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Policies for a Second Wave

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ONLINE APPENDIX

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A. Latency (σ) and infectious period (γ) parameter values

Tabulation of estimates from literature, drawn from the MIDAS COVID-19 dashboard
Accessed June 8, 2020 (https://midasnetwork.us/covid-19/)

Parameter	Value	Country	Lower Bound	Upper Bound	Age Range	Study Start Date	Study End Date	Study Publication Date	Source	Peer Re-viewed
Incubation period	4.2	China	3.5	5.1	Unspecified	1/15/2020	1/20/2020	4/8/2020	Sanche S, et al.	y
	5.2	China	1.8	12.4	Unspecified	12/24/2020	2/14/2020	4/2/2020	Zhang J, et al.	y
	5.2	China	4.4	6	Unspecified	12/1/2019	2/4/2019	2/4/2020	Lauer SA, et al.	y
	8.41	United States	6.64	9.42	Unspecified	1/21/2020	3/21/2020	5/22/2020	Liu Q, et al.	n
	10.69	United States	10.02	11.74	Unspecified	3/22/2020	4/13/2020	5/22/2020	Liu Q, et al.	n
	6.4	Vietnam	4.89	8.5	Unspecified	1/23/2020	4/13/2020	5/15/2020	Bui LV, et al.	n
	5.1	France	Unspecified	Unspecified	Unspecified	2/15/2020	5/1/2020	5/1/2020	Unlu E, et al.	n
	8.13	China	7.37	8.91	Unspecified	1/12/2020	1/23/2020	3/10/2020	Qin J, et al.	n
	8.62	China	8.02	9.28	Unspecified	1/12/2020	1/23/2020	3/10/2020	Qin J, et al.	n
	6.6	Singapore	1.8	11.4	Unspecified	1/19/2020	2/26/2020	3/6/2020	Tindale LC, et al.	n
	5.4	China	0.9	9.9	Unspecified	1/21/2020	2/22/2020	3/6/2020	Tindale LC, et al.	n
	5.2	China	1	9.4	Unspecified	1/21/2020	2/22/2020	3/6/2020	Tindale LC, et al.	n
	7.1	Singapore	6.1	8.3	Unspecified	1/19/2020	2/26/2020	3/6/2020	Tindale LC, et al.	n
	5.46	Singapore	1.34	11.1	Unspecified	1/19/2020	1/31/2020	3/6/2020	Tindale LC, et al.	n
	7.27	Singapore	1.31	17.3	Unspecified	2/1/2020	2/26/2020	3/6/2020	Tindale LC, et al.	n
	9	China	7.92	10.2	Unspecified	1/21/2020	2/22/2020	3/6/2020	Tindale LC, et al.	n
	6.9	China	2	12.7	Unspecified	1/21/2020	1/31/2020	3/6/2020	Tindale LC, et al.	n
	12.4	China	5.4	19	Unspecified	2/1/2020	2/22/2020	3/6/2020	Tindale LC, et al.	n
	4.8	China	4.2	5.4	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	4.2	China	3.5	5.1	Unspecified	12/31/2019	2/10/2020	2/11/2020	Sanche S, et al.	n
	4.6	China	3.3	5.7	Unspecified	12/31/2019	1/25/2020	1/28/2020	Linton NM, et al.	n
	5	China	4.1	5.8	Unspecified	12/31/2019	1/25/2020	1/28/2020	Linton NM, et al.	n
	5.4	China	4.2	6.7	Unspecified	12/10/2019	1/25/2020	1/26/2020	Famular, et al.	n
Time from symptom onset to death	16.1	China	13.1	20.2	Unspecified	1/15/2020	1/20/2020	4/8/2020	Sanche S, et al.	y
	15.2	China	13.1	17.7	Unspecified	12/31/2019	1/24/2020	2/17/2020	Jung S, et al.	n
	22.3	China	18	82	Unspecified	12/31/2019	1/21/2020	2/10/2020	Dorigatt I, et al.	n
	13.8	China	11.8	16	Unspecified	12/31/2019	1/25/2020	1/28/2020	Linton NM, et al.	n
Time from symptom onset to recovery	20.3	China	19.4	21.3	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	21.2	China	20.2	22.3	0-9	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	17.5	China	15.3	20	19-Oct	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	19.1	China	15.8	22.9	20-29	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	19.2	China	17.5	21	30-39	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	19.2	China	18	20.5	40-49	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	21.6	China	20	23.4	50-59	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	22.4	China	20.8	24.1	60-69	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	22.9	China	21.2	24.7	70-130	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	22.5	China	19.1	26.3	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	20.1	China	19	21.3	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	20.3	China	19.5	21.1	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	28.3	China	25.3	31.6	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	19.3	China	17.9	20.9	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	21.2	China	20.4	22	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n
	21.2	China	18	24.9	Unspecified	1/14/2020	2/12/2020	3/4/2020	Qifang B, et al.	n

For the incubation (latency) period, the mean value in the peer-reviewed studies is 4.87, which is what we use in the simulations.

For the infectious period, the estimates are all large which likely is a result of the studies focusing on hospitalization. We used two values, one from Kissler et al (2020) for an infectious period of 5 days for the results reported in the paper, and as a sensitivity check (reported below) an infectious period of 9 days.

***Update 7/29/20*: CDC COVID-19 Pandemic Planning Scenarios**
The CDC Pandemic Planning Scenarios page (https://www.cdc.gov/coronavirus/2019-ncov/hcp/planning-scenarios.html) provides the following parameter values:

- Population IFR: 0.65% in their base case. We use 0.7%, with sensitivity of 0.4% to 1.0%.

- Time from exposure to symptom onset (incubation period): 6 days. This is rounded up from 5.5 days for the mean in the meta-analysis of McAloon et al (2020); their meta-analysis median (i.e., their estimate of the median of the distribution of estimates of the mean time from exposure to symptom onset) is 5.1 days, which is very close to the value of 4.87 days used in our simulations.

