Optimal Vaccine Subsidies for Epidemic and Endemic Diseases

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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

- Manski (2010, 2017, 2021)

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 $\mathcal{R}_0$
- 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 = susceptible
- I_t = infected
- R_t = 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

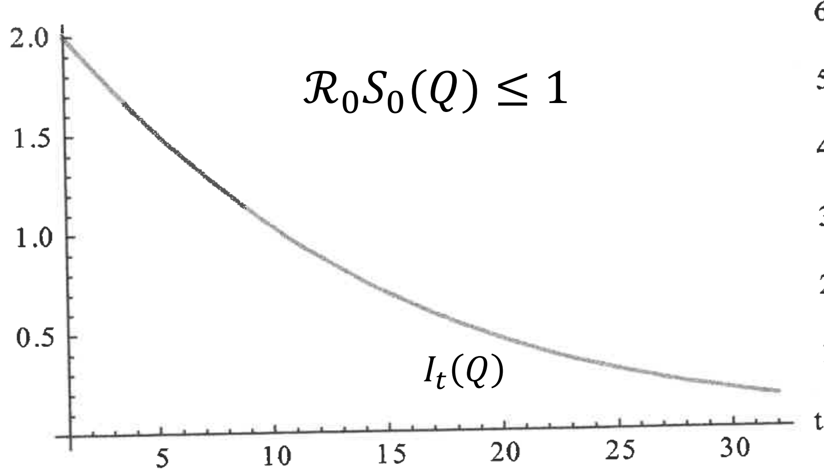
Epidemiological Model

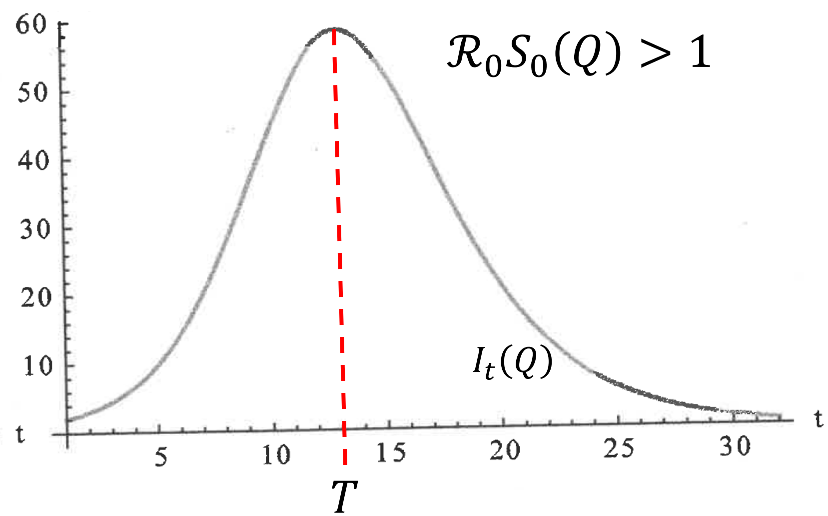
Emphasize key endogenous variable

- Add argument Q to most terms

Reproductive ratio

- Basic reproductive ratio $\mathcal{R}_0 = \beta/\alpha \in (0, \infty)$
- Effective reproductive ratio $\mathcal{R}_0 S_t(Q)$





Other basic insights

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

Economic Model

Vaccine market

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

Consumers

- Homogeneous (but see Appendix B2)
- $MPB(Q) = \theta H \Phi_I(Q) = \theta H \left[1 - \frac{S_\infty(Q)}{\hat{S}_0 - \theta Q}\right]$ can show declining in Q
- All purchase if $MPB\left(\hat{S}_0\right) > P$
- 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

- $MSB(Q) = \frac{\partial SB(Q)}{\partial Q} = \frac{\theta H \Phi_I(Q)}{1 - \mathcal{R}_0 S_\infty(Q)}$

