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See <https://www.acceleratinght.org/home>

Market Design for Vaccine Supply

Eric Budish, Chicago Booth

AEA Meetings, Jan 2022

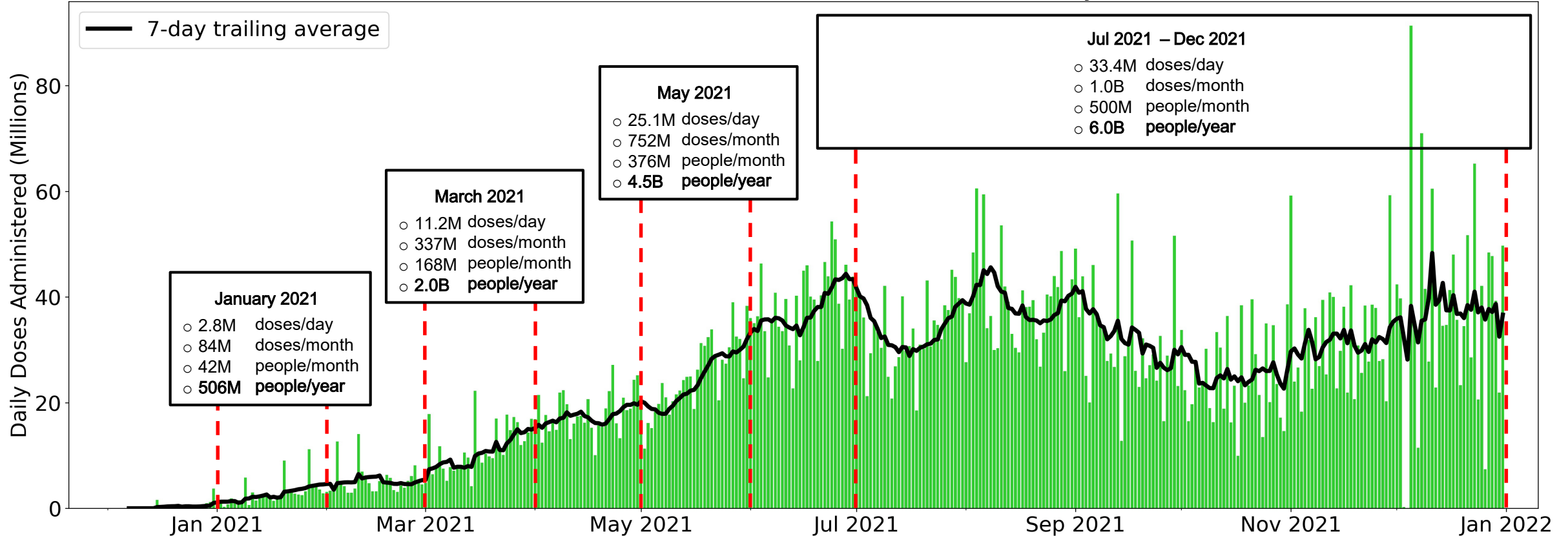
Presentation based on:

“Market Design to Accelerate Covid-19 Vaccine Supply”, *Science* Feb 2021

“Preparing for a Pandemic: Accelerating Vaccine Availability”, *AEA Papers* May 2021

Global Vaccination Data

Covid-19 Vaccine Doses Administered Globally



Source: Bloomberg Covid-19 Vaccine Tracker (Jan-Dec 2021) and Our World in Data (Dec 2020).

Global Vaccination Data--How Long?

- At realized rates of vaccination, when is world 70% vaccinated? (2 doses)
 - HICs: Aug 24th, 2021
 - World: Feb 15th, 2022

 - (HIC = high-income countries. See Science paper for assumptions about vaccine distribution to countries, based on observed deals.)

- What if full vaccination = 3 doses?
 - HICs: Nov 15th, 2021
 - World: July 26th, 2022

Our Main Point

- **Huge value to accelerating vaccine availability in pandemics through early, large -scale at-risk investment in vaccine manufacturing**
- **Example: 7bn annual courses online in Dec 2020 →**
 - Vaccinate HICs by April 2021 (4.3 months)
 - Vaccinate World by Sept 2021 (9.2 months)
 - (Our model recommended 27.5bn courses of at-risk capacity across all vaccine candidates, of which 7.1bn courses were for vaccine candidates that turned out to work ex post)
 - 3 doses? Plenty of capacity for this negative realization. HICs by June 2021, World by Jan 2022
- **Speed is extremely valuable.**
 - Each month Covid-19 kills ~200,000-300,000 people globally
 - GDP harm: \$500bn / month pre-vaccines (World Bank, IMF)
 - Cutler-Summers comprehensive harm: \$3trn / month (US figures extrapolated globally based on GDP)
 - We used \$1trn / month – likely conservative (health, economic, education, social)
 - Speed also an insurance policy – e.g. variants, boosters

Our Main Point (Simpler Statement)

- World's Easiest Cost Benefit Calculation

Billions < Trillions

Gaps Between Private and Social Incentives

Why might private-market forces not deliver these trillions of value?

1. Social value of a dose >>> Private price of a dose

- (Externalities, Price constraints e.g. due to repugnance)
- Social value: \$5800 per course (Science paper)
- Private prices: \$5-50 per course (observed deals)

2. Social value of speed >>> Private value of speed

- Thought experiment: sell 1bn courses @\$50 per in 12 months versus in 1 month.
- Either way: \$50bn of revenue.
- But latter requires 12x the fixed costs!

3. Social willingness to invest at risk >>> Private willingness

- Same point as #2 only more stark with risk
- Larry Summers metaphor: order 20 pizzas

We analyzed case of COVID -19, but conceptual points and approach may be useful for future pandemics.

