A model of Covid-19 in the US with endogenous testing, containment measures, and social distancing

Jack Homer, PhD
Barrytown, NY

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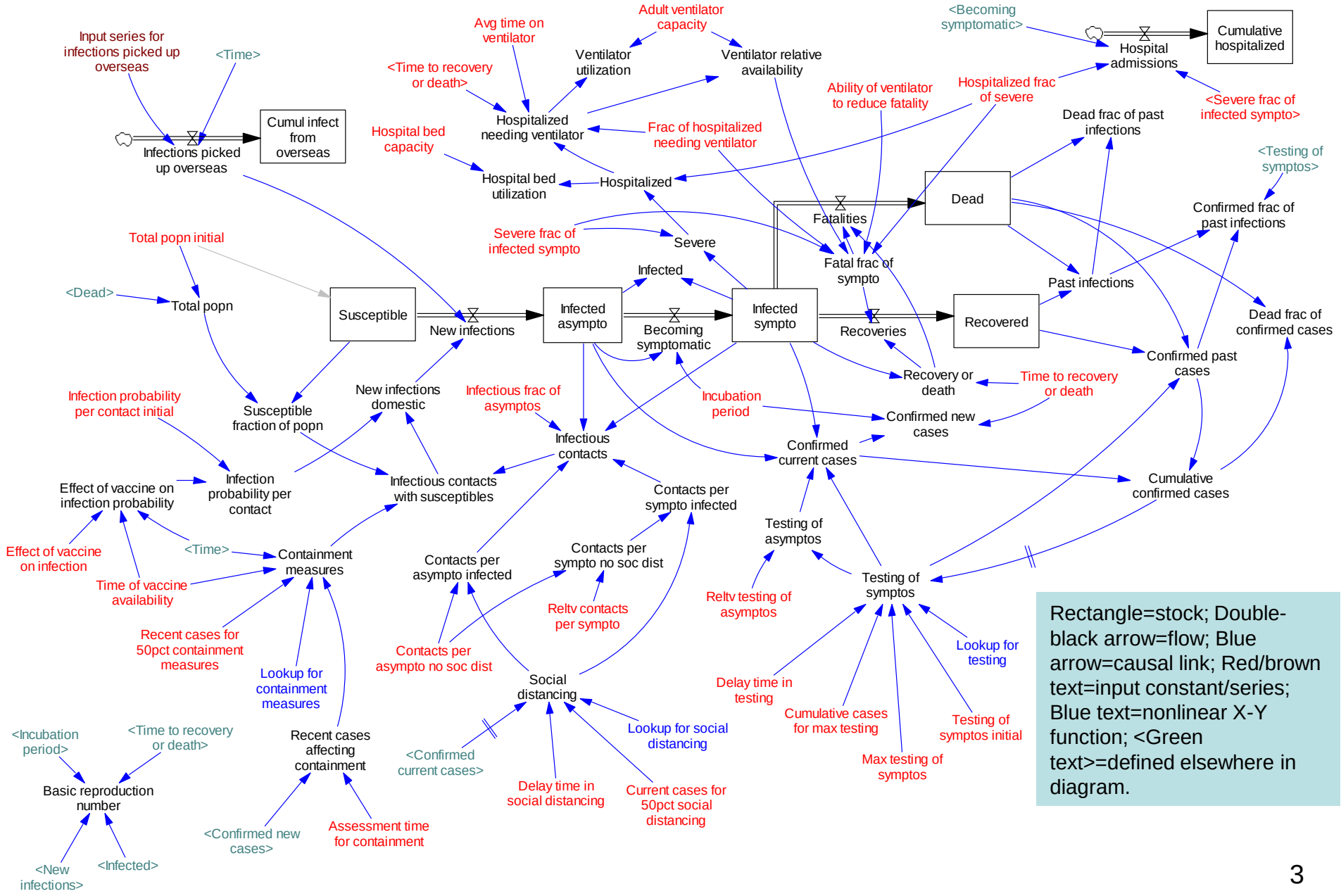
Context

- The epidemic in Hubei, China peaked and was suppressed in only two months. It infected 80,000 (1.4% of the provincial population), of whom 3,200 (4%) died.
- Globally, we so far have 250,000 confirmed cases, of whom 10,000 (4%) have died.
- Italy, Iran, Spain, Germany, South Korea, and France are other countries with many infected. Their case fatality rates range from lows of 0.3% (Germany), 1.0% (Switz.), and 1.1% (S. Korea) to highs of 7.0% (Iran) and 8.3% (Italy).
- In the US, as of March 19 we have 13,789 confirmed cases, of whom 207 (1.5%) have died. The first US case was January 20, a man who had returned from Wuhan.
- In the US, the early response was weak, in terms of testing, social distancing, and government-enforced rules for containment or quarantine. That response has grown significantly these past 2 weeks. Having been put on alert by the rapid spread in other countries, we are starting to take this seriously.
- Since 2010, annual flu has infected 9m to 45m per year and has killed 12,000 to 61,000 per year (0.13%). The 2009-2010 swine flu infected 61m and killed 12,500 (0.02%).
- Model-based projections have varied widely, but some predict tens of millions infected and hundreds of thousands dead in the US. One projection is for about 100m infected and 1 million dead.
- But these projections may fail to take the behavioral responses into account. Clearly, we are now taking Covid-19 much more seriously than the annual flu.
- How much difference could these behavioral responses make to the projections?

