$R < 1$ as an Economic Constraint

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Outline of Talk

1. **Introduction**
2. Why $R \leq 1$?
3. Initial Model
4. Low-Cost Risk Reducers (LCRRs)
5. Detailed Numerical Example: Social Value of LCRRs
6. Dynamic Considerations
7. Sense of Magnitudes
8. Conclusion: A New Play in the Pandemic Playbook
9. Appendix

Introduction

- Economists usually think about public policy with a constrained maximization problem in the back of their heads, something like

$$\begin{aligned} &\max \text{ Social Welfare} \\ &\quad \text{subject to} \\ &\text{Technological Constraints} \\ &\text{Incentive Constraints} \end{aligned} \tag{1}$$

- Health policy experts, in their response to the Covid-19 crisis, often seemed to have a constrained maximization problem in the back of their heads like

$$\begin{aligned} &\min \text{ Spread of Covid-19} \\ &\quad \text{subject to} \\ &\text{Keeping Society Functioning} \end{aligned} \tag{2}$$

Introduction

- "Minimize Spread" perspective (2) is understandable as a response to the fear of exponential growth of a deadly threat
- But, it makes it impossible to think about tradeoffs
- The extreme versions of social distancing that are called for by (2)—closing schools, shuttering entire industries, avoiding close interactions with other people—themselves have enormous costs
  - The influential March 2020 Imperial College epidemiological model discussed school closures of up to 2 years
  - Lockdowns conservatively cost the global economy $1 trillion per month (Castillo et al. 2021)
- But formulation (2) does not allow for *any* unnecessary risk

Introduction

Said Dr. Francis Collins of the "public-health mindset":

> *"If you're a public-health person and you're trying to make a decision, you have this very narrow view of what the right decision is, and that is something that will save a life. Doesn't matter what else happens. So you attach infinite value to stopping the disease and saving a life. You attach a zero value to whether this actually totally disrupts people's lives, ruins the economy, and has many kids kept out of school in a way that they never quite recovered. Collateral damage. This is a public-health mindset. And I think a lot of us involved in trying to make those recommendations had that mindset and that was really unfortunate. That's another mistake we made."*

—Dr. Francis Collins, former head of the National Institutes of Health, in July 2023 (emphasis added)

Introduction

- This paper proposes a novel pandemic response paradigm that
  1. Incorporates a version of the pure health perspective (2) into the traditional economic perspective (1)
  2. Would have been an approximately optimal way to balance traditional social/economic objectives with health objectives
  3. Is simple and intuitive, using plain vanilla static optimization
  4. Focuses attention on the right set of policy issues

Introduction

- Proposed paradigm:

$$\begin{array}{l} \max \text{ Social Welfare} \\ \quad \text{subject to} \\ \text{Technological Constraints} \\ \text{Incentive Constraints} \\ R \leq 1 \text{ Constraint} \end{array} \tag{3}$$

  - $R \leq 1$ Constraint = Reduce the Covid-19 Average Transmission Rate to Below 1 (Until Vaccines or Treatments are Widely Available)
  - Superficially looks like (1)—has usual social welfare objective
  - But will also do well at *approximating* the health objective in (2), because of the additional constraint: $R \leq 1$

Introduction: Why (3) is Approximately Optimal

- $R = 1$ is a critical threshold (widely understood)
  - Diseases with $R > 1$ eventually infect huge numbers of people
  - Diseases with $R < 1$ do not
- Threshold particularly important for Covid-19 because of both
  1. Rapid spread (few days to a week)
  2. Perceived likelihood of a successful vaccine within a year or two (correctly)
- Benefits curve: benefit of reducing R has a "kink"
  - Benefits sharply increase as R decreases towards 1
  - Benefits flatline as R decreases below 1
- Cost curve: cost of reducing R is convex and increasing
  - Society starts with the easy risk reductions first
  - Moves on to the more expensive risk reductions later
- Benefit and cost curves combine to imply that $R \leq 1$ is approximately the optimal policy target

$R \leq 1$: Two Critical Insights

1. $R \leq 1$ constraint imposes a "risk budget" on society
   - Activities differ in their value and risk
   - Society should spend its risk budget on the activities with the highest "bang for buck" (value per unit of risk)
   - Some high-risk activities should be allowed if very high value
   - Some low-risk activities should be banned if very low value
2. Society should try to satisfy $R \leq 1$ as cheaply as possible
   - Implication: value of "low-cost risk reducers" (LCRRs)
   - LCRRs = rapid testing, facemasks, six feet of social distance, open windows, stay-home-if-sick rules, handwashing, etc.
   - LCRRs decrease the societal cost of satisfying $R \leq 1$, expanding the "production possibilities frontier"

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Cumulative Infections and Deaths as a Function of R_0 and Initial Infections in the Standard SIR Model (US, 12 Months)

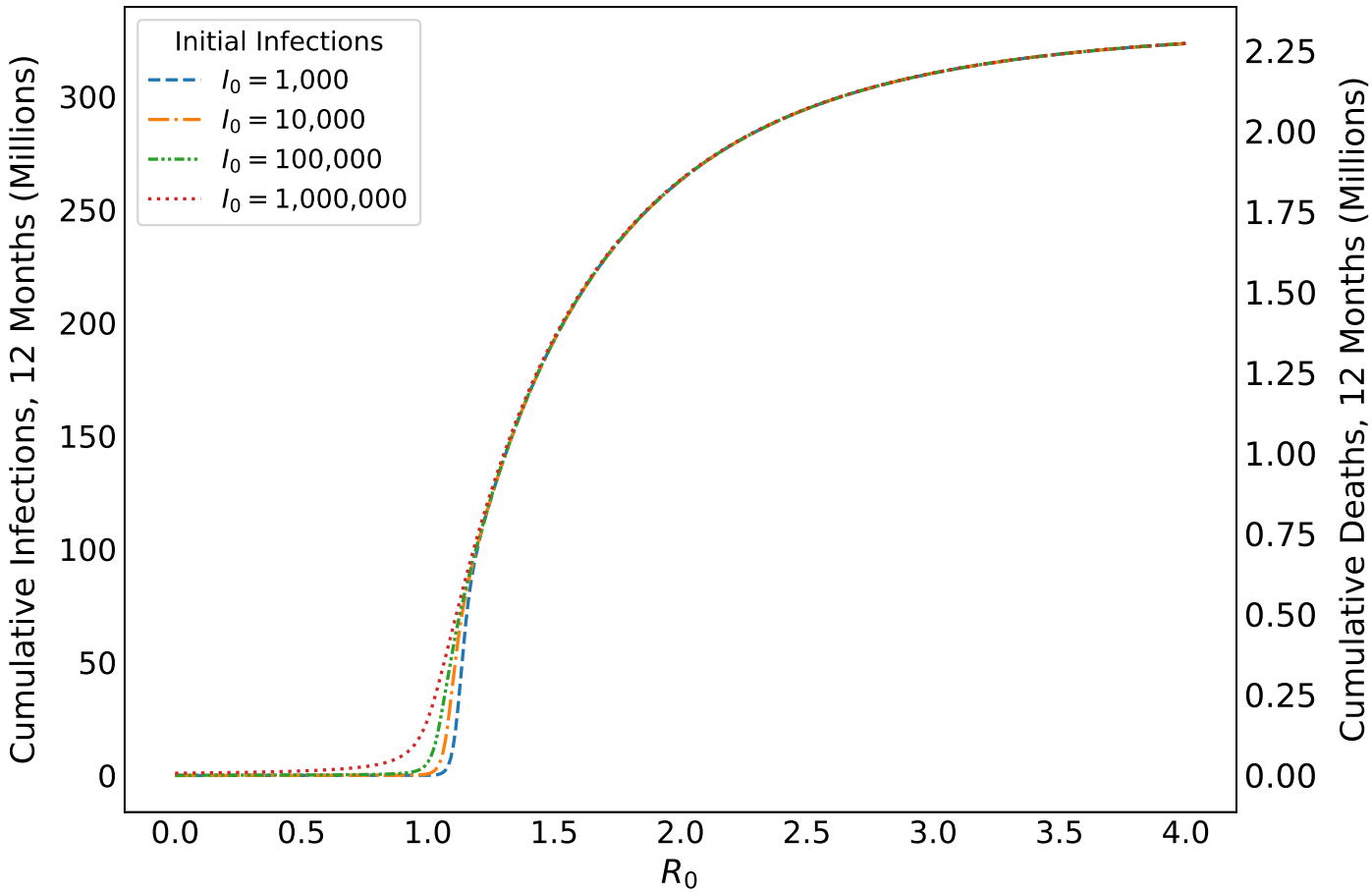

Fig. 1 *Note:* Output is based on the standard SIR model. Each line depicts a different initial infection seed. The γ parameter is fixed throughout at $1/5$, which represents a duration of infectiousness of 5 days. (The figure is similar if other reasonable values of γ are used instead.) The β parameter, which represents the rate of infectiousness, is varied such that $R_0 = \beta/\gamma$ is the value depicted along the horizontal axis. The vertical axis depicts the cumulative number of infections and deaths in the United States over a 12-month period as a function of $R_0 = \beta/\gamma$, based on an infection fatality rate of 0.7% (per CDC estimates) and a population of 330 million

Cumulative Infections and Deaths as a Function of R_0 (Initial Seed 100,000 Infections, 12 Months)

	R_0	# of Total Infections	# of Total Deaths
Lockdown	0.50	200,000	1,000
	0.60	250,000	2,000
	0.70	333,000	2,000
	0.80	498,000	3,000
$R \leq 1$ **Approach**	0.95	1,860,000	13,000
	1.00	5,810,000	40,000
Flatten the Curve	1.20	104,000,000	727,000
	1.30	140,000,000	979,000
	1.40	169,000,000	1,180,000
	1.50	192,000,000	1,350,000
Ignore	2.00	263,000,000	1,840,000
	2.50	295,000,000	2,060,000