Model: Main Ingredients

Features common to analysis in both papers

1. Harm of the pandemic is a flow – vaccinations reduce this flow harm
 - We used a flow cost of \$1 trn / month – likely conservative. (Small diff's between Science and AEAPP)
2. “Capacity equals Speed”
 - Amount of installed capacity determines speed of vaccination
3. Early doses disproportionately to High-Income Countries (HICs)
 - Richer countries should, and did, engage in more at-risk capacity investment
4. Early doses within countries to higher-value patients
 - Captures that early doses go to health-care workers, medically vulnerable

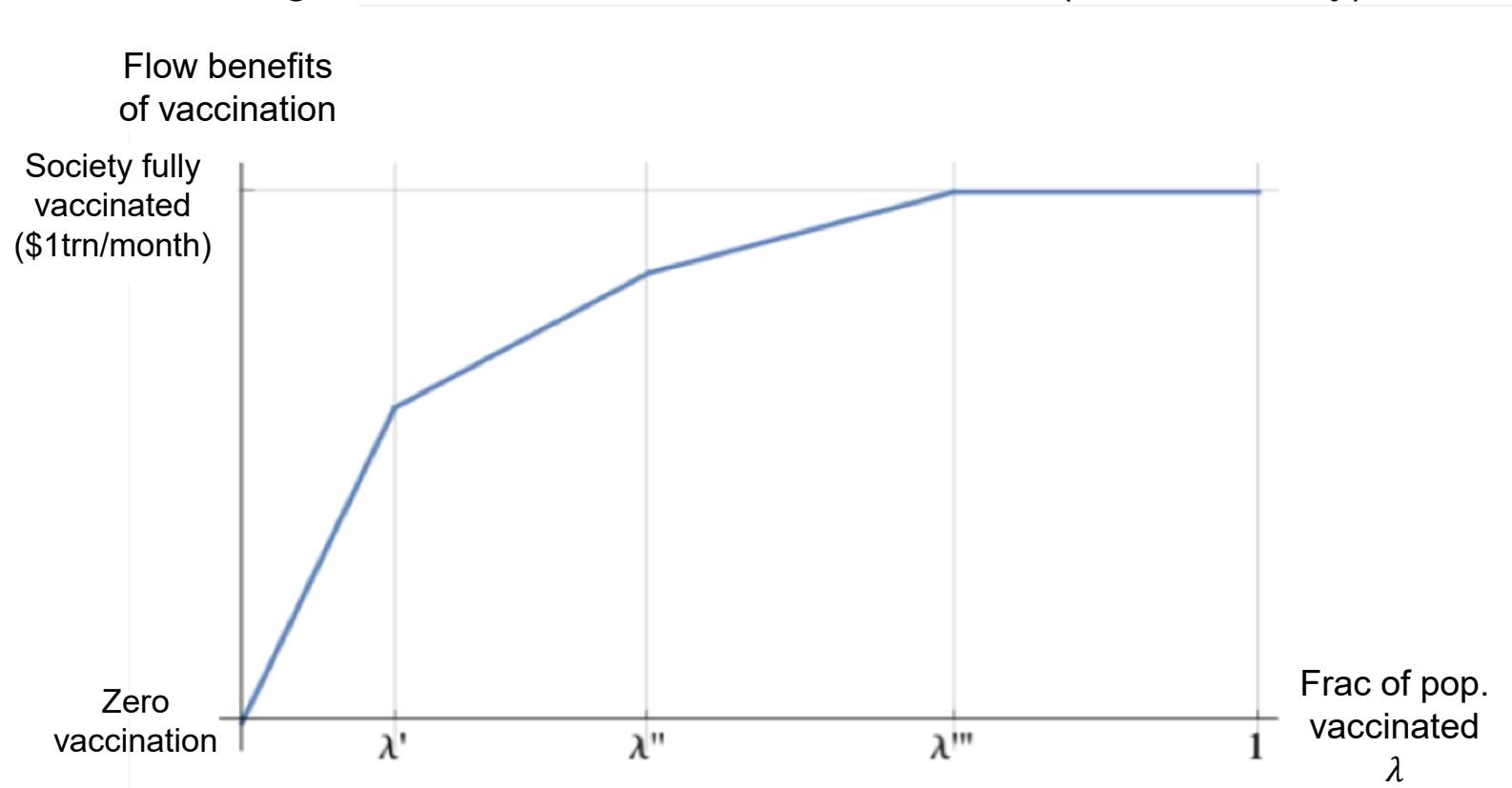
Differences in focus between papers

1. AEAPP: focused on ex-ante vaccine portfolio problem (*before* known which vaccines work)
2. Science: focused on (i) quantifying value of realized capacity, (ii) ex-post value of installing more capacity of vaccines known to work, (iii) contract and market design issues

(Some small additional differences between papers, mostly reflecting knowledge accumulating over time in fog of 2020) ⁷