An SIR model with endogenous responses

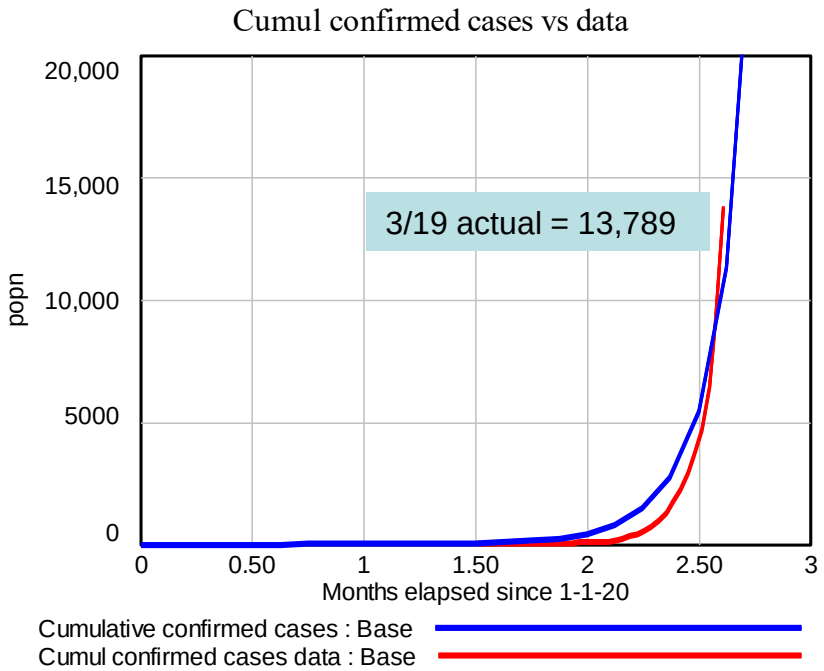


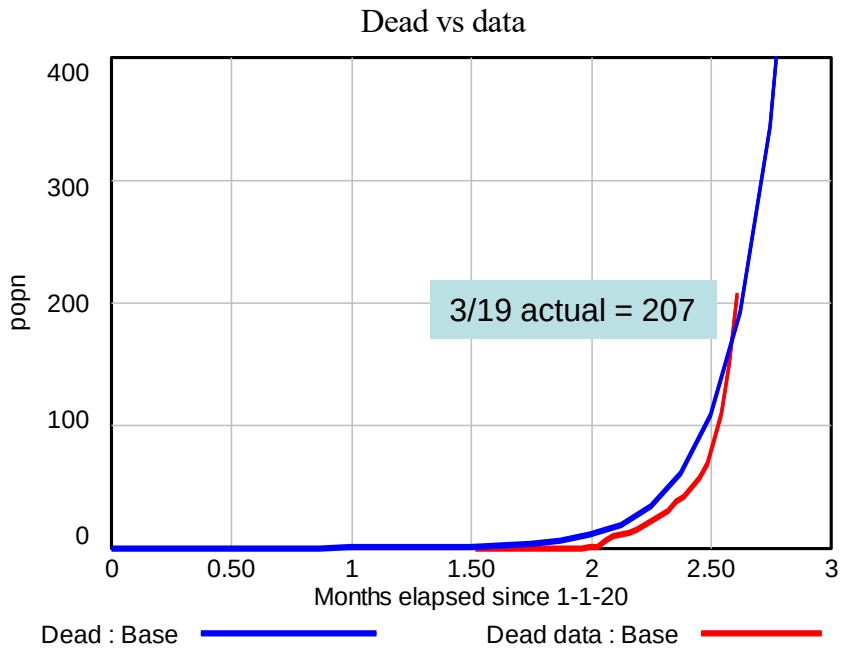
Rectangle=stock; Double-black arrow=flow; Blue arrow=causal link; Red/brown text=input constant/series; Blue text=nonlinear X-Y function; <Green text>=defined elsewhere in diagram.

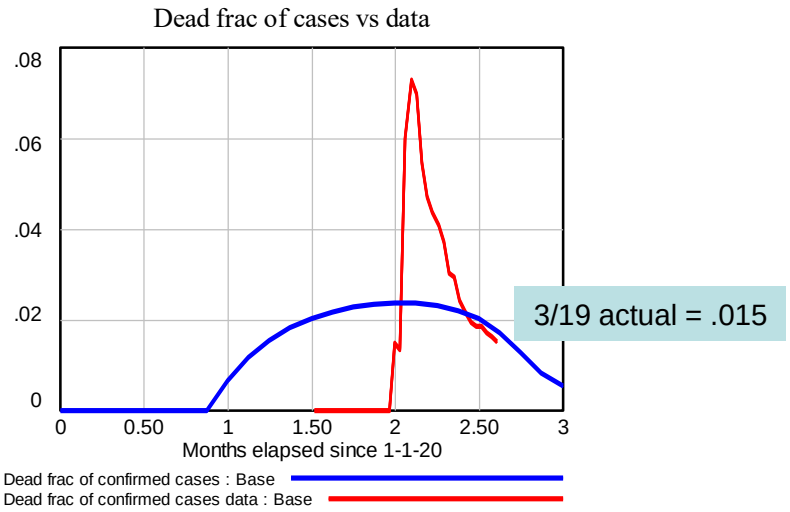
More facts & assumptions taking us to March 19

