Waning Immunity and the Second Wave: Some Projections for SARS-CoV-2

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Overview

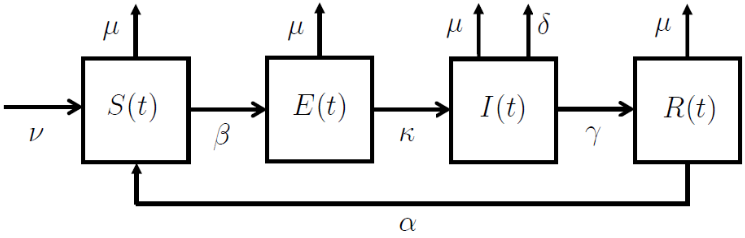
- What is appropriate framework to model COVID-19?
- Common model is SIR: *susceptible-infected-recovered*
- Some add disease-induced mortality
- Implicit simplifying assumptions of SIR model:
- No demographics: births and natural deaths
- Immunity is perfect and permanent
- For very short run analysis, perhaps defensible
- For medium and long run analysis, may be inappropriate
- Will consider effects on dynamics and social distancing of relaxing these assumptions

Main results

- Adding births radically change dynamics, even with no waning immunity
- Dynamics has two steady states, one disease-free, one endemic
- For COVID-19 parameters, dynamics display damped oscillations as system approaches endemic steady state
- Optimal policy depends on parameters and associated path can lead to asymptotic eradication or endemic steady state
- If eradication suboptimal, optimal policy follows underlying dynamics but dampens and postpones waves
- If immunity wanes, qualitative features unchanged but periodicity of oscillations changes
- If immunity wanes fast, the periodicity higher

Model

- We use SEIRS model that features
  - Pre-symptomatic (exposed) state
  - Births into susceptible class
  - Natural mortality
  - Disease-induced mortality
  - Possibly waning immunity
- This setup nests standard SIR, SIS and SI models
- Stocks and flows of the model are:



Model

- Planner's problem to choose $d(t) \in [0,1]$ to maximize

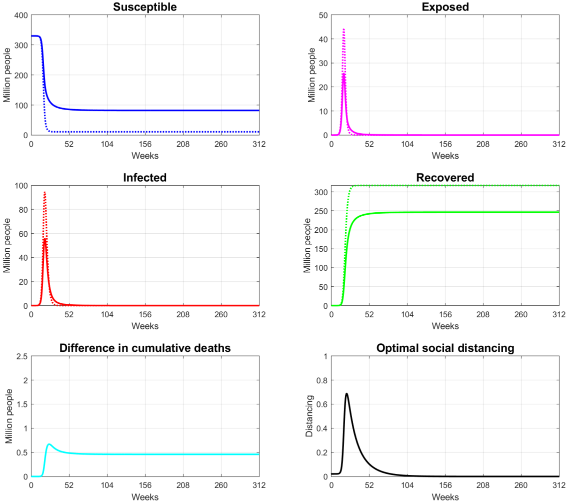
$$\int_0^\infty e^{-\rho t}\left(S(t)\pi_{\mathcal{S}} + E(t)\pi_{\mathcal{S}} + I(t)\pi_{\mathcal{I}} + R(t)\pi_{\mathcal{R}} - \frac{\theta d(t)^2}{2}\right) dt$$

- Constraints:

$$\begin{aligned}
\dot{S}(t) &= \nu - (1-d(t))\beta\left(I(t) + \varepsilon E(t)\right)\frac{S(t)}{N(t)} + \alpha R(t) - \mu S(t) \\
\dot{E}(t) &= (1-d(t))\beta\left(I(t) + \varepsilon E(t)\right)\frac{S(t)}{N(t)} - (\kappa + \mu) E(t) \\
\dot{I}(t) &= \kappa E(t) - (\gamma + \delta + \mu) I(t) \\
\dot{R}(t) &= \gamma I(t) - (\alpha + \mu) R(t) \\
\dot{N}(t) &= \nu - \mu N(t) - \delta I(t) \\
\dot{D}(t) &= \delta I(t) + \mu N(t) \\
N(t) &= S(t) + E(t) + I(t) + R(t) \\
S_0 &> \gamma/\beta, \quad S_0 + E_0 + I_0 + R_0 = N_0
\end{aligned}$$

Benchmark dynamics: permanent immunity

- Without demographics:

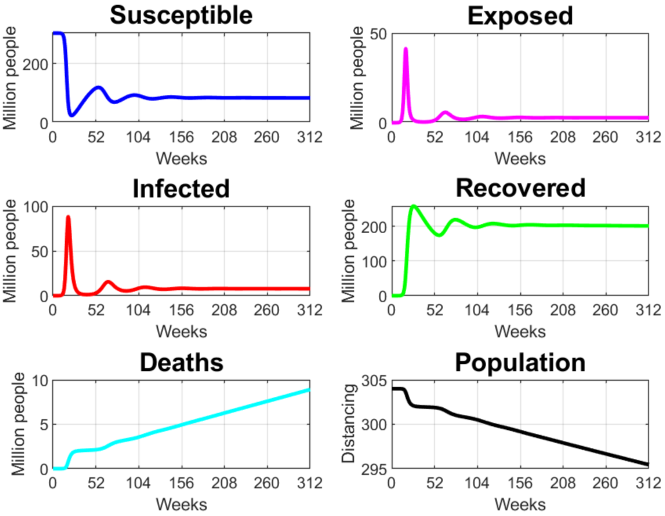


Uncontrolled dynamics: waning immunity

- Consider case of immunity waning in one year ($\alpha = 1/52$)
- In this case, susceptible pool replenished as people lose immunity
- Steady state is endemic
- Approach to steady state has damped oscillations
- Over time, pool of susceptibles build up, creating conditions for new wave

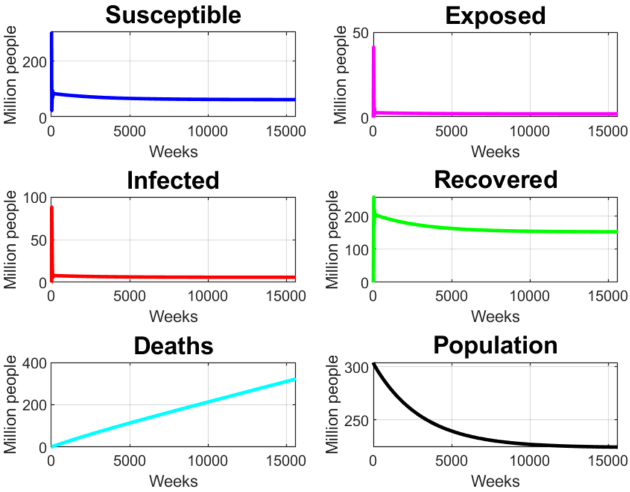
Uncontrolled dynamics: waning immunity

- First six years:



Uncontrolled dynamics: waning immunity

- First 300 years:

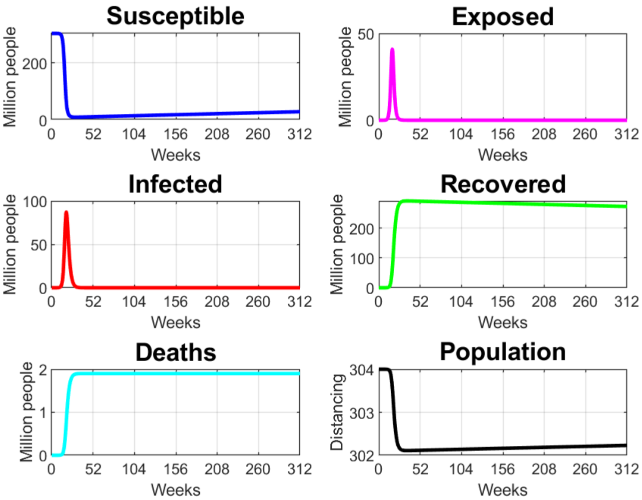


Uncontrolled dynamics: permanent immunity

- Consider case of permanent immunity
- In this case, still damped oscillations...
- Susceptible pool not replenished through waning immunity, but there are still births
- As immunity permanent, build-up of susceptible pool much slower
- So waning immunity not cause of oscillations $\rightarrow$ influences periodicity

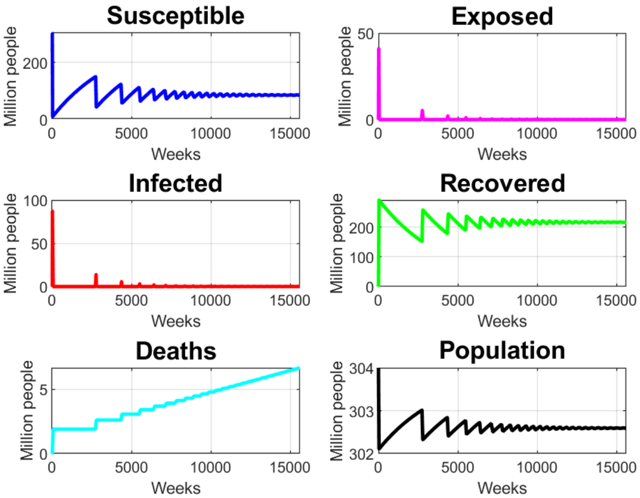
Uncontrolled dynamics: permanent immunity

