Economic Activity in San Francisco During the 1918 Influenza Epidemic

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Motivation

- trade-offs during pandemics: slowing down transmission has economic costs
- terms of trade-off depend on endogenous response (if any)
- do past pandemics inform us about stable patterns of behavior?

Motivation (2)

- the 1918–19 influenza epidemic was the most recent large pandemic before Covid-19
- natural point of comparison to study economic impacts of policy interventions
- US offers cross-sectional variation
  - start, duration, pattern (waves) of epidemic
  - start and end of policy responses ("lockdowns")
- the project:
  - combine data on deaths and mobility (seen as proxy for economic activity)
  - estimate structural model with endogenous transmission rates
  - compute counterfactuals and tradeoffs: laisser-faire, optimal policy
- this paper:
  - *daily* data on deaths and mobility for San Francisco
  - testing ground for various functional forms

- epidemic in the US
  - "herald wave" in Feb–Apr 1918, barely noticed (virulent but not lethal)
  - main wave begins late Aug 1918 in New England, spreads quickly
  - second/third waves in some places (Dec 1918–Mar 1919), usually less severe
    - another mortality peak in the winter 1919–20 (not studied)
- policies: non-pharmaceutical interventions (NPIs) at city/state level
  - "social distancing"
    - almost all cities closed schools, churches, entertainment, large gatherings
    - efforts to reduce congestion: staggered business hours in some places
  - some attempts at quarantine and isolation of infected individuals, tracing (I focus on closings)
  - no lockdowns as stringent as 2020–21

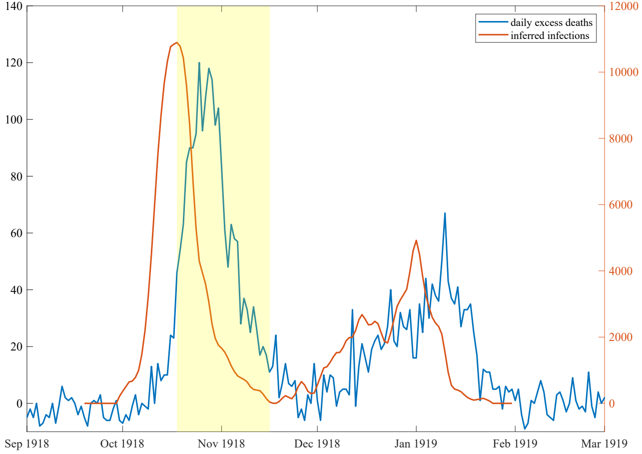
- reports of the epidemic on the East Coast by Sept 12
- first case in SF reported Sept 24, but Board of Health declined to order closings for a while
- closing (typical across almost all US cities)
  - from Oct 18 to Nov 16
  - "all places of amusement, including theaters, moving-picture theaters, concert halls, dance halls and dances in all cabarets, cafes and hotels, and all form of entertainment in any or all of them"
  - lodge and fraternal meetings
  - public amusement places (penny arcades, merry-go-rounds)
  - private dances, halls, social gatherings
  - church services
  - public and private schools and kindergartens
  - permit for any public meeting
  - theaters closure extended to Nov 23, schools to Nov 25
- masks (much less common in US cities):
  - mandatory for customer-facing workers (Oct 18)
  - recommended for all (Oct 21)
  - mandatory for all (Oct 25 - Nov 21)
- second wave:
  - no closings, but masks mandatory for all (Jan 17 - 1 Feb 1, 1919)

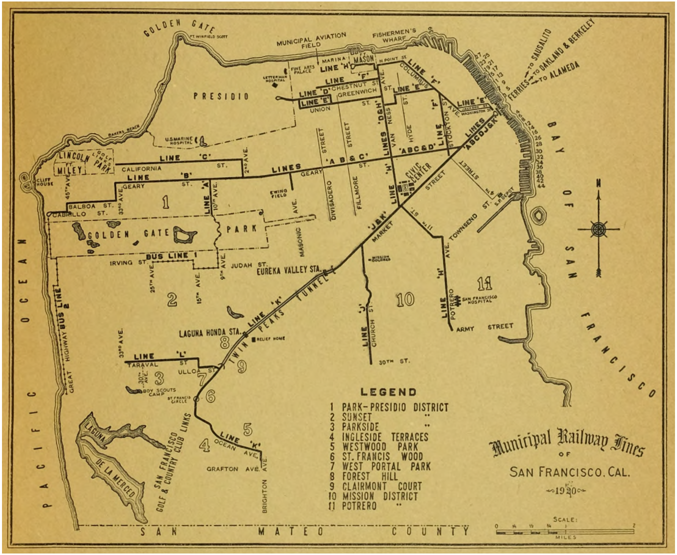
San Francisco: data

- daily ridership on public transportation
  - SF Municipal Railway: about 1/4 of total ridership
  - total ridership: 511,000/day in 1920 (= population of 511,300)
- daily excess deaths