  McAloon, C.G. et al (2020). The Incubation Period of COVID-19: A Rapid Systematic Review and Meta-Analysis of observational research. MedRxiv at https://www.medrxiv.org/content/10.1101/2020.04.24.20073957v1.

- CDC does not provide an estimate of the mean/median number of days from symptom onset to recovery.

B. Transmission involving children: literature and parameter values

This literature review and discussion was prepared by Edward Kong and Lingdi Xu (updated June 5, 2020), as advised by James Hay.

Definitions: Let α indicate an adult group, i.e. a = 2, 3, 4, 5 in the 5-age SEIRD model. As in the paper, define: ρ_{a1} = transmission from kids to adults, ρ_{1a} = transmission from adults to kids, ρ_{11} = transmission from kids to kids. For this review "kids" are ages 0-19. These factors are scaling factors multiplying β in the SIR model, normalized so that $\rho_{aa} = 1$.

Kid to adult transmission

We estimate $\rho_{a1} = 0.27$. The most useful emerging evidence for this parameter is contact tracing data. For example, estimates of the number of ***secondary infections*** produced by a given infected child, vs. the same quantity for adults. Also useful are statistics on the share of clusters started by a child vs. an adult (though this ratio must be multiplied by a correction factor accounting for the smaller number of infected children that are available to start clusters).

Adult to kid transmission

We estimate $\rho_{1a} = 0.44$, which aggregates some evidence pointing to very low rates of infection among children, early evidence that attack rates among children are similar to adults, and newer evidence (SIR-model based estimates using cross-country data + larger contact tracing studies) that finds a middle ground, where children are about half as susceptible to infection as adults. The most useful evidence for this parameter is evidence on ***attack rates*** in children vs. adults, where the attack rate is defined as the number of infections divided by the total number of contacts (e.g. # infected children / # contacts with infected individuals).

Kid to kid transmission

We are not aware of any direct literature on ρ_{11}. If transmission is entirely based on the susceptibility of the target, then we would have $\rho_{11} = \rho_{1a}$, but this hypothesis would also imply $\rho_{aa} = \rho_{a1}$ whereas we think that $\rho_{aa} > \rho_{a1}$ in actuality. On the other extreme, if transmission is entirely based on the infection source, then we would have $\rho_{11} = \rho_{a1}$, but this hypothesis implies $\rho_{aa} = \rho_{1a}$ whereas again we think that $\rho_{aa} > \rho_{1a}$. Hence, transmission appears to depend on both the source and target of infection; a 50/50 weighting of these two factors is thus reasonable, so we use $\rho_{11} = 0.5(\rho_{a1} + \rho_{1a})$.

Summary Table: Literature on transmission and susceptibility involving kids
(some studies are only informative about one direction of transmission)

Study	**Date submitted/ posted**	**Estimate for ρ_{1a}* (adults to kids)**	Study weight**	**Estimate for ρ_{a1}* (kids to adults)**	Study weight**
Lee et al	Feb 21, 2020	0.1	1	N/A	N/A
Zimmerman et al	March 3, 2020	1.0	1	N/A	N/A
Mizumoto et al	March 13, 2020	0.36	2	N/A	N/A
Jing et al	April 15	0.32	3	0.11	1
Bi et al	March 4	1.0	0 (same data as Zimmerman)	N/A	N/A
Davies et al	May 3	0.5	4	N/A	N/A
Viner et al	May 24	0.44	5	0.24	2
Heavy et al	May 12	N/A	N/A	0.0	1
L'Huillier et al	May 1	N/A	N/A	0.75	1
Total/Averages		**0.44**	16	**0.27**	5

* Studies typically do not report precisely this parameter. Hence, we calculate an estimate based on the information provided in the paper, see the notes below.
** We assign judgmental study weights (between 0 and 5) to express the relevance of the study for pinning down our parameter of interest. Estimates for ρ parameters are computed as weighted averages using these weights.

References

1. Lee, P. I., Hu, Y. L., Chen, P. Y., Huang, Y. C., & Hsueh, P. R. (2020). Are children less susceptible to COVID-19?. Journal of microbiology, immunology, and infection, S1684-1182(20)30039-6. Advance online publication. https://doi.org/10.1016/j.jmii.2020.02.011

2. Zimmermann, P., & Curtis, N. (2020). Coronavirus Infections in Children Including COVID-19: An Overview of the Epidemiology, Clinical Features, Diagnosis, Treatment and Prevention Options in Children. The Pediatric infectious disease journal, 39(5), 355–368. https://doi.org/10.1097/INF.0000000000002660

3. Mizumoto, K., Omori, R., & Nishiura, H. (2020). Age specificity of cases and attack rate of novel coronavirus disease (COVID-19). medRxiv.

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5. Bi, Q., Wu, Y., Mei, S., Ye, C., Zou, X., Zhang, Z., ... & Gao, W. (2020). Epidemiology and Transmission of COVID-19 in Shenzhen China: Analysis of 391 cases and 1,286 of their close contacts. MedRxiv.

6. Davies, N. G., Klepac, P., Liu, Y., Prem, K., Jit, M., Eggo, R. M., & CMMID COVID-19 working group. (2020). Age-dependent effects in the transmission and control of COVID-19 epidemics. MedRxiv.

7. Viner, R. M., Mytton, O. T., Bonell, C., Melendez-Torres, G. J., Ward, J. L., Hudson, L., ... & Panovska-Griffiths, J. (2020). Susceptibility to and transmission of COVID-19 amongst children and adolescents compared with adults: a systematic review and meta-analysis. medRxiv.
8. Heavey, L., Casey, G., Kelly, C., Kelly, D., & McDarby, G. (2020). No evidence of secondary transmission of COVID-19 from children attending school in Ireland, 2020. Eurosurveillance, 25(21), 2000903
9. L'Huillier, A. G., Torriani, G., Pigny, F., Kaiser, L., & Eckerle, I. (2020). Shedding of infectious SARS-CoV-2 in symptomatic neonates, children and adolescents. medRxiv.