Why $R \leq 1$ is Approximately Optimal

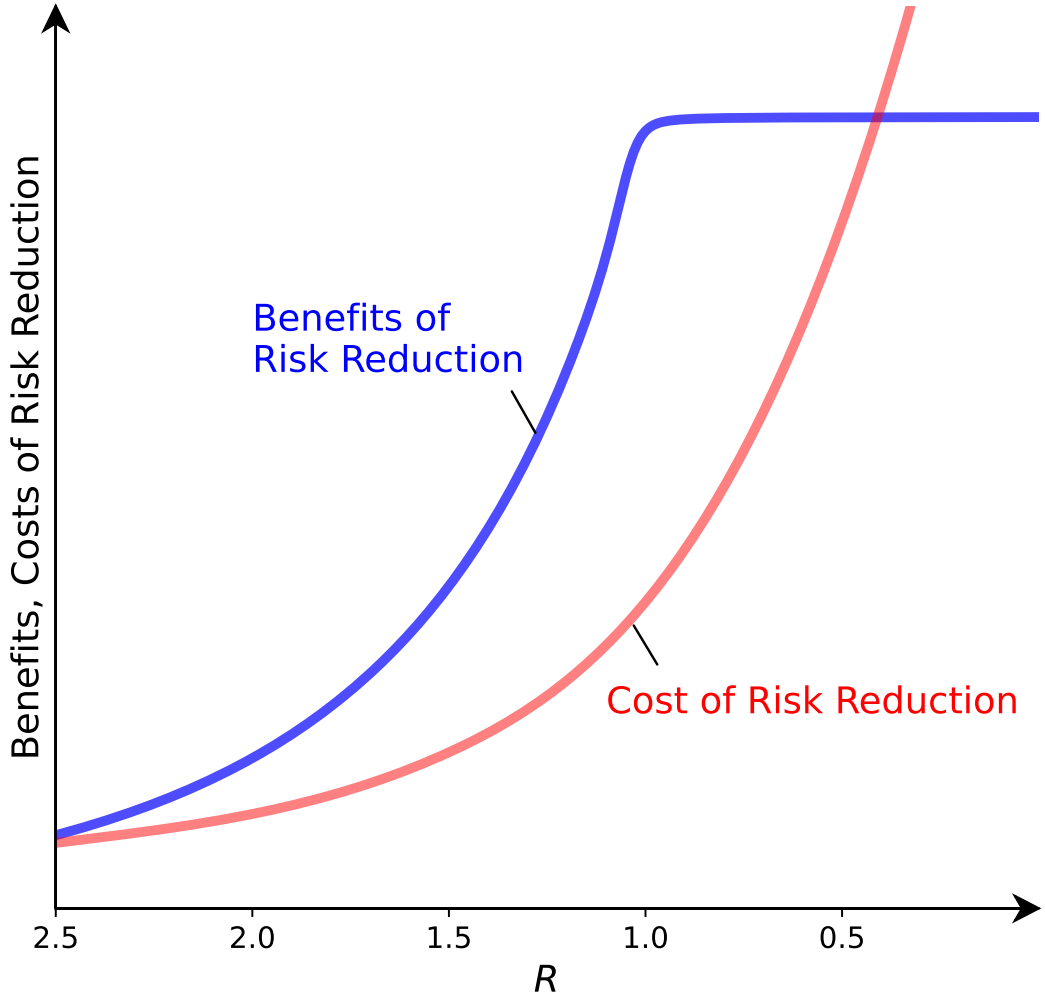

Fig. 2 *Note:* The blue line depicts the same information as the $I_0 = 100{,}000$ case of Fig. 1, but with both axes flipped as described in the text. The red line depicts a convex and increasing cost curve whose specific shape is based on the simulation example in Sect. 5. Both curves are depicted under the assumption that R_0 without any interventions or behavior changes is 2.5, per the CDC's best estimate as of September 2020. The vertical scales of both curves is calibrated in Sect. 7, see Fig. 7

Why $R \leq 1$ is Approximately Optimal

- Optimal policy chooses R to maximize benefits less costs
- Benefits curve: depicts the same information as in Figure 1 but with both axes flipped
  - Further right on the graph now means lower R
  - Higher on the graph now means people *not* infected or dead
- Cost curve: represents the economic cost of reducing the spread of the virus
- Observe that the benefits curve has "kink" at $R = 1$ but the cost curve is convex and increasing
- Thus a policy that targets $R \leq 1$:
  - Reaps almost all of the health benefits of mitigation
  - Avoids further, increasing, mitigation costs

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Model Setup

- Society chooses a vector of activities $x \in X = [0,1]^n$
- Each activity i has traditional socioeconomic benefits and costs. Notation $v_i = b_i - c_i$ (assume $v_i > 0$ for all i)
- Each activity i also has a *disease transmission risk* r_i. This represents the activity's expected contribution to transmission in a society that does not engage in any risk reduction
- Define the social welfare level pre-virus as

$$V_{pre\text{-}virus} \equiv \sum_{i=1}^{n} v_i$$

- Define the baseline virus reproduction rate as

$$R_0 \equiv \sum_{i=1}^{n} r_i$$

(the reproduction rate in a society that is both fully open and that does not take even the simplest virus precautions)

Formalizing the $R \leq 1$ Approach

- Pre-Virus Utilitarian Objective:

$$\max_{x \in X} \sum_{i=1}^{n} x_i v_i \qquad (1)$$

Solution: Fully engage in all activities

- Pure Medical Objective:

$$\min_{x \in X} \sum_{i=1}^{n} x_i r_i \qquad (2)$$

Solution: Only engage in activities with $r_i = 0$. Could be augmented with a constraint $x \geq \underline{x}$, where $\underline{x}$ denotes a minimal set of essential activities

- Maximize Social Welfare subject to $R \leq 1$:

$$\max_{x \in X} \sum_{i=1}^{n} x_i v_i \qquad (3)$$

$$\text{subject to} \sum_{i=1}^{n} x_i r_i \leq 1$$

Same economic objective as (1); the $R \leq 1$ constraint approximates the pure medical objective in (2)

Max Social Welfare Subject to $R \leq 1$: Solution

- Key ratio for each activity i:

$$\rho_i = \frac{v_i}{r_i} \tag{4}$$

  - Represents activity i's socioeconomic value per unit of disease-transmission risk
  - For activities with $r_i = 0$ define $\rho_i = \infty$

- Optimal solution: Choose activities in descending order of their ρ_i ratios until $R = 1$ is reached

- Intuition:
  - $R \leq 1$ is a "disease-transmission budget constraint"
  - r_i is the "risk price" of activity i

- Notice:
  - Some activities with high risk should be included
  - Some activities with relatively low risk should be dropped
  - Optimum sorts activities not by their *absolute* level of risk, but by their *ratio* of value to risk

Max Social Welfare Subject to $R \leq 1$: Solution

Proposition 1 *Let ρ_i^* denote the threshold at which the budget constraint is reached when choosing activities in descending order of ρ_i as defined in equation (4), i.e., the solution to*

$$\rho^* = \inf \left\{ \rho_i : \sum_{j:\rho_j > \rho_i} r_j \leq 1 \right\}. \tag{5}$$

The optimal choice of the activity vector x^* is:

$$x_i^* = \begin{cases} 1 & \text{if } \rho_i > \rho^* \\ q & \text{if } \rho_i = \rho^* \\ 0 & \text{if } \rho_i < \rho^* \end{cases}$$

where $q := \left(1 - \sum_{j:\rho_j > \rho^*} r_j\right) / \left(\sum_{j:\rho_j = \rho^*} r_j\right)$ is a constant defined to exhaust the risk budget given that all activities with $\rho_i > \rho^*$ are done in full and all activities with $\rho_i < \rho^*$ are fully dropped.

Max Social Welfare Subject to $R \leq 1$: Graphic Depiction

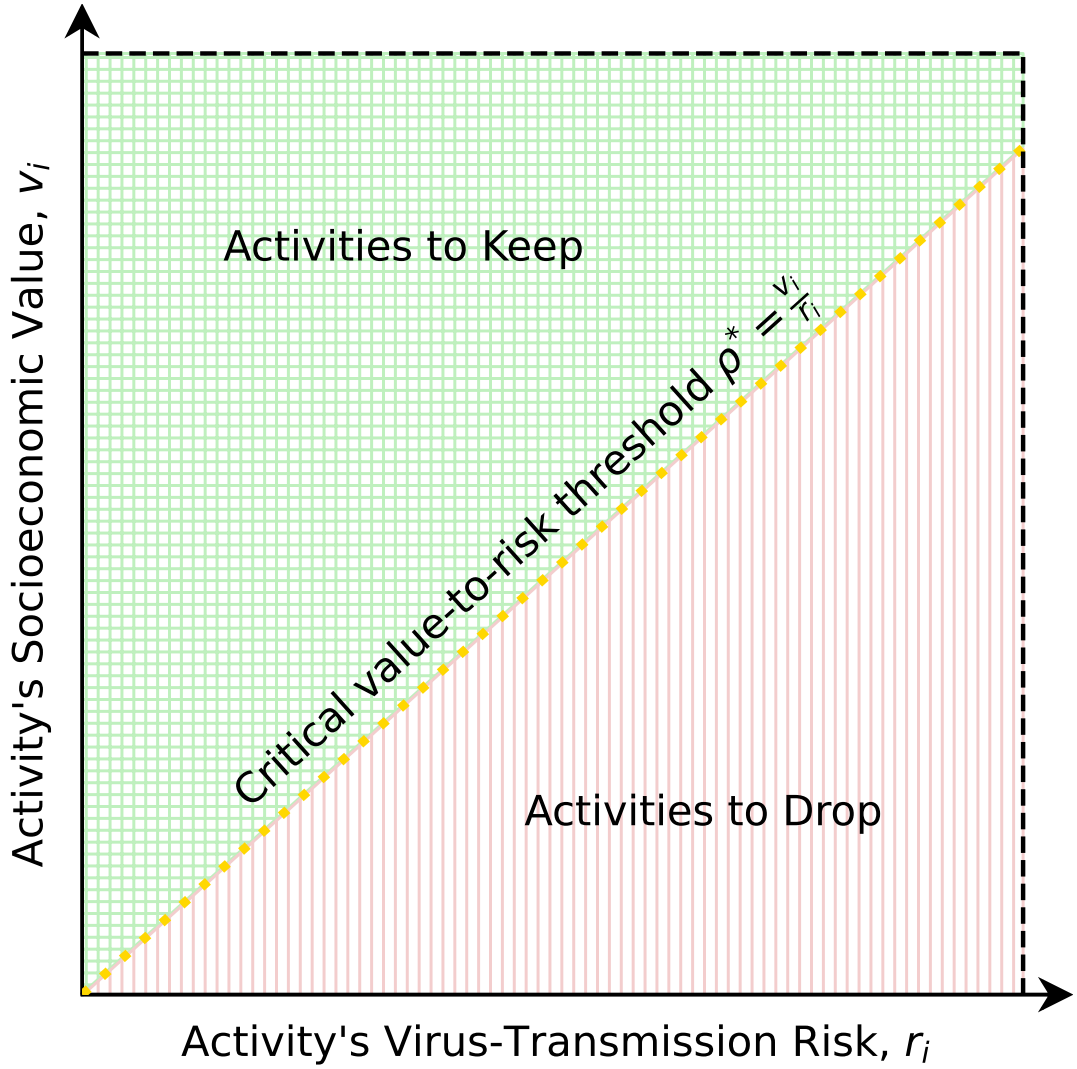

Fig. 3 *Note:* This figure illustrates the optimal mix of activities to maximize social welfare subject to $R \leq 1$. The diagonal line depicts the critical threshold ρ^* for the ratio of value-to-risk. Activities with value-to-risk ratios above ρ^* should optimally be kept and activities with value-to-risk ratios below ρ^* should optimally be dropped. The placement of the line is based on the numerical example in Sect. 5 with $R_0 = 2.5$, no LCRRs, and uniform distributions of value and risk

Why Treating $R \leq 1$ as a Constraint is Approx. Optimal

- Question: How well does (3) approximate a "true" social planner problem with health costs directly in the objective?
- To analyze, consider the actual benefits curve and cost curve from Figure 2, and also consider a "stylized" benefits curve with an exact kink at $R = 1$
- Result: Solution to (3) is within 2ε of the "true" solution if
  1. The actual benefits curve is always within ε of the stylized benefits curve, and
  2. Either the line connecting the stylized benefits curve's starting point and kink point is steeper than the cost curve at $R = 1$
     - "Mitigation is sufficiently valuable"
  3. Or the stylized benefits curve is at least as steep as the cost curve at R_0, then accelerates at least as quickly until $R = 1$
     - "Ignore is suboptimal" and "costs do not accelerate too fast"
- (Both conditions obtain by a healthy margin in the numerical example below, even without LCRRs)

Formal Mathematical Details

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Low-Cost Risk Reducers (LCRRs)

- As I emphasized in the April 1st 2020 draft of this paper:
  1. R_0 as measured (~2.5) describes the growth of Covid-19 in a population that is completely unaware of the virus
  2. We knew a lot about how Covid-19 spreads even very early on (Gawande, March 2020)
- Thus common sense at the time suggested:
  1. Implementing some relatively simple, cheap risk reductions
  2. Banning activities with particularly poor $\frac{v}{r}$ ratios
  - Could have generated 60% reduction from $R_0 = 2.5$ to $R = 1$
  - Without a severe societal lockdown!
  - Common sense subsequently borne out by a variety of evidence
- We did not need to eliminate *all* risk
- We just needed to engineer a *60% reduction* in risk

