Vaccine Progress, Stock Prices, and the Value of Ending the Pandemic

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Introduction

- May 17, 2020: Jay Powell, in an interview with CBS:

  "For the economy to fully recover, people will have to be fully confident. And that may have to await the arrival of a vaccine"

  —Lauren Fedor and James Politi, Financial Times

- May 18, 2020: Moderna releases positive interim clinical data from Phase 1 trials and announces Phase 3 trials

  U.S. stocks gained about $1 trillion of market capitalization yesterday, and while there are lots of reasons why any particular stock may have gone up or down, good news about a vaccine that might allow reopening of the economy seems like a common factor for a lot of stocks.

  —Matt Levine, Money Stuff

This Paper

- Build on the hypothesis that stock markets contain valuable information in 2020 for gauging the value of ending (shortening) the pandemic
- Our contribution is to bring novel data observed during 2020 to bear on the important question of the *ex-ante* cost of such pandemics
- Use joint behavior of stock prices and a novel vaccine progress indicator
  - Expected time to pandemic exit $\downarrow$ 1-year $\rightarrow$ stock market value $\uparrow$ 5-8%
- In a general equilibrium regime-switching model of repeated pandemics, empirical estimate identifies the welfare gain to resolving the pandemic
  - Ending the pandemic is worth 5-15% of wealth
- Extensions
  1. Learning and uncertainty about pandemic parameters
     - Resolving uncertainty about the pandemic worth as much as ending the pandemic
  2. Endogenous pandemic severity and labor externalities
  3. Endogenize option to invest in vaccine research

Market Response to Vaccine Progress

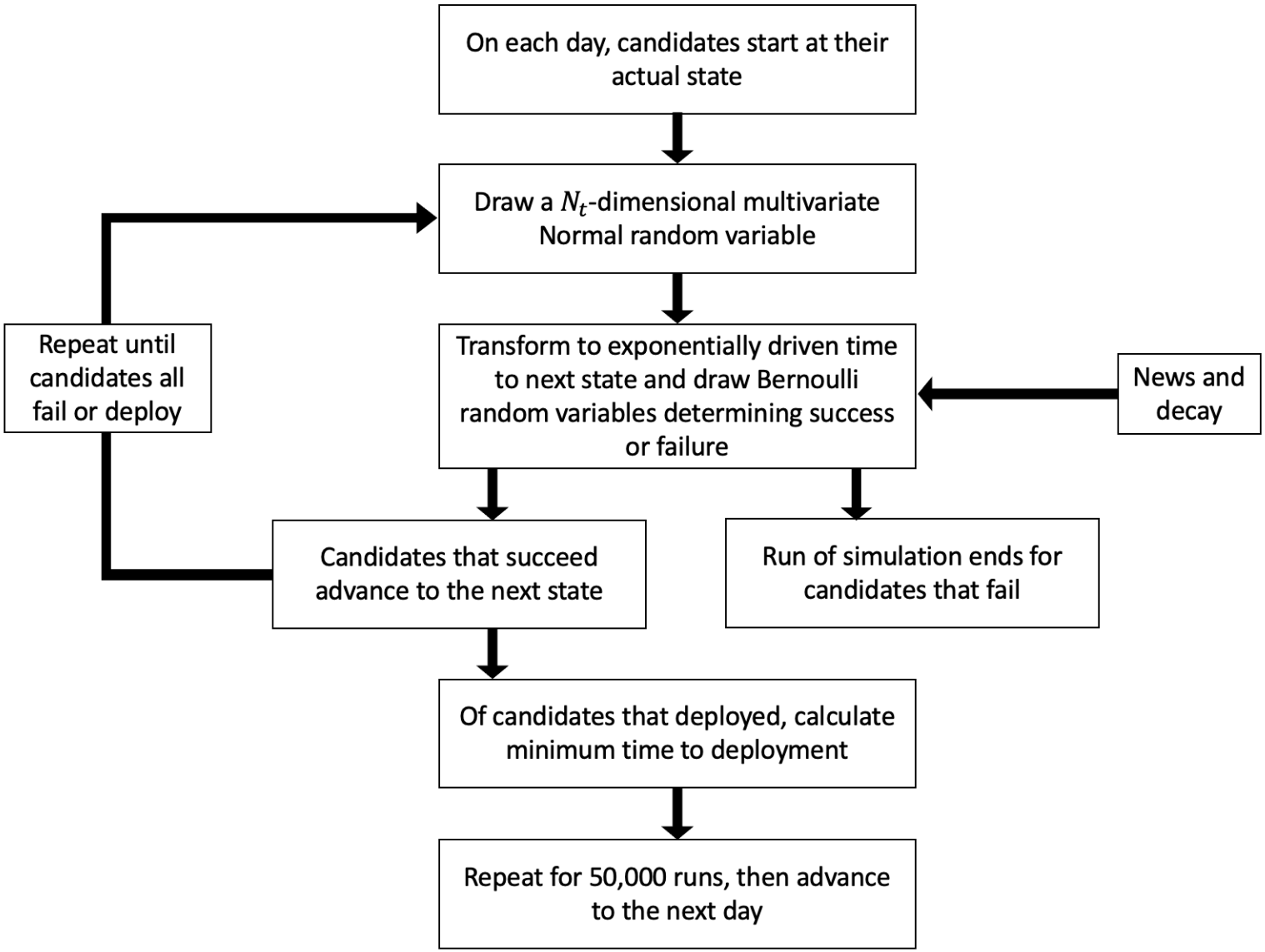
Vaccine Progress Indicator (VPI)

- Statistical model to estimate expected time to first vaccine deployment
  - Gaussian copula approach (analogy: first to default model)
  - Data on 250 candidates from London School of Hygiene & Tropical Medicine
- On each day: take the current stage of each candidate and simulate stage-by-stage progress until failure or successful deployment Description

$$\text{Stages} = \{\text{preclinical, phase 1, phase 2, phase 3,}$$
$$\text{application, approval, deployment}\}$$

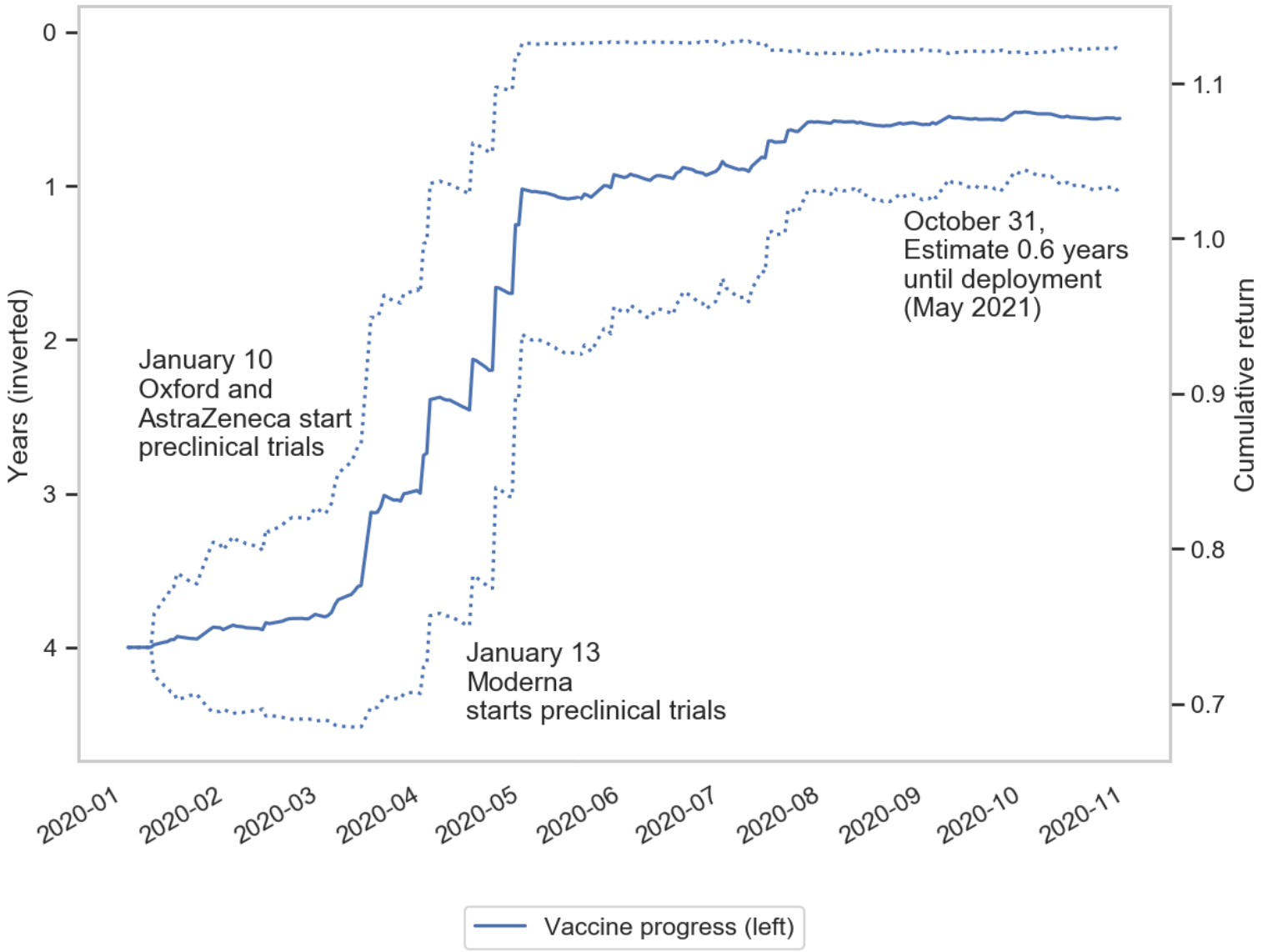
- Each stage has expected duration and probability of success/failure Details
  - Augment probabilities with *candidate-specific* news from FactSet More details
- Account for positive correlation between candidates Table Strategies
  - Properties of the same virus target, shared institutes, finite vaccine strategies
- Vaccine deployment is a final stage with *non-zero* probability of failure