Additional related references

Science Magazine -- Should schools reopen? Kids' role in pandemic still a mystery -- (news article – May 4, 2020) https://www.sciencemag.org/news/2020/05/should-schools-reopen-kids-role-pandemic-still-mystery#

Munro and Faust – UK Southampton Hospital – April 23, 2020. Title: Children are not COVID-19 super spreaders: time to go back to school

Netherlands National Institute for Public Health (RIVM), https://www.rivm.nl/en/novel-coronavirus-covid-19/children-and-covid-19

Boast A, Munro A, Goldstein H. An evidence summary of Paediatric COVID-19 literature, Don't Forget the Bubbles, 2020. Available at: http://doi.org/10.31440/DFTB.24063.

Hay et al (March 2020) Implications of the Age Profile of the Novel Coronavirus

Additional study (added 7/29/20, not used in the BPEA paper). This study, which uses contact-tracing data from Korea, reinforces very low values of transmission and susceptibility for ages 0-9 but suggests that transmissibility for 10-19 is comparable to adults, however susceptibility seems to be substantially less than for adults:

Park et al. (2020), Contact Tracing during Coronavirus Disease Outbreak, South Korea, 2020. Forthcoming, *Emerging Infectious Diseases* at https://wwwnc.cdc.gov/eid/article/26/10/20-1315_article?referringSource=articleShare.

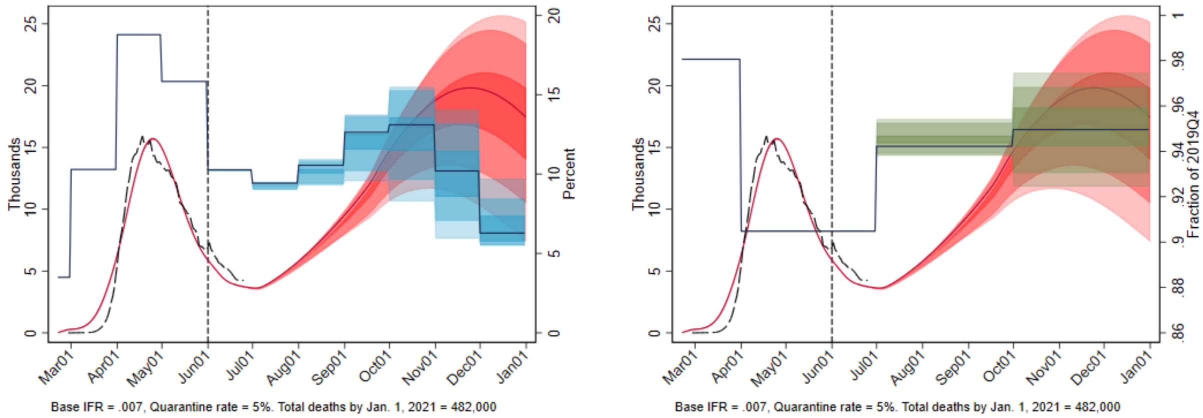
C. Estimation and simulation results for other values of the population IFR

This section provides simulation results for values of the population IFR = 0.4%, 0.5%, 0.6%, 0.7%, 0.8%, 0.9%, and 1.0%. The scenarios shown are those in the paper in Figures 1, 2, 6, 7, 8, 9, and 10, with corresponding figure numbers here C-1, C-2, C-6, etc. The figures in the paper portray the point estimate for population IFR = 0.7% with +/- 1, 1.65, and 1.96 standard error bands. In contrast, the figures here show point estimates for different values of the IFR.

The uncertainty bands arising from varying the population IFR are in some cases wider than the confidence intervals for IFR = 0.7% in the paper, and in some cases are tighter. The tighter cases are for the more restrictive control scenarios, in which infections are sharply reduced so deaths are sharply reduced.

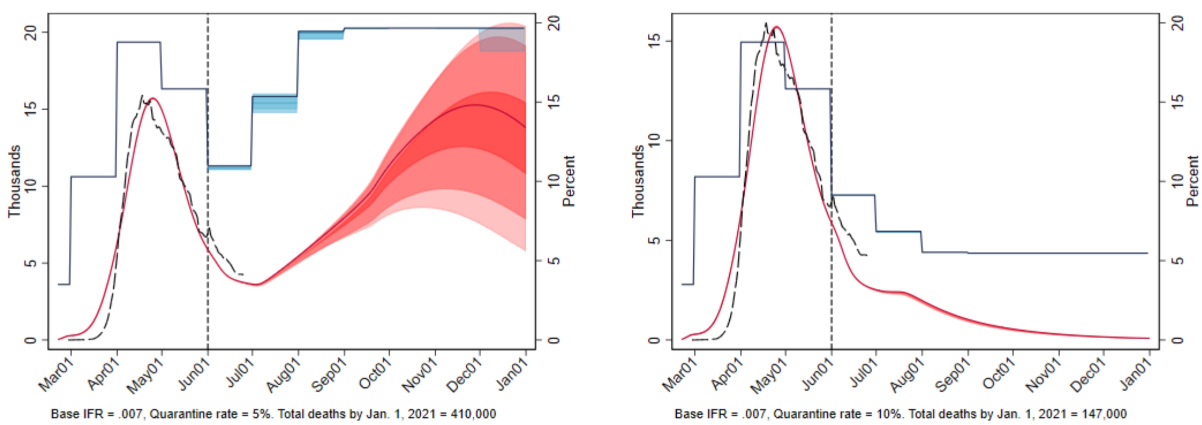
The overall uncertainty is greater than is represented by either the figures in the paper or those in this (or the next) appendix, because of modeling simplifications and especially uncertainty over key modeling parameters as discussed in the previous two sections of this appendix. Sensitivity to other changes of model parameters can be explored using the replication code by (1) specifying the parameter values, (2) estimating the remaining model parameters as discussed in the text, and (3) executing the counterfactual simulation of interest.