Low-Cost Risk Reducers (LCRRs)

- The term "Low-Cost Risk Reducers (LCRRs)" represents the suite of low-cost, simple interventions
  - Examples: facemasks, tests, six feet of distance, open windows
  - Does not include higher-cost interventions, such as lockdowns
- In model language: for each activity i, there is an LCRR that
  - Reduces the net socioeconomic value from v_i to $\hat{v}_i \leq v_i$
  - Reduces the disease-transmission risk from r_i to $\hat{r}_i \leq r_i$
- Example: Facemasks
  - Uncomfortable, reduces quality of social interactions
  - But significantly reduces risk in crowded indoor environments

LCRRs: Necessary Condition for Use

Proposition 4 *Let $\hat{\rho}_i = \frac{\hat{v}_i}{\hat{r}_i}$ denote activity i's value-to-risk ratio with LCRRs, analogous to ρ_i as defined in (4) without LCRRs. A necessary condition for it to be optimal to use the LCRR version of activity i is that LCRRs improve the activity's value-to-risk ratio:*

$$\hat{\rho}_i \geq \rho_i \tag{7}$$

- Intuition: an LCRR must increase society's "bang per buck" (per unit of virus risk), allowing the social risk budget to be stretched further, for it to be a good idea
- LCRR that would pass condition: High-quality facemasks in crowded indoor settings (reduced risk significantly)
- LCRR that would fail condition: Facemasks in low-density parks (likely did not reduce risk at all)

LCRRs: Sufficient Condition for Use

- Necessary condition is not quite sufficient. Example:
- Without LCRRs:
  - Activity 1: $v_1 = 1$, $r_1 = 1$ ($\rho_1 = 1$)
  - Activity 2: $v_2 = 0.1$, $r_2 = 1$ ($\rho_2 = 0.1$)
  - Optimum: Do Activity 1 only; total value of 1.0
- With LCRRs:
  - Activity 1: $\hat{v}_1 = 0.7$, $\hat{r}_1 = 0.5$ ($\hat{\rho}_1 = 1.4$, higher than ρ_1)
  - Activity 2: $\hat{v}_2 = 0.1$, $\hat{r}_2 = 0.5$ ($\hat{\rho}_2 = 0.2$, higher than ρ_2)
  - Optimum: Do both activities in full; total value of 0.8
- But value is higher without LCRRs than with. Intuition:
  - Harm of LCRR to the more valuable activity (1) is large
  - Freed-up risk budget is spent on lower value activity (2)
- Suggests that for LCRRs to increase welfare, the marginal activities that are enabled by LCRR adoption must be of sufficiently high value relative to the utility harm of LCRRs

LCRRs: Sufficient Condition for Use

Proposition 5 *Define* $\Delta r_i = r_i - \hat{r}_i$ *and* $\Delta v_i = v_i - \hat{v}_i$. *A sufficient condition for it to be optimal to use the LCRR version of activity* i *is that the necessary condition (7) holds, and, additionally:*

$$\underline{\rho}_i^* \geq \frac{\Delta v_i}{\Delta r_i} \tag{8}$$

where $\underline{\rho}_i^*$ *denotes the value-to-risk ratio of the marginal activity if an LCRR is adopted for activity* i*, taken as a lower bound over potential LCRR policies for activities other than* i*.*

- Right-hand side: Cost of freeing up additional risk budget by adopting LCRRs for activity i
  - Numerator: utility harm of the LCRR
  - Denominator: amount of risk budget that is freed up
- Left-hand side: Marginal use of the freed-up risk budget
- Condition: Marginal use must be high enough to justify the utility cost of the LCRR

Optimal LCRRs: What Is the Optimal Set?

- Suppose that we can design the set of LCRRs for activity i
- Then the following proposition holds:

Proposition 6 *Assume that society's marginal value-to-risk ratio ρ^* is exogenous to the LCRR policy of activity i. Let there be K_i potential LCRR policies for activity i with value and risk $(v_i^k, r_i^k)_{k=1}^{K_i}$. Let $\Delta v_i^k = v_i - v_i^k$ and $\Delta r_i^k = r_i - r_i^k$. The optimal LCRR policy for activity i is the choice that maximizes:*

$$\underbrace{\Delta r_i^k}_{\text{risk reduction from LCRR } k} \cdot \underbrace{\rho^*}_{\text{marginal value of risk budget}} - \underbrace{\Delta v_i^k}_{\text{utility harm of LCRR } k} \tag{9}$$

Optimal LCRRs: What Is the Optimal Set?

- Notice that the optimal LCRR policy for activity i is not necessarily the one that maximizes the ratio of value-to-risk
- Example: Eliminating the last epsilon of risk
  - Is great for the ratio of value-to-risk
  - Only has a small benefit for social welfare
  - May not be worth it if the utility cost of eliminating this last epsilon of risk is high
- Instead, (9) tells us that the optimal LCRR policies are those that achieve
  - Large absolute reductions of the quantity of risk
  - Small absolute harm to utility

LCRRs: Effect on the Cost of Risk Reduction Curve

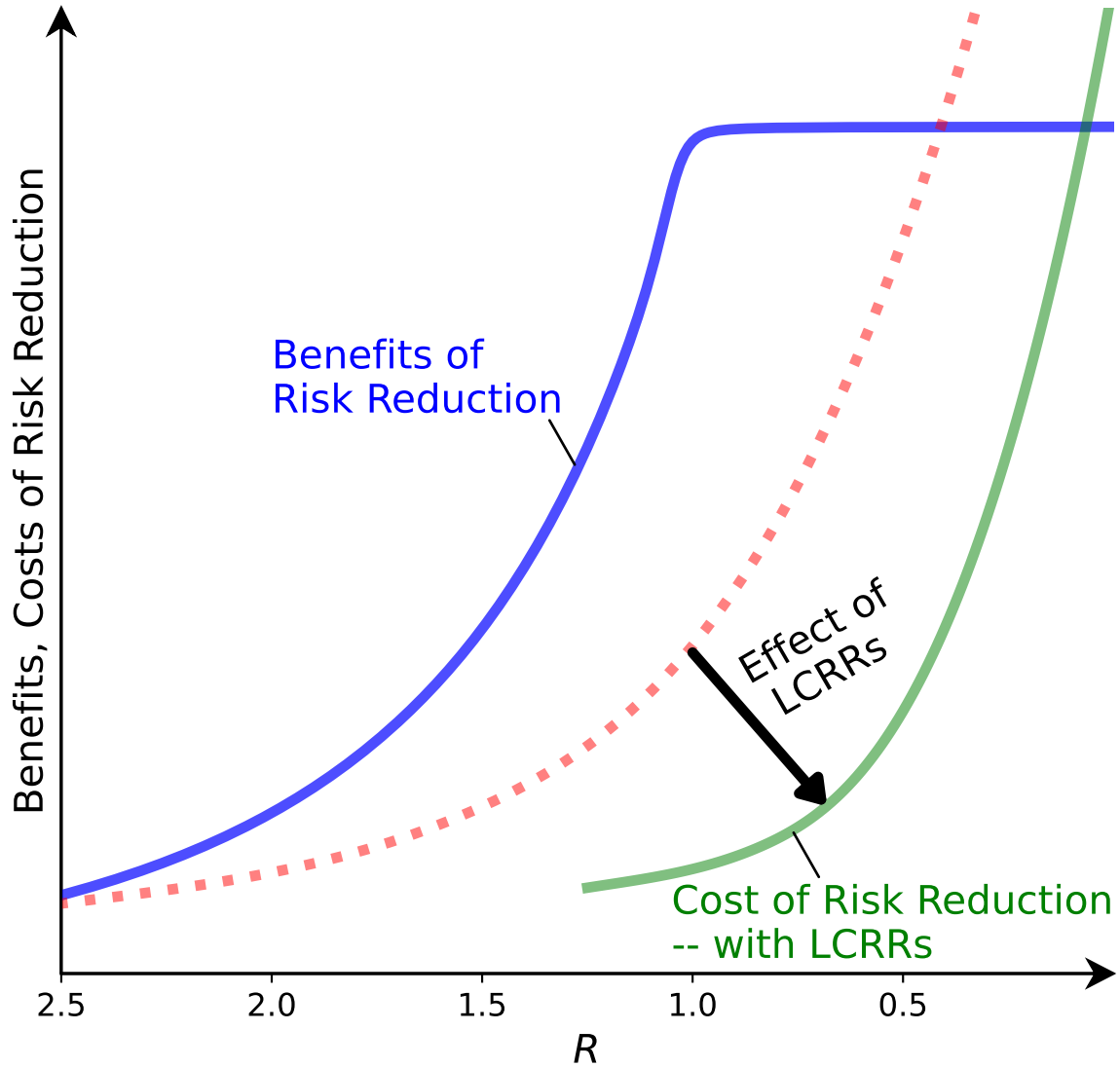

Fig. 4 *Note:* The solid-blue line and dotted-red line are the same benefits and costs of risk reduction curves as in Fig. 2. The solid-green line illustrates how low-cost risk reducers (LCRRs) lower the economic cost of risk reduction. The illustrated reduction is based on the numerical example from Sect. 5 under the assumption that LCRRs reduce risk by 50%

Remark: Schools vs. Bars

- Likely policy mistake: long-term closing of schools
- In the language of this paper's model:
  - Education has a very high social value
  - With the right LCRRs in place, relatively low risk
  - Value-to-risk ratio thus very high
- At the same time, many cities in the US allowed for bars to reopen before public schools
- Criticism of these policies was widespread
  - Bars have significantly lower value-to-risk than education
  - Very inefficient to spend scarce risk budget on opening bars over opening schools

(See Jack et al. 2023, Jack and Oster 2023, Kofoed et al. 2024, Goldhaber et al. 2023, Hanushek and Woessmann 2020, Azevedo et al. 2021)

Remark: Accelerating Vaccine Development

- Imposing $R \leq 1$ is costly
- Thus large social value to accelerating development of vaccines/treatments
- Companion work Ahuja et al. (2021):
  - Investigates optimal investment in vaccine capacity "at risk" (before it is known which vaccines will be successful)
  - With optimal investment, vaccination would have been completed in the US by March 2021, globally by October 2021
- Companion work Castillo et al. (2021) suggests this acceleration would have been worth trillions of dollars and saved millions of lives

Remark: What the Dynamic Models Missed

- This paper's approach: static optimization
  - Traditional socioeconomic goals as objective
  - $R \leq 1$ as constraint to approximate health goals
  - Non-standard, but simple and intuitive (and approximates optimal policy)
- More popular approach: dynamic optimization
  - Both socioeconomic and health goals as objective
  - SIR disease dynamics as additional constraints
  - In principle, more complete and intellectually satisfying
- However, the dynamic models missed two key features:
  1. Assumed a single representative activity (no scope for doing easy risk reductions first)
  2. No or limited LCRRs
- These two differences from my analysis prevented $R \leq 1$ from being a feature of the optimal solution (see, e.g., Alvarez et al. 2020, Acemoglu et al. 2020)

Remark: Pandemic Fatigue

- Dynamic models also assume a high degree of policy control
  - Unrealistic
  - Messages and rules may change frequently
  - Thus likely to exacerbate pandemic fatigue
- On the other hand, the static approach encourages policy makers to pick a single policy principle and stick with it
- Impossible to run the counterfactual, but imagine if policy makers had articulated early on that
  1. Their guiding principle was to allow for as much activity as possible while preventing exponential growth of the virus
  2. Masks and tests are a way of keeping schools and most of the economy open
  3. They would do all they could to speed up availability of vaccines
- If only!

