Optimal Management of an Epidemic: Lockdown, Vaccine and the Value of Life

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Introduction

- Joint work with Carlos Garriga and Sid Sanghi.
- Trade off between output and "curve flattening:"
  - How deep? How long? Recovery: Slow or Fast?
- Vaccine:
  - Impact on optimal policy? Before? After? How much is it worth ($)?
- Major determinants of outcome:
  - Preferences for consumption? Social value of averting deaths? How much will it cost to avert one death?
- Large literature in the last few hours. Closest to this paper: Alvarez et. al. (2020), and Acemoglu et. al. (2020)

Model

- To think about those questions we need both an economic model and a model of how an epidemic spreads:
  - Standard continuous time, representative agent macro model, enlarged to take into account the potential additional disutility associated with the loss of life during an epidemic.
  - SIR epidemiological model.
  - Two Phases:
    - *Phase I:* Pre-vaccine. Only available policy: stay-at-home.
    - *Phase II:* Vaccine arrives as a Poisson event and available policies are stay-at-home and vaccination rate. Option: Treatment.
- Two sources of uncertainty: standard (associated with the realization of a random variable) and model uncertainty.
- Ongoing work (some by us): relaxes assumptions about the economic model **and** the epidemiological model.

Preview of the Findings

- Wide range of estimates because of uncertainty about the right model (and data quality)
- The optimal policies depend on the state (S, I). Any policy that relaxes restrictions **after** the peak in infections is suboptimal.
  - **Random** testing is essential.
- Stylized features of the optimal lockdown policy:
  - Sharp decrease in employment (20-35%).
  - Partial (and slow) liberalization **before** the epidemic peaks.
  - Wide range (uncertainty) for the duration of the lockdown: 3 to 15 months.
  - The arrival of a vaccine need not result in complete liberalization but,in general, implies a significant "liberalization shock," even when only a small fraction can be vaccinated in the short run (week).

Preview of the Findings (cont.)

- Value of averting deaths plays a large role (curvature of preferences has a small quantitative impact)
  - The number of deaths averted (baseline) ranges from 0.01% to 0.39%
  - The cost per death averted (baseline) ranges from 2.5 to 50 million.
  - The higher the value, the longer the time until the economy returns to normal (range 4 to 15 months).
- The market value of a vaccine:
  - *Theory* predicts that as time passes a vaccine is less valuable.
  - In the baseline case, the value of a vaccine available *after six months* is about 59% of the value in the first week, and after a year 5%.
  - *Intuition*: Very infectious epidemics are short lived.

Economic Model

- Preferences:

$$\underbrace{u(\phi wL - c_V(\mu(S + (1-\zeta)I)))}_{\text{utility of net consumption}} - \underbrace{\Delta(D)}_{\text{disutility death}} .$$

  - L is available stock of labor (which depends on the progress of the epidemic).
  - $\phi \in [0, 1]$ is a measure of partial lockdown.
  - Special Case (used in the quantitative exercise)

$$u(\phi wL - \underbrace{c_V(\mu(S + (1-\zeta)I))}_{=0}) = \ln(w\phi L - \underline{c})$$

and

$$\Delta(D) = M_0 \times D$$

with $D_t = \chi\kappa\zeta I_t$.

Economic Model (cont,)

- Representative Agent: private + social disutility death.
- Value in Phase II (vaccine available) $F(S, I)$

$$F(S,I) = \max_{\{\phi_t\}\{\mu_t\}} \left[\begin{array}{c} \int_0^\infty e^{-\rho t} u(\phi_t w(1-\zeta I_t) - c_V(\mu_t Z_t)) \\ -\Delta [D_t] \, dt. \end{array} \right],$$

where $Z_t = (S_t + (1-\zeta) I_t)$ is the vaccinable pop.