Model: Flow Benefits of Vaccination

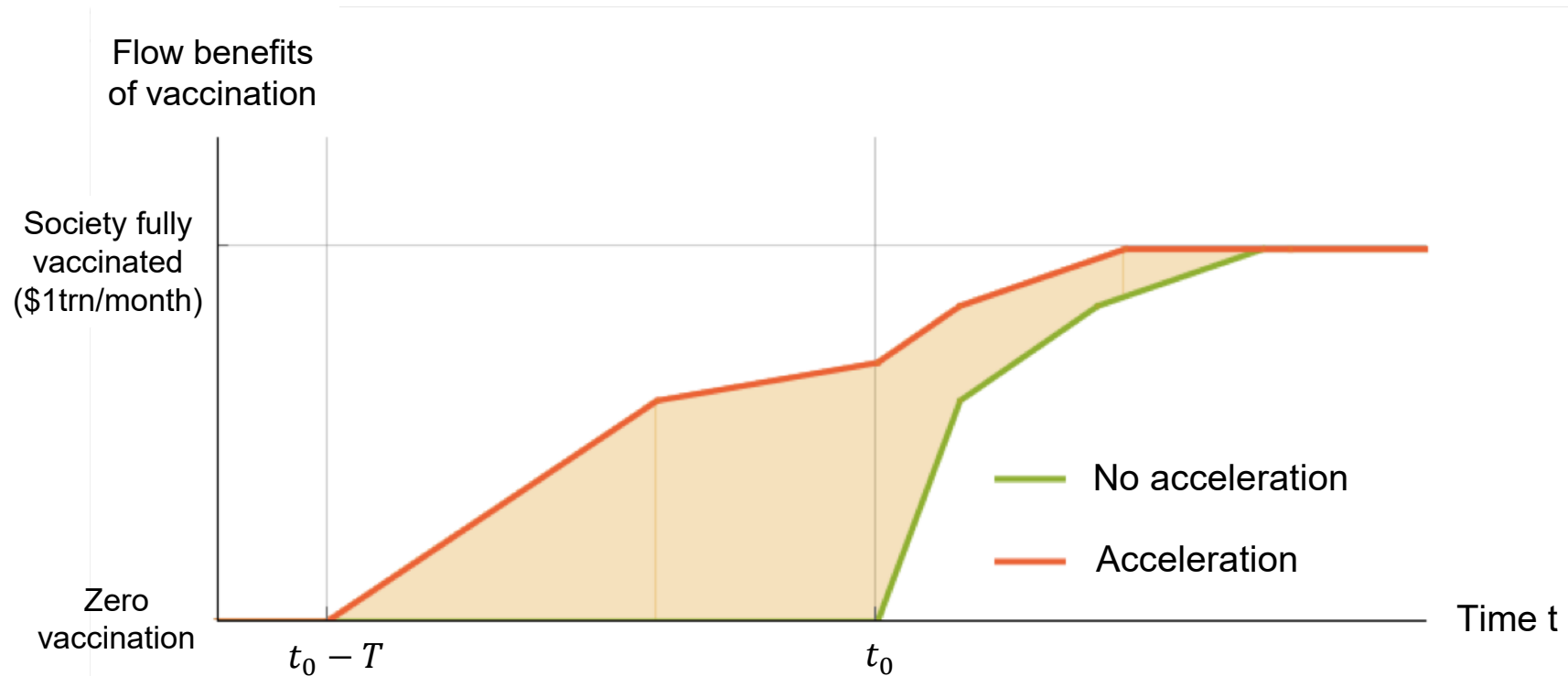
Figure A2: Flow Benefits to Vaccination (within country)



Note: λ' represents proportion of population that is high-priority (e.g., health-care workers, medically vulnerable). Benefits increase more slowly as the rest of the population is vaccinated.

Model: Benefits of Accelerating Vaccination

Figure A4: Vaccination Benefits over Time with and without Acceleration



Note: figure depicts acceleration of some portion of capacity by T time from t_0 . Remainder comes online at t_0 . For full details see AEAPP Appendix.

Model: Optimal Portfolio Problem

Country benefits

- Country i purchases portfolio $v_i = (v_{i1}, v_{i2}, \dots)$ of manufacturing capacities (courses / month) from different candidates. How large are the benefits?
 - Relative to no early investment, in which case successful vaccines are obtained but late (3 month lag, likely conservative).
- Benefits depend on two elements:
 1. Distribution of total (ex-post) effective capacity V given portfolio v_i
 2. Expected societal benefits given total effective capacity V
- Parameters based on talks with experts, but a lot of uncertainty
 - Code is available online, users can input own assumptions
 - Qualitative results are robust
 - See AEAPP appendix for detailed discussions

Optimal Portfolio Problem

Total effective capacity (expected)

- Determined by model of vaccine candidate success
- Candidate j : belongs to a platform p and subcategory s
- Successful if all the following events happen:
 - No overall problem prevents feasibility of vaccine (prob. q_o)
 - No problem at the platform level (prob. q_p)
 - No problem at the subcategory level (prob. q_s)
 - No problem at the individual vaccine level (prob. q_j , varies by clinical phase)

- Probability of success for candidate j :

$$\Pr(y_j = 1) = q_o q_p q_s q_j$$

- Total effective capacity for country i :

$$V_i = \sum_j y_j v_{ij}$$

Optimal Portfolio Problem

Table A1: Candidates in Optimal Portfolio

Platform	Subcategory	Phase	Cumulative probability	Marginal probability
Inactivated	Inactivated	Phase 3	0.288	0.288
Viral vector	Adenovirus (non-replicating)	Phase 3	0.483	0.195
RNA	LNP-encapsulated mRNA	Phase 3	0.583	0.099
Inactivated	Inactivated	Phase 3	0.658	0.074
Protein subunit	Recombinant protein	Phase 2	0.707	0.049
Protein subunit	S protein	Phase 2	0.744	0.036
Protein subunit	Recombinant protein	Phase 2	0.769	0.025
RNA	LNP-encapsulated mRNA	Phase 3	0.790	0.020
Inactivated	Inactivated	Phase 3	0.807	0.016
Viral vector	Adenovirus (non-replicating)	Phase 2	0.821	0.013
VLP	VLP	Phase 1	0.832	0.011
Viral vector	Adenovirus (non-replicating)	Phase 2	0.840	0.008
Viral vector	Measles (replicating)	Phase 1	0.847	0.006
Protein subunit	S protein	Phase 1	0.852	0.005
DNA	Electroporation	Phase 2	0.857	0.004
Protein subunit	S protein	Phase 1	0.861	0.003
Live attenuated virus	Live attenuated	Pre-clinical	0.865	0.003
DNA	Other DNA	Phase 2	0.868	0.002
Live attenuated virus	Live attenuated	Pre-clinical	0.870	0.002
Protein subunit	Recombinant protein	Phase 1	0.873	0.002
Live attenuated virus	Live attenuated	Pre-clinical	0.875	0.002
Live attenuated virus	Live attenuated	Pre-clinical	0.877	0.001
Protein subunit	S protein	Phase 1	0.878	0.001
Live attenuated virus	Live attenuated	Pre-clinical	0.880	0.001
DNA	Plasmid + adjuvant	Phase 2	0.881	0.001
RNA	mRNA	Phase 1	0.882	0.001
Live attenuated virus	Live attenuated	Pre-clinical	0.883	0.001
Protein subunit	Recombinant protein	Phase 1	0.884	0.001
Viral vector	Horsepox (replicating)	Pre-clinical	0.885	0.001
Viral vector	Influenza (replicating)	Pre-clinical	0.886	0.001