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Numerical Example: Overview

- I present a detailed numerical example in two steps

1. I depict the optimal activity mix and cost of mitigation curve under the baseline model
   - Assume social value and risk are uniformly distributed
     - i.e., activities are equally likely to be anywhere on the square of value-versus-risk
   - Consider R_0 range of 2.0–4.0, based on empirical evidence
2. I add LCRRs to the example
   - Consider risk reduction range of 30%–70%
     - Based on empirical evidence, e.g., Chu et al. (2020) meta-study: masks reduce R by 70% in health care settings, 44% in non health care settings
   - This yields the most important results of the section: magnitudes for just how economically valuable LCRRs are

Numerical Example: Initial Model without LCRRs

- Let activities' values and risks be jointly uniformly and independently distributed on $[0, \bar{v}] \times [0, \bar{r}]$
- If society engages in all activities, i.e., society engages in Program (1) above, then pre-virus social welfare is given by

$$V_0 = \int_0^{\bar{r}} \int_0^{\bar{v}} v_i \frac{1}{\bar{v}\bar{r}} dv dr = \frac{\bar{v}}{2}$$

- The reproduction rate of the virus without any LCRRs or activity restrictions is given by

$$R_0 = \int_0^{\bar{r}} \int_0^{\bar{v}} r_i \frac{1}{\bar{v}\bar{r}} dv dr = \frac{\bar{r}}{2}$$

- Without loss of generality, set $\bar{v} = 1$
- Relation $\bar{r} = 2R_0$ allows us to express $\bar{r}$ based on a parameter choice for R_0, which can be based on empirical evidence

Numerical Example: Initial Model without LCRRs

- Now consider the constrained problem in which society chooses activities to maximize social welfare subject to a constraint on R
- Formally, for any $K \in [0, R_0]$, society solves

$$\max_{x(\cdot)} \int_0^{2R_0} \int_0^1 x(v,r) \cdot v_i \frac{1}{2R_0} dvdr \tag{10}$$

subject to

$$\int_0^{2R_0} \int_0^1 x(v,r) \cdot r_i \frac{1}{2R_0} dvdr \leq K$$

- Solution characterized by value-to-risk threshold ρ^* such that
  - All activities with value-to-risk ratio above ρ^* are included
  - All activities with value-to-risk ratio below ρ^* are dropped

Remark: Super-Spreader Activities

- Can consider risk distribution with super-spreader activities
  - Includes small mass of activities with particularly large r_i
  - May be more realistic than uniform distribution
- If super-spreader activities are incorporated:
  - Significantly fewer activities need to be dropped for $R \leq 1$
  - Welfare can then be significantly higher than analyzed here
  - Caveat: Super-spreader activities must not also be an unusually large fraction of pre-virus social welfare

Numerical Example: Optimum without LCRRs

	Value of R_0				
	2.0	2.5	3.0	3.5	4.0
To Achieve $R \leq 1$:					
% Activities Dropped	37.5	45.0	50.0	53.7	56.7
% Social Welfare Dropped	18.8	27.0	33.3	38.3	42.3
Relative to Pre-Virus Economy:					
% Activities Kept	62.5	55.0	50.0	46.3	43.3
% Social Welfare Kept	81.2	73.0	66.7	61.7	57.7

Numerical Example: Optimum without LCRRs

	Value of R_0				
	2.0	2.5	3.0	3.5	4.0
To Achieve $R \leq 1$:					
% Activities Dropped	37.5	45.0	50.0	53.7	56.7
% Social Welfare Dropped	18.8	27.0	33.3	38.3	42.3
Relative to Pre-Virus Economy:					
% Activities Kept	62.5	55.0	50.0	46.3	43.3
% Social Welfare Kept	81.2	73.0	66.7	61.7	57.7

Numerical Example: Adding in LCRRs

- Now add LCRRs to the example
- For simplicity, assume that LCRRs
  - Reduce risk by a uniform percentage across activities, γ_r
  - Reduce value by a uniform percentage across activities, γ_v
- Still have a joint uniform distribution of value and risk, only now on $[0, (1-\gamma_v)\bar{v}] \times [0, (1-\gamma_r)\bar{r}$
- Thus same math from above goes through analogously
- If LCRRs are sufficiently effective, they alone can reduce R to less than 1 without any reduction in activity levels
  - This occurs if $R_0(1-\gamma_r) \leq 1$
  - For example, if $R_0 = 2.5$ and reduction in risk is at least 60%
  - With super-spreader activities, more likely conclusion is that society would only have to drop them, keeping everything else

Numerical Example: Optimum with LCRRs

		LCRR Efficacy				
	No LCRRs	30%	40%	50%	60%	70%
To Achieve $R \leq 1$:						
% Activities Dropped	45.0	32.1	25.0	15.0	0.0	0.0
% Social Welfare Dropped	27.0	13.8	8.3	3.0	0.0	0.0
Relative to Pre-Virus Economy:						
% Activities Kept	55.0	67.9	75.0	85.0	100.0	100.0
% Social Welfare Kept	73.0	86.2	91.7	97.0	100.0	100.0

Numerical Example: Optimum with LCRRs

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Effect of LCRRs on Keep/Drop

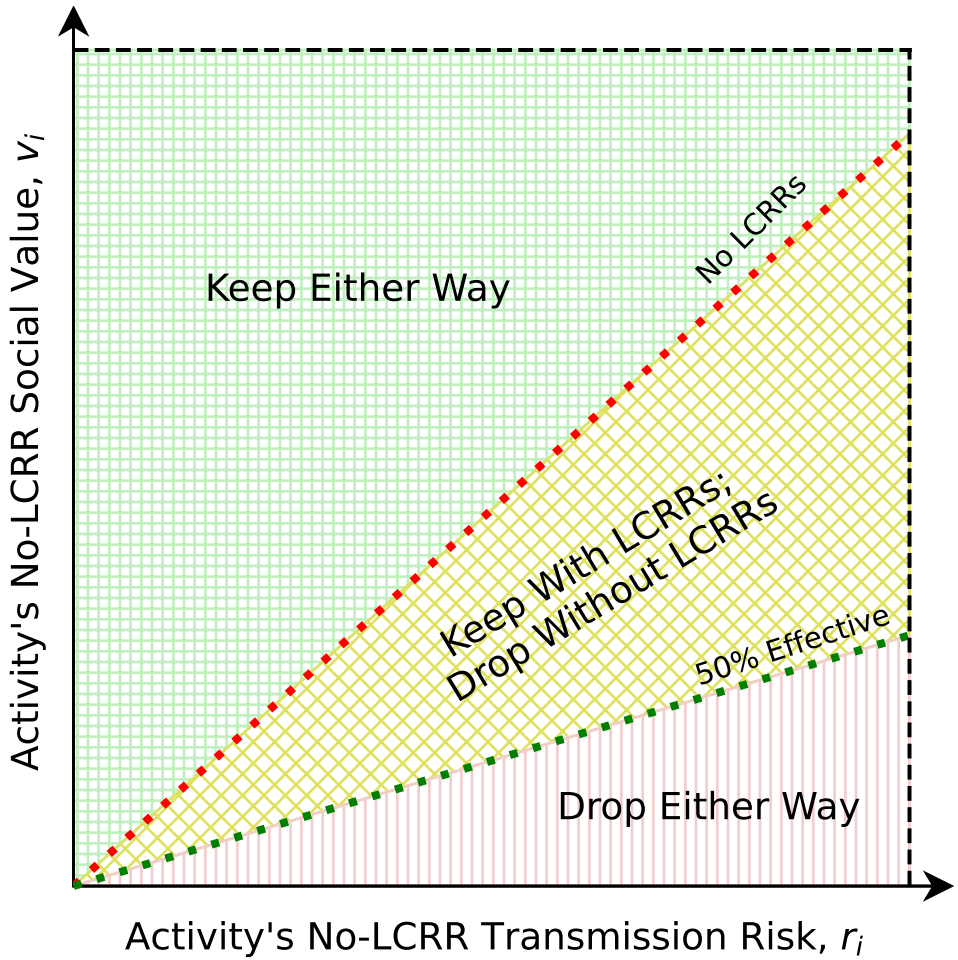

Fig. 5 *Note:* This figure illustrates how LCRRs expand the optimal set of activities used to maximize societal welfare subject to $R \leq 1$. The diagonal line labeled "No LCRRs" depicts the critical threshold ρ^* for the ratio of value-to-risk if there are no LCRRs; this is the same line as in Fig. 3 and is based on the uniform-distribution example with $R_0 = 2.5$. Without LCRRs, activities above the "No LCRRs" line should optimally be kept and activities below this line should optimally be dropped. The diagonal line labeled "50% Effective" depicts how the mix of activities expands if LCRRs are adopted and they uniformly reduce risk by 50%. Activities with social value and risk in the yellow hatched region, above the "50% Effective" line but below the "No LCRRs" line, can be included in the optimum with LCRRs whereas they are dropped without

Effect of LCRRs on the Economic Cost of Mitigation

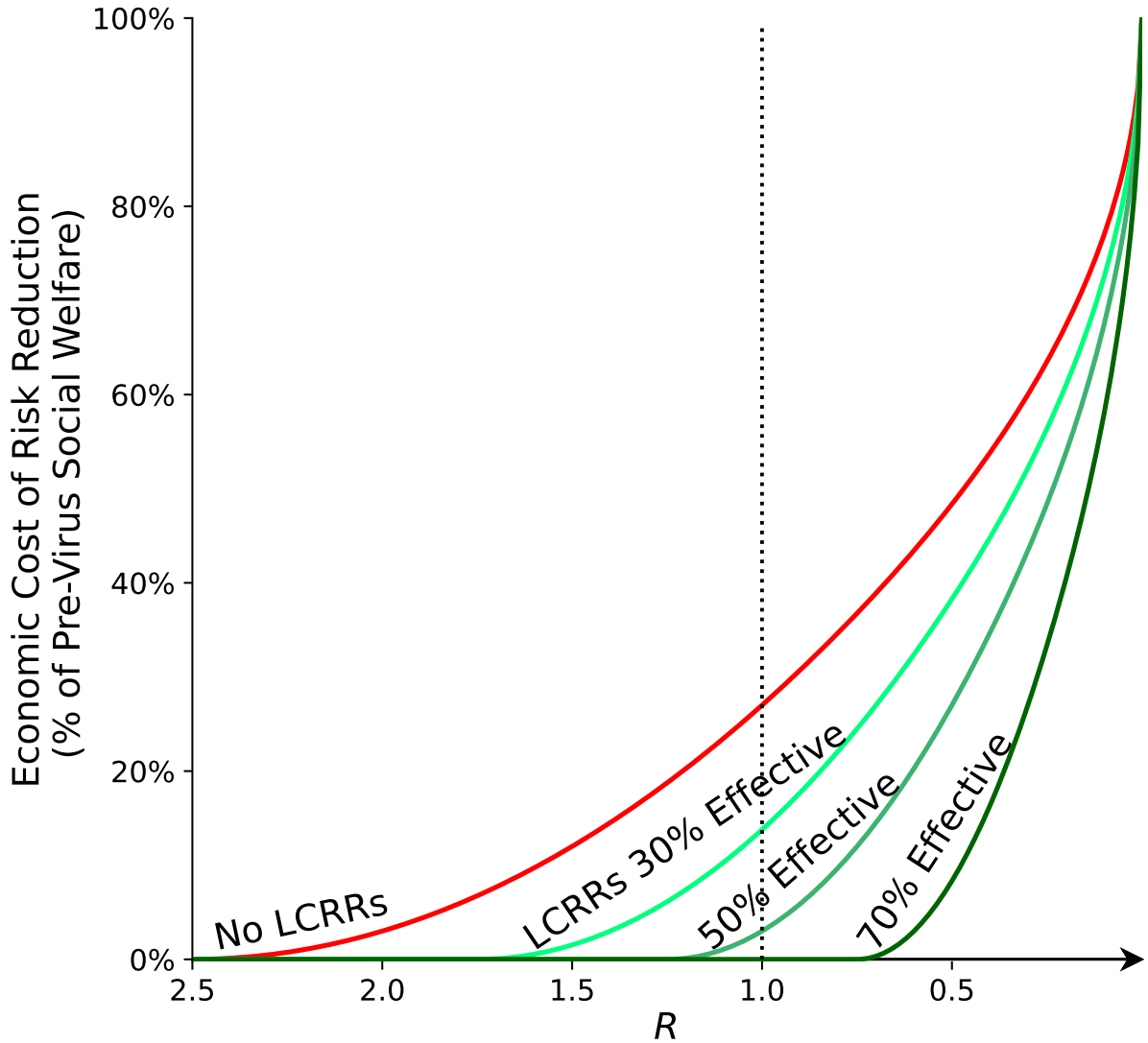

Fig. 6 *Note:* This figure presents the economic cost of risk reduction curve in the numerical example with no LCRRs and with LCRRs of varying effectiveness. The horizontal axis represents the level of mitigation and the vertical axis is the cost depicted as a percentage of pre-virus social value $V_{pre-virus}$ as defined above. These curves correspond to the illustrative cost of risk reduction curves presented in price-theory diagrams Fig. 2 (without LCRRs) and Fig. 4 (with LCRRs)