Figure C-1. Second wave from relaxed social distancing and too-early economic and non-economic reopening: Weekly deaths, the unemployment rate, and GDP



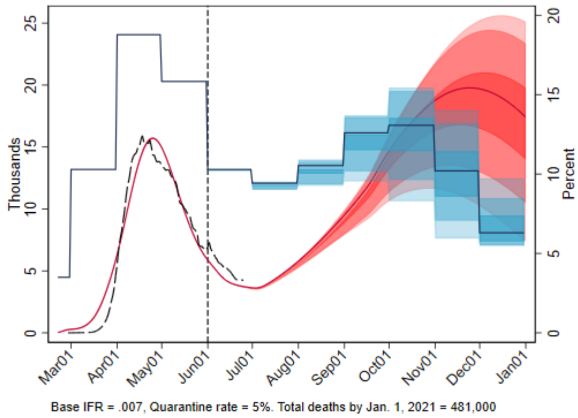
Notes: Each chart shows the level of weekly COVID-19 deaths, actual (black dashed) and simulated. The chart on the left shows the unemployment rate (measured by hours lost) and the chart on the right shows the level of quarterly GDP, indexed to February 2020 = 1. Bands denote point estimates for the population IFR = 0.4% to 1.0% in increments of 0.1 pp. Total deaths on Jan. 1 in the figure notes corresponds to the central case a population IFR = 0.7% (these values are the same as the point estimate reported in the paper for the corresponding case). Source: Authors' calculations. Simulation begins on June 1 (vertical dashed line).

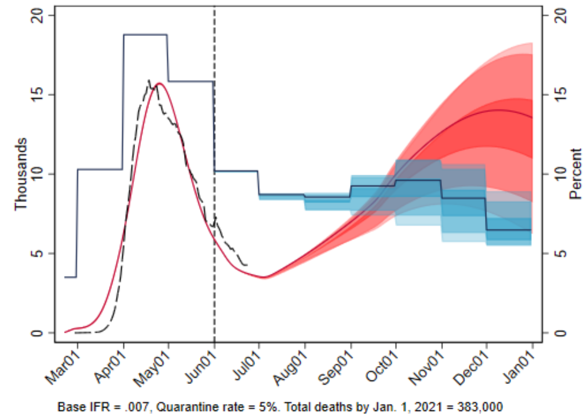
Figure C-2. Responding to the second wave by closing businesses (left), or by strong protections for the elderly, strict mask usage, increasing testing and quarantine, combined with a smart economic reopening and reopening schools (deaths and unemployment rates)



Notes: Both charts show weekly deaths and the monthly unemployment rate. Total deaths on Jan. 1: 410,000 (left) and 147,000 (right). See the notes to Figure C-1.

Figure C-6. Economic NPIs: Greater use of the GDP-to-Risk index (left)
and full working from home (right)

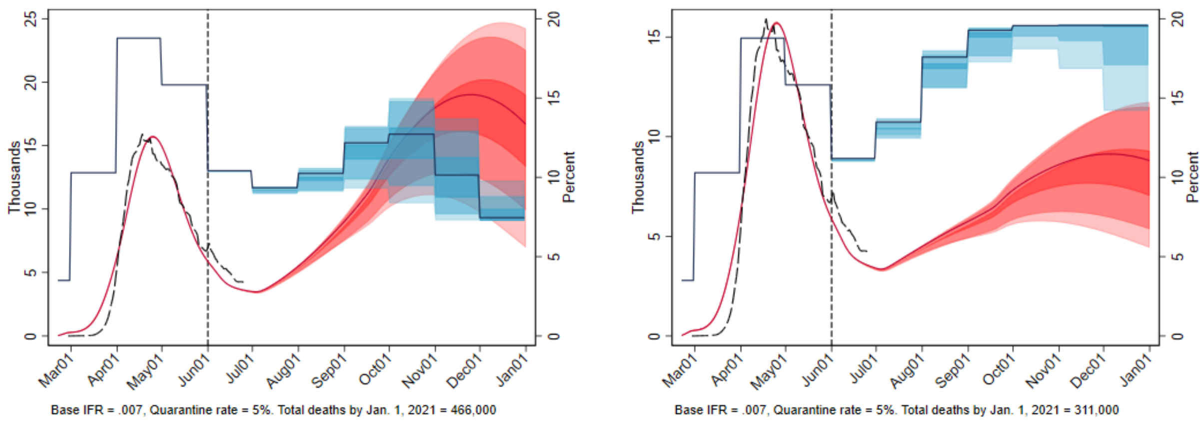




Notes: Baseline is the fast reopening second wave scenario in

Figure . Total deaths by Jan. 1: 481,000 (left) and 383,000 (right). See the notes to Figure C-1.

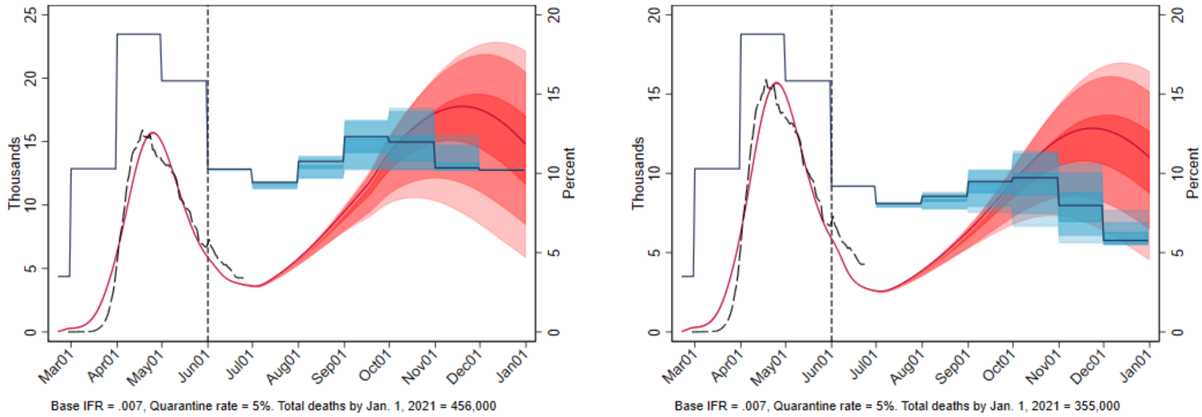
Figure C-7. Economic NPIs: No on-site workers age 65+ (left) and all three (aggressive sectoral, work-from-home, no age 65+) combined with economic shutdown (right)