Solving the Portfolio Problem as of August, 2020

Figure A6: Probability of at Least One Successful Vaccine

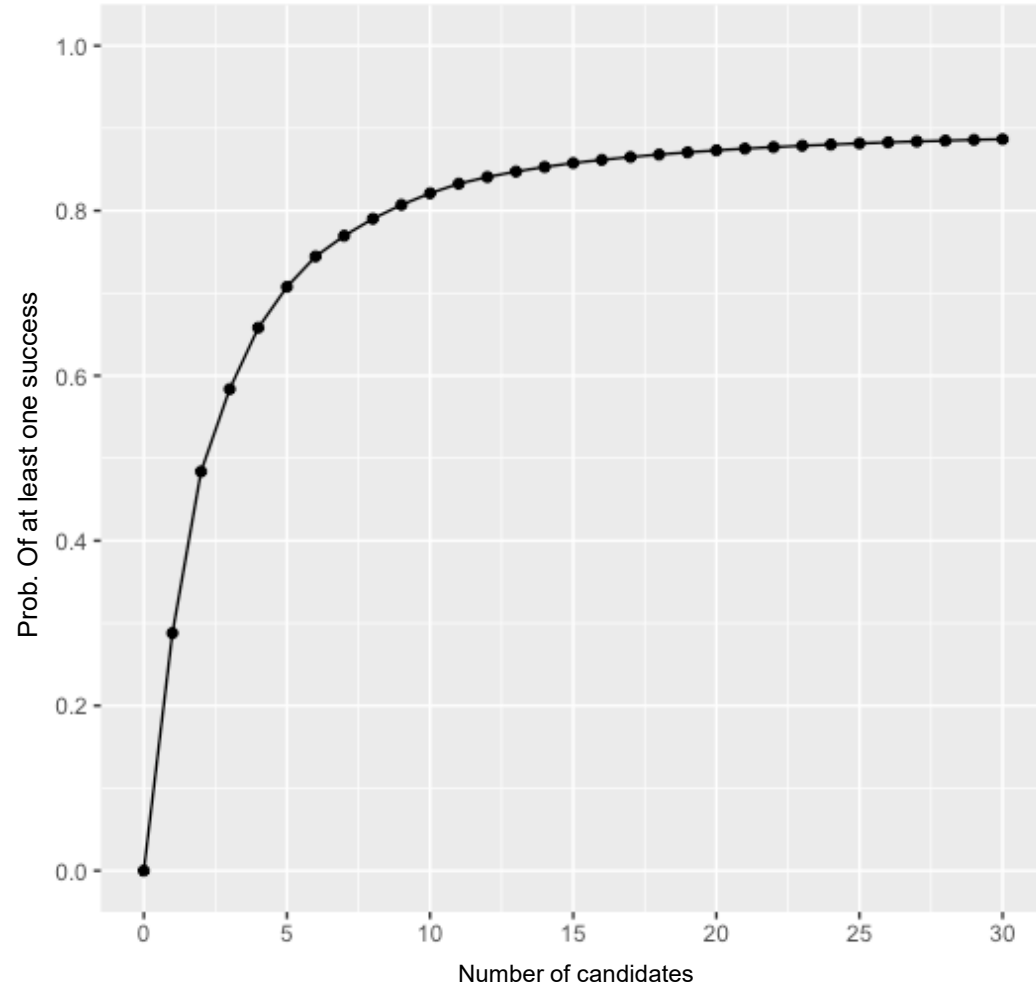
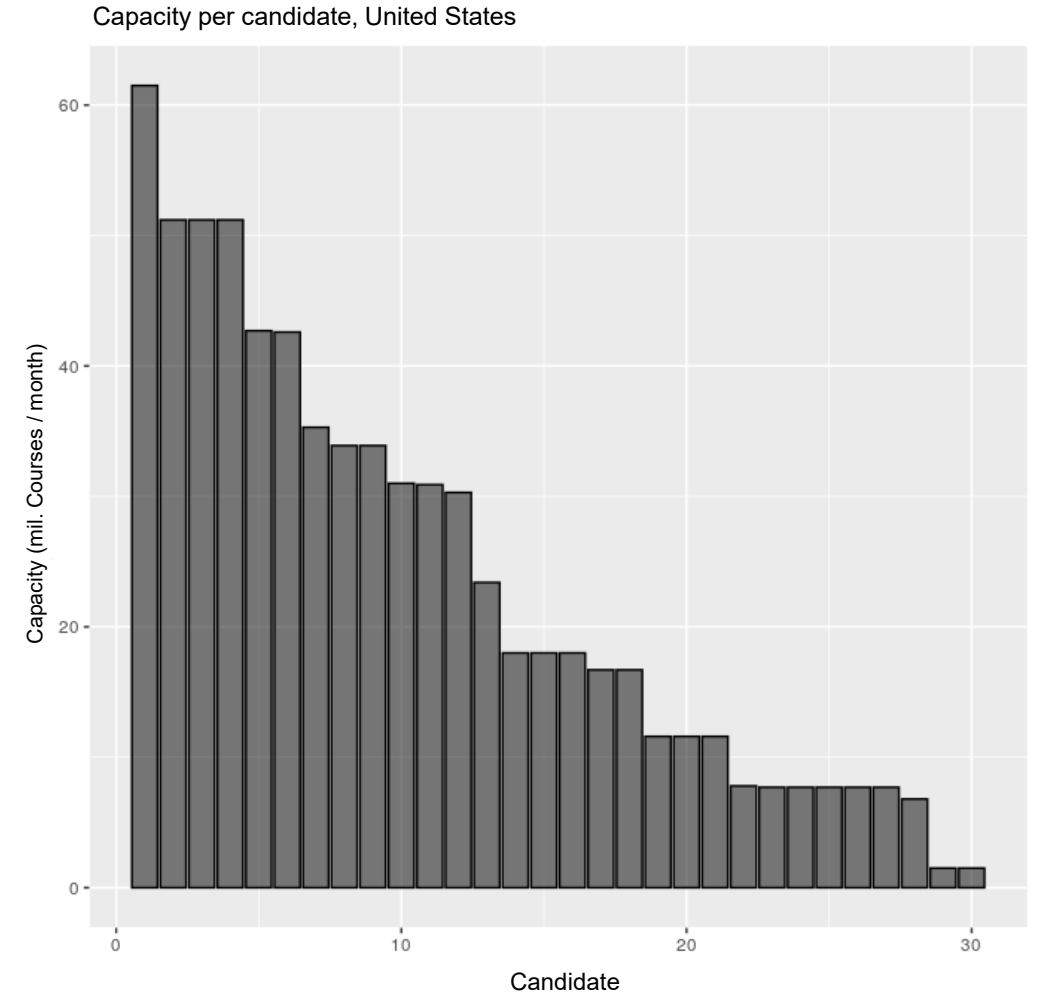