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Dynamic Considerations

- So far, v_i ignores virus considerations; virus enters through r_i
- If level of infections is high enough, this will affect v_i because of fear of catching the virus (Goolsbee and Syverson, 2021)
- Capture this idea by replacing v_i with $v_i^{exposed} < v_i$
- Intuitively, social welfare is then lower for any target R
- Formally, for any $K \in [0, R_0]$, define V_k as before and define $V_K^{exposed}$ as the value in the optimal solution to program:

$$\max_{x \in X} \sum_{i=1}^{n} x_i v_i^{exposed}$$

subject to

$$\sum_{i=1}^{n} x_i r_i \leq K$$

- Then we have $V_K^{exposed} < V_K$ for all $K \in [0, R_0]$

Dynamic Considerations

- This illustrates the value of treating $R \leq 1$ as a constraint before the stock of infections grows
- A society that does not take early action and faces a high stock of infections may wish to
  1. First significantly reduce the stock of infections (i.e., $R \ll 1$)
  2. Then transition to a steady state with $R \leq 1$
- Several papers suggest that since $v_i^{exposed}$ seems likely to decrease monotonically with the stock of infections, R may automatically equilibrate to around 1
  - But at a high stock of infections and with a fearful, low-utility society in "epidemic limbo" (McAdams 2021)

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Sense of Magnitudes: Potential Health and Economic Costs of the $R \leq 1$ Policy Paradigm

Initial Stock of Infections	10,000	100,000	1,000,000
Health Outcomes:			
Total Infections	718,000	5,810,000	24,900,000
Total Deaths	5,000	40,000	174,000
Socioeconomic Outcomes:			
% Activities Maintained	85.0%	85.0%	85.0%
% Social Welfare Maintained	97.0%	97.0%	97.0%
Overall Magnitudes:			
Health Cost	\$35 B	\$282 B	\$1.22 T
Economic Cost	\$660 B	\$660 B	\$660 B
Total Cost	\$695 B	\$942 B	\$1.88 T

Note: Total Infections and Total Deaths in 12 months. Assumes R_0 of 2.5, LCRR efficacy of 50%, population of 330 million, VSL (Value of Statistical Life) of \$7 million, and annual GDP of \$22 trillion. Economic cost estimated as $(1 - \%$ Social Welfare Maintained$) \times$GDP. Health cost estimated as VSL $\times$ Total Deaths

Sense of Magnitudes: Cost of $R \leq 1$

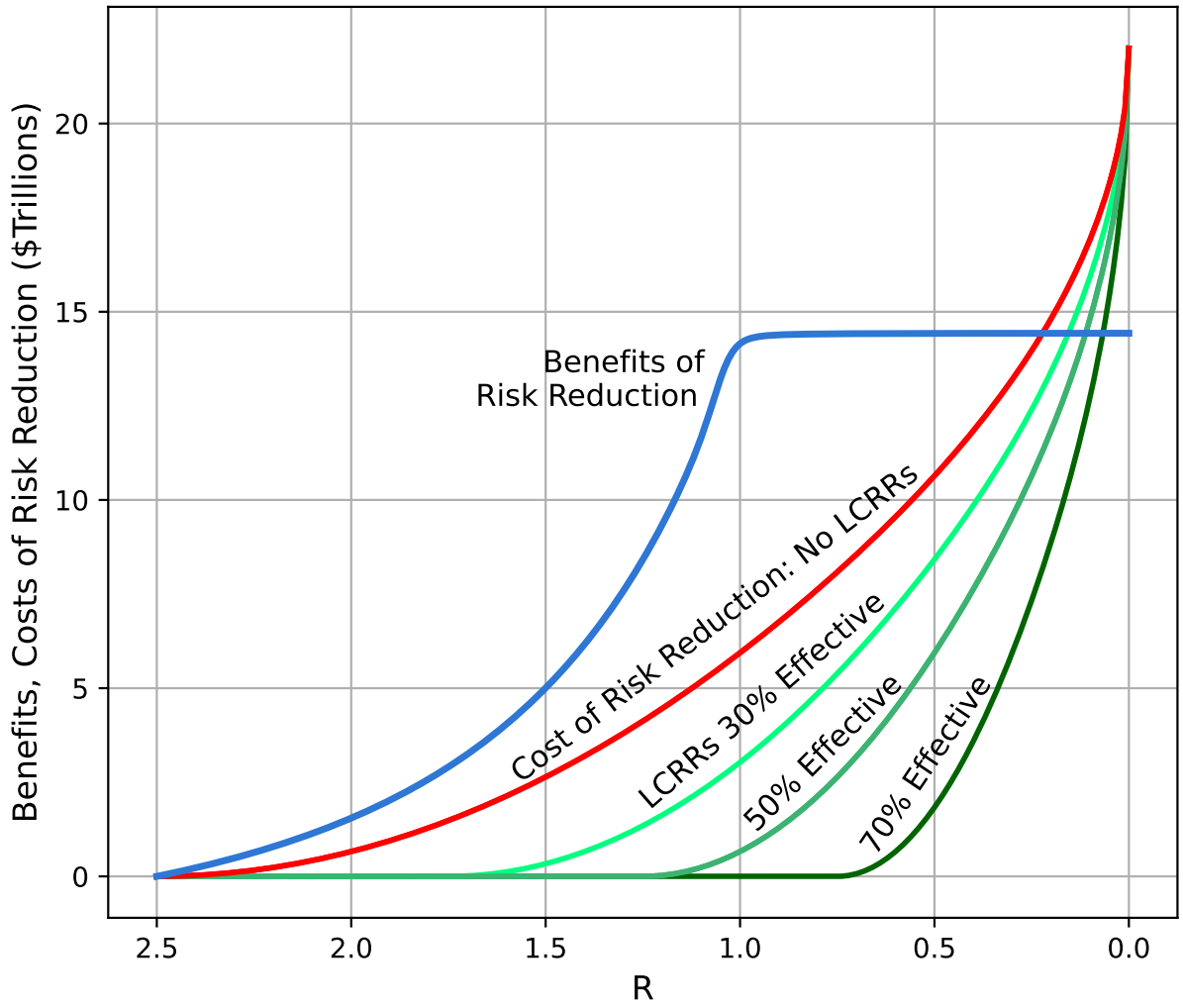

Fig. 7 *Note:* The Benefits curve is the same as in Fig. 2, with the vertical scale based on a VSL of $7 million. The Cost curves are the same as in Fig. 6 with the vertical scale set using $V_{pre-virus}$ = $22 trillion, which was US forecast GDP for 2020

Potential Health and Economic Costs for Dynamic Policies

Note: Assumes an initial stock of 1 million infections. Considers a dynamic plan with a target of $R \ll 1$ for an initial phase, followed by a target of $R \leq 1$ for the remainder of the year. I numerically compute the optimal R target for the early period.

Scenario:			
Duration of Initial Phase	30 days	60 days	90 days
Optimal R Target for Initial Phase	0.59	0.76	0.83
Health Outcomes:			
Cumulative Infections in Phase 1	2,290,000	3,900,000	5,430,000
Stock of Infections Entering Phase 2	91,000	54,000	40,000
Cumulative Infections during Phase 2	4,160,000	2,170,000	1,370,000
Cumulative Total Infections	6,450,000	6,070,000	6,800,000
Cumulative Total Deaths	45,000	42,000	48,000
Socioeconomic Outcomes:			
% Activities Kept during Phase 1	60.4%	70.6%	74.8%
% Social Welfare Kept during Phase 1	79.1%	88.5%	91.5%
Time-Weighted % Activities Kept	83.0%	82.6%	82.5%
Time-Weighted % Social Welfare Kept	95.5%	95.6%	95.7%
Overall Magnitudes:			
Health Cost	\$314 B	\$297 B	\$333 B
Economic Cost	\$984 B	\$968 B	\$957 B
Total Cost	\$1.30 T	\$1.26 T	\$1.29 T

Potential Health and Economic Costs for Dynamic Policies

- Observe from the table that
  1. The longer is the period with the lower R target, the less strict the lower R target can be, and vice versa
  2. What the early period does is invest in reducing the stock of infections (in each of the optimal plans the stock is reduced from 1 million to under 100,000)
  3. A dynamic plan lowers the number of deaths significantly, at higher cost to socioeconomic value during the $R \ll 1$ period
- The dynamic plan likely has additional economic gains in this scenario of late policy action due to the fear of the virus channel documented by Goolsbee and Syverson (2021)

Sense of Magnitudes: Actual Policy Costs

- Compare $R \leq 1$ costs to actual costs in the US
  - Focus on 12 months from March 2020 to February 2021
- Health costs:
  - Actual policy resulted in 512,978 deaths ($3.6T at $7M VSL)
  - Corresponds to weighted-average R of 1.12–1.14
  - Hundreds of thousands more deaths than in any $R \leq 1$ scenario
- Economic costs:
  - $1 trillion of lost GDP and $3.5 trillion of economic stimulus
  - Trillions of dollars higher than in any $R \leq 1$ scenario
- Educational losses to children:
  - Estimated NPV of lost GDP growth of $14–$28 trillion (Hanushek and Woessmann 2020)
  - Estimated NPV of lost earnings of $20 trillion globally (Azevedo et al. 2021)
  - Using LCRRs and some of society's risk budget to keep schools open could have avoided this tragedy

Sense of Magnitudes: Summary

- It thus seems plausible that the approach advocated in this paper could have:
  - Saved hundreds of thousands of lives
  - Saved trillions of dollars
  - Reduced severe harms to a generation of students

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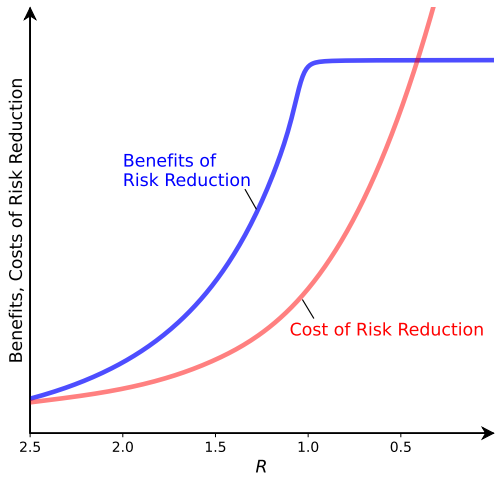
Conclusion: A New Play in the Pandemic Playbook?