- Covid-19 is contagious while symptomatic plus one day earlier.
- The basic reproduction number (R_0) for Covid-19 has been estimated as 1.4-3.9, prior to any behavioral responses. In Wuhan, the estimated R_0 fell quickly from 2.35 to 1.0 as a result of quarantine/confinement measures (Kucharski et al. Lancet).
- If we assume (a) we normally average 120 face-to-face contacts per month; (b) when sick, that number is cut in half; (c) the risk per contagious contact is 21.5%, and (d) the period from infection to recovery or death is 2 weeks—then we get an R_0 of 3.7.
- That number will decline as behavioral responses kick in, reducing the risky contacts.
- I assume that 14.5% of symptomatic cases are life-threatening (severe), that all severe cases are hospitalized, that 20% of the hospitalized need a ventilator (average 2 weeks), and that 50% come off the ventilator while 50% die.
- The US has 900k hospital beds, about 300k of them unoccupied at any given time. The US also has 100k ICU beds, and 60k-160k respiratory ventilators (I assume 120k usable ventilators; and that non-ICU beds can be converted to ICU beds.)
- I assume that prior to March, only 18% of actual symptomatic cases were tested and confirmed, and only 3% of asymptomatic cases. This is before any ramp-up in testing. I assume also that all Covid-19 deaths are correctly identified.
- A model with the above assumptions (and including 275 cases picked up overseas or while on cruises during January-March) generates curves for confirmed cases and deaths similar to the actuals through March 19 (see next slide).

