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Effect of Removing Lockdown Strategies on the Spread of COVID-19 in New Jersey

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Effect of Removing Lockdown Strategies on the Spread of COVID-19 in New Jersey

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Modelling Results

Following the typical mathematical modelling of infectious disease using deterministic compartmental models, a Susceptible-Exposed-Symptomatic Infectious-Asymptomatic Infectious-Recovered-Hospitalised-Dead population model with age structure and empirically-based contact information has been developed to understand the transmission of COVID-19 throughout New Jersey as well as the effect of lockdown measures and the removal or easing of different lockdown measures [1]. The age structure used in the model is based on decomposing the population into the following age groups: $[0-5], [5-10], \ldots, [70-75], [75-80]$, and $[80+]$. The social contact matrices were obtained for the USA from surveys and Bayesian imputation [2].

The social contact matrices are divided into work, school, home, and other settings and show the average number of contacts between age groups in each of these settings. By developing a COVID-19 model that includes age and social structure, we are able to assess the impact of specific social distancing/lockdown measures that have been implemented to contain the epidemic in New Jersey. To reflect the local (state-wide) spread of the pandemic, the model was parameterised for New Jersey by incorporating available empirical information. The available empirical data and parameter values for New Jersey were taken from the New Jersey Department of Health [3], specifically the state's information on COVID-19, as well as sites that have assessed the local reproduction number (i.e. [4]). When New Jersey specific data/values were unavailable, more general information from the wider COVID-19 literature and other comparable health services were used.

The model enables one to assess the differential impact of removing specific lockdown measures on specific dates. Figures 1-4 show the number of symptomatic infectious individuals, hospitalisations, and cumulative deaths. In each figure, the model simulations begin on March 04, 2020

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with lockdown measures implemented on March 16, 2020. The lockdown measures started to be incrementally eased on May 02, 2020 with the opening of state parks and golf courses. On May 18, 2020 construction resumed and curbside deliveries were allowed, beaches and lakeshores were reopened on May 22, 2020, and elective surgeries resumed on May 26, 2020. From this point, we explore different possible scenarios of removing the remaining lockdown measures (Figures 1 and 2), or re-implementing the lockdown measures when the number of infectious individuals increases (Figures 3 and 4). In all easing scenarios there is implicit in the resumption of normality an awareness of the need for social distancing either through the wearing of masks or separation of individuals. Therefore, the probability of disease transmission (determined empirically from NJ assessments of the reproduction number [4]) is lower than when no social distancing is occurring, as was the case before the pandemic began.

Table 1 provides an overview of the number of fatalities depending on the form of easing of lockdown measures. If everything were to open on June 1, with schools opening in September, or if, instead, the lockdown continued until the beginning of August with early school openings, then the cumulative number of fatalities are approximately equal (Figure 1). A similar cumulative effect will occur with an incremental easing of lockdown measures throughout the summer with an opening of schools in September (Figure 2).

With testing and contact tracing, it is possible to properly assess how many individuals are infected with the disease. Excellent testing and tracing protocols allow for more control when the number of symptomatic cases starts to increase so that responsive lockdown and easing measures can be implemented quickly. With a robust testing and contact tracing system in place, the number of fatalities can be minimised as far as possible (Figure 3 and Table 1). However, if one does not have a robust testing and tracing program in place as lockdown measures are eased, then the re-implementation of lockdown measures due to an increase of infectious individuals will be too slow. As a result, there will be a subsequent rise in infections and associated deaths that could have been avoided with a more robust testing program in place (Figure 4 and Table 1).

It is important to note that due to the current lack of adequate testing, in addition to the limited understanding of the physiological effects of the novel virus, there is great uncertainty in the parameter values, which leads to uncertainty in model simulations. Although the model output is robust to changes in parameter values, one should not rely solely on the predictions made by an individual model using a single set of parameter values. Instead, these results should be used to qualitatively improve understanding of the progression of the disease. In particular, the results contained within this document show the differential impact of removing specific lockdown measures on specific dates, and the danger in removing the measures before adequate testing and contact tracing have been implemented.