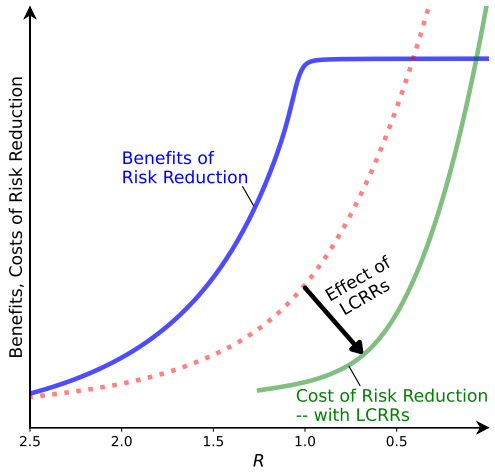
- This paper has argued that the Covid-19 pandemic called for a novel play in the pandemic playbook
  1. Pre-vaccine, treat $R \leq 1$ as a constraint and maximize social welfare subject to this constraint
  2. Use low-cost risk reducers (LCRRs) and targeted activity bans to get to $R \leq 1$ as efficiently as possible
  3. Accelerate vaccination to essentially the maximum extent possible (as studied in companion papers, Ahuja et al. (2021) and Castillo et al. (2021))

The Infectious-Threat Playbook

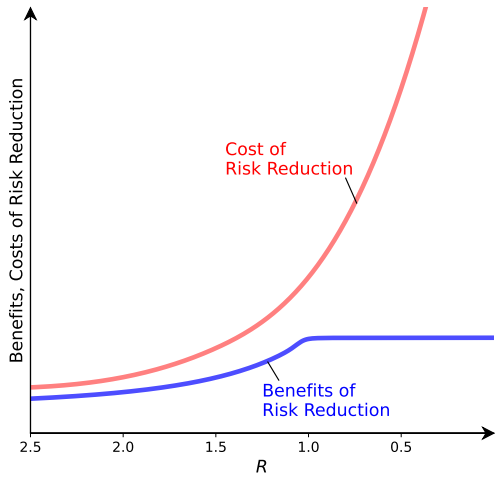
Panel A: $R \leq 1$ is Optimal



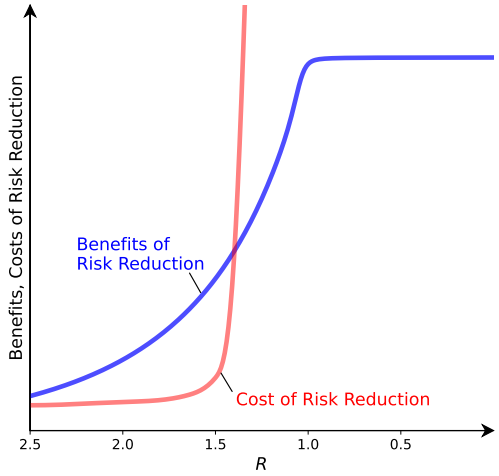
Panel B: $R \leq 1$ with LCRRs



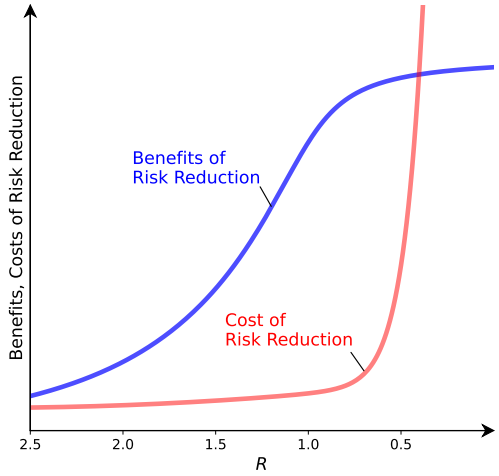
Panel C: Optimal to Ignore



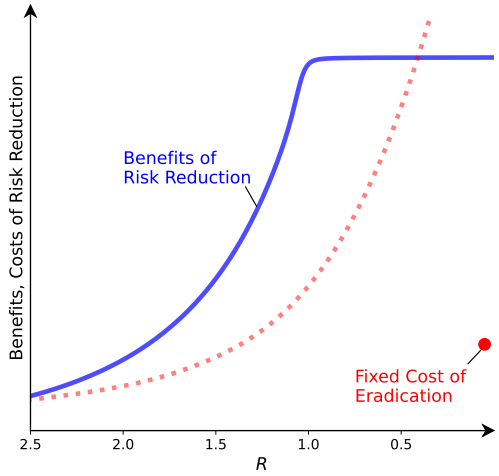
Panel D: Optimal to Partially Mitigate



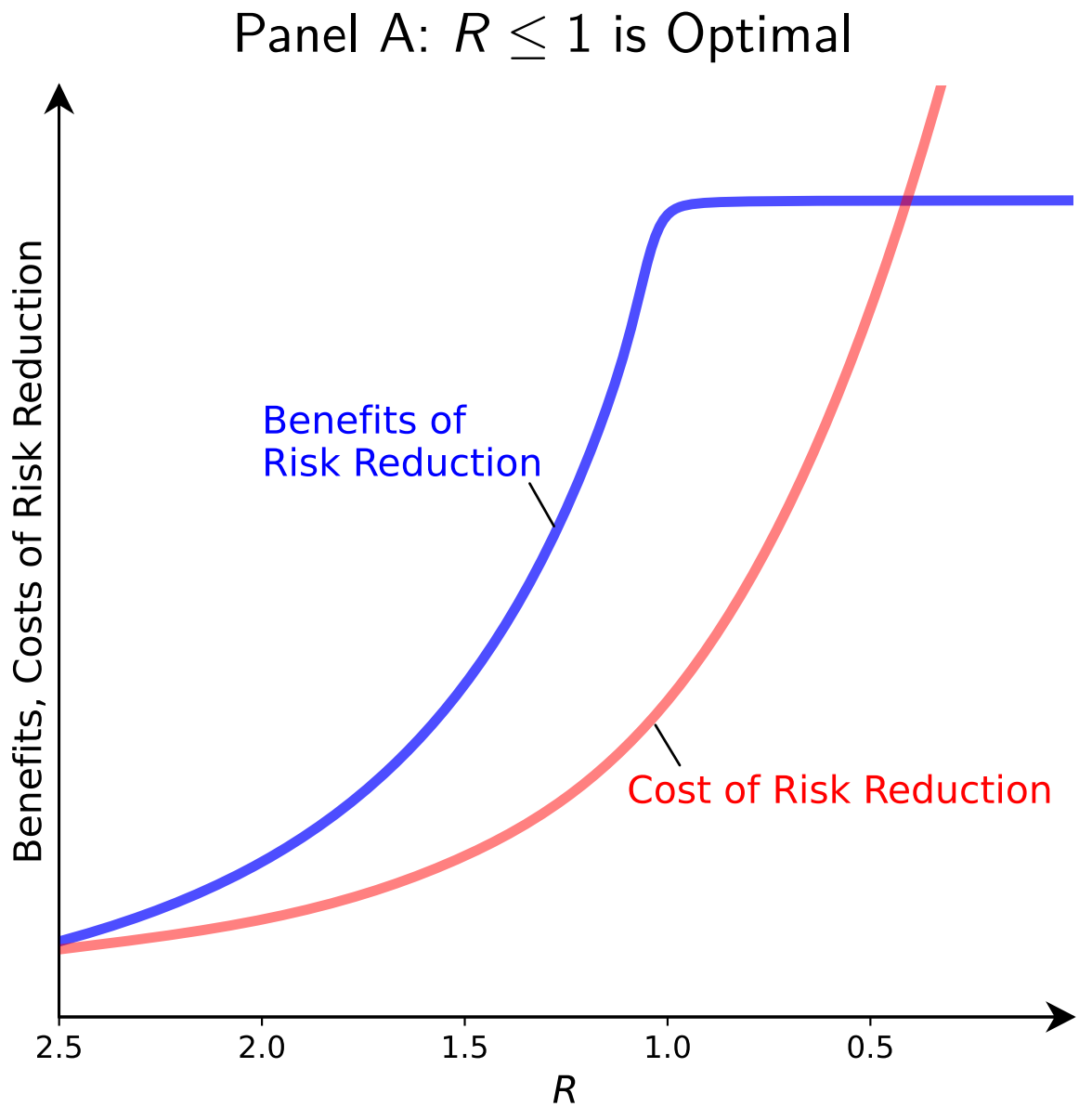
Panel E: Optimal to Suppress to $R \ll 1$



Panel F: Optimal to Eradicate



The Infectious-Threat Playbook



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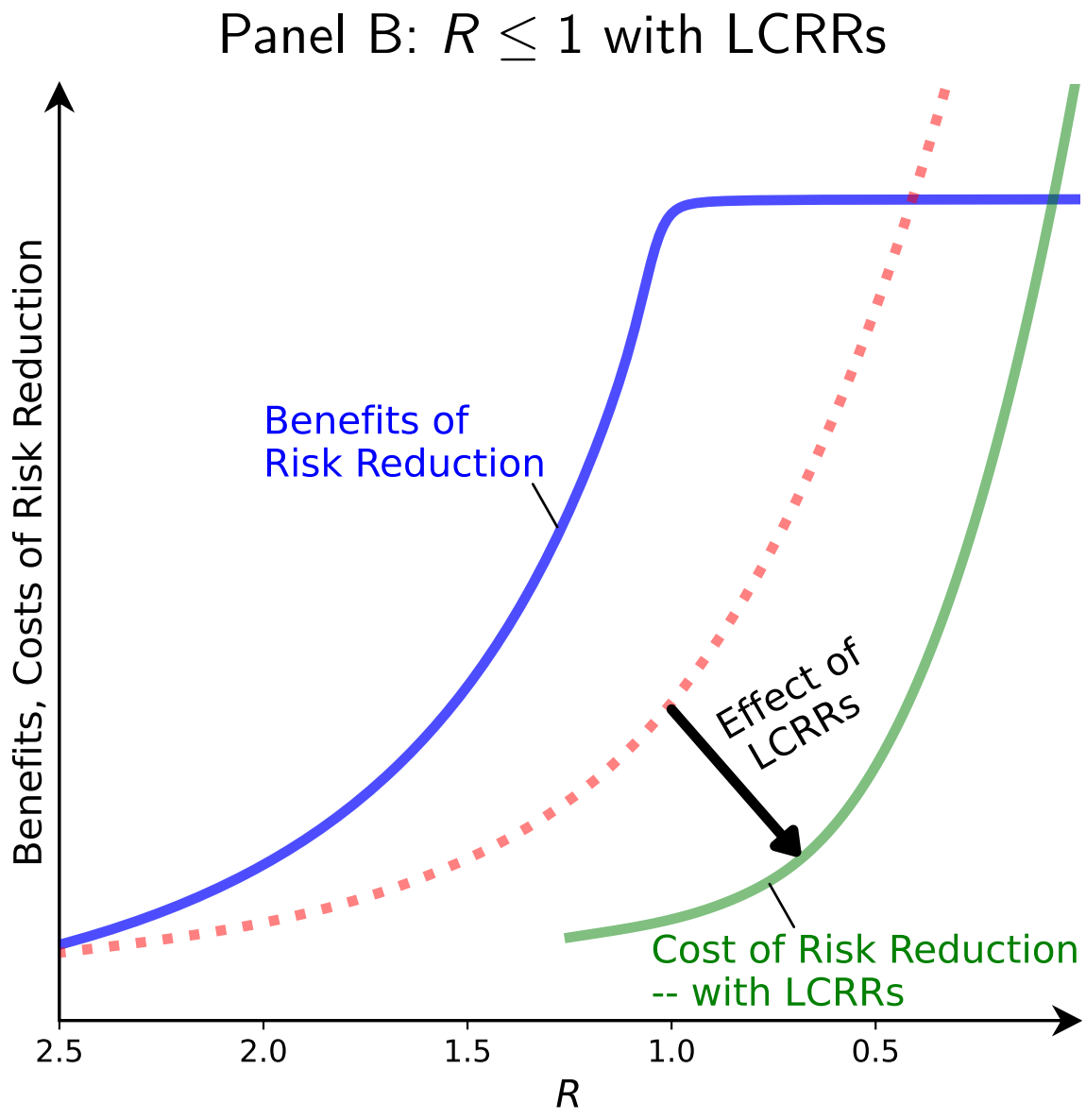

