Optimal Vaccine Subsidies for Epidemic and Endemic Diseases

Matthew Goodkin-Gold  
Harvard University

Michael Kremer  
University of Chicago

Christopher Snyder  
Dartmouth College

Heidi Williams  
Stanford University
Introduction

Vaccine classic example of positive externality (indeed public good)
• Prevent my transmitting to you, reducing your benefit from getting vaccinated
• When is this effect strongest?
• If disease not too virulent, may die out; in any event, transmission not an issue
• If disease very virulent, most people get vaccinated

Market structure may matter
• Firm with market power may cut back quantities further to stoke demand

Public policy
• Externality provides reason for intervention. Which diseases deserve most attention?
• Look at subsidies. Which diseases require biggest subsidies?
• Comparative statics in transmissibility ($\mathcal{R}_0$)

Objective
• Theoretical study
• Use toy model: abstract from distancing, variants, etc.
• For qualitative economic understanding, not quantitative forecasting
• Want rigorous answer in model with some epidemiology
• End with Covid calibration
• See if “interesting” part of parameter space may be relevant
Literature

Forecasting and policy advice
- Atkeson, Kopecky & Zha 2020
- Buckner, Chowell & Springborn 2021

Social distancing
- Eichenbaum, Rebelo & Trabandt 2020
- Farboodi, Jarosch & Shimer 2020
- Gans 2020
- Jones, Philippon & Venkateswaran 2020
- McAdams 2020
- Rachel 2020
- Toxvaerd 2020
- Early work on behavioral responses
  - Kremer (1996), Reluga (2010),
  - Fenichel (2013), Toxvaerd (2019)

Policy under uncertainty

Vaccine externalities
- Brito, Sheshinski & Intrilligator 1991
- Chen & Toxvaerd 2014
- Francis 1997
- Geoffard & Philipson 1997
- Gersovitz 2003
- Gersovitz & Hammer 2004, 2005
- Funk et al. 2010
- Manfredi & D'Onofrio 2013
- Boulier, Datta & Goldfarb (2007)
- Geoffard & Philipson (1997)
- Galeotti & Rogers (2013)
- Mechoulan (2007)

Empirical
- Cook et al. 2009
- Ward 2014
- Bethune & Korinek 2020
- Greenwood et al. 2019
- Aguirregabiria et al. 2020
- Bisin & Moro 2020
Literature

Closest
- Mamani, Adida & Dey (2012)
- Adida, Dey & Mamani (2013)

Focuses
- General, analytical results instead of simulations
- Aid to grasping epidemiological and economic forces
- Rather than quantitative forecasting or specific policy advice
- Rigor where possible
- Rational economic agents
- Account for supplier market power
- Comparative statics in $R_0$
- Social welfare

New results
- Analytic (if not closed-form) expressions for susceptibles and other variables
- Increasing social returns
- Vaccines versus drugs
Epidemiological Model

SIR model
• $S_t = \text{susceptible}$
• $I_t = \text{infected}$
• $R_t = \text{recovered}$
• Standard; simplest model generating epidemics and vaccine benefits

Vaccination at recruitment
• Model rapid vaccination campaign
• Rollout at $t = 0$: $V_0 = \theta Q$

Unit population
• $S_t + I_t + R_t + V_t = 1$

Laws of motion
• $\dot{S}_t = -\beta I_t S_t$
• $\dot{I}_t = \beta I_t S_t - \alpha I_t$
• $\dot{R}_t = \alpha I_t$
• $\dot{V}_t = 0$

Initial conditions
• $S_0 = \hat{S}_0 - \theta Q$
• $I_0 = \hat{I}_0$
• $R_0 = 1 - \hat{I}_0 - \hat{S}_0$
• $V_0 = \theta Q$

Parameters
• $\alpha \in (0,1)$ recovery rate
• $\beta > 0$ transmissions per contact
• $\theta \in (0,1)$ vaccine efficacy
• $\hat{I}_0, \hat{S}_0$ stocks at vaccine rollout
Epidemiological Model

Emphasize key endogenous variable
- Add argument $Q$ to most terms

Reproductive ratio
- Basic reproductive ratio $R_0 = \beta / \alpha \in (0, \infty)$
- Effective reproductive ratio $R_0 S_t(Q)$