- hand collected from `Ancestry.com`
- all deaths between 1 Sep 1918 and 15 Apr 1919, and same period in 1912–16
- compute daily excess deaths relative to 1912–16 (adjusting for population growth)
    - as a check, deconvolute deaths using transfer function to infer infections (Goldstein et al., 2009)

Excess Deaths, Inferred Infections




GOLDEN GATE
PRESIDIO
MUNICIPAL AVIATION FIELD
FISHERMEN'S WHARF
MARINA
FT. MASON
FINE ARTS PALACE
LETTERMAN HOSPITAL
LINE 'H'
LINE 'F'
LINE 'D'
LINE 'E'
CHESTNUT ST.
GREENWICH ST.
UNION ST.
N POINT ST.
COLUMBUS
STOCKTON AVE.
LINES 'D&H'
LINES 'ABC&D'
LINES 'ABCDJ&K'
VAN NESS AVE.
HYDE ST.
FERRIES
TO SAUSALITO
TO OAKLAND & BERKELEY
TO ALAMEDA
BAY OF SAN FRANCISCO
U.S. MARINE HOSPITAL
BAKERS BEACH
LINCOLN PARK
GOLF LINKS
FT. MILEY
CLIFF HOUSE
LINE 'C'
CALIFORNIA ST.
LINE 'B'
GEARY ST.
LINES 'A B & C'
GEARY ST.
2ND AVE.
10TH AVE.
LINE 'A'
45TH AVE.
33RD AVE.
BALBOA ST.
CABRILLO ST.
GOLDEN GATE PARK
EWING FIELD
DIVISADERO STREET
FILLMORE STREET
MASONIC AVE.
CIVIC CENTER
MARKET
'J&K'
MISSION DOLORES
TOWNSEND ST.
S.P. DEPOT
IRVING ST.
BUS LINE 1
JUDAH ST.
9TH AVE.
25TH AVE.
15TH AVE.
EUREKA VALLEY STA.
TUNNEL
TWIN PEAKS
LINE 'K'
PACIFIC OCEAN
GREAT HIGHWAY BUS LINE 2
LAGUNA HONDA STA.
RELIEF HOME
LINE 'J'
CHURCH ST.
30TH ST.
LINE 'H'
POTRERO AVE.
SAN FRANCISCO HOSPITAL
ARMY STREET
33RD AVE.
LINE 'L'
TARAVAL ST.
ULLOA ST.
30TH AVE.
BOY SCOUTS CAMP
ST. FRANCIS CIRCLE
LAGUNA DE LA MERCED
SAN FRANCISCO GOLF & COUNTRY CLUB LINKS
LINE 'K'
OCEAN AVE.
GRAFTON AVE.
BRIGHTON AVE.
SAN MATEO COUNTY
1
2
3
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10
11
LEGEND
1 PARK-PRESIDIO DISTRICT
2 SUNSET "
3 PARKSIDE "
4 INGLESIDE TERRACES
5 WESTWOOD PARK
6 ST. FRANCIS WOOD
7 WEST PORTAL PARK
8 FOREST HILL
9 CLAIRMONT COURT
10 MISSION DISTRICT
11 POTRERO "
Municipal Railway Lines
OF
SAN FRANCISCO, CAL.
1930
SCALE:
MILES