Model vs. data through March 19



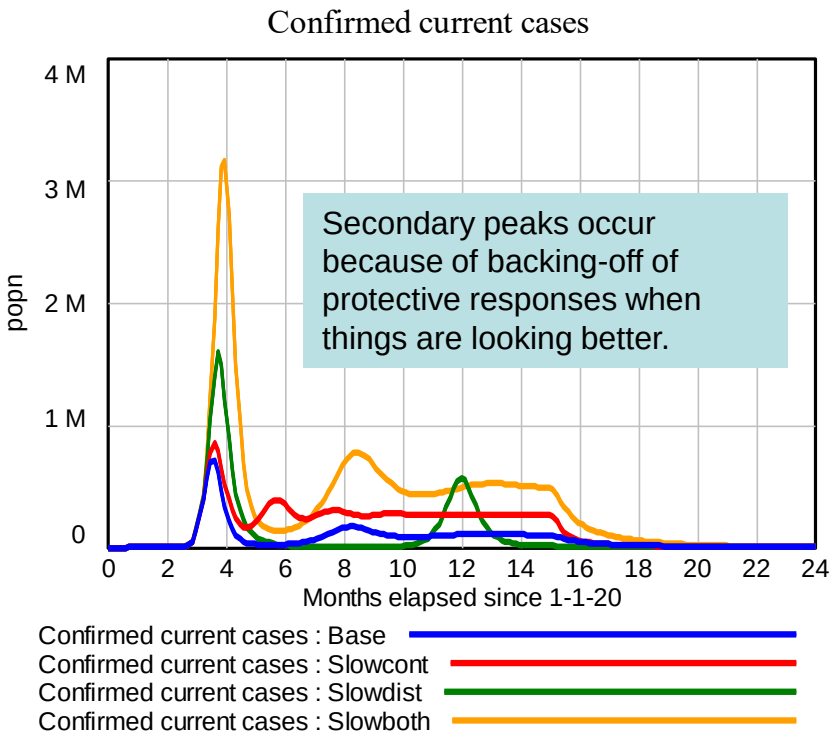


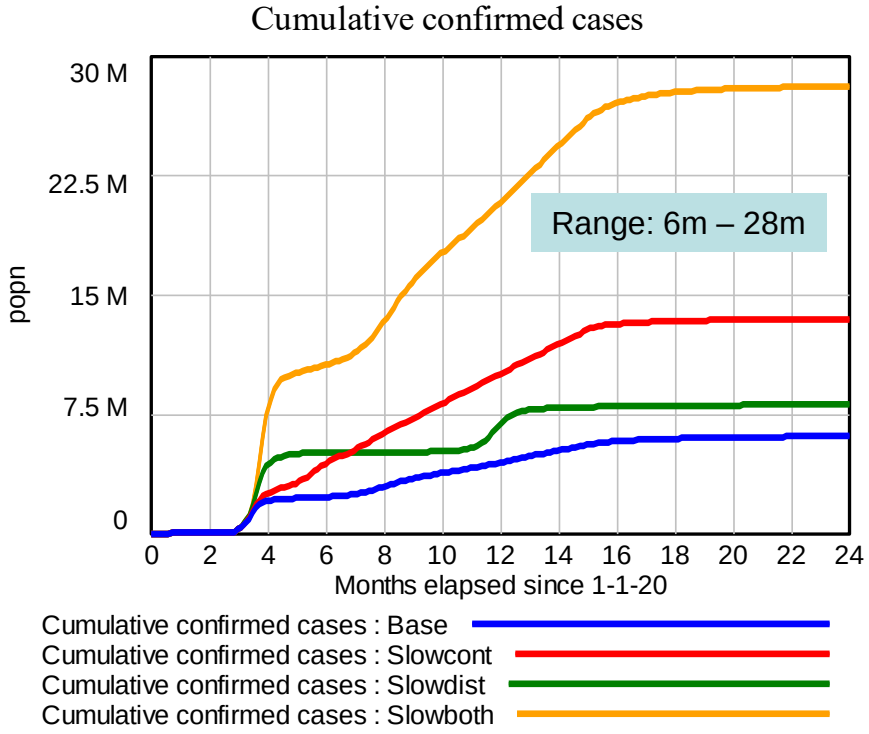


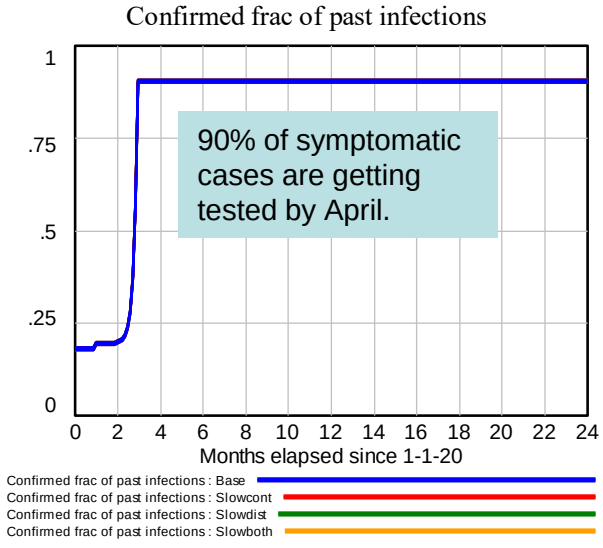
Further assumptions and simulation tests performed

- Testing: The testing fraction of those with symptoms (fever, dry cough) starts at 18% and rises to 90% at 45k cumulative confirmed cases.
- Containment measures: These measures reduce the exposure of uninfected people who lie outside of regions of high infection. They are instituted when there have been many confirmed cases nationally in recent months. I assume for the base case (more hopeful) a quarterly (3-month) assessment period, and a curve that implements 50% containment at 400,000 past-quarter cases nationally, rising to 90% containment at 1.2 million. A less responsive (slower, more pessimistic) alternative would be 50% containment at 2 million past-quarter cases.
- Social distancing: Changes in personal and business behavior reduce the number of contacts within each affected region. People adjust their behavior quickly based on the past week's news about the current number of confirmed cases. I assume for the base case a curve with 50% social distancing at 200,000 past-week cases nationally, rising to 90% distancing at 600,000. A less responsive (slower) alternative would be 50% distancing at 1 million past-week cases.
- Season: Covid-19 so far appears equally contagious in cooler and warmer regions; I assume no summer weakening.
- Vaccine: I assume in all runs a vaccine available 4/1/2021, with 80% coverage. I assume no other mitigating drugs before that.
- 4 runs: Base; Slower containment ("Contslow"); Slower distancing ("Distslow"); Slower both ("Bothslow"). Runs start 1/1/20 and run for 24 months through end of 2021. Computation/recording interval=0.125 month (3.8 days).