- Value in Phase I (only stay-at-home) $V(S, I)$

$$V(S,I) = \max_{\{\phi_t\}} E \left[\begin{array}{c} \int_o^{T_\eta} e^{-\rho t} [u(\phi_t w L_t) - \Delta(D_t)] \, dt \\ + e^{-\rho T_\eta} F(S_{T_\eta}, I_{T_\eta}) \end{array} \right],$$

Epidemiological Model

- Standard SIR. The laws of motion of the state:

$$\dot{S} = -\underbrace{\beta(\phi S)(\phi(1-\zeta)I)}_{\text{contagion}} - \underbrace{\mu S}_{\text{vaccination}} + \underbrace{\gamma(1-S-I)}_{\text{loss of immunity}},$$

$$\dot{I} = \beta\phi^2(1-\zeta)SI - \kappa I.$$

$$L = 1 - \zeta I.$$

- In this model

$$\mathcal{R}_0 = \frac{\beta(1-\zeta)}{\kappa}.$$

- If $\phi = 1$ and $\mu = 0$, the steady state is

$$S^* = \frac{1}{\mathcal{R}_0}, \text{ and } I^* = \frac{\gamma}{\gamma+\kappa}(1-S^*)$$

Epidemiological Model (comment)

- In general $\mathcal{R}_t$ (not $\mathcal{R}_0$) is (in this model) defined as

$$\mathcal{R}_t = \frac{\beta(1-\zeta)\phi^2 S_t}{\kappa}$$

  and it decreases as ϕ and S decrease.
- Over a small interval the rate of growth of infections is $\lambda_t = \kappa(\mathcal{R}_t - 1)$ and the doubling time is

$\mathcal{R}_t$	Doubling Time (weeks)
2.8	1.2
2.0	2,1
1,5	3.4
1,1	23.1

Some Theoretical Results

- Optimal ϕ solves

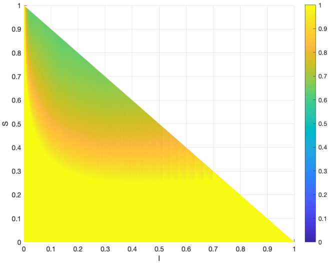
$$\frac{u'(\phi w(1-\zeta I) - c_V(\mu(S+(1-\zeta)I)))(1-\zeta I)}{2\beta\phi(1-\zeta)SI} = (F_S - F_I)\,.$$

- **Result (Phase II)**: Assume that the utility function is strictly increasing and strictly concave and that the marginal cost of vaccination is positive even at zero (that is, $c_V'(0) > 0$) then, for a small enough γ, there exists a steady state characterized by $\phi^* = 1$ and $\mu^* = 0$ and the epidemiological variables are (S^*, I^*)
- **Result**: The Phase I model has a steady state that coincides with the steady state in Phase II.
- **Take away**: This last result implies that, in the limit, the additional value provided by the availability of a vaccine converges to zero!

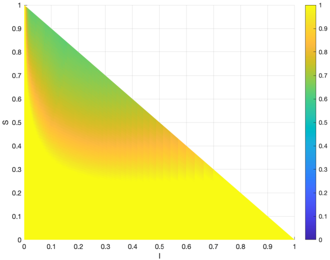
Quantitative Exercise

- $\mathcal{R}_0$ is 2.8. (we also look at $\mathcal{R}_0$
- All lives matter (value statistical life).
- We assume that the infectious period lasts 3 weeks.
- We assume that, in expectation, it takes about 50 weeks for a vaccine to become available (Phase II).
- Costless administration of a vaccine once it becomes available ($\mu = \bar{\mu}$).
- *Baseline*: The vaccine arrives in week 50 (which is also the expected arrival time)

Optimal Policy in Phase I



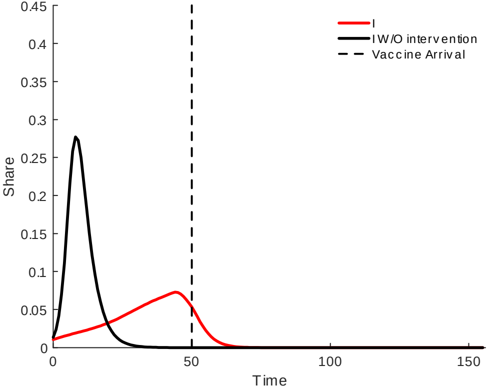
Phase I: Optimal ϕ



Phase II: Optimal ϕ

- Optimal policy depends on both (S, I)
- Vaccine arrival eases policy (small shift to the right) but *does not* result in zero lockdown (depends on the state)

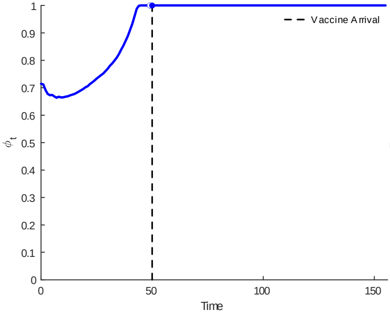
The Path of the Epidemic: Flattening the Curve



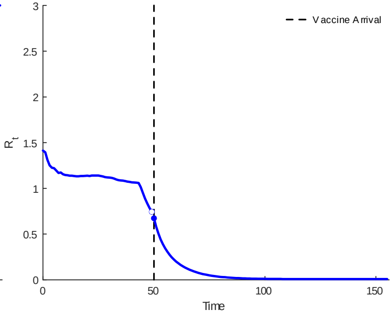
Time Path Epidemic

- Why flattening (peak at 44)? Waiting for a vaccine.