SF Muni Revenues

The San Francisco Examiner (San Francisc… • 04 Nov 1918, Mon • Page 7

re being brought to bear
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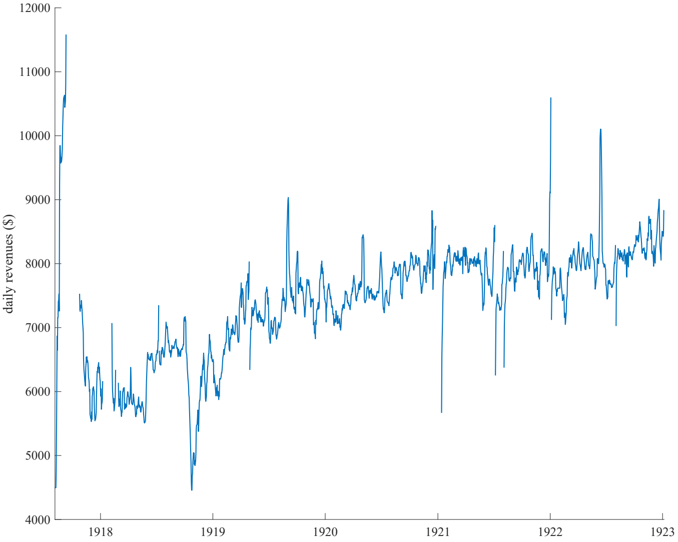
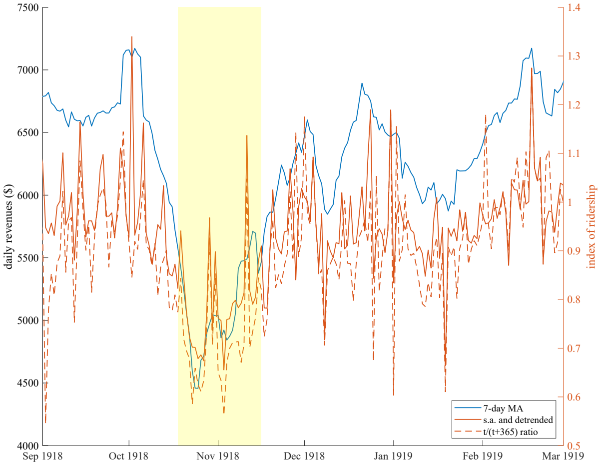
City Street Cars Average $5,885 Daily

The following are the receipts of the Municipal Street Railway system for last week: Sunday, $3,772.20; Monday, $4,900.75; Tuesday, $6,164.23; Wednesday, $4,690.20; Thursday, $5,723.54; Friday, $4,853.20; Saturday, $5,205.95; total, $35,310.07.

SF Muni Revenues



SF Muni Revenues



- goal: jointly model the epidemic and economic activity
- elements
  - agents choose work/consumption, knowing it exposes them to infection
  - epidemiological model: SEIR with transmission rate determined by agents' economic activities
- Simplified version of Eichenbaum, Rebelo, and Trabandt (2021), SEIR model from Bootsma and Ferguson (2007)

Population is partitioned into S_t susceptibles, E exposed, I infected, and R removed:

$$S_t + E_t + I_t + R_t = 1.$$

Laws of motion:

$$\begin{aligned}
\dot{S}_t &= -\lambda_t I_t S_t \\
\dot{E}_t &= \lambda_t S_t I_t - \alpha E_t \\
\dot{I}_t &= \alpha E_t - \nu I_t \\
\dot{R}_t &= \nu I_t
\end{aligned}$$

Deaths:

$$D_t = \mu \int_0^\infty f(s)\lambda(t-s)S(t-s)I(t-s)ds$$

where the delay function $f(s)$ is the distribution of time from exposure to death.

Infections:

$$-(S_{t+1} - S_t) = \lambda_t S_t I_t = \pi_1 (S_t c_t^s)(\phi I_t c_t^i) + \pi_2 (S_t n_t^s)(\phi I_t n_t^i) + \pi_3 S_t I_t.$$

- Agent understands that working/consuming exposes him
- True probability of not being infected:

$$1 - [\phi(\pi_1 w^2 + \pi_2) n_t^i n_t + \pi_3] I_t$$

  is affine function of agent's choice n_t
- Perceived probability assumed to have same functional form:

$$a_t - b_t n_t$$

  with a_t, b_t functions of the epidemic's state

Agent's problem

$$\max_{n_t, c_t} \quad (a_t - b_t n_t)W + \frac{c_t^{1-\sigma}}{1-\sigma} - v\frac{n_t^{1+\epsilon}}{1+\epsilon}$$
$$\text{s.t.} \quad c_t = wn_t$$

- FOC leads to c_t, n_t as functions of b_t
- $\sigma = 1$, $\epsilon = 1$:

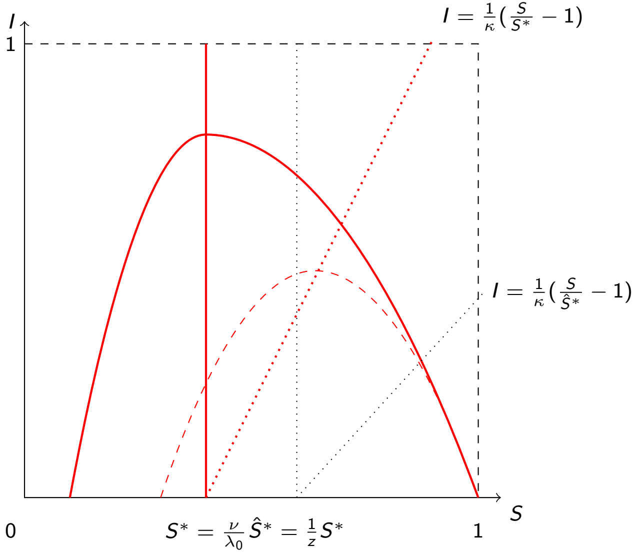
$$\frac{n}{n^*} = \sqrt{1+\alpha_t^2} - \alpha_t$$
$$\alpha_t = \frac{1}{2} W n^* b_t.$$

$$
\begin{aligned}
y^* - y_t &= 1 - (S_t + E_t + \phi I_t)(\sqrt{1+\alpha_t^2} - \alpha_t) \\
\frac{\lambda_t}{\lambda_0} &= \left(\frac{n_t}{n^*}\right)^2 = 1 + 2\alpha_t^2 - 2\alpha_t\sqrt{1+{\alpha_t}^2} \\
\alpha_t &= \frac{1}{2} W n^* b_t.
\end{aligned}
$$