Notes: Baseline is the fast reopening second wave scenario in

Figure . Total deaths by Jan. 1: 466,000 (left) and 311,000 (right). See the notes to Figure C-1.

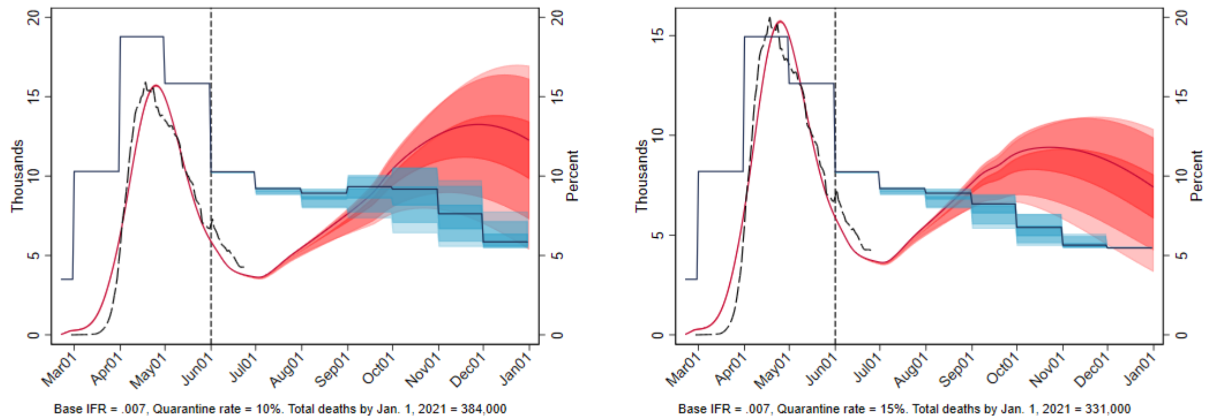
Figure C-8. Non-Economic NPIs: No School (left), Enhanced Protections for Ages 75+ (right)



Notes: Baseline is the fast reopening second wave scenario in

Figure . Total deaths by Jan. 1: 456,000 (left) and 355,000 (right). See the notes to Figure C-1.

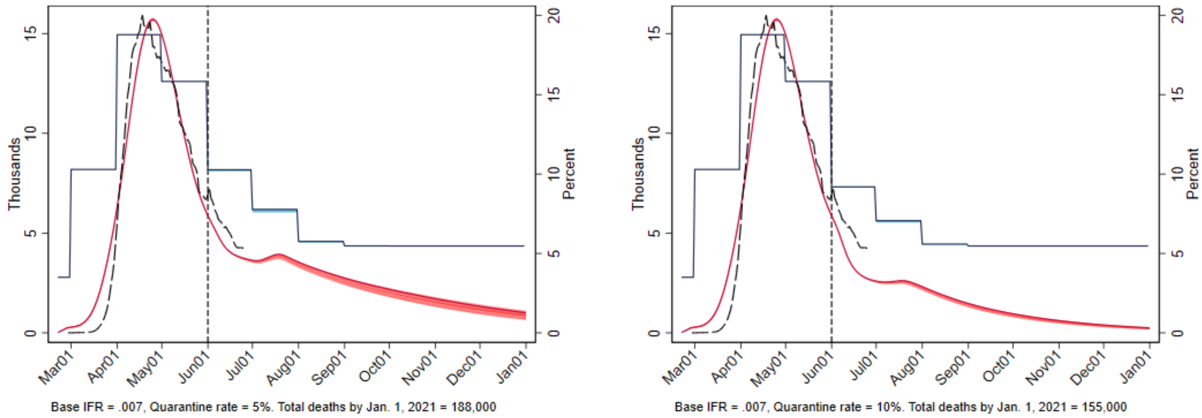
Figure C-9. Non-Economic NPIs: 10% (left) and 15% (right) Quarantine



Notes: Baseline is the fast reopening second wave scenario in

Figure . Total deaths by Jan. 1: 384,000 (left) and 331,000 (right). See the notes to Figure C-1.

Figure C-10. Non-Economic NPIs: Strong Personal Distancing (left) and
Strong Personal Distancing + 10% Quarantine + Enhanced 75+ Protections (right)



Notes: Baseline is the fast reopening second wave scenario in

Figure . Total deaths by Jan. 1: 188,000 (left) and 155,000 (right). See the notes to Figure C-1.

D. Estimation and simulation results for infectious period of 9 days

The infectious period is poorly estimated in the medical literature, and in particular there are estimates of a much longer mean infectious period than the 5 days we use in the main simulations. This section therefore reports a sensitivity analysis using a longer mean infectious period of 9 days, so $\gamma = \exp(1/9)-1$. We maintain the latency period of 4.87 days. The other calibrated parameters are identical to those used in the paper. The model was reestimated using the alternative value of γ, with parameter estimates shown in Table D-1.

