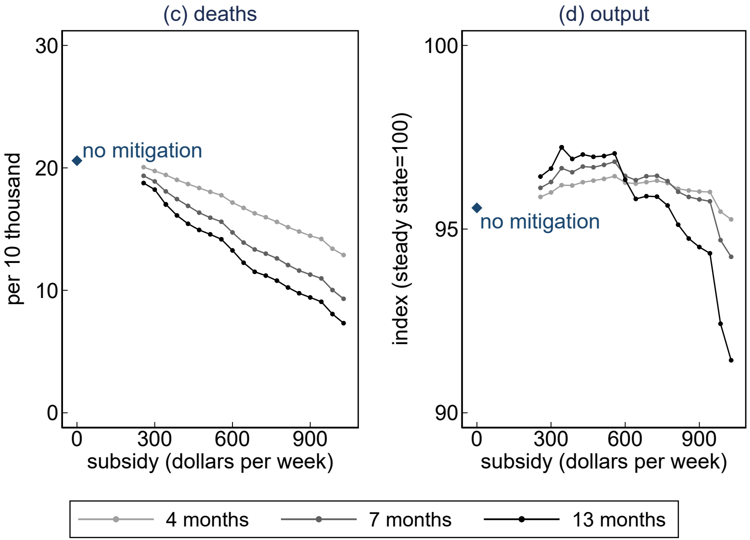
Optimal Policies

- Investigate the properties of optimal mitigation policies, within a limited set of instruments
  - subsidy amount
  - duration
  - speed of phase-out
  - lockdown, with varying intensities
- Characterize:
  - Constrained optimal policy (welfare-maximizing Pareto improvement)
  - Output maximizing policy

Larger & longer subsidies improve welfare ...



... lead to less deaths and *possibly* lower output



How mitigation policies can increase output

- Mitigation policies can increase output (relative to no mitigation)
- This is due to two opposing effects
  1. Direct effect: subsidy reduces labor supply, holding fixed the severity of the pandemic
  2. Indirect effect: subsidy attenuates the pandemic, leading to increased labor supply
- For moderate subsidy amounts (less than $600), only low-wage workers reduce their hours, leading to a small decline in output
- Because low-wage hours are almost exclusively outside, almost all of the reduction in hours contribute to mitigating the virus, making it safer to engage in more economic activities

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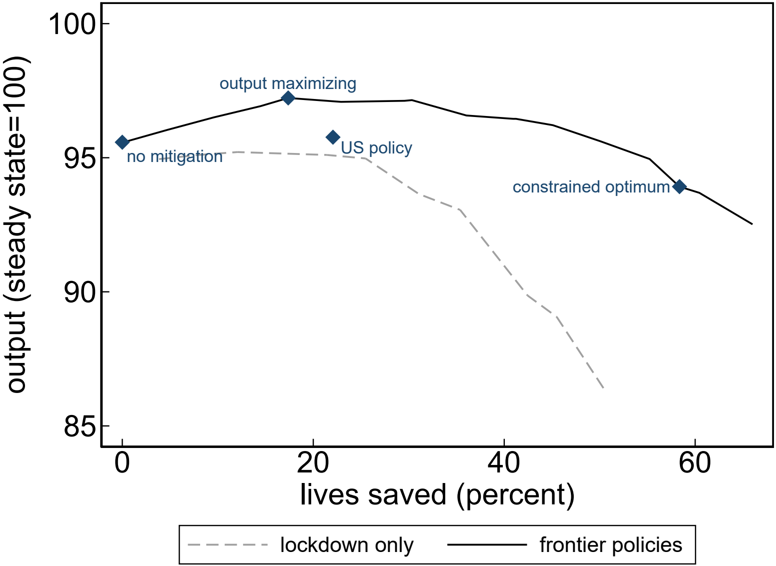
Not necessarily a trade-off between lives and output



Optimal policy breakdown

	no mitigation	maximizing policy	optimal policy	subsidy only	tax only
subsidy ($/week)	0	350	1050	1050	0
duration (months)	0	13	7	7	7
cons. tax (pct)	0	0.4	36.5	0	36.5
lockdown	no	no	no	no	no
welfare	–8.0	–6.8	–4.3	–4.3	–8.2
working-age	–4.9	–4.1	–2.3	–2.0	–5.3
retired	–20.4	–17.7	–11.8	–13.4	–19.6
low-wage	–3.1	–2.5	–0.8	–0.1	–3.7
high-wage	–6.8	–5.7	–3.9	–4.0	–6.8
low-wealth	–6.0	–4.9	–2.7	–2.2	–6.4
high-wealth	–10.0	–8.6	–5.7	–6.4	–9.8
policy support		100.0	100.0	100.0	37.9
2-year output	95.6	97.2	93.9	93.7	96.0
deaths per 10k	20.6	17.0	8.6	12.0	18.0

Notes: Welfare reports consumption equivalents (percent). 2-year output is indexed to 2-year output in the pre-pandemic steady state.