Flow Chart for Constructing the VPI

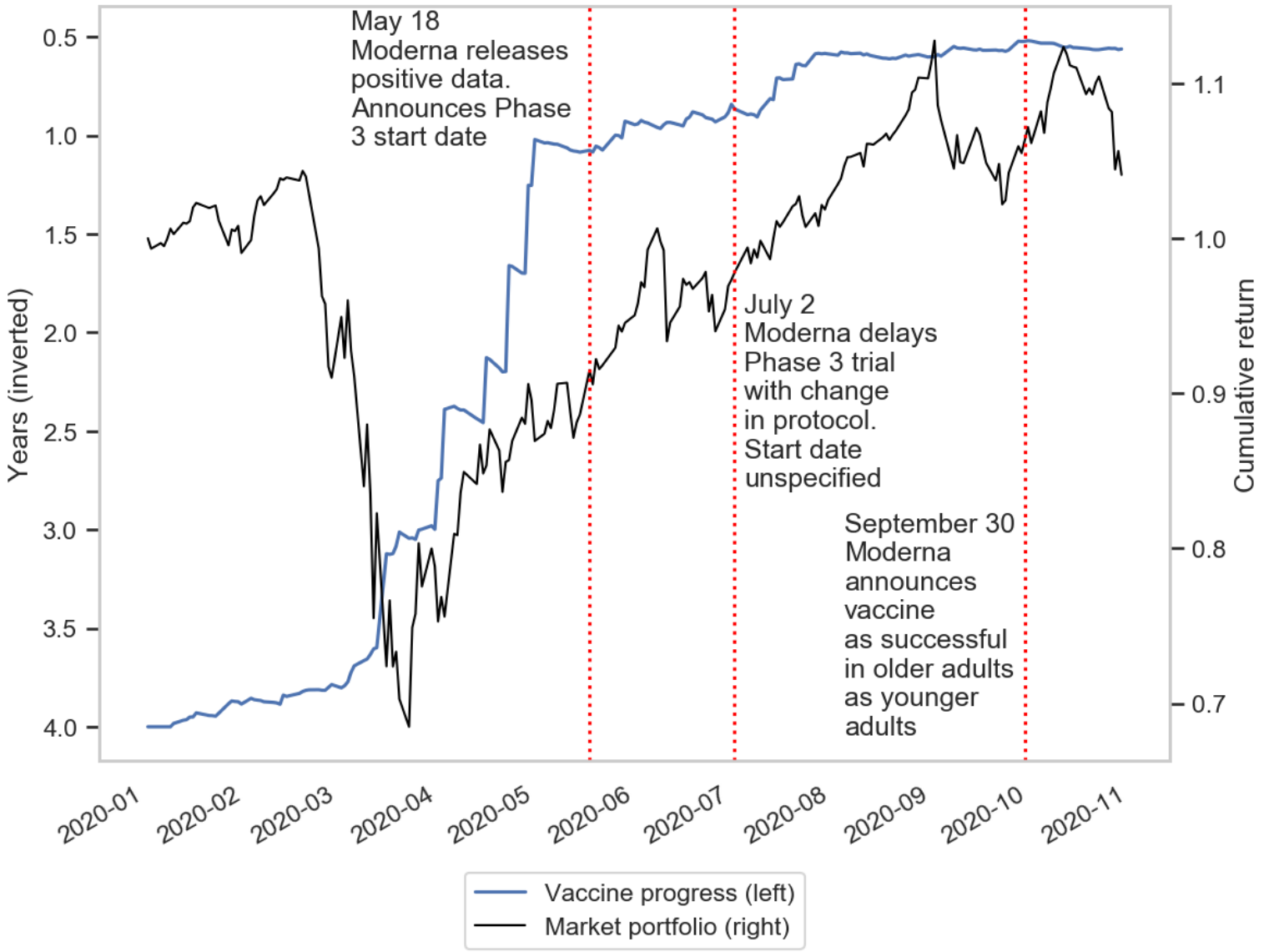


Step-by-step details of simulation

Time to Vaccine Deployment



News About Moderna



Market Response to Vaccine Progress

- Run regressions of daily market returns on vaccine progress, 1/1 - 10/31
  - Exclude days with large moves due to other news (Baker et al. 2020) Plot

$$R^e_{m,t} = \alpha + \sum_{h=-2}^{2} \beta_h \Delta \text{VPI}_{t+h} + \gamma_1 R^e_{m,t-1} + \gamma_2 R^e_{m,t-2} + \sum_{j=1}^{28} \delta_j \mathbb{1}_{\text{jump } j} + \epsilon_t$$

- Additionally implement methodology of Kogan et al. (2017) (KPSS)
  - Empirical Bayes estimation patent value using returns around patent dates
  - Vaccine progress news is positive, like value of patent

	OLS	KPSS Prior 1	KPSS Prior 2
$\sum_{h=-2}^{2} \beta_{t+h}$	-8.593	-6.365	-4.086
	(0.653)	(1.345)	(1.056)

Note: OLS results show standard deviation from a two-sided F-test. KPSS results show posterior standard deviations.

Full table | Table with OLS robustness checks | XS results

- Market response pins down value of ending the pandemic in the model

Model and Calibration

Regime-Switching Model of Repeated Pandemics

- Within each pandemic, characterize vaccine progress with sub-states
  - State $s \in \{0, \underbrace{1, \ldots, S-1}_{\text{pandemic}}, S\}$
  - Transition probabilities:

$$
\begin{aligned}
P(s_{t+dt} = 1 | s_t = 0 \text{ or } S) &= \eta dt \\
P(s_{t+dt} = s-1 | s_t = s \in [1, S-1]) &= \lambda_d(s) dt \\
P(s_{t+dt} = s+1 | s_t = s \in [1, S-1]) &= \lambda_u(s) dt
\end{aligned}
$$

- Capital dynamics (physical and human capital)

$$dq = \mu(s) q dt - C dt + \sigma(s) q dB_t - \chi(s) q dJ_t$$

- Poisson shock J_t captures the risk of economic loss when pandemics hit
  - When the Poisson process is triggered, capital stock goes to $q(1 - \chi(s))$