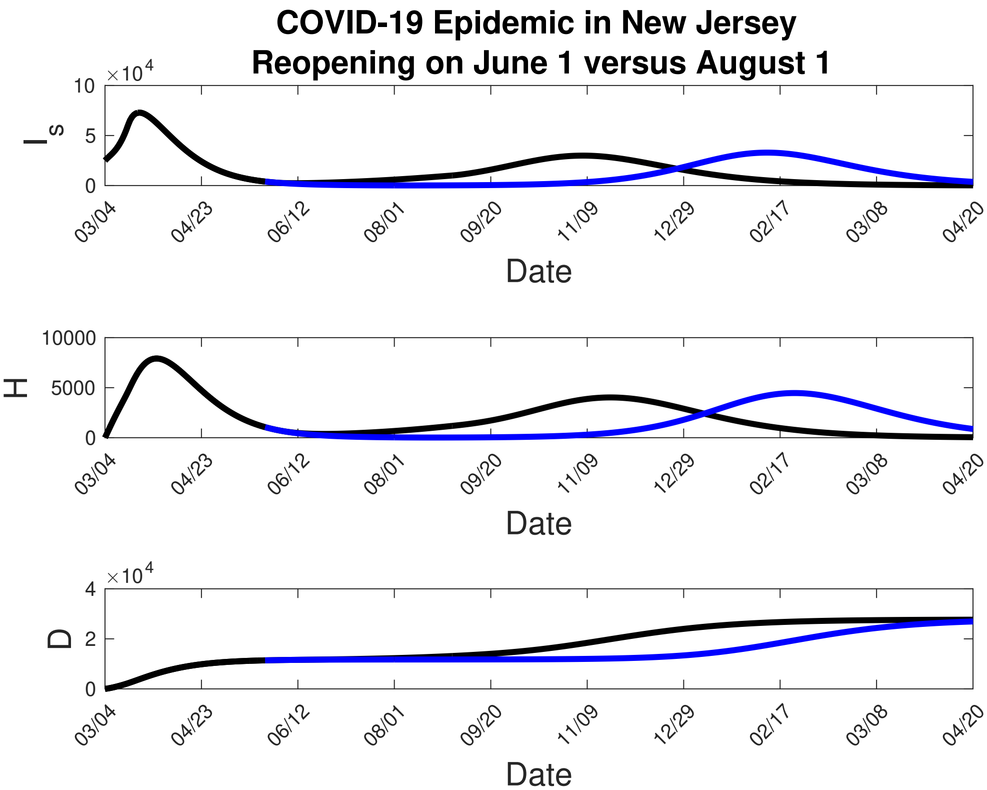

Figure 1: Number of symptomatic infectious individuals, hospitalisations, and cumulative deaths over an approximately one year period beginning on March 04, 2020 with lockdown measures implemented on March 16, 2020. Starting on May 02, 2020 there began an incremental release of lockdown measures including the opening of state parks and golf courses on May 02, the resumption of construction and opening of curbside deliveries on May 18, the opening of beaches and lakeshores on May 22, and the resumption of elective surgeries on May 26. If all remaining lockdown measures are removed on June 01, 2020, with the exception of schools which are assumed to open on September 01, 2020 one sees the recurrence of a major "second wave" outbreak of infectious disease with a peak in November, 2020 (black curve). If instead, the partially reopened state as of May 26, 2020 is maintained until August 01, 2020 at which point all remaining lockdown measures are removed including an early reopening of schools, one sees a similar "second wave" that is delayed so that the peak is in February, 2021 (blue curve).