Figure A5: Distribution of Investment across Candidates



Optimal Portfolio Problem

Table A2: Baseline Optimal Portfolio

Country	Mean number of candidates	Total capacity (mil. courses per month)	Expected effective capacity (mil. courses per month)	Total capacity (courses per month per 1000 pop.)	Expected benefits (per cap.)	Total cost (per cap.)
World	8.82	2290.05	538.87	304.40	137.41	36.53
High Income	18.26	1418.03	307.97	1196.54	699.25	143.58
Middle Income	6.73	906.88	239.27	170.21	40.71	20.43
Low Income	1.26	2.33	0.61	2.18	0.58	0.26
United States	27.00	462.30	97.97	1415.06	923.36	169.81
European Union	17.00	477.58	105.12	1093.85	603.46	131.26
Germany	21.00	113.30	24.22	1366.61	855.50	163.99
United Kingdom	21.00	85.30	18.41	1283.47	763.14	154.02
Canada	21.00	45.90	9.93	1238.61	719.27	148.63
New Zealand	18.00	5.80	1.27	1198.10	670.71	143.77
Australia	21.00	34.50	7.37	1380.96	879.99	165.71
Chile	12.00	10.90	2.67	581.98	183.03	69.84
Israel	19.00	10.20	2.24	1148.29	633.38	137.79
Hong Kong	20.00	9.40	2.02	1261.58	740.41	151.39
Japan	18.00	129.50	28.96	1023.72	494.81	122.85

World Optimum:
 27.5bn courses at-risk
 6.5bn courses in expectation
 Global cost \$275bn
 Global benefits > \$1trn, even for just 3 months of acceleration.

Optimal Portfolio Problem: How Much Should We Have Built? When Would We Have Been Done?

TABLE 1—ADVANCE CAPACITY EXPANSION EFFECTS

Advance capacity investment	At-risk capacity of approved vaccines (bn courses)	Benefits relative to zero at-risk (\$billion)	Vaccination complete by
<i>Panel A. United States</i>			
Recommended	1.05	556.9	Mar. 2021
Actual	0.45	389.9	Jul. 2021
Zero	—	—	Oct. 2021
<i>Panel B. World</i>			
Recommended	7.12	3,358.1	Oct. 2021
Actual	3.00	1,606.4	Oct. 2022
Zero	—	—	Jan. 2023

Note: See AEAPP, Table 1 and Appendix A.1. Zero at-risk scenario utilizes actual capacity, built with a 3 month lag. See Science paper for discussion of realized at-risk capacity. 3bn annual courses represents our estimate of 1H 2021 capacity as of Feb 2021.

What Was Actual Early 2021 Capacity Worth?

Global value of vaccine capacity

GLOBAL CAPACITY (BILLION COURSES)	GLOBAL BENEFIT (TRILLION \$)		TIME TO 70% VACCINATION (MONTHS)	
	GDP ALONE	COMPREHENSIVE	HIGH-INCOME COUNTRIES	WORLD
1	5.3	10.5	31.5	66.0
2	7.5	15.0	16.5	33.7
3	8.7	17.4	11.5	23.0
4	9.4	18.8	9.0	17.6
5	9.8	19.7	7.5	14.4

= \$5800 per course of installed capacity

Vaccine capacity assumes ramp-up such that half of the indicated capacity is available starting January 2021 and the remainder starting April 2021. First two columns estimate global benefit in monetary terms from specified capacity over a 24-month period. Last two columns estimate time until 70% of high-income countries or world population is vaccinated using available capacity. Allocation of capacity to countries of different income levels is based on reported bilateral deals and assumes that global capacity is fully utilized until the target of 70% of world population is vaccinated. Calculations are based on the model outlined in the text and detailed further in the SM.

Note: See Science Paper Table 1 and Online Appendix.

Should We Build More? (From Vantage of Early 2021)

Global value of additional 1 billion annual courses of capacity

SCENARIO		ADDITIONAL GLOBAL BENEFIT (BILLION \$)		SPEED-UP TO 70% VACCINATION (MONTHS)	
ADDITIONAL CAPACITY ONLINE	BASILINE CAPACITY (BILLION COURSES)	GDP ALONE	COMPREHENSIVE	HIGH-INCOME COUNTRIES	WORLD
April 2021	2	970	1940	4.5	10.2
	3	495	989	2.1	5.0
	4	270	540	1.2	2.9
July 2021	2	636	1273	3.5	9.2
	3	288	576	1.4	4.3
	4	129	257	0.6	2.3

= \$1000 per course of additional capacity

First two columns estimate global benefit in monetary terms from 1 billion courses of capacity, coming online April or July 2021, added to specified baseline capacity. In all scenarios, baseline capacity ramps up such that half is available starting January 2021 and the remainder starting April 2021. Additional global benefits (which can be added to baseline from the previous table to compute total benefits) are computed over a 24-month period. Last two columns estimate the speed-up of vaccination of 70% of high-income countries or world population relative to baseline time from the previous table. See the previous table for additional notes.