Agent's Preferences and Optimization Problem

- Unit mass of identical agents with Epstein-Zin preferences
- Conjecture the value function is ($H(s)$ are constants to be determined)

$$\mathbb{J}(s) \equiv \frac{H(s)q^{1-\gamma}}{1-\gamma}$$

- Optimal consumption in state s is

$$C(s) = \frac{(H(s))^{-\psi\theta^{-1}}\, q}{\rho^{-\psi}}$$

- Where $0 < \rho < 1$ is the discount factor, $\gamma \geq 0$ the RRA, $\psi \geq 0$ the EIS,

$$\theta^{-1} \equiv \frac{1-\psi^{-1}}{1-\gamma}$$

Solution

- Denote

$$g(s) \equiv \frac{(1-\gamma)\rho}{(1-\psi^{-1})} - (1-\gamma)\left(\mu(s) - \frac{1}{2}\gamma\sigma(s)^2\right) - \left([1-\chi(s)]^{1-\gamma} - 1\right)$$

- Then $\{H\}$'s are given by the system of S recursive equations, for $s \in \{1, \ldots, S-1\}$ and $H(S) = H(0)$

$$g_0 = \frac{(1-\gamma)}{(\psi-1)}\rho^{\psi}\left(H(0)\right)^{-\psi\theta^{-1}} + \eta\left[\frac{H(1)}{H(0)} - 1\right]$$

$$g_1 = \frac{(1-\gamma)}{(\psi-1)}\rho^{\psi}\left(H(s)\right)^{-\psi\theta^{-1}} + \lambda_d(s)\left[\frac{H(s-1)}{H(s)} - 1\right] + \lambda_u(s)\left[\frac{H(s+1)}{H(s)} - 1\right]$$

- Pandemic intensity parameters only affect solution via g_1

Value of Ending the Pandemic

- Define as certainty equivalent change in the agent's lifetime value function upon a transition from pandemic state s to non-pandemic state 0 (or S)

$$V(s) = 1 - \left(\frac{H(s)}{H(0)}\right)^{\frac{1}{1-\gamma}}$$

- Fraction of wealth that, if surrendered, would be fully compensated by the utility gain of reverting to the non-pandemic state

- Determined by the ratio of MPC ($c \equiv dC/dq$), adjusted by EIS

$$V(s) = 1 - \left(\frac{c(s)}{c(0)}\right)^{-\frac{1}{\psi-1}} = 1 - \left(\frac{C(s)}{C(0)}\right)^{-\frac{1}{\psi-1}}$$

Model's Analogue to Empirics

- In the model, "market portfolio" is a claim to economy's output $dq + Cdt$
  - Denote price of claim to output as P (solved from a matrix system) Matrix system
- Define $T^\star$ as the time when state S is attained and the pandemic ends
  - Its expectation, $\mathbb{E}[T^\star]$, is solved from a matrix system Matrix system
- The model's analogue of the market's response to vaccine progress is

$$\frac{\Delta \log P}{\Delta \mathbb{E}[T^\star]}$$

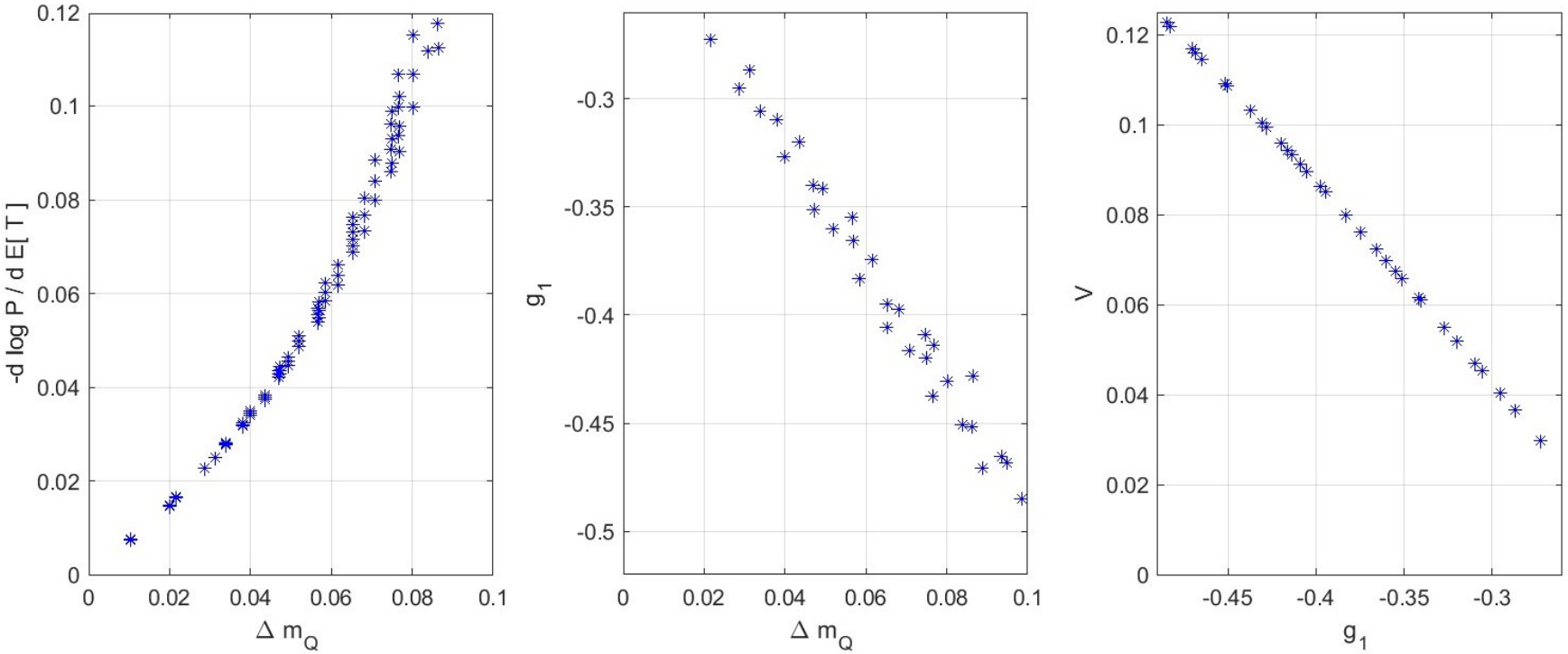
Calibration Strategy

- **Problem**: Parameter space is large
  1. preference parameters: γ, ρ, ψ
  2. normal time parameters: $\mu(0), \sigma(0)$
  3. pandemic parameters: $\mu(s), \sigma(s), \chi(s)$ for $s \in \{1, S-1\}$
  4. state switching parameters: $\eta, \lambda_u, \lambda_d, S$

- **Insight**: Empirical quantity measured above effectively identifies sufficient statistic for pandemic parameters (3)
  - $\Delta m_Q =$ decline in (risk neutral) expected growth rate of q in pandemic states

- In addition
  - Set (4) effectively reduces to two quantities: pandemic frequency and duration
  - Take standard values from macro-finance literature for (1) and (2) Parameter values