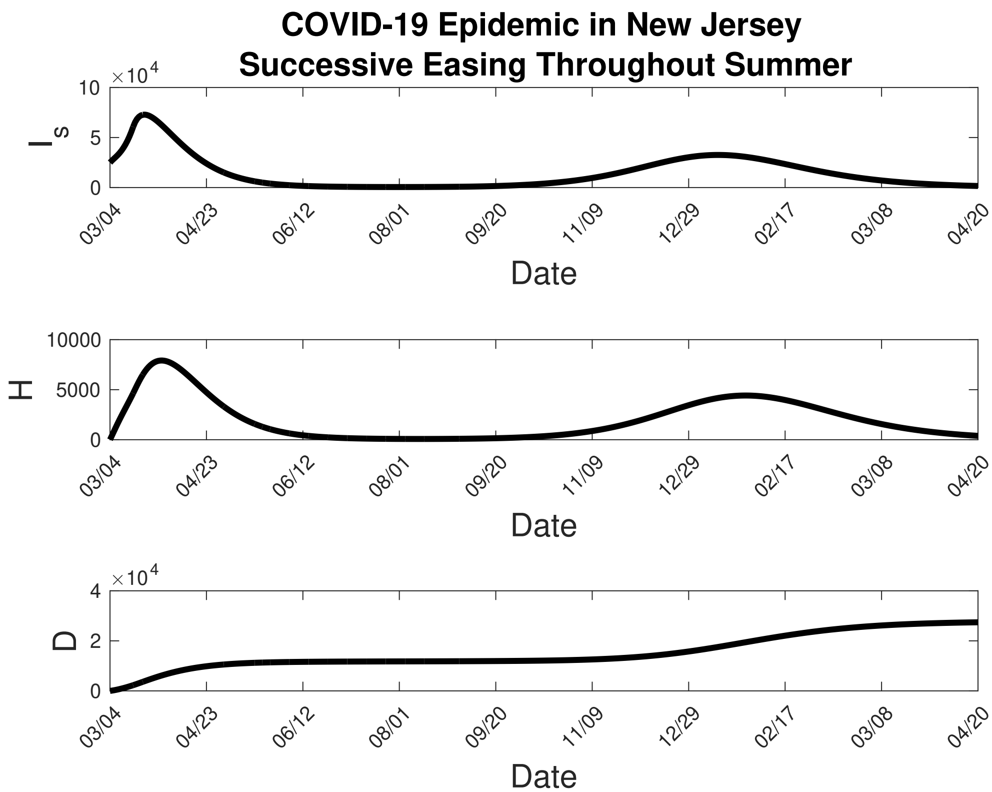

Figure 2: Number of symptomatic infectious individuals, hospitalisations, and cumulative deaths over an approximately one year period beginning on March 04, 2020 with lockdown measures implemented on March 16, 2020. Starting on May 02, 2020 there began an incremental release of lockdown measures including the opening of state parks and golf courses on May 02, the resumption of construction and opening of curbside deliveries on May 18, the opening of beaches and lakeshores on May 22, and the resumption of elective surgeries on May 26. If all remaining lockdown measures are incrementally removed every ten days throughout the summer until everything but schools are open by mid-August, and with schools assumed to open on September 01, 2020 one sees the recurrence of a major "second wave" outbreak of infectious disease with a peak in January, 2021.