Optimal Policy: Baseline



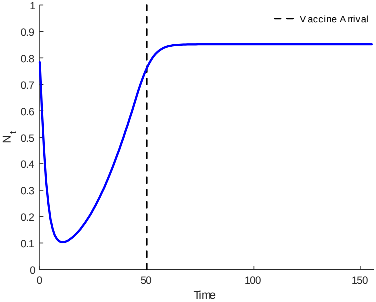
Optimal Lockdown Policy

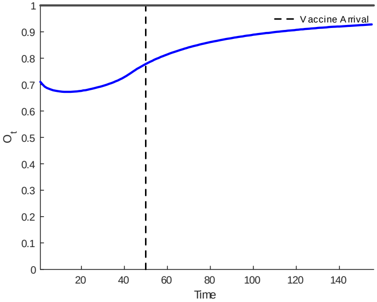


Reproduction Number

- Large initial decrease in ϕ (.71) and it bottoms out in week 7 (.66). It hits one as the epidemic peaks!
- Partial liberalization occurs before the peak.
- The $\mathcal{R}_t$ (reproduction number) is greater than one until week 44.

Consequences: Relative Deaths and Output Cost





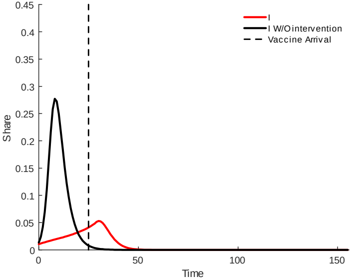
Relative Deaths (left panel) and Output Loss (right panel)

- Relative Deaths are low early ... about 85% in the long run.
- Output cost is large:
  - After one year output is about 22% below capacity.
  - After three years, the economy has been (on average) more than 7% below capacity.
- Cost per death averted (0.10%): 12.6 million!

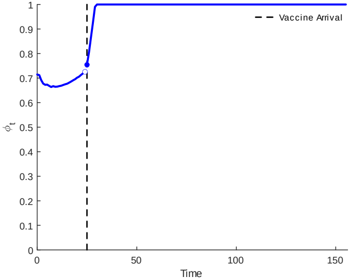
The Path of the Epidemic: Early Vaccine (25 weeks)

- Luck (good luck in this case) has a large impact on the outcome:
  - Epidemic peaks in week 30 (vs. 44), and $\phi = 1$ in week 30.
  - Many more deaths are averted (0.39% vs 0.10%) at a much lower cost (2.5 million vs. 12.6 million)
  - Output loss after a year is smaller (17% vs. 22%), and in the long run as well (5% vs 17%).
- At the time the vaccine becomes available the drift of the stock of susceptible individuals decreases (some no longer susceptible because they are vaccinated):
  - Optimal ϕ keeps increasing (small jump).
  - Higher vaccination $\longrightarrow$ lower cost of controlling epidemic $\longrightarrow$ optimally lower cost in terms of foregone output.
  - Consequence: rate of infection **increases**.

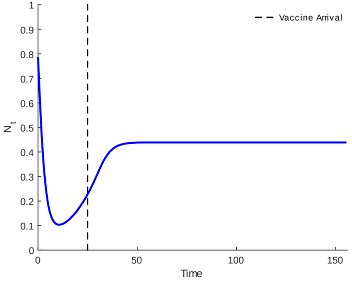
The Path of the Epidemic: Early Vaccine (25 weeks)