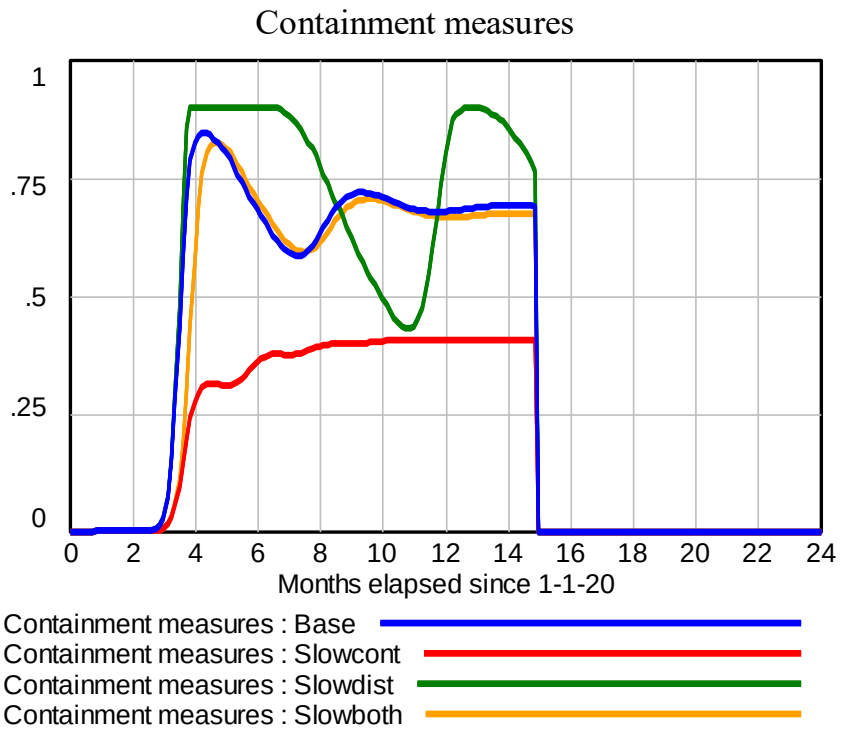
Results: Confirmed cases

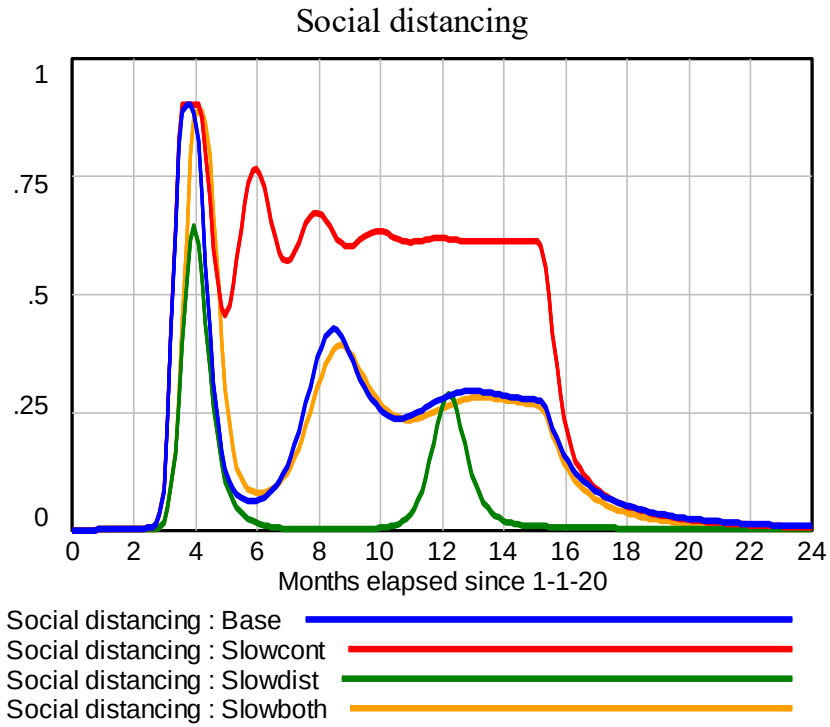






Results: Containment & Social distancing (0-100%)





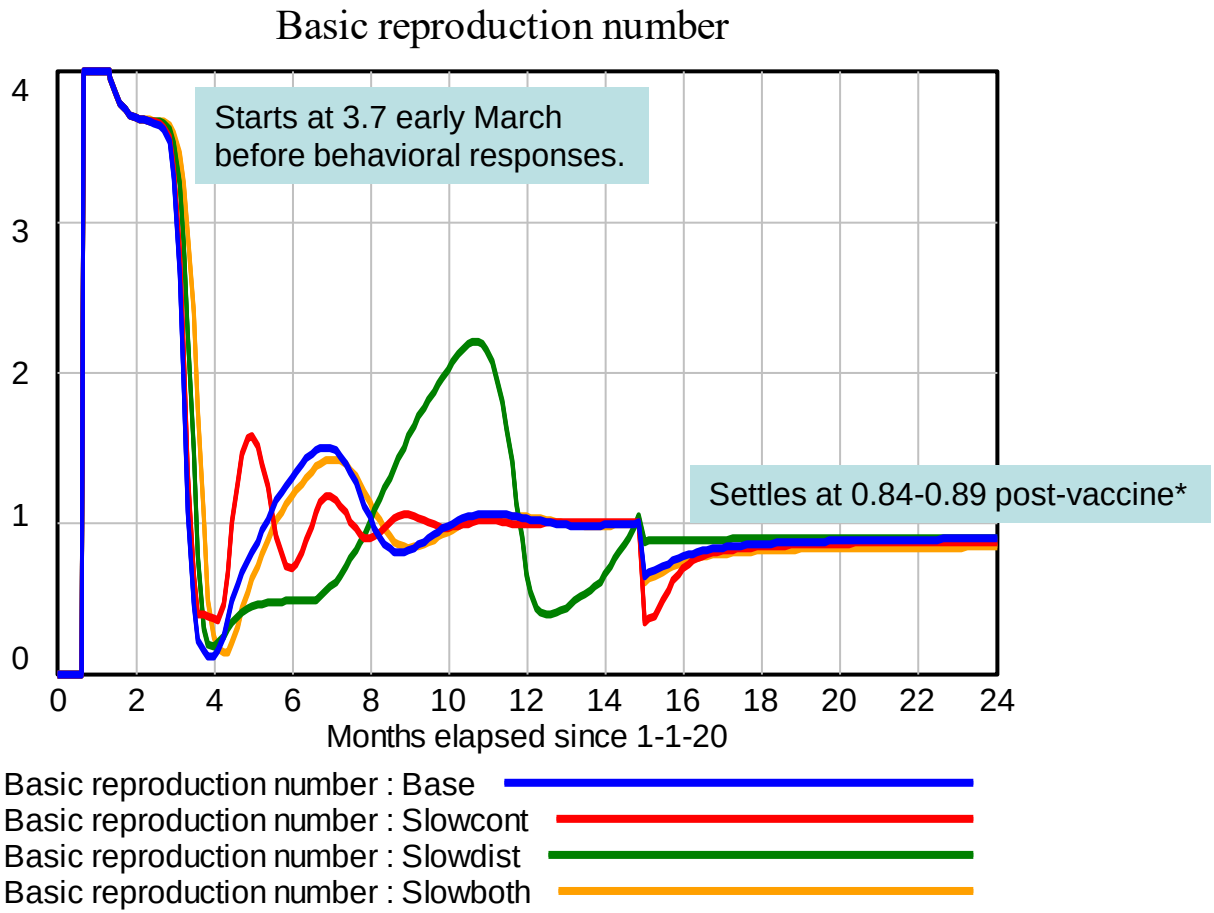
In the base case (blue scenario, more responsive), containment measures rise to 85% by May, settling at 69% by the end of 2020. Social distancing rises to its maximum of 90% by late April, plunges to 6% by late June, then settles at 28% by the end of 2020.