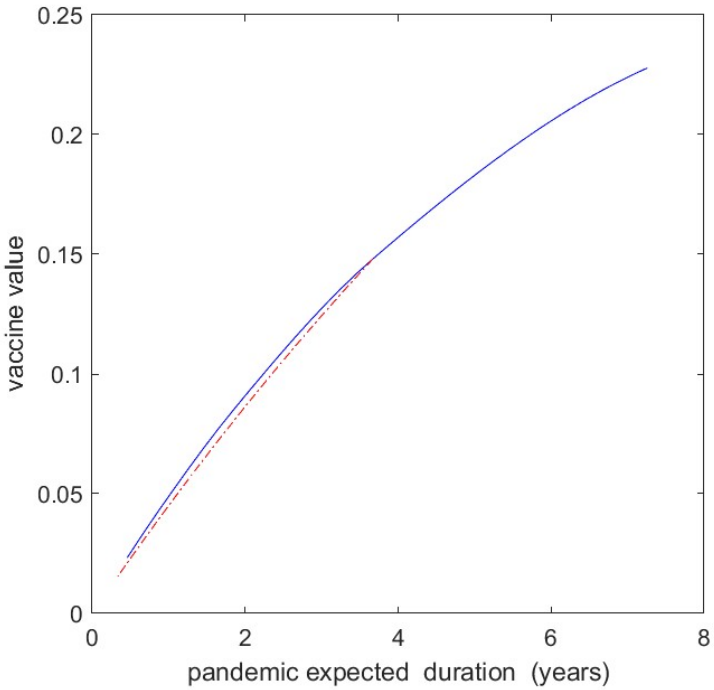
IDENTIFICATION

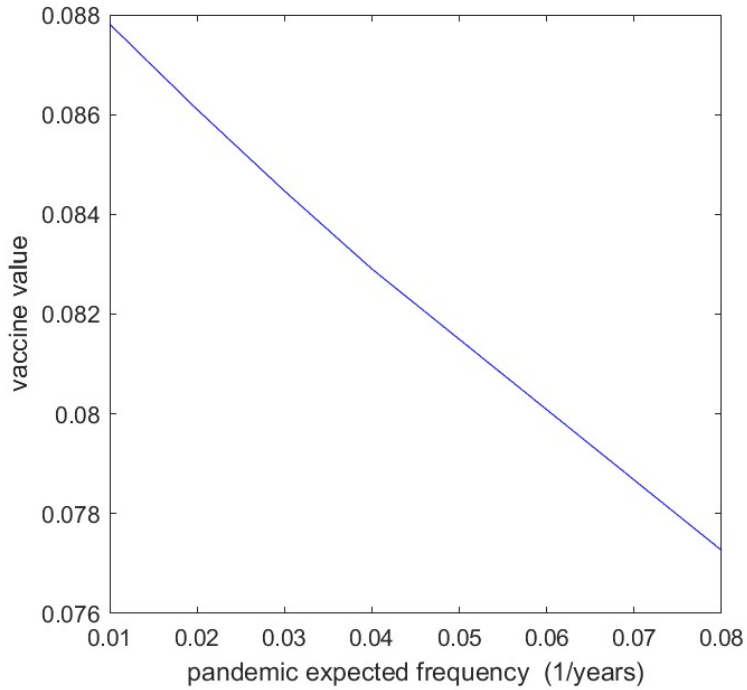


- First fix timing: Spring 2020 from VPI
  - Unconditional expected duration of pandemic is 4 years
  - Current expected time to exit is 2 years
- Then each * corresponds to a different set of pandemic parameters
- Market response to vaccine progress pins down pandemic parameters

Results

Value of Ending the Pandemic





- With expected duration equal to 1 year, value of a cure is 5% of wealth and increases to 15% when expected duration is 4 years
- Value of a one-time cure is lower when pandemics are more frequent

Value of Shortening the Pandemic

- Defined V as the value of *ending* the pandemic

Initial Expected Duration	Expected Duration After Intervention (Years)							
	3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.0
4.0								15.8
3.5								14.1
3.0								12.4
2.5								10.3
2.0								8.6
1.5								6.6
1.0								4.5
0.5								2.3

Value of Shortening the Pandemic

- Defined V as the value of *ending* the pandemic
- Similarly estimate the value of an intervention that *shortens* the pandemic
  - E.g., partially successful vaccine or incomplete vaccination by the population which cuts pandemic duration

		Expected Duration After Intervention (Years)							
		3.5	3.0	2.5	2.0	1.5	1.0	0.5	0.0
Initial Expected Duration	4.0	2.0	4.0	5.9	7.9	9.9	11.9	13.9	15.8
	3.5	–	2.0	4.0	6.1	8.1	10.1	12.1	14.1
	3.0	–	–	2.1	4.1	6.2	8.3	10.3	12.4
	2.5	–	–	–	2.1	4.2	6.2	8.3	10.3
	2.0	–	–	–	–	2.2	4.3	6.5	8.6
	1.5	–	–	–	–	–	2.2	4.4	6.6
	1.0	–	–	–	–	–	–	2.2	4.5
	0.5	–	–	–	–	–	–	–	2.3

Discussion

1. Is 5-15% of total wealth economically sensible?
   - Similar to literature computing welfare gains to eliminating disasters
   - Tallarini Jr (2000) finds reducing business cycle risk costs 13% (conservative)
   - Barro (2009) reports willing to pay up to 20% of permanent income to eliminate disaster risk
   - Pindyck and Wang (2013) estimates willingness to pay to reduce impact of a disaster to 15% of capital stock at 7%
2. How much is "5% of q" in actual money?
3. Consistent with other ways of assessing the cost of COVID-19?

Discussion

1. Is 5-15% of total wealth economically sensible?
2. How much is "5% of q" in actual money?
   - Model's q is total wealth / capital stock / source of consumption
   - As components of total wealth:
     - 5% of US household wealth at end of 2019 was $5 trillion
     - 40% decline in US market capitalization at onset of pandemic was $9 trillion
   - In calibration, annual consumption

     $C \approx 0.04q \implies 0.05q = (0.05/0.04) \times \$13.4\text{trillion (2019) or } V \approx \$17 \text{ trillion}$
3. Consistent with other ways of assessing the cost of COVID-19?

Discussion

1. Is 5-15% of total wealth economically sensible?
2. How much is "5% of q" in actual money?
3. Consistent with other ways of assessing the cost of COVID-19?
   - Literature estimating COVID-19 cost from foregone health & economic activity
   - Cutler and Summers (2020) estimate total economic cost to be $16 trillion
     - Writing in mid-2020 and assumed the pandemic "will be substantially contained by the fall of 2021"
     - $\Longrightarrow$ Estimate of a rate of loss for one year

Extensions

Extensions

1. Learning and uncertainty about pandemic parameters
   - Relax assumption that agents know the regime switching probabilities
   - Welfare gain rises sharply relative to full-information model

Additional Welfare Gain Under Uncertainty

	$\hat{\lambda}$		
$\hat{\eta}$	0.2	0.5	1.0
0.01	0.176	0.230	0.191
0.05	0.109	0.196	0.205

   - Agent would be willing to pay as much for the resolution of parameter uncertainty as for resolving the pandemic itself

More details | Welfare gain under parameter uncertainty | Value of eliminating pandemics | Value of information

2. Endogenize pandemic severity by including labor choice
3. Endogenize option to invest in vaccine research

Extensions

1. Learning and uncertainty about pandemic parameters
2. Endogenize pandemic severity by including labor choice
   - Agents increase exposure to health risk by supplying labor
     - Tradeoff augmenting capital vs. reducing capital loss from health shocks
   - Agents optimally withdraw labor, and magnitude of withdrawal determines equilibrium severity of the shocks to output
   - Agents' privately optimal labor choice does not internalize exposure created for other agents
     - Central planner imposes a stricter labor contraction (or lockdown) and subjects economy to less damage, so welfare gain is ≈15% lower

More details | Endogenous pandemic parameters via labor | Externality and welfare gain

3. Endogenize option to invest in vaccine research

Extensions

1. Learning and uncertainty about pandemic parameters
2. Endogenize pandemic severity by including labor choice
3. Endogenize option to invest in vaccine research
   - Speed of progress is an equilibrium outcome
   - Optimal research effort imposes a constraint on parameters that does not affect our empirical identification of pandemic duration and severity
   - Given observed market response to vaccine progress and expected pandemic duration, welfare calculation is not significantly altered

Conclusion

- Estimate the value of ending the pandemic using the joint behavior of stock prices and a vaccine progress indicator based on the chronology of stage-by-stage progress of individual vaccine candidates and related news
- Calibrate regime-switching general equilibrium model to match stock market response to scientific progress
  - With standard preference parameters, value of a cure is worth 5-15% of wealth, depending on expected duration
- Value rises steeply with uncertainty about expected frequency and duration of pandemic
  - Understanding the fundamental biological and social determinants of future pandemics may be as important as resolving the immediate crisis
- With endogenous pandemic severity via labor choice, value rises with degree of exposure externality

Appendix

Vaccine States

- Vaccines typically take years of research, preclinical testing and clinical trials

State	Description
Preclinical Testing	Antigen discovery and development of vaccine formulation Test on cells and animals
Phase I Safety Trials	Small number of people receive the vaccine. Test safety, dosage, immune system response
Phase II Expanded Trials	Hundreds of people, split into groups, receive the vaccine. Test response by group
Phase III Efficacy Trials	Thousands of people receive the vaccine. See how many are infected vs. placebo
Approval	Regulators review trial results