- transmission λ_t is the square of agent's choice n_t
- agent's choice n_t function of a statistic of the epidemic α_t
- b_t so far unspecified (agent's perception of marginal risk from working)
- imposing rational expectations leads to

$$
\begin{aligned}
\alpha_t &= \frac{1}{2} \frac{\kappa I_t}{\sqrt{1+\kappa I_t}} \\
\frac{n}{n^*} &= \frac{1}{\sqrt{1+\kappa I_t}} \\
\frac{\lambda_t}{\lambda_0} &= \frac{1}{1+\kappa I_t}.
\end{aligned}
$$

with $\kappa = W\lambda_0$

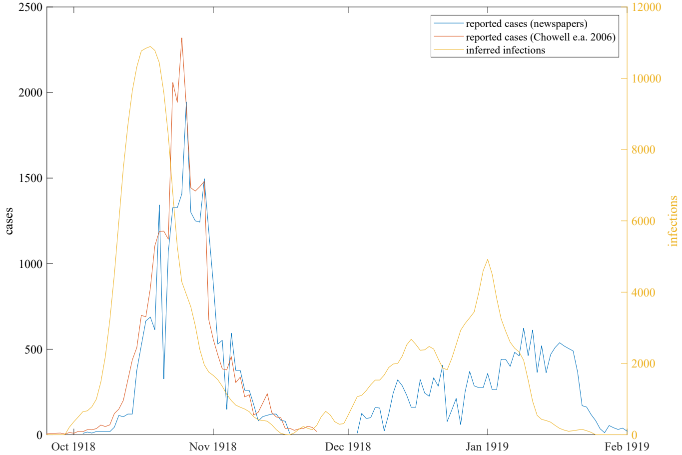


$I = \frac{1}{\kappa}(\frac{S}{S^*} - 1)$
I
1
$I = \frac{1}{\kappa}(\frac{S}{\hat{S}^*} - 1)$
S
0
$S^* = \frac{\nu}{\lambda_0}\,\hat{S}^* = \frac{1}{z}S^*$
1

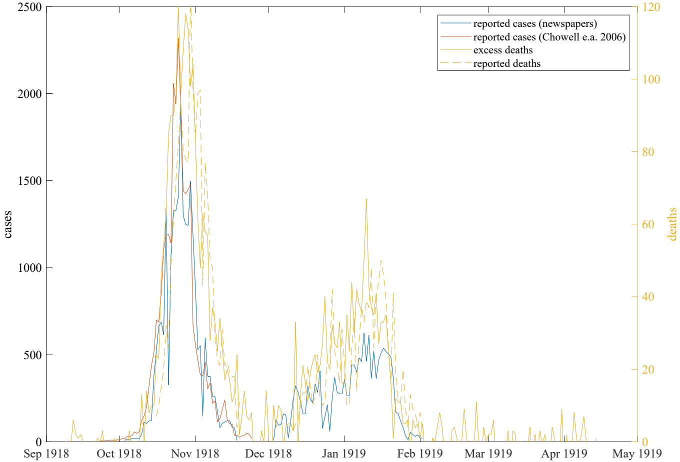
IS REH reasonable?

- REH delivers a nice closed-form solution
- estimable parameter κ has structural interpretation
- but is it reasonable?
  - did agents know the model? previous pandemic 1889–90, SIR model published in 1927
  - quality of the contemporaneous information set?