Marginal externality

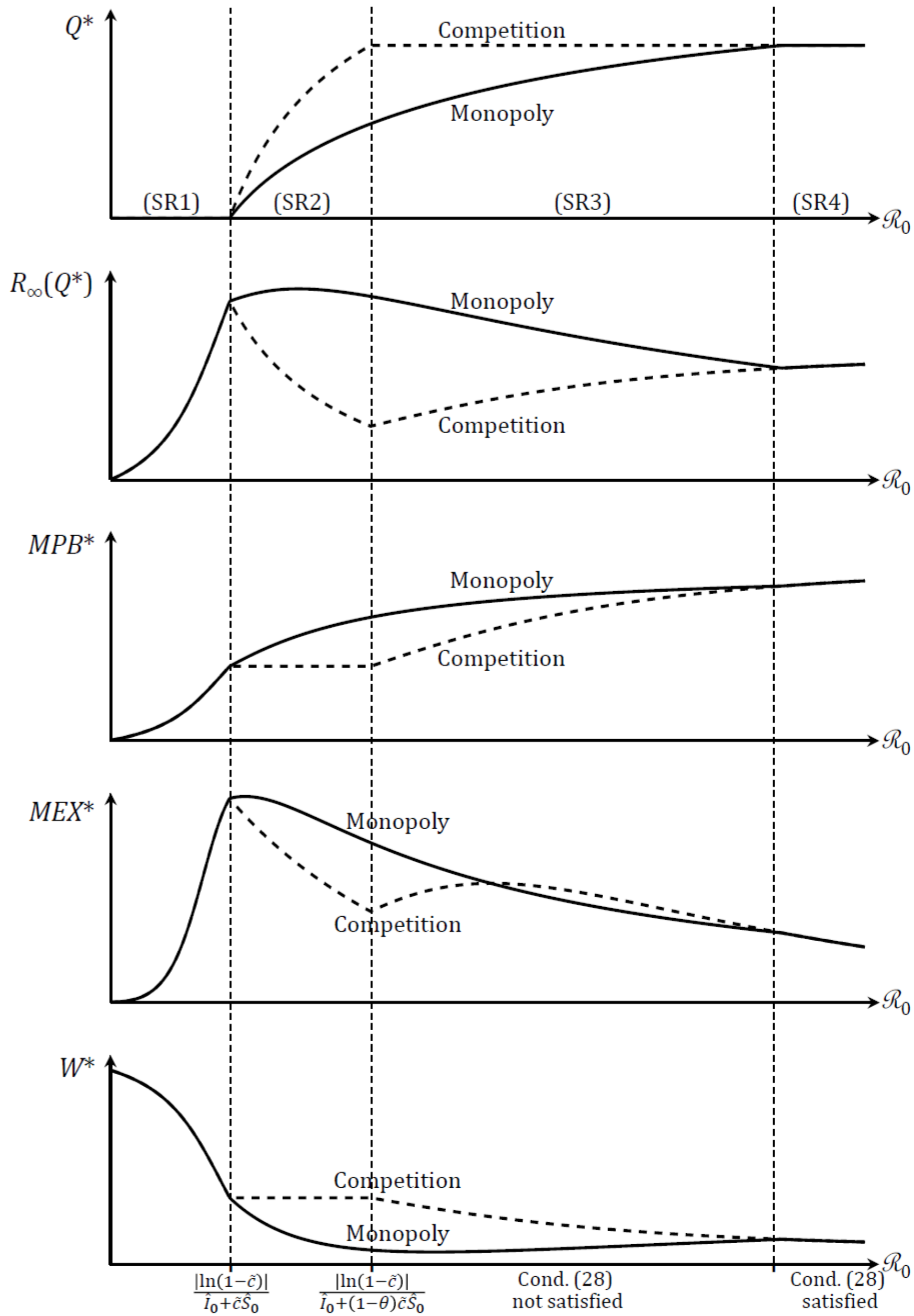
- $MEX(Q) = MSB(Q) - MPB(Q) = \frac{\theta H \Phi_I(Q) \mathcal{R}_0 S_\infty(Q)}{1 - \mathcal{R}_0 S_\infty(Q)} = \mathcal{R}_0 S_0(Q) \left[\frac{S_\infty(Q)}{S_0(Q)}\right] MSB(Q)$

Number of direct infections I would have caused

Probability they would have remained uninfected but for me

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 $\mathcal{R}_0$
- GS^{**} has an interior peak in $\mathcal{R}_0$
- $GS_m^{**} \geq GS_c^{**}$

Specific results

$Q^{**} = 0$	Q^{**} interior	$Q^{**} = \hat{S}_0$
$GS_c^{**} = 0$	$GS_c^{**} = MEX(Q^{**})$	$GS_c^{**} = \max[0, c - MPB(\hat{S}_0)]$
$GS_m^{**} = 0$	$GS_m^{**} = \frac{\hat{S}_0}{\hat{S}_0 - \theta Q^{**}} GS_c^{**}$	$GS_m^{**} = \max\left[0, GS_c^{**} + \frac{\theta MEX(\hat{S}_0)}{1-\theta}\right]$

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

- Qth 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-infective, 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 $\mathcal{R}_0$ 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

- $\mathcal{R}_0 = 1.5$
- $\hat{I}_0 = 0.19\%, \hat{R}_0 = 6.2\%$
- 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
- $\tilde{c} = \frac{c}{\theta H} = 2.13 \times 10^{-5} \approx 0$

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 $\mathcal{R}_0$

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