From The New York Times

- Combined phases to accelerate vaccine development

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Vaccine Strategies

Strategy	Description	Examples
Genetic (RNA, DNA)	Vaccines that deliver one or more of the coronavirus's own genes into our cells to provoke an immune response	Moderna, BioNTech-Pfizer-Fosun Pharma
Viral Vector	Vaccines that contain viruses engineered to carry coronavirus genes. Some viral vector vaccines enter cells and cause them to make viral proteins. Other viral vectors slowly replicate, carrying coronavirus proteins on their surface	Johnson & Johnson, AstraZeneca-Oxford
Protein-Based	Vaccines that contain coronavirus proteins but no genetic material	Sanofi-GSK, Novavax
Inactivated / Attentuated	Vaccines created from weakened coronaviruses or those killed with chemicals	Sinovac, Sinopharm
Repurposed	Vaccines already in use for other diseases	Baylor College of Medicine

From The New York Times

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State Durations and Probabilities of Success

- Each state has estimated expected duration τ_s, and probability of success or upward state transition π_s^{base}

State	τ_s (years)	π_s^{base} (%)
Preclinical	0.6	5
Phase I	0.2	70
Phase II	0.2	44
Phase III	0.4	69
Application	0.1	88
Approval	0.5	95

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Candidate Correlations

- Account for positive correlation between candidates using a Gaussian copula approach Description of vaccine strategies
  - Properties of the same virus target, share common institute, finite vaccine strategies
  - Correlation between candidates $n \neq n'$

$$\rho(n, n') = \begin{cases} 0.2 & \text{baseline} \\ \text{add } 0.2 & \text{if shared institute} \\ \text{add } 0.1 & \text{if shared strategy} \end{cases}$$

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Augmenting Probability of Success with News

- 233 articles from 1/1 to 10/31 from FactSet StreetAccount More details

- Articles are categorized into positive and negative news types
  - Positive: Moderna positive data on 5/18 Moderna article
  - Negative: AstraZeneca/Oxford pause on 9/8, Johnson & Johnson pause on 10/13 AstraZeneca/Oxford article Johnson & Johnson article

Positive		Negative	
News type	$\Delta\pi$ (%)	News type	$\Delta\pi$ (%)
Announce next state	+5	Pause in state	-25
State ahead of schedule	+2	State behind schedule	-15
Release positive data	+5	Release negative data	-60
Positive regulatory action	+3	Negative regulatory action	-50
⋮		⋮	

Full table of all news types Number of articles by news type Top 10 candidates by number of articles

- Deterministic decay of 0.5% each day after entering a new state

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Example of FactSet News

- Coded as positive data release

Follow-up: Moderna announces interim phase 1 data for mRNA vaccine (mRNA-1273) against novel coronavirus ($66.69, 0.00)
Monday, May 18, 2020 11:33:01 AM (GMT)

- Moderna announced positive interim clinical data of mRNA-1273, its vaccine candidate against novel coronavirus (SARS-CoV-2), from the Phase 1 study led by the National Institute of Allergy and Infectious Diseases (NIAID), part of the National Institutes of Health (NIH).
- Immunogenicity data are currently available for the 25 µg and 100 µg dose level (ages 18-55) after two doses (day 43) and at the 250 µg level (ages 18-55) after one dose (day 29). Dose dependent increases in immunogenicity were seen across the three dose levels, and between prime and boost within the 25 µg and 100 µg dose levels.
- At this time, neutralizing antibody data are available only for the first four participants in each of the 25 µg and 100 µg dose level cohorts. Consistent with the binding antibody data, mRNA-1273 vaccination elicited neutralizing antibodies in all eight of these participants, as measured by plaque reduction neutralization (PRNT) assays against live SARS-CoV-2. The levels of neutralizing antibodies at day 43 were at or above levels generally seen in convalescent sera.
- mRNA-1273 was generally safe and well tolerated, with a safety profile consistent with that seen in prior Moderna infectious disease vaccine clinical studies. The sole incidence of a grade 3 adverse event in the 25 µg and 100 µg dose cohorts was a single participant at 100 µg who experienced grade 3 erythema (redness) around the injection site. To date, the most notable adverse events were seen at the 250 µg dose level, comprising three participants with grade 3 systemic symptoms, only following the second dose. All adverse events have been transient and self-resolving. No grade 4 adverse events or serious adverse events have been reported.
- Preclinical results from a viral challenge study in mice conducted in collaboration with NIAID and its academic partners are also available. In this study, vaccination with mRNA-1273 prevented viral

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Pause in AstraZeneca and Oxford Trial

AstraZeneca COVID-19 vaccine subject diagnosed with transverse myelitis - NYT (8348.0000p, 0)
Wednesday, September 09, 2020 01:55:44 AM (GMT)

- The article says that transverse myelitis, often brought on by viral infections, is an inflammatory syndrome affecting the spinal cord.
- A person familiar with the situation tells the NYT that the timing of the diagnosis and whether it's linked to the vaccine being tested isn't known.
- The source tells the NYT that the subject was enrolled in a Phase 2/3 trial in the UK; AstraZeneca doesn't confirm the diagnosis or the subject's location.
- The NYT reports that Moderna announced today that its trial is continuing, regardless of the pause in the AstraZeneca trial.

Reference Links:

- NY Times

Industries: Biotechnology & Drugs, Major Drugs
Primary Identifiers: AZN-GB, MRNA-US
Related Identifiers: AZN-GB, MRNA-US
Subjects: Articles, Reports, Conjecture, Media Summaries, Published Reports
Related Stories:

- Follow-up: AstraZeneca COVID-19 vaccine study put on hold due to suspected adverse reaction in participant in the U.K. - Stat News ($54.70, 0.00)

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Pause in Johnson & Johnson Trial

Johnson & Johnson Covid-19 vaccine study paused- STAT news ($151.84, 0.00)
Tuesday, October 13, 2020 12:47:31 AM (GMT)

- STAT reports J&J confirmed the pause, due to an unexplained illness in a study participant, though noted the study is not currently under a clinical hold, highlighting that "it is not always immediately apparent" whether the individual received a treatment or a placebo
  - The article notes the data and safety monitoring board met late Monday to review the case
- A source familiar with the study tells STAT considering the size of the trial this development is not surprising

Editor's note: Added secondary ticker for EBS, which has vaccine-related contracts with JNJ. **Reference Links:**

- STAT
- J&J statement

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Augmenting Probability of Success with News and Decay

- Augment vaccine timeline with relevant news
  - Using stock-level data requires separating vaccine portion of pharmaceutical companies and/or presence of government investment and caps on user fees

- Let $\omega_{n,t} \in \Omega$ denote news published at t about candidate n and let $\Delta\pi : \Omega \to [-1, 1]$ map news to changes in probabilities. Summing the cumulative effect of news from sample start t_0 to t,

$$\Delta\pi_{n,t}^{\text{news}} = \sum_{t'=t_0}^{t} \Delta\pi(\omega_{n,t'})$$

- Next decay probability of success each day after entering a new state. Denote the cumulative decay through t as $\Delta\pi_{n,t}^{\text{decay}}$

- Combine baseline probability of success with news and decay

$$\pi_{n,s,t}^{\text{total}} = \frac{\exp \Upsilon_{n,s,t}}{1 + \exp \Upsilon_{n,s,t}}$$

where $\Upsilon_{n,s,t} = \log \frac{\pi_s^{\text{base}}}{1-\pi_s^{\text{base}}} + 2\left[\Delta\pi_{n,t}^{\text{news}} - \Delta\pi_{n,t}^{\text{decay}}\right]$

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News Parameters

Positive		Negative	
News type	$\Delta\pi$ (%)	News type	$\Delta\pi$ (%)
Announce next state	+5	Pause in state	-25
State ahead of schedule	+2	State behind schedule	-15
Release positive data	+5	Release negative data	-60
Positive regulatory action	+3	Negative regulatory action	-50
Positive preclinical progress	+1	Negative preclinical progress	-2
Positive enrollment	+1	Negative enrollment	-5
Dose starts	+1		
State resumes after pause	+5		

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Data and parameters - Continued

- Count by news type (news articles from January 1 to October 31)

News Type	Number of Articles
Release positive data	79
Announce next state	45
Positive regulatory action	30
Positive preclinical progress	22
Announce dosage start	21
Positive enrollment	17
State ahead of schedule	7
State resumed	5
State paused	4
State behind schedule	1
Negative regulatory action	1
Negative enrollment	1
Total	233

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Data and parameters - Continued

- Top 10 candidates by news count (news articles from January 1 to October 31)