Note: See Science Paper Table 2.

Contract Design

- Guiding principle: benefit of purchasing vaccine at risk comes from earlier access
- If contracts specify # of doses, without binding delivery dates, inadequate incentives for speed
 - Producers may just add countries to the back of the queue.
 - Firms' incentives to fulfill orders more quickly << social benefit.
- Could delivery dates be made binding with penalties/bonuses?
 - Unlikely.
 - Given huge gap between private and social incentives, penalties/bonuses would have to be very high
 - Likely unacceptable level of risk, potential unintended consequences
- **Conclusion: contract directly on manufacturing capacity**
 - Pay for capacity installation, in exchange for option to buy doses near marginal cost
 - Notice: this is “Push” not “Pull”. Extensive discussion in papers.

Stretching Capacity

- First doses first
 - Giving second doses after 12 (rather than 4) weeks allows more people to receive a first dose sooner. Likely first dose conveys a lot of the overall protection.
 - This is likely to reduce mortality and infections, supported by data from UK (adopted)
- Lowering dosage
 - Optimal dosage for vaccines unknown to scientists
 - Firms may not have strong incentives to optimize doses to maximize social benefits
 - E.g. trial results from AstraZeneca suggested a half-dose followed by a full dose more effective.
 - Could increase vaccine capacity substantially.
- Lower efficacy vaccines
 - Calculation: Suppose country can access a 70% effective vaccine now, or a 95% effective one in three months. Higher benefits starting with immediately available one.
- Testing
 - Test delayed, lower dosing strategies
 - Test against new strains
 - Head-to-head tests, no need for control groups, wide scale, fast

Vaccine Exchange

- Some countries may end up with vaccine allocations that are not optimally matched to their needs
 - Cold chain
 - Local strains
 - Countries may trade off efficacy for increases in quantity or vice versa
 - Concentrate on few candidates for logistics
- A vaccine exchange mechanism in COVAX would enable countries to engage in mutually beneficial trades
- Later stage, high-income countries may have vaccine to donate
 - Donate through exchange
 - Fair process
 - Minimize international transport cost
- Related to academic research on combinatorial assignment markets (Budish, 2011, *JPE*; Prendergast, 2017, *JEP*)

Lessons for Future Pandemics

- Capacity equals speed.
- Invest at risk.
- Some installed capacity will turn out not to be used ex post (vaccines that don't work). That's part of the optimum.
- This time: we lost ~3-6 months. Actual capacity caught up to recommended only in 2H 2021.

- Private incentives for speed not aligned with social incentives
- Especially at fixed, socially-constrained, prices.
 - A pharma firm that sells 1bn courses at \$40/course earns the same \$40bn if sold over 12 months as if sold over 1 month ... but the latter requires 12 times the fixed costs
- Especially for investment at risk

A New Play in the Pandemic Playbook?

- We needed a new play in the “Epi Playbook”
- Possibly why the policy response was so muddled.
- Existing playbook:
 - Eradicate (e.g. SARS)
 - Minimize (e.g. HIV)
 - Ignore (e.g. common cold)
- The play we needed this time:
 - Vaccinate as fast as possible
 - In interim, not “minimize” but “Maximize Utility s.t. $R < 1$ ”
 - That is: prevent exponential growth as cheaply as possible
 - (See Budish, Nov 2020 NBER WP)

A New Play in The Pandemic Playbook?

Four features of Covid-19, relative to past pandemics, that justifies a new approach:

1. Mortality / morbidity cost high

- $R \leq 1$ a desirable policy goal even at meaningful expense
- For U.S.: even $R = 1.5 \rightarrow 200$ million infections in 12 months

2. Eradication likely not feasible

- By the time of policy intervention, eradication unrealistic for many countries
- (If eradication were feasible: like a one-time fixed cost, versus ongoing costs of containment)

A New Play in The Pandemic Playbook?

Four features of Covid-19, relative to past pandemics, that justifies a new approach:

3. $R \leq 1$ feasible with modestly expensive measures

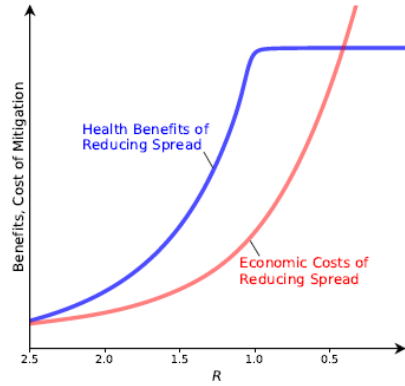
- Medical experts quickly converged on a suite of public-health responses
- Atul Gawande: “if you have hygiene, distancing, mandatory masks, and screen everybody for symptoms so that they stay home and get tested, that shuts the virus down”

4. Minimize unboundedly expensive

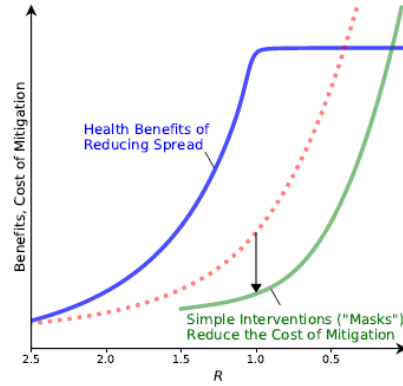
- When eradication is infeasible, second-best is “minimize” (Osterholm)
- However, hard to think about tradeoffs *if the interventions themselves are very expensive*
- Useful contrast: HIV