When containment is slow but distancing responsive (red scenario), distancing kicks in more strongly.

When distancing is slow but containment responsive (green scenario), containment kicks in more strongly.

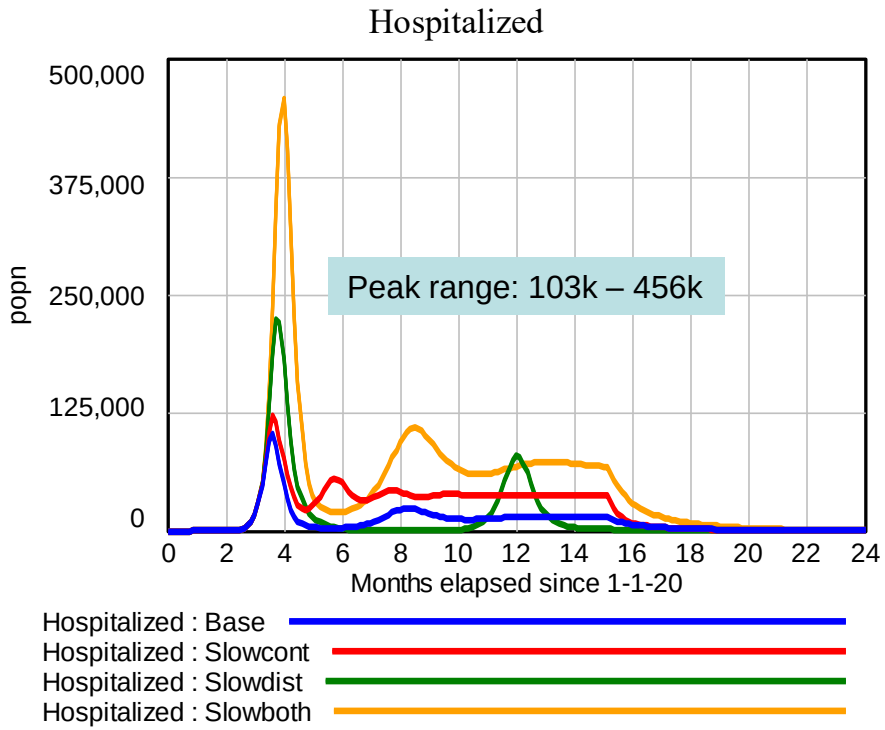
When they are both slow (yellow scenario), the net effect is a pattern like the base run but delayed by a critical few weeks. This delay in response explains the difference between 6 million and 28 million cumulative cases.