Candidate	Number of Articles
Moderna	37
BioNTech / Fosun Pharma / Pfizer	25
Oxford / AstraZeneca	23
Johnson & Johnson / Beth Israel Deaconess Medical Center	21
Inovio Pharmaceuticals	18
Novavax	14
Arcturus / Duke	10
Vaxart	9
Medicago / GSK / Dynavax	8
Takis / Applied DNA / Evvivax	8

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Each day, one run repeats steps 1 to 3 until candidates have all failed or deployed

1. Draw two 259-dimensional multivariate Normal random variables
$$z_t^u, z_t^d \sim \mathcal{N}(0, \mathcal{R})$$
2. For each candidate, transform to exponentially driven time to success and failure
$$t_{n,s,t}^u = -\frac{\log \Phi(z_{n,t}^u)}{\lambda_{n,s,t}^u} \quad \text{and} \quad t_{n,s,t}^d = -\frac{\log \Phi(z_{n,t}^d)}{\lambda_{n,s,t}^d}$$
where
$$\lambda_{n,s,t}^u = \frac{\pi_{n,s,t}^{\text{total}}}{\tau_s} \quad \text{and} \quad \lambda_{n,s,t}^d = \frac{1 - \pi_{n,s,t}^{\text{total}}}{\tau_s}$$
3. If $t_{n,s,t}^u > t_{n,s,t}^d \implies$ candidate's run is over
   If $t_{n,s,t}^u < t_{n,s,t}^d \implies$ candidate advances states, continue run

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Simulation - Continued

4. Candidate's time to deployment

$$T_n = \begin{cases} \sum_s t^u_{n,s,t} & \text{candidate deploys} \\ \infty & \text{candidate fails} \end{cases}$$

5. Minimum time to vaccine deployment across candidates for this run

$$T^*_m = \min_n T_n$$

Then repeat for 50,000 simulations, calculate cross-simulation average T^D, and advance to $t + 1$

On each day across runs,

$$\mathbb{E}[T^*] = (1 - \mu)T^D + \mu T^{ND}$$

where μ is the fraction of simulations with all candidates failing and $T^{ND} = 4$ years is an estimate of the expected time to first success by a project other than those currently active.

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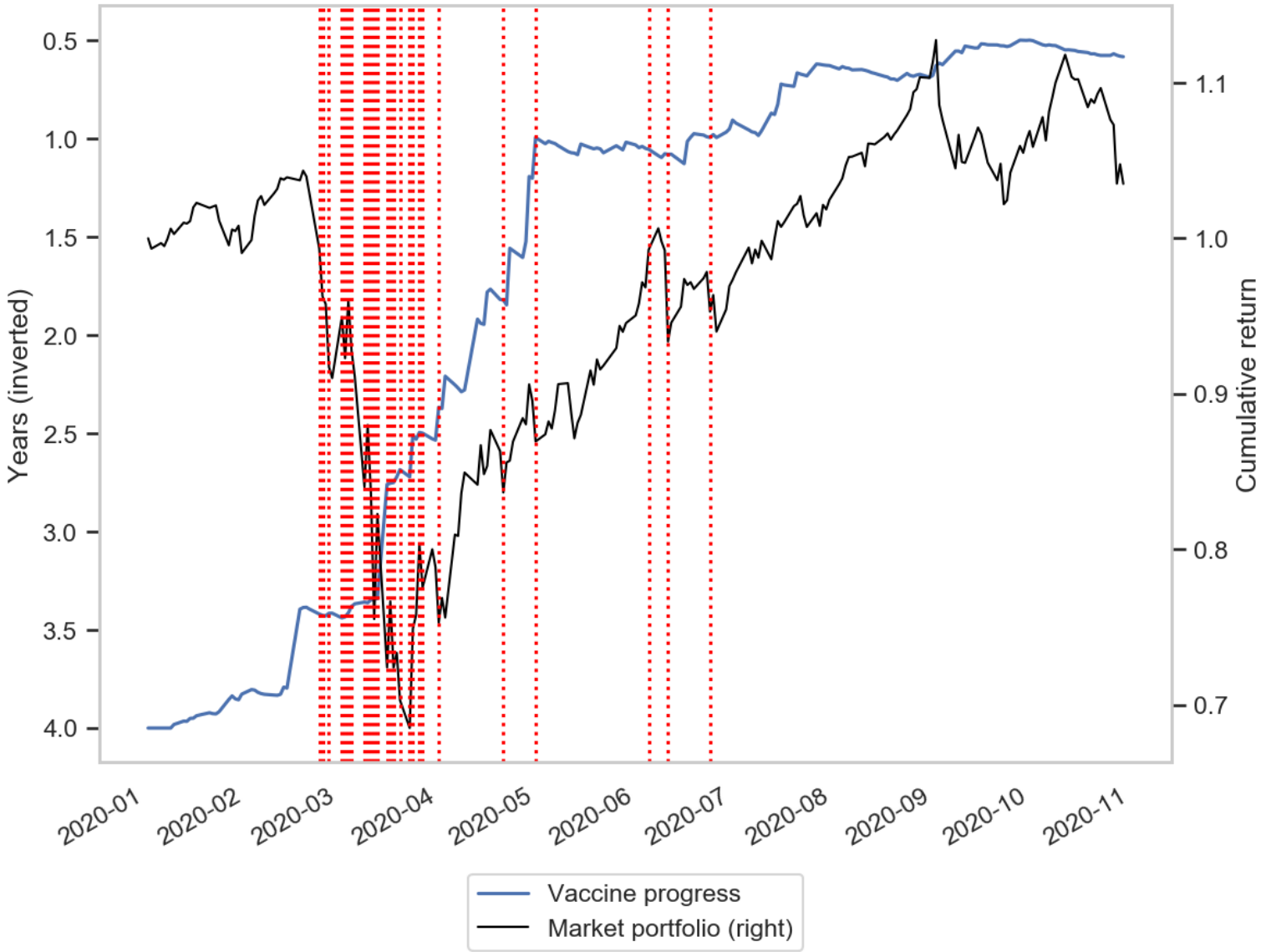
Jump Days from Baker et al. (2020b)



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Stock Market Sensitivity to Vaccine Progress

$$R^e_{m,t} = \alpha + \sum_{h=-2}^{2} \beta_h \Delta \text{VPI}_{t+h} + \gamma_1 R^e_{m,t-1} + \gamma_2 R^e_{m,t-2} + \sum_{j=1}^{28} \delta_j \mathbb{1}_{\text{jump } j} + \epsilon_t \quad (1)$$

	(1)	(2)	(3)
	OLS	KPSS Prior 1	KPSS Prior 2
γ_1	-0.070	-0.088	-0.096
	(0.067)	(0.035)	(0.035)
γ_2	0.131	0.163	0.168
	(0.092)	(0.035)	(0.035)
$\sum_{h=-2}^{2} \beta_{t+h}$	-8.593	-6.365	-4.086
	(0.653)	(1.345)	(1.056)
α	0.204	0.240	0.279
	(0.097)	(0.079)	(0.078)
N	206	206	206

Note: Sample period is 1/1/2020 to 10/31/2020. OLS results show Newey-West standard errors with 4 lags in parentheses, and $\sum_{h=-2}^{2} \beta_{t+h}$ shows standard deviation from a two-sided F-test. KPSS results show posterior standard deviations. Prior 1 assumes a unit standard deviation for the pre-truncated normal distribution for all β's. Prior 2 assumes a pre-truncated standard deviation of 1 for β_t, 0.7 for β_{t-1} and β_{t+1}, and 0.5 for β_{t-2} and β_{t+2}.