Epi Playbook

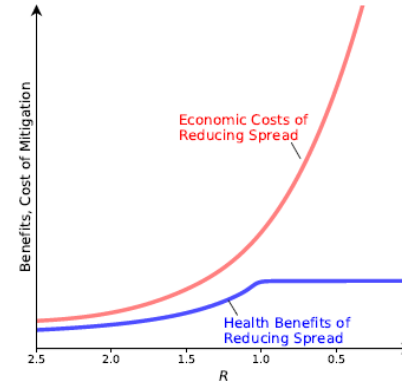
Panel A: $R \leq 1$ is Optimal



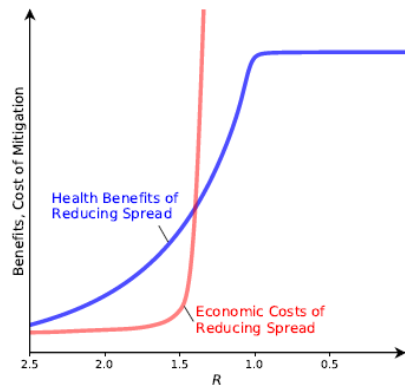
Panel B: $R \leq 1$ with Simple Interventions



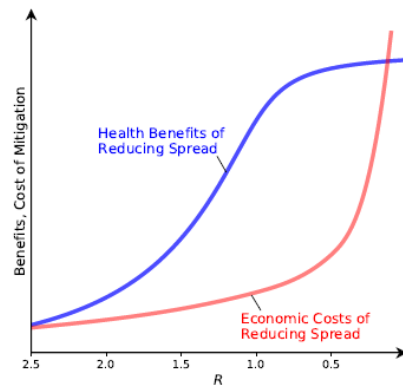
Panel C: Optimal to Ignore



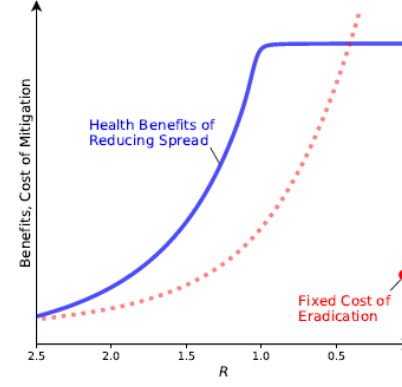
Panel D: Optimal to Partially Mitigate



Panel E: Optimal to Suppress to $R \ll 1$



Panel F: Optimal to Eradicate



Source: Eric Budish, "Maximize Utility subject to $R < 1$: A Simple Price-Theory Approach to Covid-19 Lockdown and Reopening Policy", NBER Working Paper. (Initial draft April 2020, Updated Nov 2020)

Conclusion

- Vaccines a medical and economic triumph
- 9 bn shots in 2021
- Science paper: realized capacity worth \$17-\$20 trillion.

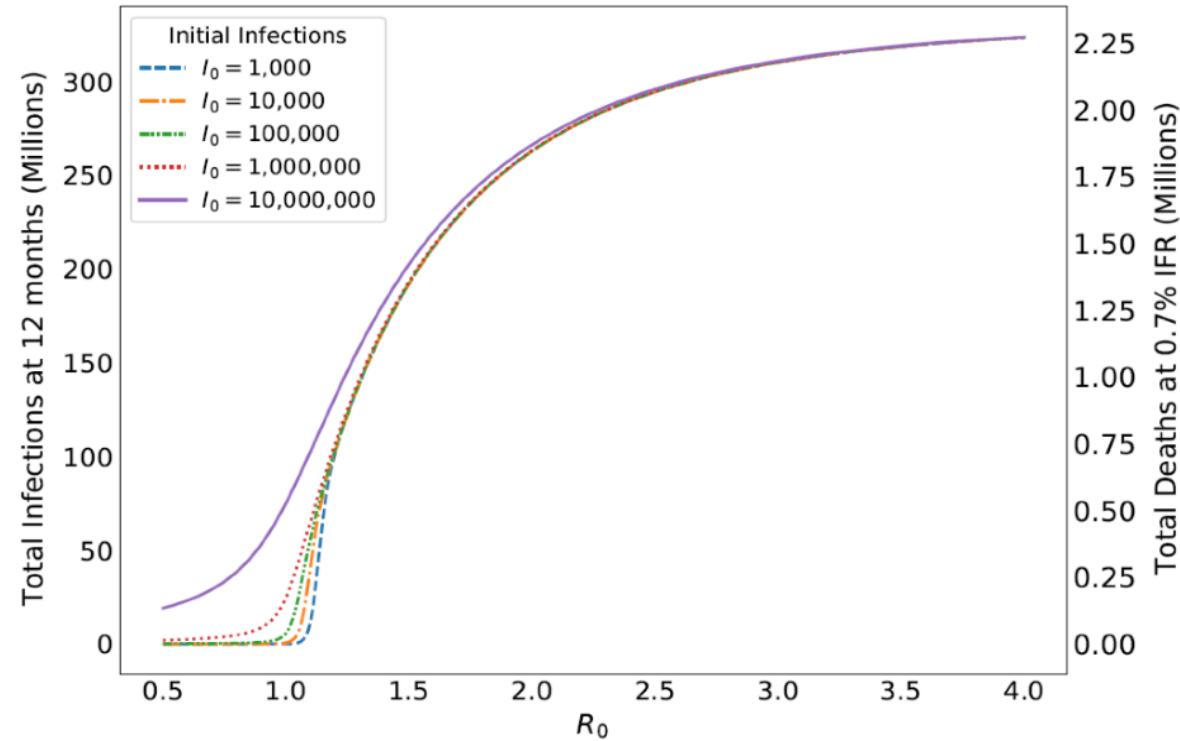
- Still, hard not to lament that we didn't do more:

- # of Deaths in US since Apr 2021: 274,094
- # of Deaths in HIC since Apr 2021: 592,667
- # of Deaths globally since Nov 2021: 434,892
- Rise of variants: Delta, Omicron

- Missed opportunity to save million+ lives, trillions of dollars.
- Education, well being