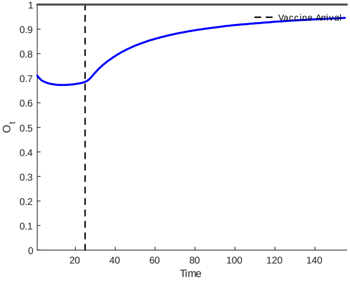
(a) Path of I



(b) Optimal ϕ



(c) Relative Deaths



(d) Output Loss

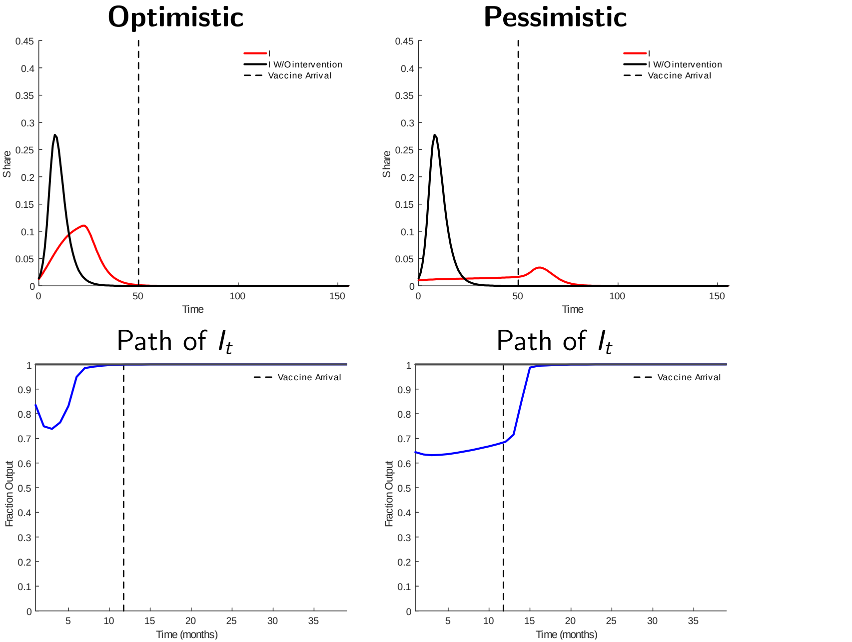
The Path of the Epidemic: Optimistic vs Pessimistic Scenarios

- *Optimistic*: High vaccination rate (95% in 12 weeks) and lower case fatality rate ($\chi = 0.04$)
- *Pessimistic*: Lower vaccination rate (95% in 60 weeks), and higher case fatality rate ($\chi = 0.06$)

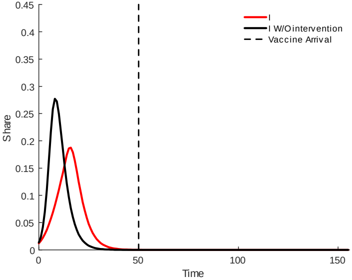
Scenario Comparison

Indicator	*Baseline*	*Optimistic*	*Pessimistic*
Y loss (1Y) (%)	22%	9.0%	35%
Y loss (3Y) (%)	7%	3.0%	12%
Full Recovery (months)	11	5.5	14.5
Deaths Averted (%)	0.10%	0.04%	0.39%
Cost per Death Averted ($)	12.6M	12.8M	5.5M

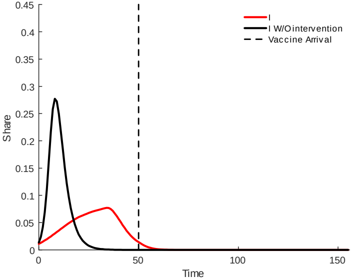
Optimal Policy: Optimistic vs Pessimistic Scenarios



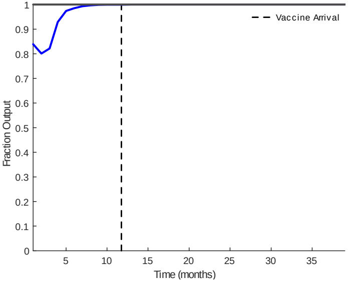
Impact of Case Fatality Rate



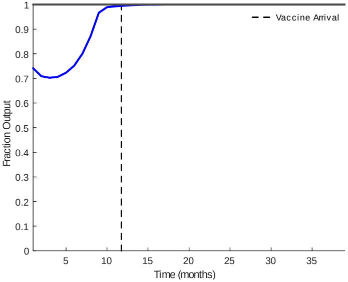
$I_t \ (\mu = 0.15, \chi = 0.025)$



$(\mu = 0.15, \chi = 0.050)$



$O_t \ (\mu = 0.15, \chi = 0.025)$



$O_t \ (\mu = 0.15, \chi = 0.025)$

Impact of Case Fatality Rate

- Lower fatality rate implies a much more relaxed stay-at-home policy and output recovers fast.
- If the fatality rate is low (e.g. $\chi = 0.01$) then the optimal policy is no lockdown ($\phi = 1$) when there is reasonable vaccination capacity (the whole population can be vaccinated in 20 weeks).