Comparison of Table D-1 with Table 1 in the paper shows that, for the longer infectious period, (1) the initial number of infections is estimated to be greater, (2) the transmission factor β is estimated to be lower, and (3) the RMSE is slightly higher for the 9- than the 5-day latency period. The first two observations follow from the logic of the SIR model: with a longer time in which to transmit, the transmission rate must be lower to match the actual deaths data, and the initial number of infections must be greater. The lower RMSE for the 5-day period provides empirical support for the value of γ used in the paper.

Figure D-4 shows the time path of $R^{effective}$ for the estimated model with the 9-day infectious period. (Figure D-4 is computed as Figure 4 in the paper except for the 9-day infectious period and the associated new estimated coefficients.) The fit, compared to the nonparametric estimate, is slightly worse than in Figure 4 in the paper, providing additional evidence in support of the 5-day period used in the paper.

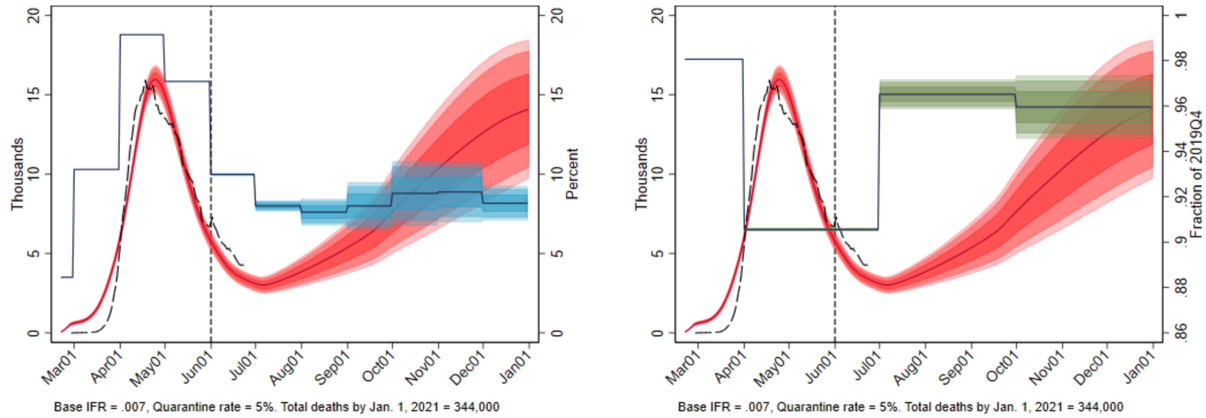
The simulation results are shown in Figures D-1, D-2, D-6, D-7, D-8, D-9, and D-10, each of which corresponds to Figures 1, 2, etc. in the paper, except the D figures use the 9-day latency period. Comparison of the two sets of figures reveals that all the conclusions in the paper are robust to using the longer latency period.

Table D-1. Estimated parameter values

IFR	$\hat{I}_0$	$\hat{\beta}$	$\hat{f}_0$	$\hat{f}_1$	$\hat{f}_2$	RMSE
0.005	15.75	0.030	0.002	1.25	1.60	1.256
	(1.50)	(0.004)	(0.001)	(0.07)	(0.10)	
0.007	11.73	0.030	0.006	1.33	1.63	1.282
	(1.26)	(0.005)	(0.007)	(0.085)	(0.12)	
0.009	9.23	0.030	0.007	1.34	1.63	1.291
	(0.95)	(0.005)	(0.007)	(0.07)	(0.11)	

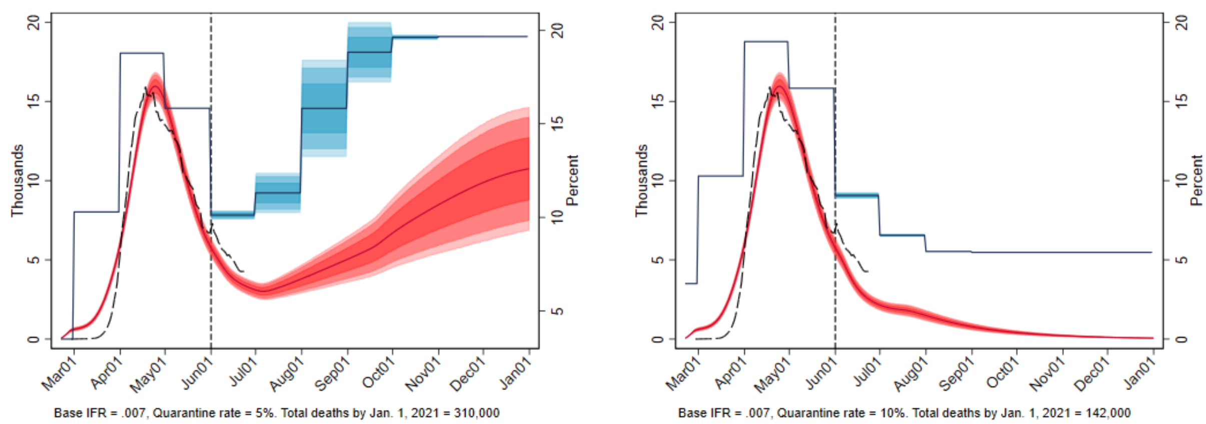
Notes: The parameters I_0 and β and are respectively the initial number of infections on Feb. 21 (in thousands) and the adult transmission rate. The coefficients f_0, f_1, and f_2 parameterize the scaling factor φ_t. Given the IFR in the first column and the other model parameters given in the text, the parameters in the table are estimated using data on the 7-day moving average of deaths (units: thousands) from March 15 through June 12. Nonlinear least squares standard errors are given in parentheses.