Epi Playbook

Figure 1: Why $R \leq 1$: Exponential Growth

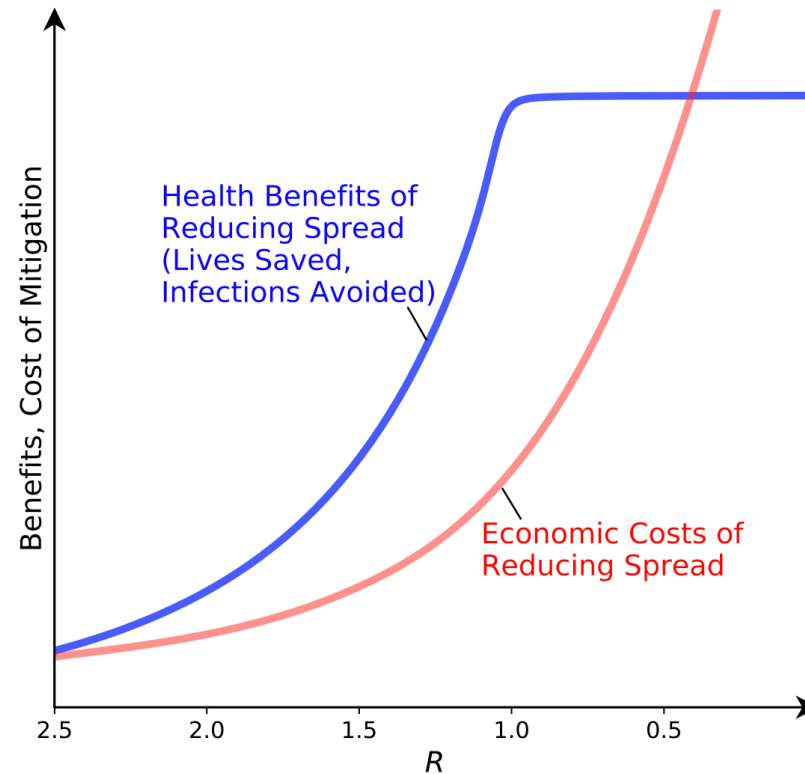


Note: Output is based on the standard SIR model. Each line depicts a different initial infection seed. The γ parameter is fixed throughout at $1/5$, which represents a duration of infectiousness of 5 days. The β parameter, which represents the rate of infectiousness, is varied such that $R_0 = \beta/\gamma$ is the value depicted along the horizontal axis.

Source: Eric Budish, "Maximize Utility subject to $R < 1$: A Simple Price-Theory Approach to Covid-19 Lockdown and Reopening Policy", NBER Working Paper. (Initial draft April 2020, Updated Nov 2020)

Epi Playbook

Figure 2: Why $R \leq 1$ May be Optimal Policy: Basic Price-Theory Intuition

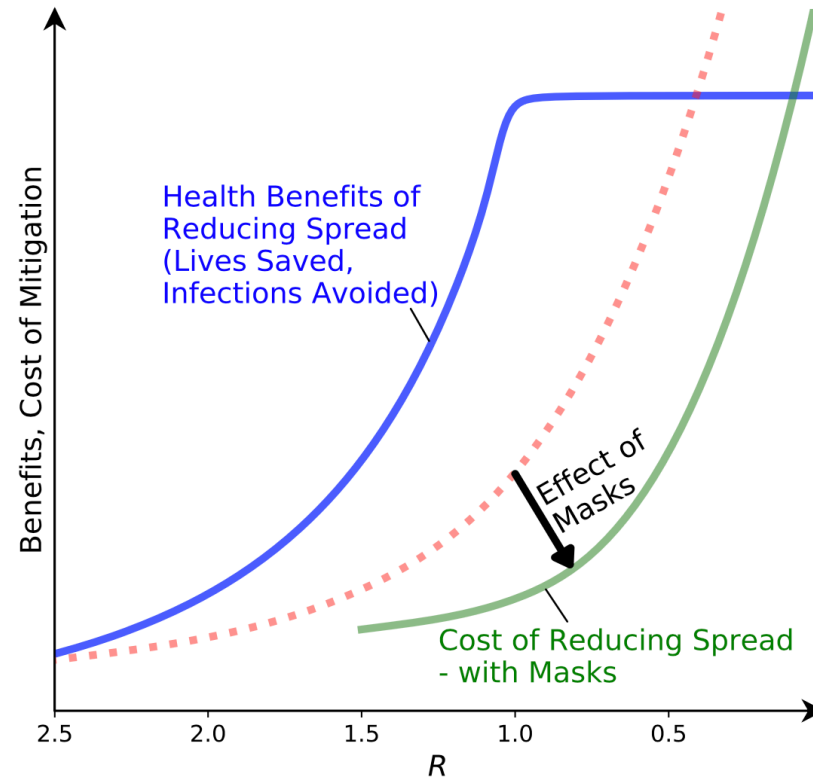


Note: The blue line depicts the same information as the $I_0 = 100,000$ case of Figure 1, but with both axes flipped as described in the text. The red line depicts a convex cost curve; as emphasized in the text, the convex shape of the cost curve is microfounded in Sections 3 and 4 but its rate of change and its location relative to the blue line are both unknown. Both curves are depicted under the assumption that R_0 without any interventions or behavior changes is 2.5, per the CDC's current best estimate.

Source: Eric Budish, "Maximize Utility subject to $R < 1$: A Simple Price-Theory Approach to Covid-19 Lockdown and Reopening Policy", NBER Working Paper. (Initial draft April 2020, Updated Nov 2020)

Epi Playbook

Figure 4: Simple Interventions Reduce the Cost of Mitigation



Note: This figure illustrates the effect of simple interventions, denoted “masks” in the model, on the economic cost of mitigation. The solid-blue line and dotted-red line are the same as in Figure 2. The solid-green line illustrates the lowering of the economic cost of mitigation from masks. The reduction is illustrative and is based on the numerical example from Section 5 under the assumptions that masks reduce risk by 40% and harm utility by 5%.

Source: Eric Budish, “Maximize Utility subject to $R < 1$: A Simple Price-Theory Approach to Covid-19 Lockdown and Reopening Policy”, NBER Working Paper. (Initial draft April 2020, Updated Nov 2020)