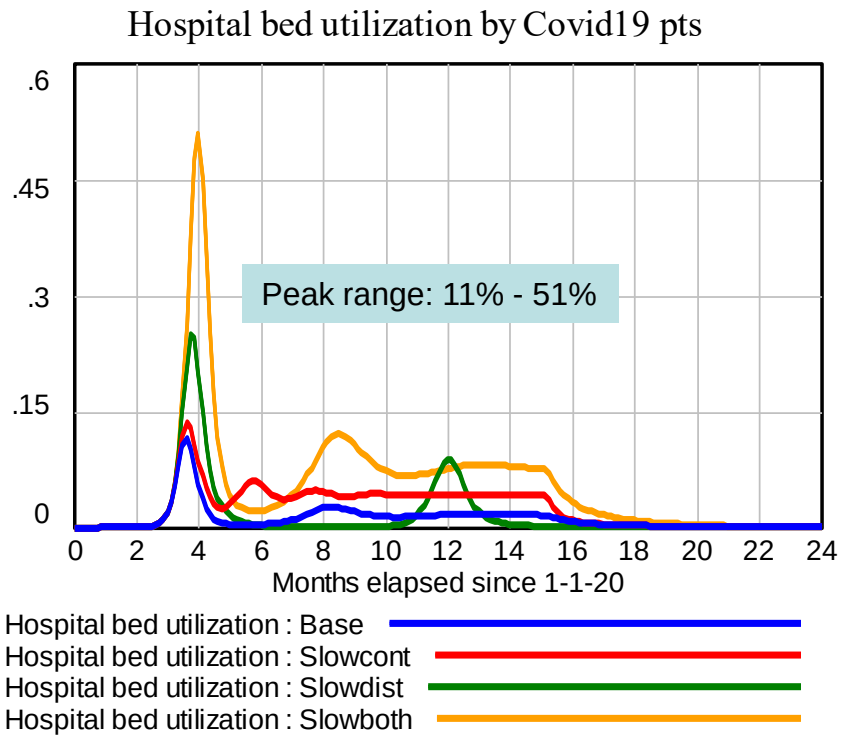
Results: Basic reproduction number R_0



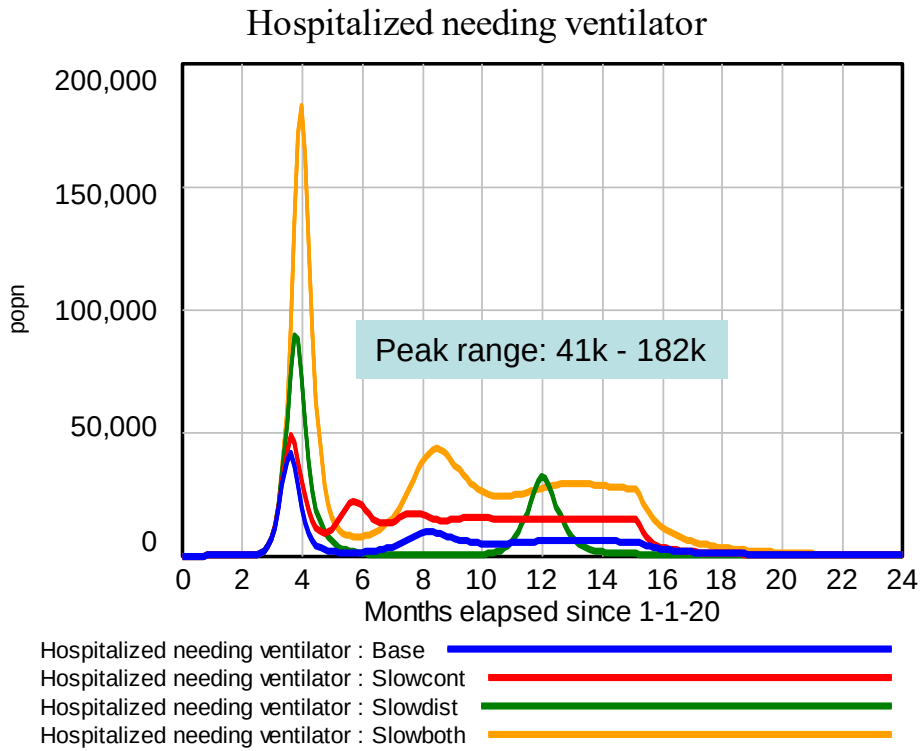
The epidemic surges when R_0 is greater than 1 and falls when R_0 is less than 1.
In all runs, there is a strong response by month 4 (early May 2020), followed by fluctuation due to periodic backing-off of the response, until the vaccine arrives month 15 (April 2021)