Conclusion

- Quantitative life-cycle economic-epidemiology model
  - measure the heterogeneous welfare effects of COVID-19
  - evaluate mitigation policies
- Stay-at-home subsidies dominate stay-at-home orders
- Optimal mitigation policies involve large subsidies and no lockdowns
- There need not be a tradeoff between saving lives and output

Appendix

Equilibrium ▸ back

- Let $X = K \times E \times H$ denote the state space over wealth, productivity, and health
- Let a σ-algebra over X defined by the Borel sets, $\mathcal{B}$, on X.
- A *steady-state recursive equilibrium*, given fiscal policies $\{\tau_c, \tau_\ell, s\}$, is
  - value functions $\{v_j\}_{j \in J}$,
  - policy functions $\{c_{ji}, c_{jo}, \ell_{ji}, \ell_{jo}, k'_j\}_j$,
  - producer plans $\{Y_f, L_f, K_f\}$
  - prices $\{w, r\}$,
  - distribution of newborns ω
  - invariant measures $\{\mu_j\}_j$

  such that:

Equilibrium (2) ▸ back

1. Given prices, workers and retirees optimize
2. Given prices, firms optimize
3. Goods and factor markets clear
4. Government budget holds:

$$s \int_X \sum_{j \geq J^R} d\mu_j(k, \varepsilon, h) =$$

$$\tau_\ell \int_X \sum_{j < J^R} w \eta_{jh} \varepsilon \left[\ell_{ji}(k, \varepsilon, h) + \ell_{jo}(k, \varepsilon, h) \right] d\mu_j(k, \varepsilon, h)$$

$$+ \tau_c \int_X \sum_{j \in J} \left[cji(k, \varepsilon, h) + cjo(k, \varepsilon, h) \right] d\mu_j(k, \varepsilon, h)$$

Equilibrium (3) ▸ back

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

$$\mu_j(\mathcal{K}, \mathcal{E}, \mathcal{H}) = \int_X \psi_{j-1} \mathbb{1}_{\{k'_{j-1}(k,\varepsilon,h) \in \mathcal{K}\}} \sum_{\varepsilon' \in \mathcal{E}} \sum_{h' \in \mathcal{H}} \Gamma_{\varepsilon,\varepsilon'} \Pi_{jhh'} d\mu_{j-1}(k, \varepsilon, h)$$
$$+ \int_X (1 - \psi_j) \mathbb{1}_{\{k'_{j+1}(k,\varepsilon,h) \in \mathcal{K}\}} \sum_{\varepsilon' \in \mathcal{E}} \sum_{h' \in \mathcal{H}} \Gamma_{\varepsilon,\varepsilon'} \Pi_{jhh'} d\mu_j(k, \varepsilon, h)$$

and

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

Equilibrium (4) ▸ back

6. The newborn distribution satisfies:

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

Derivation of $\bar{u}$ back

- Pre-pandemic steady-state value

$$v_j(k,\varepsilon) = \frac{\left((c_i^*)^{\gamma}(c_o^*)^{1-\gamma}\right)^{1-\sigma}}{1-\sigma} - \varphi\frac{(\ell_i^* + \ell_o^*)^{1+\nu}}{1+\nu} + \bar{u} + \beta\sum_{\varepsilon' \in E}\Gamma_{\varepsilon,\varepsilon'}\left[\psi_j v_{j+1}(k',\varepsilon') + (1-\psi_j)v_j(k',\varepsilon')\right]$$

  - $c_i^*, c_o^*, \ell_i^*, \ell_o^*$: pre-pandemic steady-state policy functions

Derivation of $\bar{u}$ (2) back

- Imposing optimality conditions

$$v_j(k,\varepsilon) = \frac{\left[(c^* + \Delta_c)\,\gamma^\gamma(1-\gamma)^{1-\gamma}\right]^{1-\sigma}}{1-\sigma} - \varphi\frac{(\ell_i^* + \ell_o^*)^{1+\nu}}{1+\nu} + \bar{u}$$
$$+ \beta(1+\Delta_s)\sum_{\varepsilon' \in E}\Gamma_{\varepsilon,\varepsilon'}\left[\psi_j v_{j+1}(k',\varepsilon') + (1-\psi_j)v_j(k',\varepsilon')\right]$$

  - $c^* = c_i^* + c_o^*$
  - Δ_c, Δ_s: small one-time deviations to consumption and survival probability

Derivation of $\bar{u}$ (3) back

- $$\frac{\partial v}{\partial \Delta_s} = \beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon,\varepsilon'} \left[\psi_j v_{j+1}(k', \varepsilon') + (1-\psi_j) v_j(k', \varepsilon')\right]$$
- $$\frac{\partial v}{\partial \Delta_c} = (c^* + \Delta_c)^{-\sigma} \left(\gamma^\gamma (1-\gamma)^{1-\gamma}\right)^{1-\sigma}$$

- The VSL—defined as the marginal rate of substitution between survival and consumption—can be expressed as

$$VSL = \left.\frac{\frac{\partial v}{\partial \Delta_s}}{\frac{\partial v}{\partial \Delta_c}}\right|_{\Delta_c=0,\ \Delta_s=0} = \frac{\beta \sum_{\varepsilon' \in E} \Gamma_{\varepsilon,\varepsilon'} \left[\psi_j v_{j+1}(k', \varepsilon') + (1-\psi_j) v_j(k', \varepsilon')\right]}{c^{*\,-\sigma} \left(\gamma^\gamma (1-\gamma)^{1-\gamma}\right)^{1-\sigma}}$$

- Set $\bar{u}$ such that $\frac{E(VSL)}{\bar{c}} = \frac{\$11.5e6}{\$44271 \times 14/365} = 6772$ or $\frac{\$7.4e6}{\$30989 \times 14/365} = 6226$