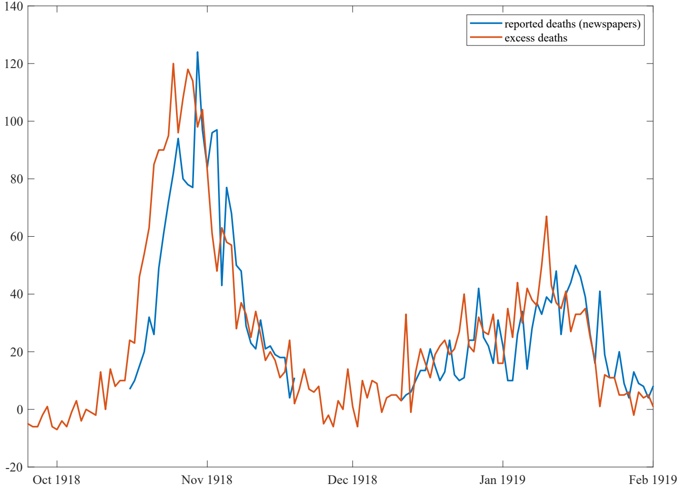
Reported Cases, Inferred Infections, Reported Deaths



Reported Cases, Inferred Infections, Reported Deaths



Reported Deaths and Excess Deaths



Ad-hockery

- epidemiologists have used ad-hoc parametrizations of λ_t
- Bootsma and Ferguson (2007) use same functional form as REH:

$$\lambda_t = \frac{1}{1 + \kappa f(t)}$$

  where $f(t)$ a function of current and past deaths
  - $f(t) = \int_0^T D(t-s)ds$ (`Hill`)
  - $\dot{f}(t) = D_t + (1-\tau)f(t)$ (`Alt`)
- this effectively assumes:

$$b_t = \frac{f(t)}{\sqrt{1 + Wn^* f(t)}}$$

- alternative: specify $b_t = \kappa f(t)$, λ_t as predicted by model (`model`)

- lockdown parameters: start date, end date, intensity p_c
- how do they affect the transmission rate?
- Bootsma and Ferguson (2007): multiplicative $\hat{\lambda}_t = (1 - p_c)\lambda_t$ (effectively same as Eichenbaum, Rebelo, and Trabandt 2021)
- alternative: lockdown as upper bound on economic activity (`Min`)

$$\frac{n_t}{n^*} = \min\{\bar{n}_t, \sqrt{1 + \alpha_t^2} - \alpha_t\}$$

- Data: deaths D_t, activity y_t (proxied by ridership), dates of interventions
- α and ν calibrated (ϕ calibrated at 0.7 for now)
- given parameters $\theta = (\mu, R_0, \kappa, \tau, p_c)$, model predicts deaths $\hat{D}$ and activity $\hat{y}$
- MCMC estimation, using a Poisson LL for deaths and Gaussian LL for activity

$$\mathcal{L}(D, y, \theta) \propto \sum_t \log(\hat{D}_t(\theta))D_t - \hat{D}_t(\theta) - \frac{(y_t - \hat{y}_t(\theta))^2}{2\sigma} - \frac{\log(\sigma)}{2}$$

- for each value of θ, epidemic simulated (step: 0.1 day)
  - note: starting date of epidemic must be solved for as well