Figure D-1. Second wave from relaxed social distancing and too-early economic and non-economic reopening: Weekly deaths, the unemployment rate, and GDP



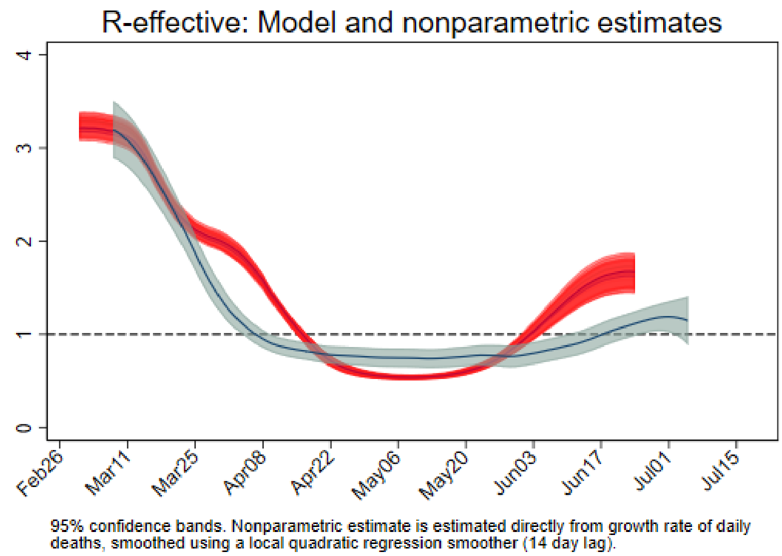
Notes: Each chart shows the level of weekly COVID-19 deaths, actual (black dashed) and simulated. The chart on the left shows the unemployment rate (measured by hours lost) and the chart on the right shows the level of quarterly GDP, indexed to February 2020 = 1. Bands denote +/- 1, 1.65, and 1.96 standard deviations arising from sampling uncertainty for the estimated parameters. The population-wide IFR is 0.7%, and the assumed quarantine rate and end-of-year cumulative death rate is given in the figure note. Total deaths on Jan. 1 are in the figure captions. Source: Authors' calculations. Simulation begins on June 1 (vertical dashed line).

Figure D-2. Responding to the second wave by closing businesses (left), or by strong protections for the elderly, strict mask usage, increasing testing and quarantine, combined with a smart economic reopening and reopening schools (deaths and unemployment rates)



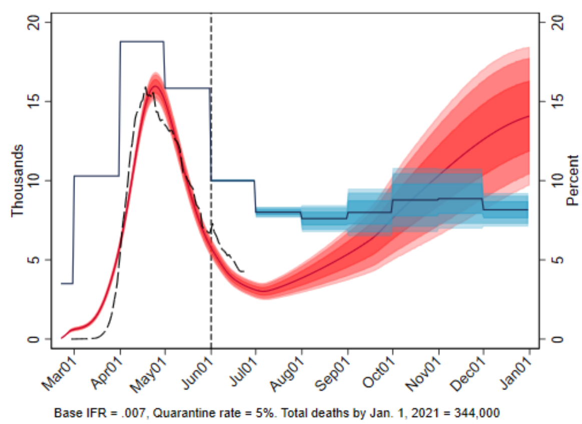
Notes: Both charts show weekly deaths and the monthly unemployment rate. See the notes to Figure D-1.

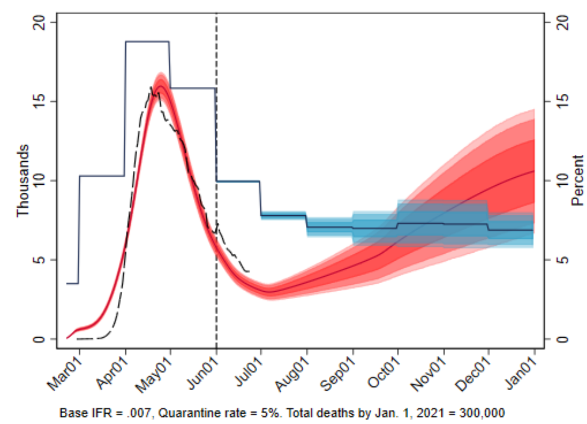
Figure D-4. Model-implied (red) and nonparametric (gray) estimates of R^{eff}



Notes: 95% confidence bands shown. The model-implied estimate is computed from the estimated model, for population IFRs = 0.4% to 1.1%. The nonparametric estimate is computed using **Error! Reference source not found.** with the change in deaths estimated over 7 days and daily deaths averaged over the week, using a local quadratic smoother. Nonparametric estimate is shifted by 14 days to approximate the lag from infections to deaths.

Figure D-6. Economic NPIs: Greater use of the GDP-to-Risk index (left) and full working from home (right)

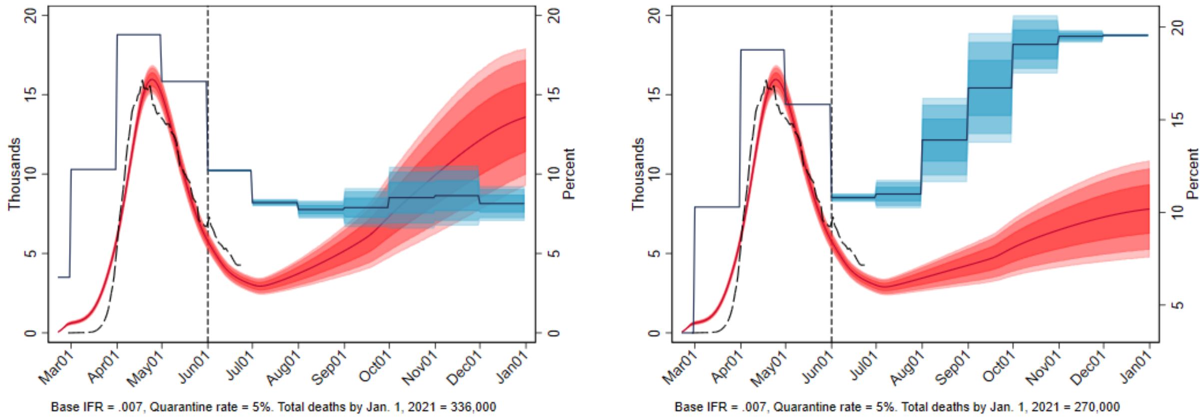




Notes: Baseline is the fast reopening second wave scenario in

Figure . See the notes to Figure D-1.