- First six years:

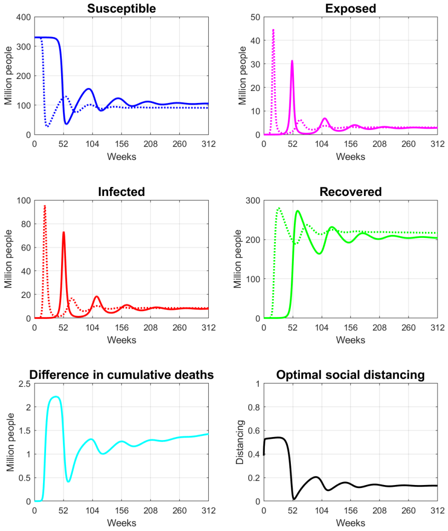


Uncontrolled dynamics: permanent immunity

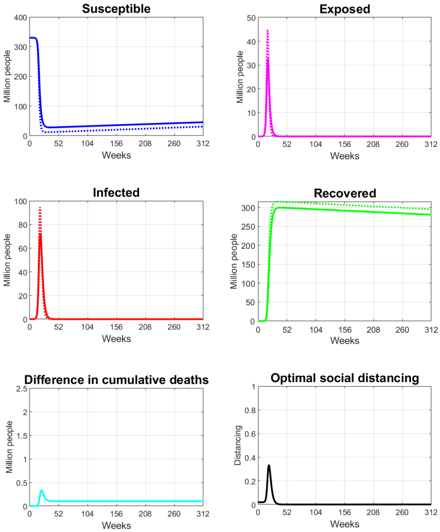
- First 300 years:



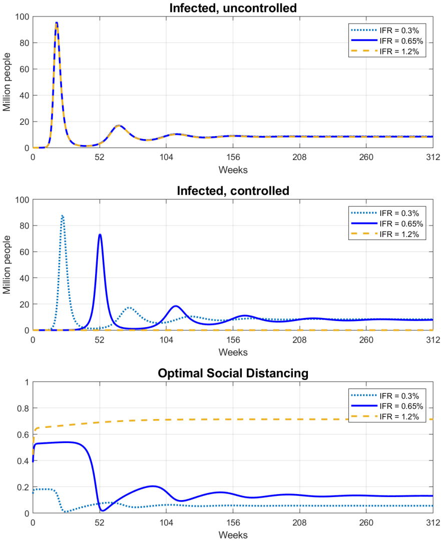
Controlled dynamics: waning immunity (one year)



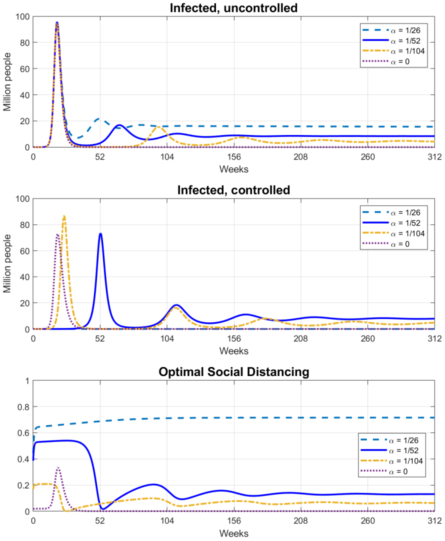
Controlled dynamics: permanent immunity



Controlled dynamics: sensitivity to infection fatality rate



Controlled dynamics: sensitivity to speed of waning



Summary

- Population turnover and waning immunity can both yield dynamics with
  - Endemic steady state where disease not eradicated
  - Damped oscillations as steady state approached
- Optimal social distancing mirrors underlying dynamics
- Faster waning of immunity similar to increased fatality rate
- Both cause increase in social distancing
- For sufficiently high fatality/fast waning, optimal to switch to asymptotic eradication
- **Consequences for social cost-benefit analysis**
- Ignoring possibility of waning immunity can severely underestimate cost of inaction