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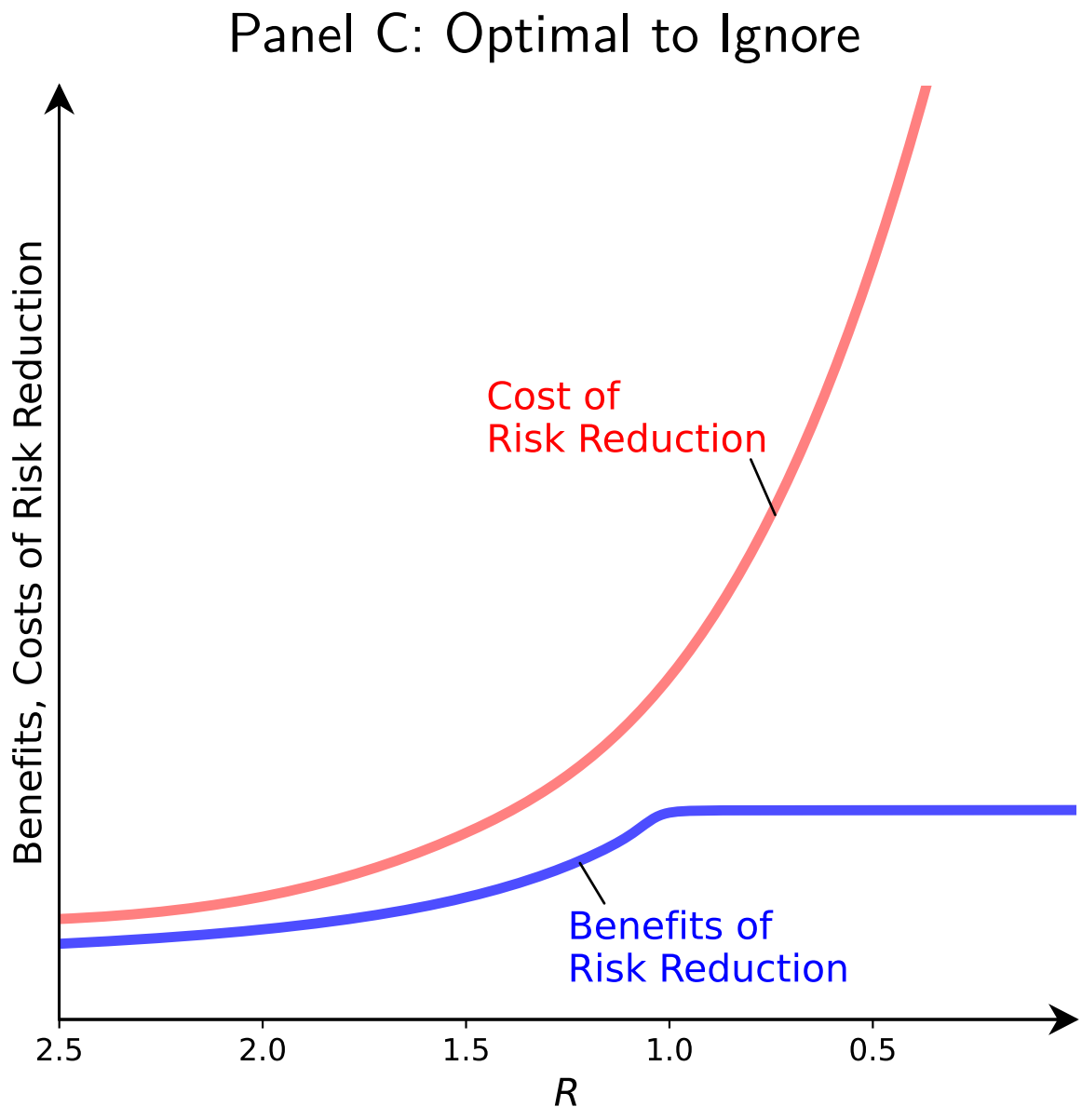
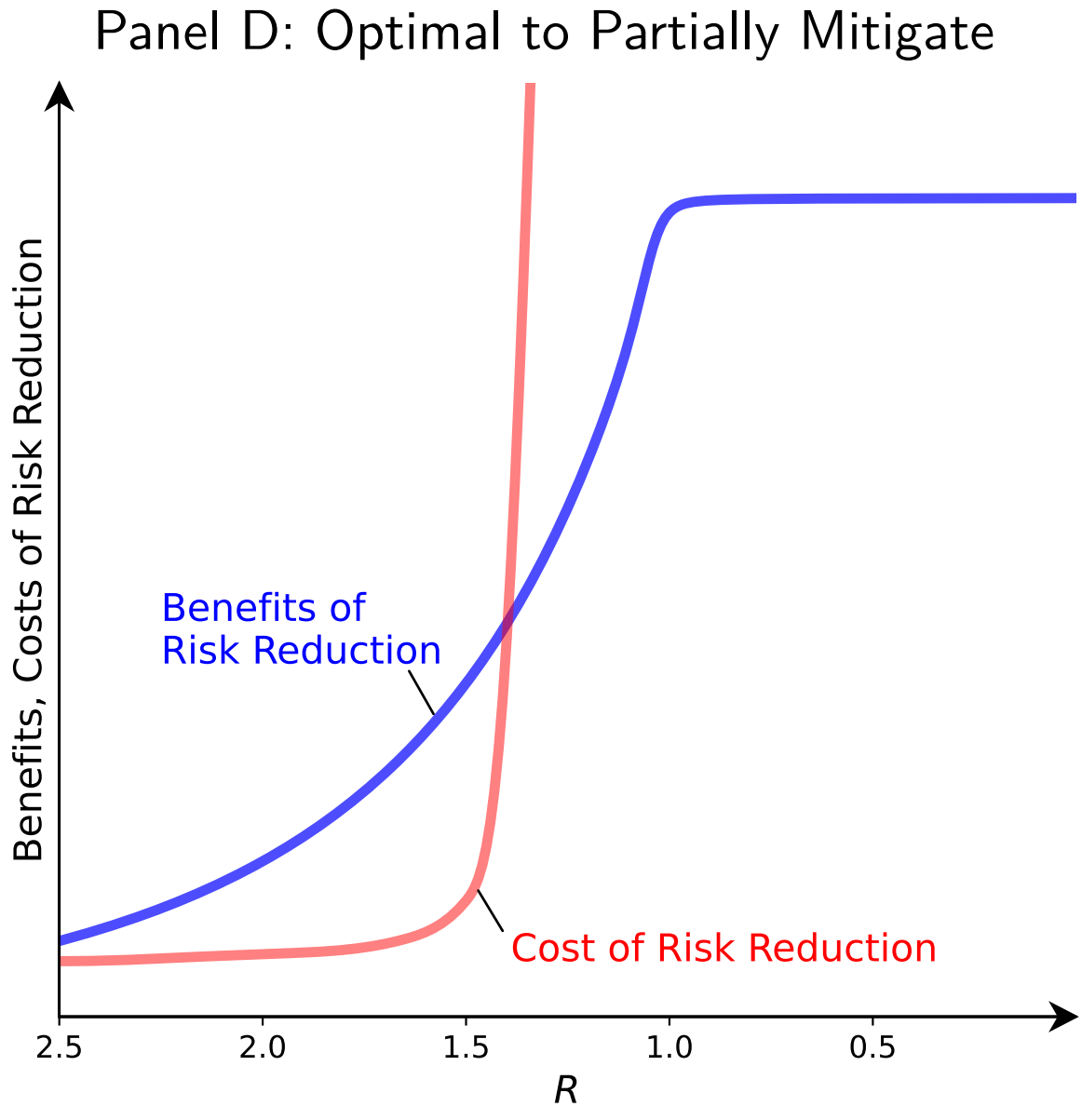


The Infectious-Threat Playbook



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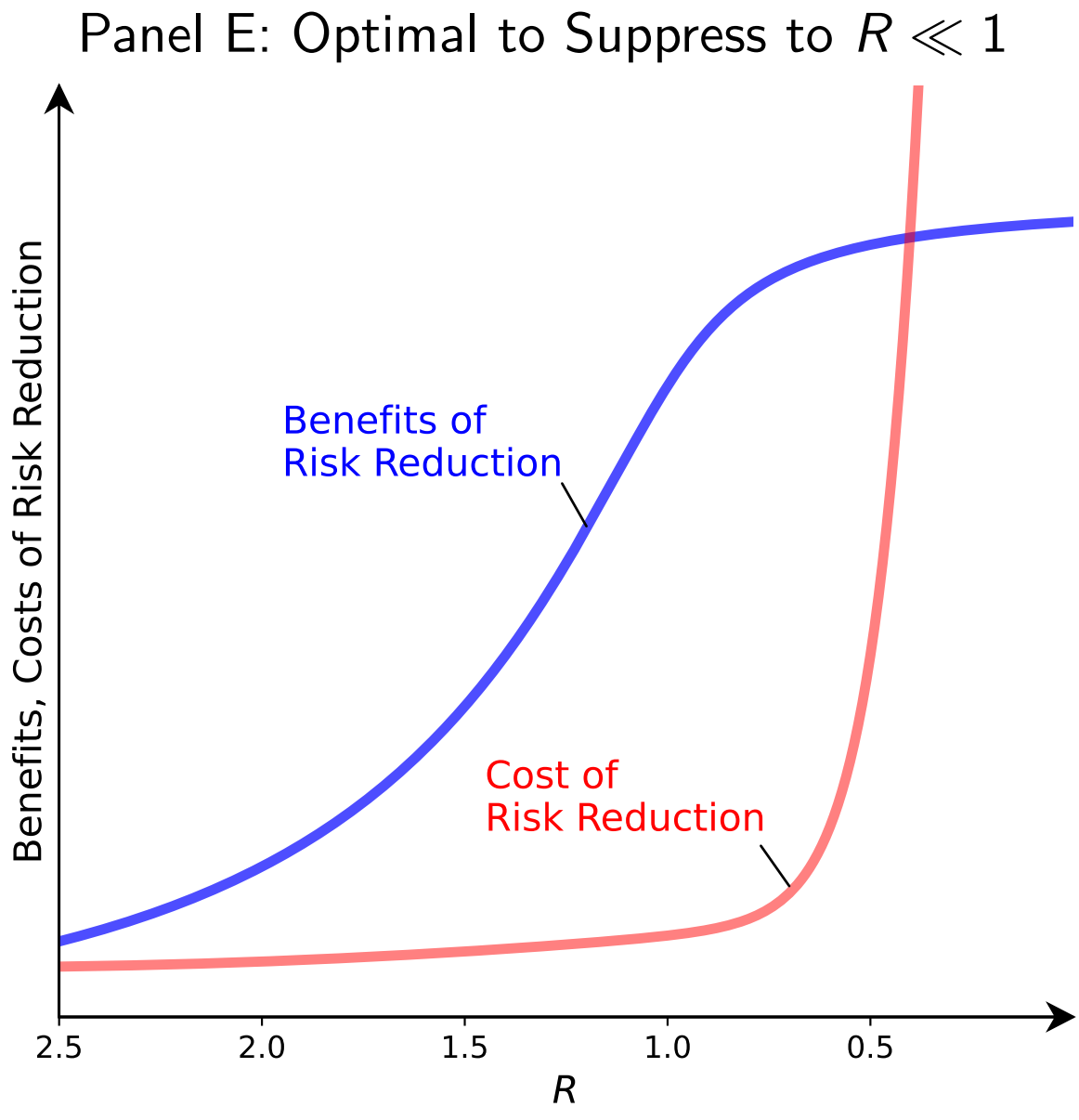