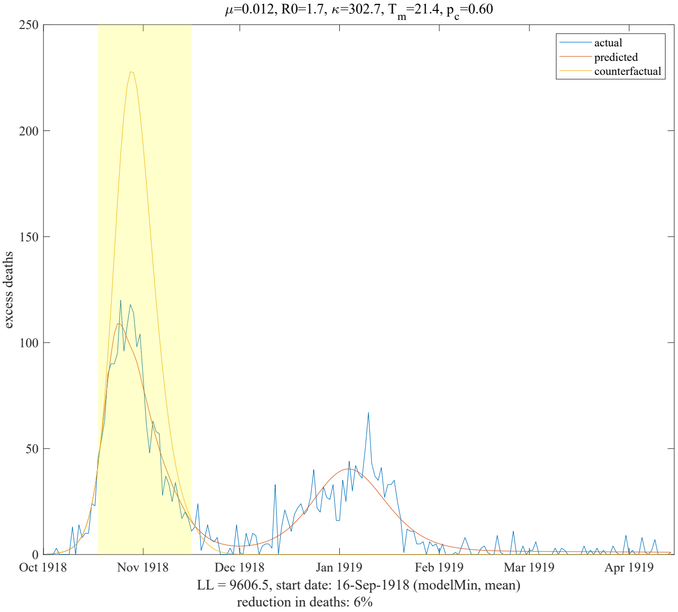
Estimates without ridership data

model (LL)	μ (%)	R_0	κ	τ (%)	T_m	p_c	deaths (%)
Hill	1.22	2.25	320.1		17	0.41	5
9211.3	[1.17,1.27]	[2.24,2.27]	[284,357]		[16.2,18.3]	[0.39,0.43]	[3,7]
HillAlt	1.17	2.42	638.5	1		0.42	2
9208.7	[1.13,1.21]	[2.41,2.43]	[563,719]	[0.93,1.10]		[0.40,0.43]	[-1,4]
HillMin	1.22	2.39	369.3		22	0.61	9
9233.8	[1.18,1.27]	[2.38,2.4]	[333,406]		[21.3,23.1]	[0.61,0.62]	[7,10]
HillAltMin	1.15	2.66	660.8	0.76		0.66	7
9221.9	[1.1,1.19]	[2.65,2.67]	[586,741]	[0.69,0.83]		[0.65,0.67]	[5,9]
HillAltInf	1.10	2.86	213.3	0.4		0.46	-2
9186.5	[1.06,1.14]	[2.83,2.88]	[187,241]	[0.36,0.44]		[0.44,0.49]	[-4,1]
HillAltInfMin	1.08	2.99	223.9	0.39		0.70	-2
9187.1	[1.04,1.12]	[2.97,3.01]	[196,253]	[0.34,0.44]		[0.69,0.71]	[-4,2]
Power	1.22	2.20	259.7		16	0.40	1
9203.2	[1.17,1.27]	[2.19,2.22]	[231,289]		[15.3,17.5]	[0.38,0.42]	[-2,4]
PowerAlt	1.18	2.36	515.0	1		0.39	-4
9203.9	[1.13,1.22]	[2.34,2.37]	[456,577]	[0.96,1.15]		[0.37,0.42]	[-6,-1]
PowerAltMin	1.15	2.65	533.7	0.73		0.66	3
9226.1	[1.1,1.19]	[2.64,2.67]	[477,594]	[0.67,0.80]		[0.65,0.66]	[-0,5]
Exp	1.22	2.20	259.8		16	0.40	1
9203.2	[1.17,1.27]	[2.19,2.22]	[232,289]		[15.3,17.5]	[0.38,0.42]	[-2,4]
ExpAlt	1.18	2.36	515.3	1		0.39	-4
9203.9	[1.13,1.22]	[2.34,2.37]	[456,577]	[0.96,1.15]		[0.37,0.42]	[-6,-1]
ExpAltMin	1.15	2.65	534.0	0.73		0.66	3
9226.1	[1.1,1.19]	[2.64,2.67]	[478,593]	[0.67,0.80]		[0.65,0.66]	[-0,5]
model	1.22	2.20	261.3		17	0.40	1
9203.9	[1.18,1.27]	[2.19,2.22]	[233,291]		[15.4,17.6]	[0.38,0.42]	[-1,4]
modelAlt	1.18	2.36	519.2	1		0.39	-4
9204.6	[1.13,1.22]	[2.34,2.37]	[460,582]	[0.96,1.14]		[0.37,0.42]	[-6,-1]
modelMin	1.22	2.39	312.0		21	0.61	5
9235.3	[1.17,1.26]	[2.37,2.4]	[285,340]		[20.5,22.4]	[0.60,0.62]	[3,7]
modelAltMin	1.15	2.65	537.9	0.73		0.66	3
9225.9	[1.1,1.19]	[2.64,2.67]	[481,598]	[0.67,0.80]		[0.65,0.66]	[1,6]