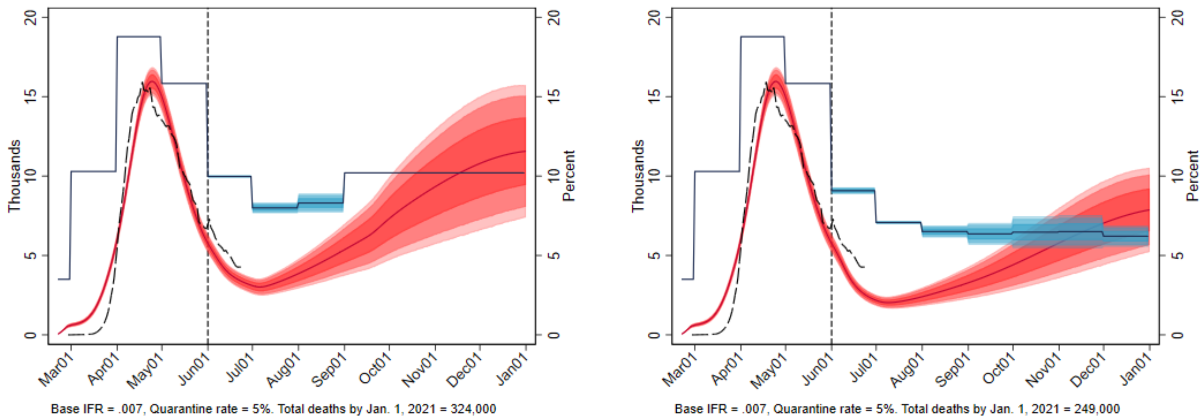
Figure D-7. Economic NPIs: No on-site workers age 65+ (left) and all three (aggressive sectoral, work-from-home, no age 65+) combined with economic shutdown (right)



Notes: Baseline is the fast reopening second wave scenario in

Figure See the notes to Figure D-1.

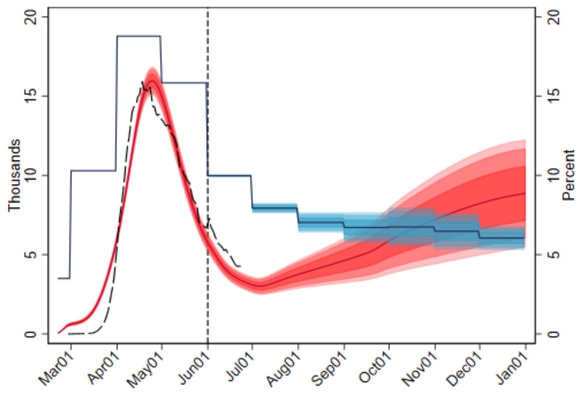
Figure D-8. Non-Economic NPIs: No School (left), Enhanced Protections for Ages 75+ (right)

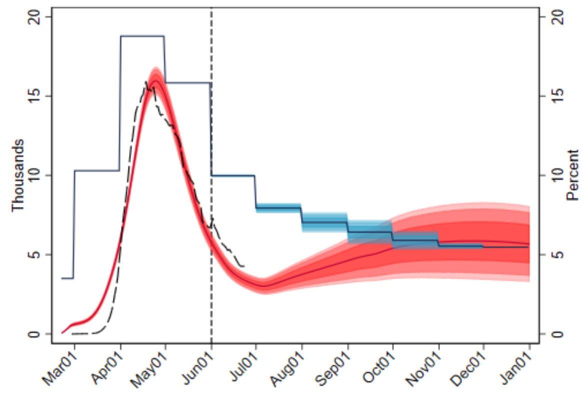


Notes: Baseline is the fast reopening second wave scenario in

Figure . See the notes to Figure D-1.

Figure D-9. Non-Economic NPIs: 10% (left) and 15% (right) Quarantine

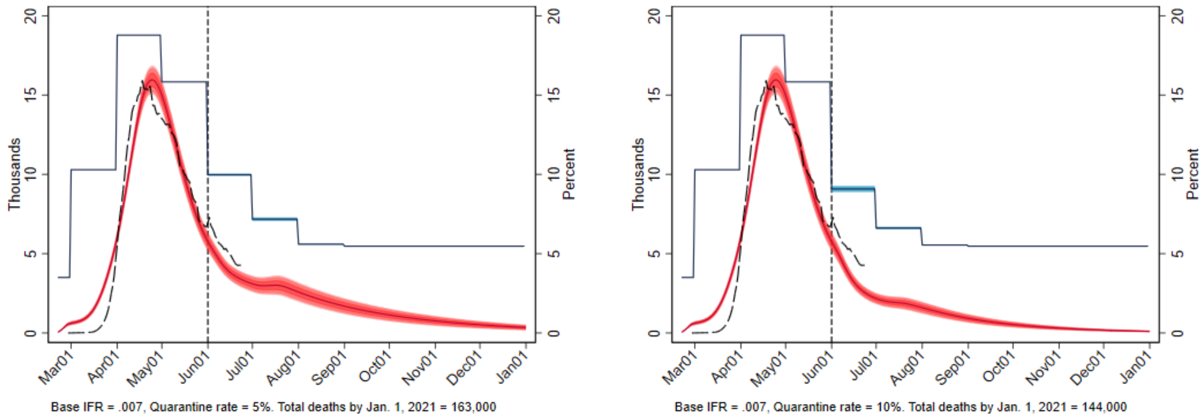




Notes: Baseline is the fast reopening second wave scenario in

Figure . See the notes to Figure D-1.

Figure D-10. Non-Economic NPIs: Strong Personal Distancing (left) and
Strong Personal Distancing + 10% Quarantine + Enhanced 75+ Protections (right)



Notes: Baseline is the fast reopening second wave scenario in

Figure . See the notes to Figure D-1.