Table with OLS robustness checks | Back to slide

Stock Market Sensitivity - Robustness

$$R^e_{m,t} = \alpha + \sum_{h=-2}^{2} \beta_h \Delta \text{VPI}_{t+h} + \gamma_1 R^e_{m,t-1} + \gamma_2 R^e_{m,t-2} + \sum_{j=1}^{28} \delta_j \mathbb{1}_{\text{jump } j} + \epsilon_t$$

	(1)	(2)	(3)	(4)	(5)	(6)
News	All states	None	Current state	All states	All states	All states
Depreciation	Y	N	Y	Y	Y	Y
Cor(n, n')	0.2	0.2	0.2	0.4	0.2	0.2
$\pi^{\text{base}}_{\text{approval}}$	0.95	0.95	0.95	0.95	0.85	0.95
Ex-China and Russia	Y	Y	Y	Y	Y	N
γ_1	-0.070	-0.067	-0.068	-0.075	-0.073	-0.080
	(-1.04)	(-1.01)	(-1.02)	(-1.10)	(-1.08)	(-1.50)
γ_2	0.131	0.116	0.127	0.131	0.134	0.111
	(1.43)	(1.32)	(1.42)	(1.42)	(1.46)	(1.37)
$\sum_{h=-2}^{2} \beta_{t+h}$	-8.593	-8.806	-6.746	-7.541	-8.582	-7.134
	(8.21)	(5.50)	(5.37)	(5.52)	(8.62)	(3.69)
α	0.204**	0.195*	0.226**	0.220**	0.203**	0.210**
	(2.11)	(1.94)	(2.28)	(2.27)	(2.11)	(2.14)
N	206	206	206	206	206	206

Note: Data from 1/1/2020 to 10/31/2020. Column 3 increases the $\Delta\pi$ from news on positive data releases, positive enrollment and dose starts to 15%, 5% and 5%, respectively. Table uses Newey-West standard errors with 4 lags; t-statistics are shown in parentheses while $\sum_{h=-2}^{2} \beta_{t+h}$ has a two-sided F-test. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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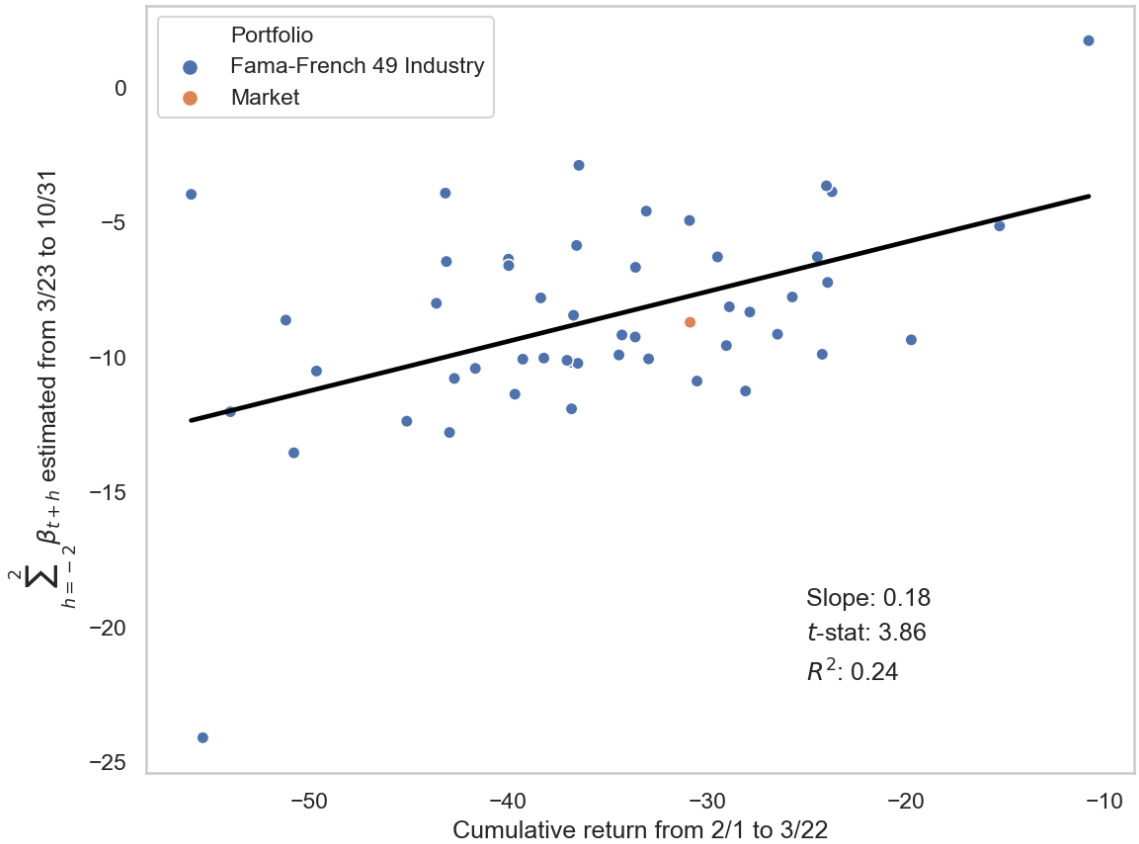
Fama-French 49 Industry Results

- Exposure to COVID-19: cumulative return from 2/1 to 3/22
- Vaccine progress sensitivity: re-run regression from 3/23 to 10/31 for each industry
- ↑ exposure and sensitivity: oil, fabricated products, recreation
- ↓ exposure and sensitivity: pharmaceutical products, food, software



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The Price of an Output Claim

- Setting the instantaneous expected excess returns to P equal to minus the covariance of those returns with the kernel yields a set of $S+1$ linked PDEs. Conjecture/verify solved by linear form $P = p(s)\, q$ where $p(s)$ are constants.

- The constants solve matrix system, where $\tilde{\cdot}$ represent jump intensities under the risk-neutral measure

$$\begin{bmatrix} r(0)+c(0)-(\mu-\gamma\sigma^2)+\tilde{\eta} & -\tilde{\eta} & 0 & \cdots \\ -\tilde{\lambda}_d & r(s)+c(s)-(\ell^*)^\alpha(\mu-\gamma\sigma^2)+\chi\Delta\tilde{\zeta}+\tilde{\lambda}_d+\tilde{\lambda}_u & -\tilde{\lambda}_u & 0 \\ 0 & \ddots & \ddots & \ddots \\ \vdots & \ddots & \ddots & \ddots \\ -\tilde{\lambda}_u & 0 & \cdots & \end{bmatrix} p$$

$$= \begin{bmatrix} (\mu-\gamma\sigma^2) \\ (\ell^\star)^\alpha(\mu-\gamma\sigma^2)-\chi\Delta\tilde{\zeta} \\ \vdots \\ \vdots \\ \vdots \end{bmatrix}.$$

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Expected Time to Vaccine

- To connect with empirical work, also need expression for the expected time to exit the pandemic conditional on being in state $s > 0$
- Denote this expectation $\mathbb{E}[T^\star]$
- It can be written as $E(s)$ where E solves the matrix system

$$\begin{bmatrix} 1 & -1 & 0 & \cdots & 0 \\ \frac{-\lambda_d}{\lambda_u+\lambda_d} & 1 & \frac{-\lambda_u}{\lambda_u+\lambda_d} & \cdots & \frac{-\lambda_u}{\lambda_u+\lambda_d} \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \frac{-\lambda_u}{\lambda_u+\lambda_d} \\ \frac{-\lambda_d}{\lambda_u+\lambda_d} & \cdots & \cdots & \frac{-\lambda_d}{\lambda_u+\lambda_d} & 1 \end{bmatrix} E = \begin{bmatrix} \frac{1}{\lambda_u} \\ \frac{1}{\lambda_u+\lambda_d} \\ \vdots \\ \vdots \\ \vdots \end{bmatrix}$$

- The quantity estimated in the data is in the model

$$\frac{\Delta \log P}{\Delta \mathbb{E}[T^\star]}$$

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Endogenizing Pandemic Parameters

- Extend model to include optimal labor choice that is responsive to threat of infection. In pandemic states $s \in \{1, \ldots, S-1\}$

$$dq = \ell^{\alpha} q \mu dt - Cdt + \sigma \ell^{\alpha/2} q dB_t - \Big[\underbrace{\ell\varepsilon + k + KL}_{\chi(\ell, L)}\Big] q dJ(t)$$

where

$\ell \in [0, \overline{\ell}]$: Labor supply

$\alpha \in (0, 1)$: Elasticity of instantaneous expected output with respect to labor

ε : Private exposure to pandemic $\propto \ell$

k : Private exposure to pandemic

L : Aggregate labor supply

K : Exposure to pandemic (externality) $\propto L$

- In each state s, choose optimal consumption $C(s, L^*(s))$ and labor $\ell(s, L^*(s))$ to maximize objective function $\mathbb{J}(S)$
- Equilibrium fixed point $L^*(s) = \ell(s, L^*(s))$

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Equilibrium Labor

- Equilibrium labor in non-pandemic states, $L(0) = L(S) = \bar{\ell}$
  - $\bar{\ell}$ is exogenous and considered as natural rate of labor supply
  - No disutility from labor