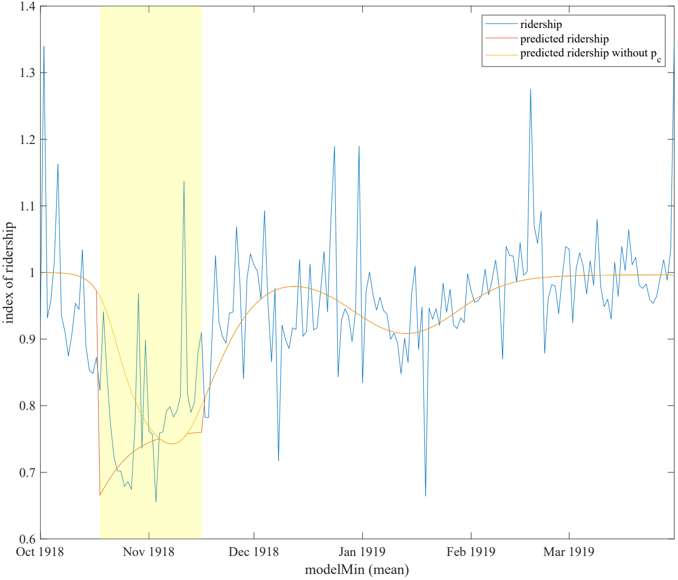
Estimates with ridership data

model (LL)	μ (%)	R_0	κ	τ (%)	T_m	p_c	deaths (%)
Hill	1.21	2.26	312.4		17	0.41	6
9581.6	[1.17,1.26]	[2.24,2.27]	[277,349]		[16.0,18.1]	[0.39,0.43]	[4,8]
HillAlt	1.16	2.42	635.0	1		0.41	2
9580.2	[1.12,1.21]	[2.41,2.44]	[558,716]	[0.96,1.13]		[0.39,0.43]	[-1,4]
HillMin	1.21	2.39	355.3		22	0.61	9
9603.9	[1.17,1.26]	[2.38,2.4]	[320,392]		[21.1,22.9]	[0.60,0.62]	[8,10]
HillAltMin	1.15	2.59	630.7	0.81		0.65	6
9585.8	[1.1,1.19]	[2.58,2.61]	[556,710]	[0.74,0.88]		[0.64,0.66]	[4,8]
HillAltInf	1.09	2.78	202.7	0.44		0.45	-2
9552.4	[1.05,1.13]	[2.76,2.8]	[177,229]	[0.39,0.48]		[0.43,0.47]	[-4,1]
HillAltInfMin	1.09	2.81	208.0	0.45		0.67	-3
9548.4	[1.05,1.12]	[2.79,2.83]	[179,238]	[0.39,0.50]		[0.67,0.68]	[-5,0]
Power	1.21	2.21	253.9		16	0.40	1
9572.7	[1.17,1.26]	[2.19,2.22]	[226,283]		[15.1,17.3]	[0.38,0.42]	[-1,4]
PowerAlt	1.17	2.36	513.6	1.1		0.39	-4
9575.8	[1.13,1.21]	[2.34,2.37]	[454,577]	[0.98,1.18]		[0.37,0.41]	[-6,-1]
PowerAltMin	1.15	2.59	522.3	0.78		0.64	1
9591.4	[1.11,1.19]	[2.57,2.6]	[465,582]	[0.72,0.85]		[0.64,0.65]	[-2,4]
Exp	1.21	2.21	253.9		16	0.40	1
9572.8	[1.17,1.26]	[2.19,2.22]	[225,284]		[15.1,17.3]	[0.38,0.42]	[-1,4]
ExpAlt	1.17	2.36	512.9	1.1		0.39	-4
9575.8	[1.13,1.21]	[2.34,2.37]	[453,577]	[0.98,1.18]		[0.37,0.41]	[-6,-1]
ExpAltMin	1.15	2.59	521.8	0.78		0.64	1
9591.4	[1.11,1.19]	[2.57,2.6]	[465,582]	[0.72,0.85]		[0.64,0.65]	[-2,4]
model	1.21	2.21	256.3		16	0.40	2
9573.6	[1.17,1.26]	[2.19,2.22]	[228,286]		[15.2,17.4]	[0.38,0.42]	[-1,4]
modelAlt	1.17	2.36	517.9	1.1		0.39	-3
9576.5	[1.13,1.21]	[2.35,2.37]	[457,583]	[0.98,1.17]		[0.37,0.41]	[-6,-1]
modelMin	1.21	2.39	302.7		21	0.60	6
9606.5	[1.16,1.25]	[2.38,2.4]	[276,331]		[20.4,22.3]	[0.60,0.61]	[4,7]
modelAltMin	1.15	2.59	524.9	0.78		0.64	2
9591.1	[1.11,1.19]	[2.57,2.6]	[468,586]	[0.72,0.85]		[0.64,0.65]	[-1,5]

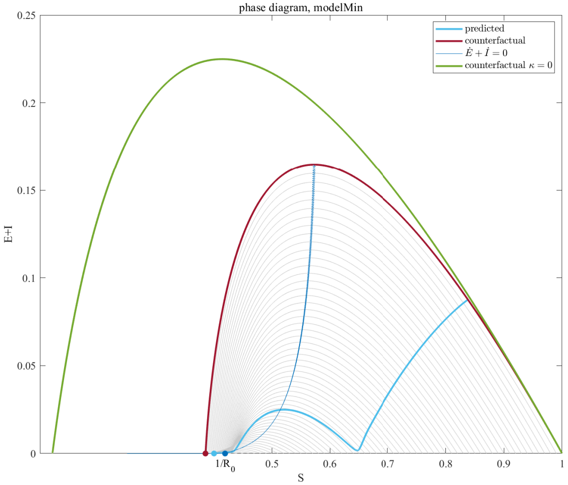
Deaths, predicted and actual (best model)



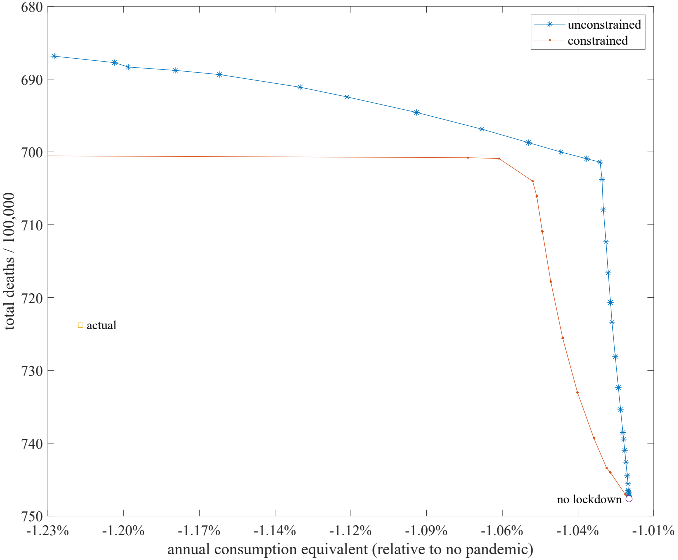
Ridership, predicted and actual (best model)