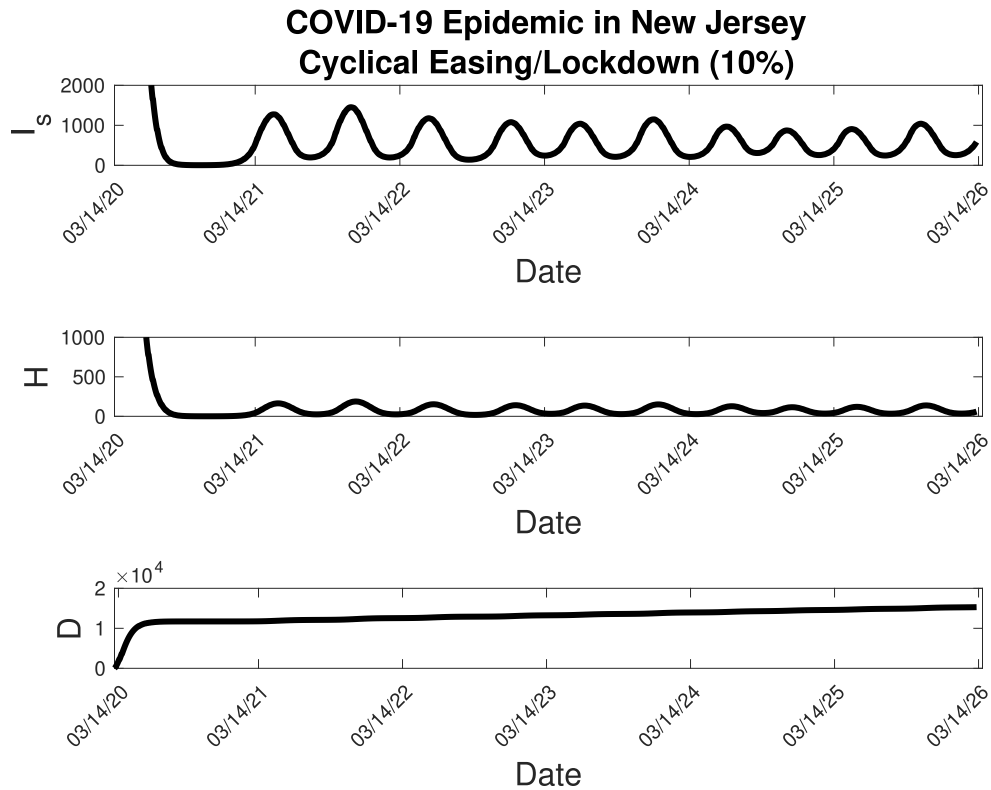

Figure 3: Number of symptomatic infectious individuals, hospitalisations, and cumulative deaths over a multi-year period beginning on March 04, 2020 with lockdown measures implemented on March 16, 2020. Starting on May 02, 2020 there began an incremental release of lockdown measures including the opening of state parks and golf courses on May 02, the resumption of construction and opening of curbside deliveries on May 18, the opening of beaches and lakeshores on May 22, and the resumption of elective surgeries on May 26. After the slow relaxation of lockdown measures that took place in May, successive easing measures are continued at intervals of ten day periods. If the number of symptomatic cases increases above a threshold of 10% more than the number of cases measured on May 22, then lockdown measures are successively tightened until the number of symptomatic cases falls below the threshold. At this time easing of lockdown measures resumes unless the number of symptomatic cases again rises above the threshold and tightening again begins.