Other basic insights
- In either case, epidemic eventually subsides: $I_\infty(Q) = 0$
- Social benefit depends on consumers who remain healthy: $S_\infty(Q)$
- $S_\infty(Q) = \frac{1}{R_0} | \mathcal{L}(-R_0(\hat{S}_0 - \theta Q)e^{-R_0(\hat{I}_0 + \hat{S}_0 - \theta Q)}) |$
Economic Model

Vaccine market
- Direct-to-consumer sales
- Later layer on government subsidies, other programs

Consumers
- Homogeneous (but see Appendix B2)
- \( MPB(Q) = \theta H \Phi_t(Q) = \theta H \left[ 1 - \frac{S_\infty(Q)}{\hat{S}_0 - \theta Q} \right] \) can show declining in \( Q \)
- All purchase if \( MPB(\hat{S}_0) > P \)
- None purchase if \( MPB(0) < P \)
- Otherwise fraction purchases, determined by \( MPB(Q) = P \)

Firms
- Constant average and marginal cost \( c \in (0, \theta H) \)
- Perfect competition: \( P_c^* = c \)
- Monopoly: \( Q_m^* \) solves \( \max_Q [MPB(Q) - c]Q \) subject to \( Q \leq \hat{S}_0 \)
Normative Measures

Social benefit
• \( SB(Q) = H[S_\infty(Q) + \theta Q] \)

Welfare
• \( W(Q) = SB(Q) - cQ \)

Marginal social benefit
• \( MSB(Q) = \frac{\partial SB(Q)}{\partial Q} = \frac{\theta H \Phi_1(Q)}{1 - R_0 S_\infty(Q)} \)

Marginal externality
• \( MEX(Q) = MSB(Q) - MPB(Q) = \frac{\theta H \Phi_1(Q) R_0 S_\infty(Q)}{1 - R_0 S_\infty(Q)} = \left[ R_0 S_0(Q) \left( \frac{S_\infty(Q)}{S_0(Q)} \right) \right] MSB(Q) \)

Probability they would have remained uninfected but for me
Number of direct infections I would have caused
Cumulate Marginal social benefit over these “but for” consumers
Equilibrium

Goal
- Comparative statics in $\mathcal{R}_0$
- Graph is for particular simulation. Work is to determine generality.

Regions
- (SR1) no purchases
- (SR3) first best under comp
- (SR4) first best under monop
- (SR2) interior

Key takeaways
- $MPB^* \uparrow, Q^* \uparrow$
- $R_\infty(Q^*), MSB^*, MEX^*$ have interior peaks that quite often are global peaks
- $W_c^* \downarrow, W_m^*$ can increase
Government Subsidies

Government’s objective
• Lexicographic preferences over (welfare, saving expenditures)

Targets first best
• Interior $Q^{**}$ satisfies $MSB(Q^{**}) = c$
• May have corner at no vaccination $Q^{**} = 0$
• May have corner at universal vaccination: $Q^{**} = \hat{S}_0$

Per-unit subsidy
• $GS^{**}$ minimum subsidy obtaining first best

General results
• $GS^{**} = 0$ for extremely low and extremely high $R_0$
• $GS^{**}$ has an interior peak in $R_0$
• $GS_m^{**} \geq GS_c^{**}$

Specific results
\begin{align*}
Q^{**} &= 0 & Q^{**} \text{ interior} & Q^{**} &= \hat{S}_0 \\
GS_c^{**} &= 0 & GS_c^{**} &= MEX(Q^{**}) & GS_c^{**} &= \max[0, c - MPB(\hat{S}_0)] \\
GS_m^{**} &= 0 & GS_m^{**} &= \frac{\hat{S}_0}{\hat{S}_0 - \theta Q^{**}} GS_c^{**} & GS_m^{**} &= \max \left[ 0, GS_c^{**} + \frac{\theta MEX(\hat{S}_0)}{1 - \theta} \right]
\end{align*}
Increasing Social Returns