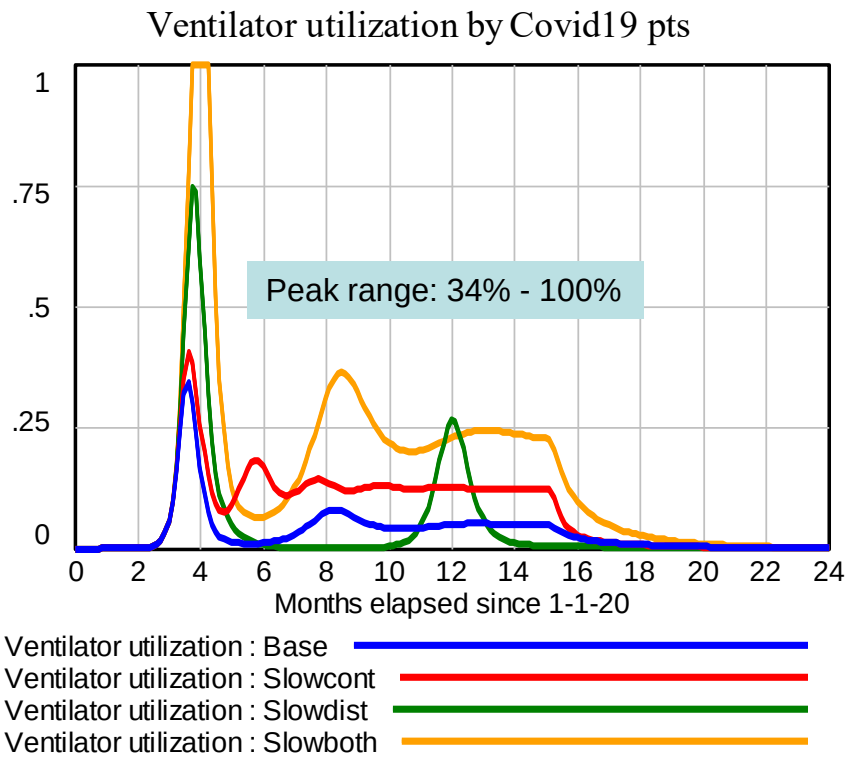
Results: Hospitalized

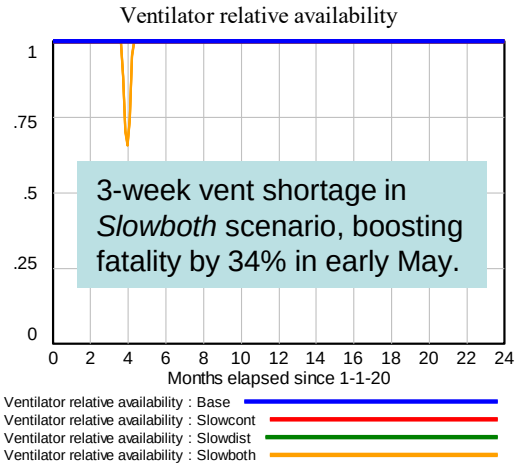




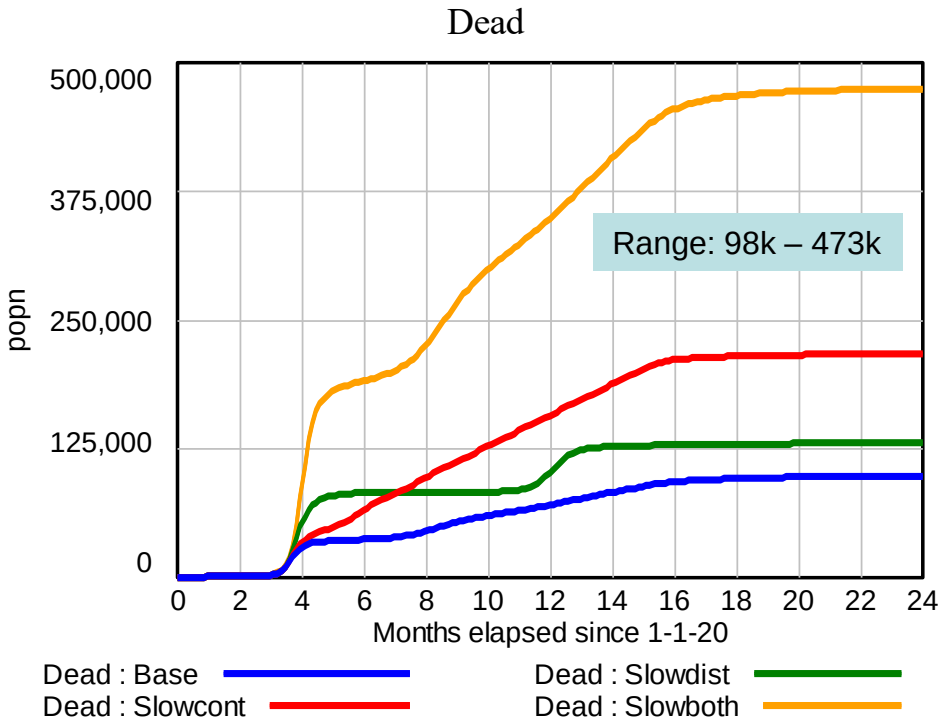
Results: Ventilator utilization

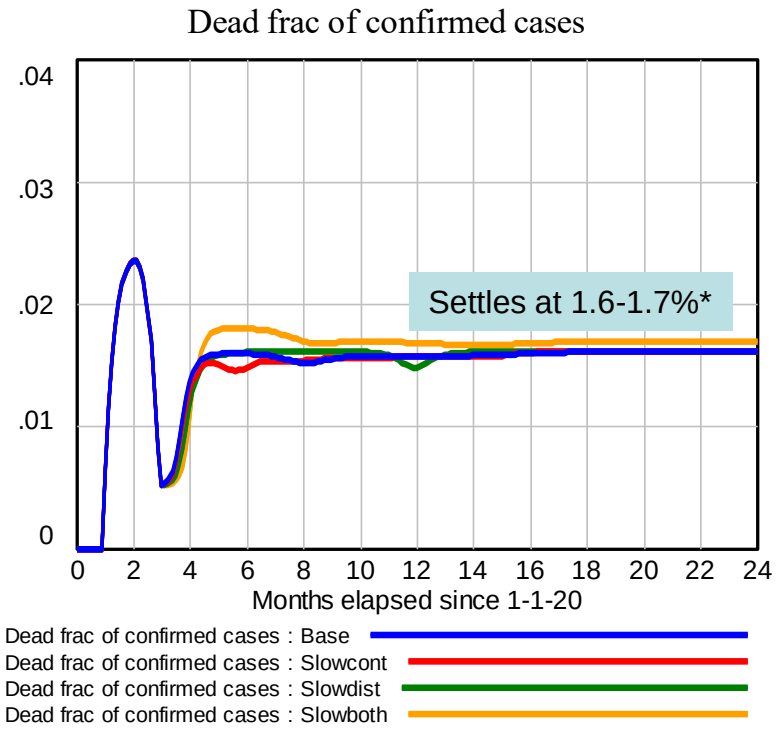






Results: Total deaths & reported case-fatality rate





*1.7% for *Slowboth* scenario because of 3-week vent shortage, see previous slide.

Conclusion

- The results here come from a model with several key numerical assumptions, especially around behavioral responses. As the 4 runs illustrate, if the assumptions are modified, the overall results change over some range of possibility.
- My assumptions about the behavioral responses were informed by what we been seeing recently in the US: a good response, even in regions not yet hard-hit. The message is out, and it is having an effect.
- Because of the responses, and despite the absence of a vaccine, I conclude this epidemic will not infect a third or half of the population as some have predicted. Rather, we are likely to see 6m-28m cases in the US in total, resulting in 100k-500k deaths. This projection assumes a vaccine available by next April.
- I also conclude that our hospital system overall has enough bed capacity to handle the peak load late April/early May; and enough ventilator capacity except during those 3 weeks in the more pessimistic *Slowboth* scenario. We would need 180k ventilators (rather than the assumed 120k) to avoid this shortage in the pessimistic scenario.
- I have not addressed here the impact of containment measures and social distancing on the economy, including the supply of food and other necessities. This supply is important, affecting our ability to maintain strong containment and distancing.