- Equilibrium labor in pandemic states $\ell^\star(s)\ \forall s \in \{1, \ldots, S-1\}$ solves

$$\chi\left(L(s), L(s)\right) = k + (\varepsilon + K)L(s) = 1 - \left(L(s)\right)^{\frac{1-\alpha}{\gamma}}\nu$$

  where

$$\nu \equiv \left[\frac{\alpha\left(\mu - \frac{1}{2}\gamma\sigma^2\right)}{\zeta\varepsilon}\right]^{-\frac{1}{\gamma}}$$

- If infection parameters vary across states, then $\ell^\star(s)$ would also vary with s

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Endogenous Pandemic Parameters via Labor

- Model implies degree of pandemic damage via endogenous $\mu(s), \sigma(s), \chi(s)$

- Many ways to choose parameters to match Δm_Q as identified via empirical work
  - We fix α, k and explore variation in K, ϵ

	$\ell^\star$				Δm_Q		
	$K \rightarrow$				$K \rightarrow$		
	0.85	0.82	0.80		0.05	0.06	0.06
ω	0.79	0.77	0.74	ω	0.05	0.06	0.06
$\downarrow$	0.74	0.72	0.70	$\downarrow$	0.05	0.06	0.06
	0.69	0.67	0.65		0.05	0.05	0.06

Note: $\alpha = 0.5$, $k = 0.006$, $\eta = 0.4$, $\lambda = 0.5$

- Some empirical evidence suggests labor contraction ≈20% in April 2020

Table 1 from Cajner et al. (2020)

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Externality and Value of a Cure

- Labor's impact on pandemic exposure (via *KL* term) not internalized
- Compare value of a cure under social efficient (central planner) solution

	$\ell^\star_{cp}/\ell^\star$				V_{cp}/V		
	$K \rightarrow$				$K \rightarrow$		
	0.38	0.30	0.25		0.87	0.82	0.77
ω	0.39	0.31	0.25	ω	0.88	0.83	0.79
$\downarrow$	0.40	0.32	0.26	$\downarrow$	0.89	0.84	0.80
	0.40	0.33	0.27		0.90	0.86	0.82

Note: $\alpha = 0.5$, $k = 0.006$, $\eta = 0.4$, $\lambda = 0.5$

- Vaccine less valuable with central planner; more so when externality is stronger
- Policy implication: absence of central planner makes agents more willing to pay for vaccine

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2-State Model with Uncertainty

- Study effect of learning and uncertainty around the frequency and duration of pandemics on the value of vaccines
- 2-state model, $s \in S = \{0, 1\}$ where 0 is non-pandemic and 1 is pandemic, with transition probabilities

$$P(s_{t+dt} = 1 | s_t = 0) = \eta dt \quad \text{and} \quad P(s_{t+dt} = 0 | s_t = 1) = \lambda dt$$

- Imperfect information: agents have beliefs about intensity parameters η, λ

$$\eta \sim \Gamma(a^\eta, b^\eta) \quad \text{and} \quad \lambda \sim \Gamma(a^\lambda, b^\lambda)$$

then observe regime switches and update hyperparameters by Bayes' rule

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Solution

- Value function now depends on:
  - Number of experienced pandemics
  - Point estimates of switching intensities

- HBJ equations form infinite dimensional system indexed by M, where M runs over even numbers

$$g_0 = \rho^{\psi}\left(\frac{\theta}{\psi}\right) H_M^{-\psi/\theta} + \hat{\eta}\left(\frac{H_{M+1}}{H_M} - 1\right) - \frac{(\hat{\eta})^2}{a^{\eta} H_M}\frac{\partial H_M}{\partial \hat{\eta}}$$

$$g_1 = \rho^{\psi}\left(\frac{\theta}{\psi}\right) H_{M+1}^{-\psi/\theta} + \hat{\lambda}\left(\frac{H_{M+2}}{H_{M+1}} - 1\right) - \frac{(\hat{\lambda})^2}{a^{\lambda} H_{M+1}}\frac{\partial H_{M+1}}{\partial \hat{\lambda}}$$

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Value of a Cure under Parameter Uncertainty

Low Uncertainty / Low EIS

$\hat{\eta}$ \ $\hat{\lambda}$	0.2	0.5	1.0
0.01	0.308	0.136	0.068
0.05	0.430	0.214	0.111

Low Uncertainty / High EIS

$\hat{\eta}$ \ $\hat{\lambda}$	0.2	0.5	1.0
0.01	0.327	0.148	0.074
0.05	0.429	0.239	0.130

High Uncertainty / Low EIS

$\hat{\eta}$ \ $\hat{\lambda}$	0.2	0.5	1.0
0.01	0.813	0.720	0.613
0.05	0.831	0.751	0.658

High Uncertainty / High EIS

$\hat{\eta}$ \ $\hat{\lambda}$	0.2	0.5	1.0
0.01	0.503	0.378	0.265
0.05	0.538	0.435	0.335

Note: Table shows the fraction of wealth the agent would be willing to surrender for a one-time transition out of the pandemic state. High (low) EIS sets $\psi = 1.5$ ($\psi = 0.15$). Agents know the parameters λ and η in low uncertainty, and in high uncertainty have posterior standard deviation equal to their point estimates of them. All use coefficient of relative risk aversion $\gamma = 4$, rate of time preference $\rho = 0.04$, elasticity of expected output with respect to labor $\alpha = 0.5$, output volatility $\sigma = 0.05$, expected output growth $\mu = 0.05$, and exposure to the pandemic via private labor $\varepsilon = 0.4$, unrelated to labor $k = 0.1$, and via aggregate labor $K = 0.4$, and P_t intensity $\zeta = 1$.

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Value of Eliminating Pandemics

Low Uncertainty / Low EIS

$\hat{\eta}$ \ $\hat{\lambda}$	0.2	0.5	1.0
0.01	0.308	0.136	0.068
0.05	0.430	0.214	0.111

Low Uncertainty / High EIS

$\hat{\eta}$ \ $\hat{\lambda}$	0.2	0.5	1.0
0.01	0.327	0.148	0.074
0.05	0.429	0.239	0.130

High Uncertainty / Low EIS

$\hat{\eta}$ \ $\hat{\lambda}$	0.2	0.5	1.0
0.01	0.813	0.720	0.613
0.05	0.831	0.751	0.658

High Uncertainty / High EIS

$\hat{\eta}$ \ $\hat{\lambda}$	0.2	0.5	1.0
0.01	0.503	0.378	0.265
0.05	0.538	0.435	0.335

Note: Table shows the fraction of wealth the agent would exchange to live in a world with no pandemics. High (low) EIS sets $\psi = 1.5$ ($\psi = 0.15$). Agents know the parameters λ and η in low uncertainty, and in high uncertainty have posterior standard deviation equal to their point estimates of them. All use coefficient of relative risk aversion $\gamma = 4$, rate of time preference $\rho = 0.04$, elasticity of expected output with respect to labor $\alpha = 0.5$, output volatility $\sigma = 0.05$, expected output growth $\mu = 0.05$, and exposure to the pandemic via private labor $\varepsilon = 0.4$, unrelated to labor $k = 0.1$, and via aggregate labor $K = 0.4$, and P_t intensity $\zeta = 1$.

Value of Information

		Low EIS				High EIS		
		$\hat{\lambda}$				$\hat{\lambda}$		
		0.2	0.5	1.0		0.2	0.5	1.0
$\hat{\eta}$	0.01	0.733	0.675	0.587	0.01	0.270	0.273	0.209
	0.05	0.708	0.682	0.617	0.05	0.200	0.255	0.236

Note: Table shows the fraction of wealth the agent would be willing to surrender for a one-time transition from high to low parameter uncertainty. High (low) EIS sets $\psi = 1.5$ ($\psi = 0.15$). Agents know the parameters λ and η in low uncertainty, and in high uncertainty have posterior standard deviation equal to their point estimates of them. All use coefficient of relative risk aversion $\gamma = 4$, rate of time preference $\rho = 0.04$, elasticity of expected output with respect to labor $\alpha = 0.5$, output volatility $\sigma = 0.05$, expected output growth $\mu = 0.05$, and exposure to the pandemic via private labor $\varepsilon = 0.4$, unrelated to labor $k = 0.1$, and via aggregate labor $K = 0.4$, and P_t intensity $\zeta = 1$.