The Impact of the Value of Life

- The function that captures the disutility of deaths is

$$\Delta(D) = M_0 D.$$

  - Where M_0 is the value of statistical life.
- Scenarios: Present value of income

M_0	('000)
Very High	1,330
High	440
Baseline	347
Low	243

Value of Life: Output and Deaths

The Impact of the Value of Life				
	Deaths Av.	Cost (M)	Y Loss (1Y) (%)	Y Loss (3Y) (%)
440	0.17%	8.87	27	8.5
347	0.10%	12.6	22	7.0
243	0.017%	19.6	5.9	1.9

- In all four cases the other parameters and the realization are held constant.

Value of Life: Speed of Recovery

The different valuations also influence the timing of the recovery.

The Impact of the Value of Life				
	Y Loss (3Y) (%)	Trough (months)	$\phi = 1$	Rel. Deaths
440	8.5	3	12	0.75
347	7	2	11	0.85
243	1.9	3/4	4	0.97

The Value of a Vaccine

- The utility value of a vaccine depends on the state and it is given by $F(S, I) - V(S, I)$.
- We showed that $\lim_{t\to\infty} F(S_t, I_t) - V(S_t, I_t) = 0$.
- The cost is driven by the change in consumption that yields the same utility.

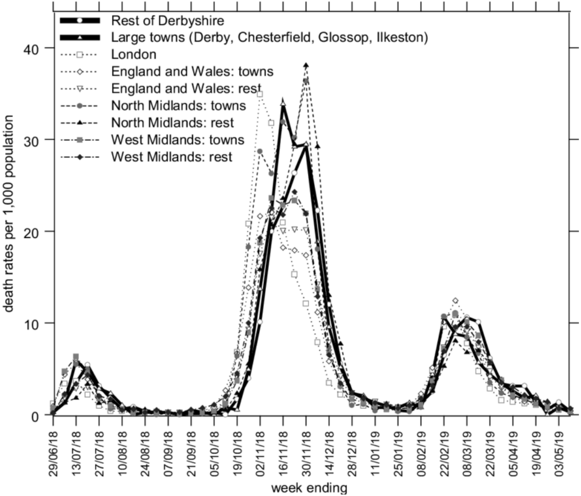
The Value of a Vaccine: Different Scenarios

- These are the results for the different scenarios

Value of a Vaccine (Trillion)				
	Arrival Time (weeks)			
Scenarios	1	4	25	50
Baseline	3.44	3.34	2.02	0.16
Optimistic	3.15	2.79	0.33	0.002
Pessimistic	3.07	3.03	2.56	1.91

- Value decreases with time.
- Better health infrastructure (higher μ and lower χ) $\rightarrow$ more depreciation.

Duration: 1918-1919 Pandemic in England



- Deaths: 228,000 (about 0.5% of the population)
- GDP loss; Between 1-2% for 1 or 1 1/2 year (Barro et. al.)

The Value of a Vaccine and the Disutility of Deaths

$\Delta(D)$ **and the Value of a Vaccine** (Trillion)				
	Arrival Time			
PV ('000)	1	4	25	50
440	3.74	3.72	2.6	0.56
347	3.44	3.34	2.02	0.16
243	1.75	1.43	0.02	small

- Value of life has a first order effect.

Concluding Comments

- **Stylized features of optimal policies**.
  - Shock treatment aspect to them. Duration is highly variable.
  - Relaxation starts **before** the epidemic reaches its peak, and in some cases can result in an increase in the rate of infection.
- **Stylized features of suboptimal policies**.
  - Liberalization starts after the epidemic peaks are suboptimal.
  - Uniformly respond to increases in the rate of infection by tightening stay-at-home rules are suboptimal.
- **Vaccines**.
  - Pre-vaccine policies depend on the likelihood of a vaccine.
  - The market value of a vaccine decreases rapidly (especially if the infection curve cannot be flattened).
- **The Value of Life**.
  - Value of life has a first order effect on optimal policy.
  - Averting deaths is costly.