Benefit function
- Concave in typical settings
- Might vaccines have increasing returns, say pushing past herd-immunity threshold?
- If so, may be benefits from concentrating in region rather than spreading evenly

Formal definitions
- Look for increasing social returns (ISR)
- Means $MSB(Q)$ increasing in $Q$

General condition
- $p$th vaccine unit exhibits ISR iff $\mathcal{R}_0 \left[ \frac{S_0(Q) + S_\infty(Q)}{2} \right] > 1$

Specific conditions
- Vaccine exhibits initial ISR if $\mathcal{R}_0 \hat{S}_0 \geq 2$
- Vaccine exhibits ISR everywhere if $\mathcal{R}_0 \hat{S}_0 \geq 2/(1 - \theta)$

Intuition
- Only possible source of ISR is external benefits
- If epidemic super-inflective, vaccinating just a few offers little protection to others since will likely contract from someone else. Need substantial cut in susceptible stock.
Universal Vaccination

Ineffective vaccine
• Universal vaccination can be far short of 100% successful immunizations
• Threat of contracting from unsuccessfully vaccinated provides benefit even to last consumer

Perfectly effective vaccine
• Literature often says can’t get universal vaccination even with perfect competition
• Last consumer has no one to contract disease from
• In our model, still an incentive to vaccinate
• Universal vaccination = all susceptibles
• Last susceptible vaccinated still faces threat
• Disease reservoir provided by $\hat{I}_0$ initially infected
• Can get first best (all consumers buy) even under monopoly for $R_0$ high enough
Vaccines Versus Drugs

Public-good aspect to vaccines
• One’s vaccination reduces transmission and thus others’ $MPB(Q)$
• Reduces demand, making market less lucrative for firm

Drug
• If treats symptoms without reducing transmission, doesn’t have this effect

Simple model
• Monopoly firm
• Costless production (easy normalization)

Results
• Drug more profitable than vaccine
• Firm’s bias toward drug highest for moderate $\mathcal{R}_0$
• Welfare generally higher with vaccine because of positive externality
• Possible offsetting effect that drug may help initially infected
• If so, equilibrium welfare higher with drug for extremely low and extremely high $\mathcal{R}_0$
Covid Calibration

Calibrate October 2020 situation
• When emergency use authorization for vaccines were being considered
• Relevant timeframe for early vaccine campaign
• “Classic” Covid

U.K. statistics
• $R_0 = 1.5$
• $\hat{I}_0 = 0.19\%, \hat{R}_0 = 6.2\%$
• Implies $\hat{S}_0 = 93.6\%$

Vaccine parameters
• $\theta = 80\%$ (midpoint of efficacy range for two Pfizer doses)
• $c = $40 per course
• $H = 12$ YLL x 1 DALY/YLL x 3 PGDP/DALY x $65,253$ USGDP = $2.35$ million
• $\bar{c} = \frac{c}{\theta H} = 2.13 \times 10^{-5} \approx 0$
Covid Calibration

Parameter space
- In (SR3), where first best obtains under competition but not monopoly

Monopoly outcome
- Monopoly price = 23% of harm, 21% of consumers purchase
- DWL = 29% of first-best welfare
- Optimal subsidy = 55% of equilibrium monopoly price
- Suggests bulk purchase policy more reasonable

Increasing social returns
- Increasing social returns from stockpile up to 22% of susceptible population
- Two separate, equal-sized states: concentrate supply in one unless stockpile exceeds 31% of its population, then spread evenly
Conclusion

Moderate infectiveness cause for biggest concern

- Low transmissibility, disease hardly spreads
- High transmissibility, little consumer “moral hazard”
- Moderate transmissibility is where market needs biggest prod
- Total infections, external benefit, optimal subsidy have interior peak in $R_0$

Results robust across variety of models

- Epidemiological model
  - Here, short-run epidemic
  - Also long-run endemic (Appendix B4) maintaining effective reprod. ratio = 1
- Market structures
  - Here, perfect competition and monopoly
  - Also Cournot (Appendix B2)
- Consumer types
  - Here, homogeneous
  - Also heterogeneous (in harm: Appendix B3)

Future work

- Bring in endogenous distancing
  - Voluntary by consumers
  - Mandated