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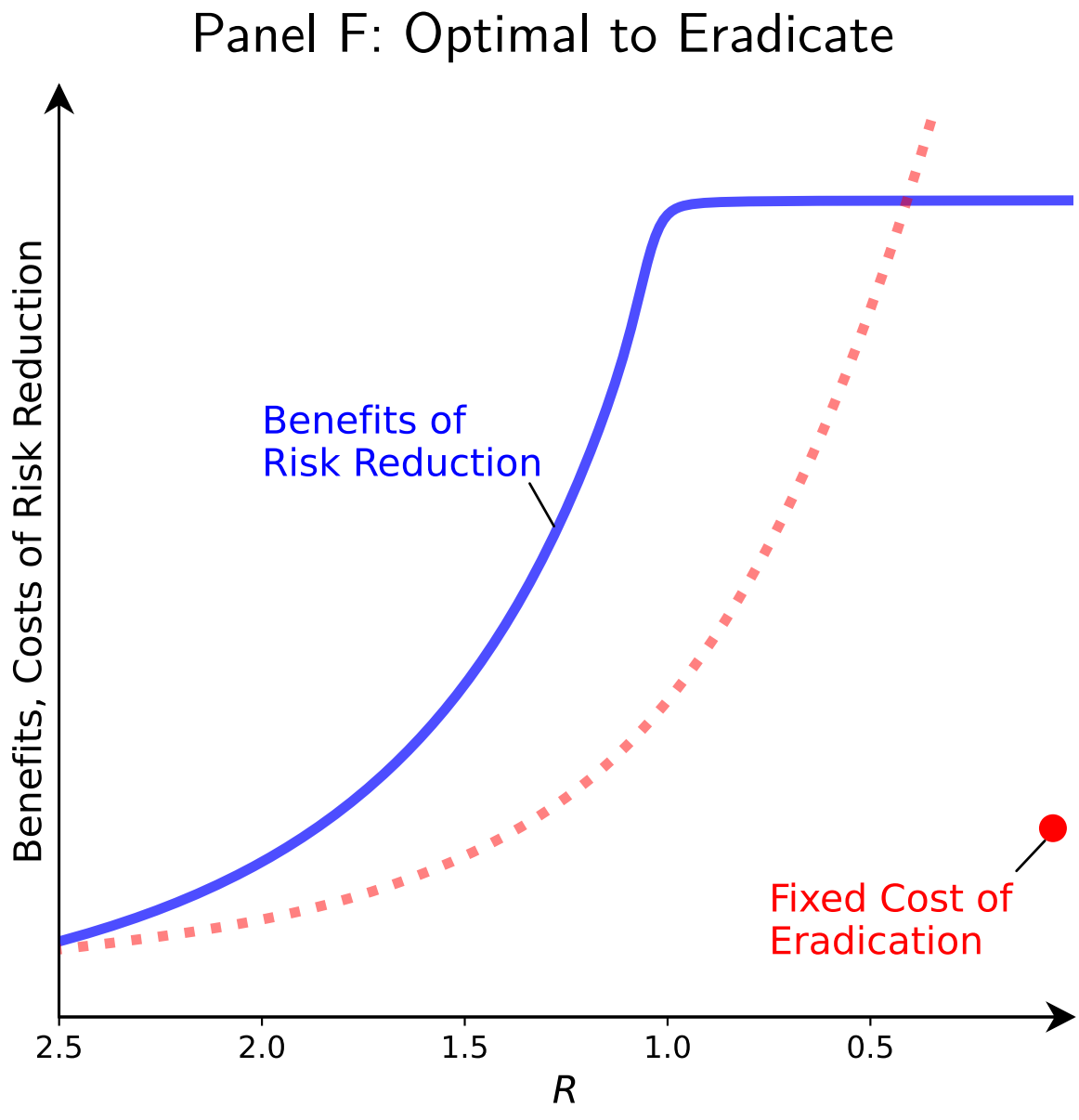

Conclusion: A New Play in the Pandemic Playbook?

- The epidemiologist Dr. Michael Osterholm wrote: "As epidemiologists, we have two goals. The first is to prevent. When that is not possible, the second is to minimize..."
- The public-health instinct is a useful heuristic for optimal policy in scenarios depicted in Panels D, E and F
- Specifically, understand "minimize" to mean
  - Pursuing eradication if feasible at a fathomable fixed cost
  - Engaging in all of the interventions on the flat parts of the cost curve, but then stopping when the curve gets much steeper
- However, the public-health instinct to minimize, and to regard the economy and education as merely "collateral damage," was profoundly suboptimal in the case depicted in Panels A and B that corresponds to Covid-19
- Covid-19 demanded a new play in the pandemic playbook.

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Why Treating $R \leq 1$ as a Constraint is Approx. Optimal

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- Let us prove formally why treating $R \leq 1$ as a constraint is approximately optimal
- Define health cost function $h : [0, R_0] \to \mathbb{R}^+$
  - Input: virus reproduction rate
  - Output: society's health cost (e.g., VSL $\times$ number of deaths in a 12-month period)
- Consider the social planner problem

$$\max_{x \in X} \sum_i x_i v_i - h\left(\sum_i x_i r_i\right) \tag{6}$$

- Goal: Give conditions under which the solution to (3) is an approximately optimal solution to (6)

Defining the Benefit and Cost of Risk Reduction Curves

- It will be convenient to work with benefit and cost of risk reduction curves as in Figure 2
- To define the benefit of risk reduction function:
  - Let $\Delta \in [0, R_0]$ denote amount of risk reduction
  - Define $b(\Delta) = h(R_0) - h(R_0 - \Delta)$
- To define the cost of risk reduction function:
  - Let V_K denote the value in the optimal solution to program

$$\begin{aligned} \max_{x \in X} \quad & \sum_{i=1}^{n} x_i v_i \\ \text{subject to} \quad & \sum_{i=1}^{n} x_i r_i \leq K \end{aligned}$$

  - Define $c(\Delta) = V_{\textit{pre-virus}} - V_{(R_0 - \Delta)}$

Convexity of Cost of Risk Reduction

Proposition 2 *The cost of risk reduction function* $c(\Delta)$ *is increasing and convex in the quantity of risk reduction* Δ*.*

- Intuition: one has to drop more and more attractive activities the larger is the desired reduction in transmission, with attractiveness defined in terms of the value-to-risk ratio $\rho_i = \frac{v_i}{r_i}$

Kinked Benefits of Risk Reduction Function

- When does the solution to (3) solve (6) optimally?
- It will be mathematically convenient to work with a limiting case of $h(\cdot)$ and $b(\cdot)$ in which
  1. The infection seed I_0 grows small
  2. The time horizon grows long
- This limiting case has an exact kink at $R = 1$, i.e. at $\Delta = R_0 - 1$
- Formally, fix a population size POP, infection fatality rate IFR, and value of statistical life VSL. Define the limiting case for the $b(\cdot)$ function as follows:

Definition 1 *Let* $\overline{\pi} : [0, R_0] \to \mathbb{R}^+$ *be computed as the proportion of the population infected in the SIR model in the limiting case of* $I_0 \to 0$ *and an infinite horizon. Define function* $\overline{h} : [0, R_0] \to \mathbb{R}^+$ *by* $\overline{h} = POP \times IFR \times VSL \times \overline{\pi}$*, the dollar value of lives lost in this limit. Define the kinked benefits of risk reduction function* $\overline{b} : [0, R_0] \to \mathbb{R}^+$ *according to* $\overline{b} = \overline{h}(R_0) - \overline{h}(R_0 - \Delta)$.

Kinked Benefits of Risk Reduction Function

- The kinked benefits of risk reduction function $\overline{b}(\cdot)$ has the following properties:
  - $\overline{b}(0) = 0$
  - $\overline{b}(\Delta)$ is convex and increasing on the range $[0, R_0 - 1]$
  - $\overline{b}(\Delta)$ is constant on the range $[R_0 - 1, R_0]$
- Solution to (3) would be an exactly optimal solution to (6) if the actual benefit of risk reduction function were $\overline{b}(\cdot)$
- For approximate optimality result, need to define what it means for the true $b(\cdot)$ function to approximate the stylized $\overline{b}(\cdot)$ function

Definition 2 *Function $b(\cdot)$ is said to ϵ-approximate the kinked benefits of risk reduction function $\overline{b}(\cdot)$ if $|b(\Delta) - \overline{b}(\Delta)| < \epsilon$ for all $\Delta \in [0, R_0]$.*

Formal Approximate Optimality Result

Proposition 3 *Assume that the cost of risk reduction function* $c(\cdot)$ *satisfies either of the following two conditions relative to the kinked benefits of risk reduction function* $\overline{b}(\cdot)$*:*

(i) The marginal cost of mitigation at $R \leq 1$ *(i.e., at* $\Delta = R_0 - 1$*) is bounded by:* $c'(R_0 - 1) < \frac{\overline{b}(R_0) - \overline{b}(0)}{R_0 - 1}$.
["Mitigation is sufficiently valuable"]

Or (ii) Both

(a) $c'(0) \leq \overline{b}'(0)$ *["Ignore is suboptimal"]; and*
(b) $c''(x) \leq \overline{b}''(x)$ *for* $x \in [0, R_0 - 1]$.
["Mitigation costs do not accelerate too fast"]

Then: a solution to (6) with $\sum_i x_i^* r_i = 1$ *is exactly optimal for the kinked benefits of risk reduction function* $\overline{b}(\cdot)$*. If the true benefits of risk reduction function* $b(\cdot)$ ϵ*-approximates the kinked benefits of risk reduction* $\overline{b}(\cdot)$*, a solution to (6) with* $\sum_i x_i^* r_i = 1$ *is approximately optimal to within* 2ϵ *of the optimal solution.*

Formal Approximate Optimality Result

- In words: Proposition 3 tells us that imposing $R \leq 1$ as a constraint yields a solution that approximates the optimum if either of two conditions hold:

1. *"Mitigation is sufficiently valuable"*
   - Marginal cost of mitigation at $R \leq 1$ is small in relation to the health benefits of completely eliminating the virus versus the worst case of completely ignoring the virus
2. Or, *"ignore is suboptimal"* and *"mitigation costs do not accelerate too fast"*
   - Locally sub-optimal to ignore the virus
   - Acceleration of the cost of mitigation curve is smaller than acceleration of the benefits of risk reduction curve up to $R \leq 1$

- In the numerical example both conditions obtain by a decent margin even without LCRRs
  - Conditions hold even more strongly with use of LCRRs

Back to "Why Treating $R \leq 1$ as a Constraint is Approx. Optimal"