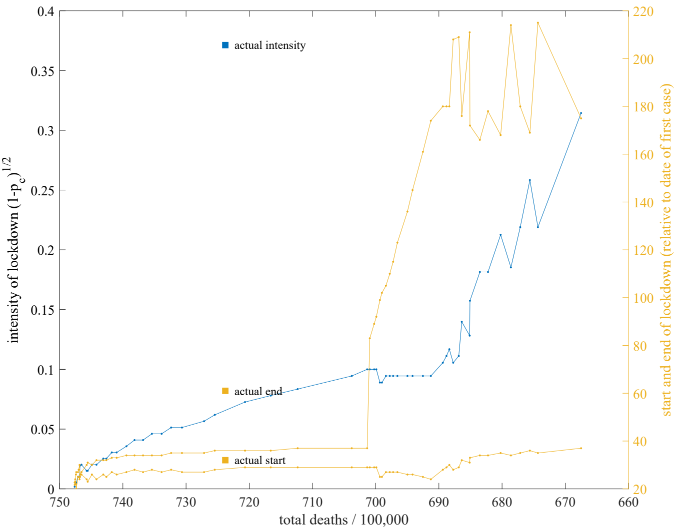
Phase Diagram



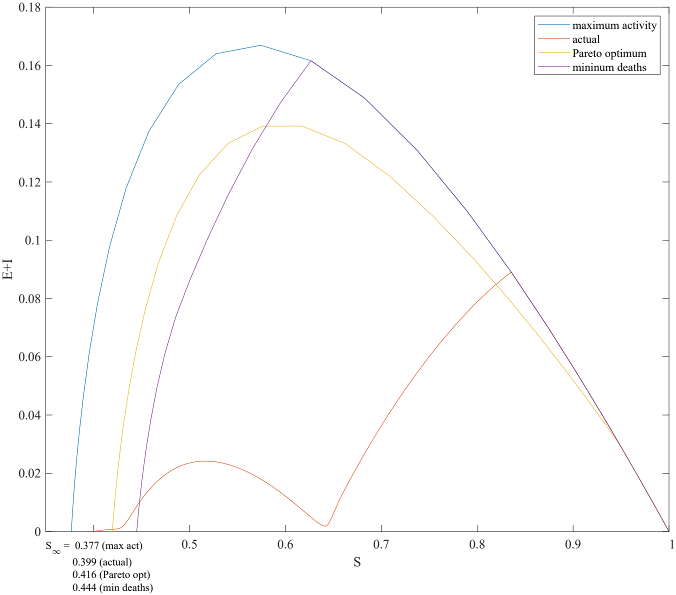
Pareto Frontier



Policies along the frontier



Policies along the frontier



Optimal policy

- they could have done better
  - actual policy was within the frontier
  - which point would have been chosen depends on relative weights on deaths and utils/labor
    - under REH, value of life can be inferred from estimated κ
    - not clear under ad-hoc behavioral responses
    - could be calibrated
- gains in terms of deaths would have been modest but positive and (for most weights) worthwhile
- why did they co what they did?
  - they knew little (and knew it)
  - no realistic hope of a vaccine
  - no SIR model! (Kermack and McKendrick, 1927)
  - perceived tradeoffs, "ICU constraint"

William A. Evans, recent president of the American Public Health Association (*Chicago Tribune* Oct. 6, 1918):

> *Influenza will sweep over the country as it did in 1891 and as it has always done. We cannot escape it, but we can spread the cases over several weeks instead of having them all lump together as they usually come when the epidemic attacks men in barracks. If the epidemic can be spread out to a moderate extent our hospitals' nurses and physicians can handle the situation.*

Conclusion

- ridership data validates epidemiological model
- behavioral response deviates markedly from REH
- lockdown saved some lives, but not many
- some room for better policy
  - earlier but shorter intervention
  - longer but weaker intervention
  - optimum probably closer to the former
- (tentative) masks were effective (and costless)
- same model on cross-sectional data:
  - some $\kappa - \tau$ indeterminacy: revisit functional form?
  - R_0 goes up with time: adjust the seed