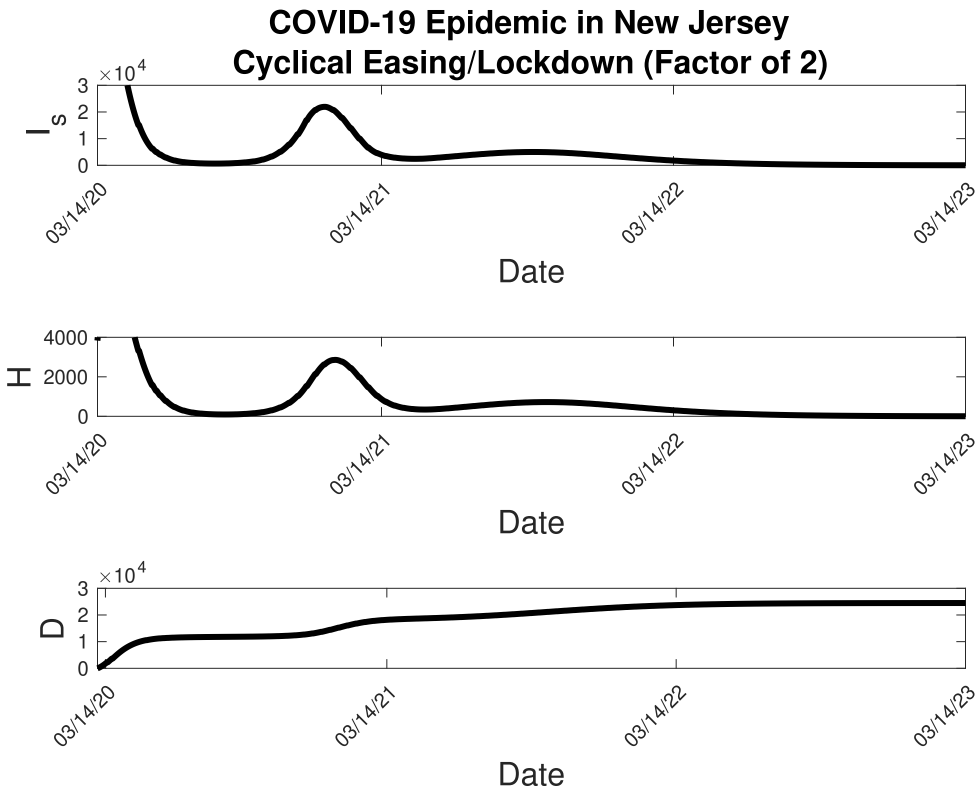

Figure 4: Number of symptomatic infectious individuals, hospitalisations, and cumulative deaths over a multi-year period beginning on March 04, 2020 with lockdown measures implemented on March 16, 2020. Starting on May 02, 2020 there began an incremental release of lockdown measures including the opening of state parks and golf courses on May 02, the resumption of construction and opening of curbside deliveries on May 18, the opening of beaches and lakeshores on May 22, and the resumption of elective surgeries on May 26. After the slow relaxation of lockdown measures that took place in May, successive easing measures are continued at intervals of ten day periods. If the number of symptomatic cases increases above a threshold that is twice the number of cases measured on May 22, then lockdown measures are successively tightened until the number of symptomatic cases falls below the threshold. At this time easing of lockdown measures resumes unless the number of symptomatic cases again rises above the threshold and tightening again begins.

Scenario	**Cumulative number of deaths**
NJ Department of Health at May 22[5]	**11133**
Model at May 22	11322
Open June 1 (Fig. 1)	27704
Open August 1 with early opening of schools (Fig. 1)	26895
Successive easing of lockdown throughout summer (Fig. 2)	27419
Cyclical easing/lockdown based on threshold (10%) (Fig. 3)	15289
Cyclical easing/lockdown based on threshold (20%)	18788
Cyclical easing/lockdown based on threshold (50%)	23294
Cyclical easing/lockdown based on threshold (100%)	24165
Cyclical easing/lockdown based on threshold (200%) (Fig. 4)	24496
Cyclical easing/lockdown based on threshold (500%)	26448
Cyclical easing/lockdown based on threshold (700%)	31133

Table 1: Number of cumulative deaths for each model scenario. The number of fatalities as of May 22, 2020 determined by the model is 11322, whereas the empirical assessment as described by the NJ COVID-19 Daily Case Summary [5] is 11133. The cyclical easing/lockdown scenario is based on assessing the increase in new symptomatic cases relative to the number of symptomatic cases on May 22, 2020 and implementing increased lockdown measures in the event of an increase past the specified threshold, or conversely relaxing lockdown conditions if the number of symptomatic cases drops below the threshold. When considering cyclical easing/lockdown for thresholds larger than 700%, the implementation of lockdown or relaxation measures will result in the same number of cumulative deaths as that seen for the 700% threshold.

Mathematical Model with Age Structure

This population model includes Susceptible, Exposed, symptomatic Infectious, asymptomatic Infectious, Hospitalised, Recovered, and Dead individuals in 17 age groups: $[0-5],[5-10],\ldots,[70-75],[75-80]$, and $[80+]$. The governing equations for each of the i age groups are given by

$$\begin{aligned}
\dot{S}(i) &= -\lambda(i)S(i), &(1)\\
\dot{E}(i) &= \lambda(i)S(i) - \gamma E(i), &(2)\\
\dot{I}_{\text{symp}}(i) &= f(i)\gamma E(i) - \sigma_{\text{symp}} I_{\text{symp}}(i), &(3)\\
\dot{I}_{\text{asymp}}(i) &= (1-f(i))\gamma E(i) - \sigma_{\text{asymp}} I_{\text{asymp}}(i), &(4)\\
\dot{H}(i) &= h(i)\sigma_{\text{symp}} I_{\text{symp}}(i) - \alpha_h H(i), &(5)\\
\dot{R}(i) &= (1-h(i)-d(i))\sigma_{\text{symp}} I_{\text{symp}}(i) + \sigma_{\text{asymp}} I_{\text{asymp}}(i) + (1-d_h(i))\alpha_h H(i), &(6)\\
\dot{D}(i) &= d(i)\sigma_{\text{symp}} I_{\text{symp}}(i) + d_h(i)\alpha_h H(i), &(7)
\end{aligned}$$

where

$$\lambda(i) = \rho \sum_{j=1}^{17} C(ij)\frac{I_{\text{symp}}(j)}{N(j)} + \rho \sum_{j=1}^{17} C(ij)\frac{I_{\text{asymp}}(j)}{N(j)}, \tag{8}$$

and where $S(i)$, $E(i)$, $I_{\text{symp}}(i)$, $I_{\text{asymp}}(i)$, $H(i)$, $R(i)$, and $D(i)$ respectively denote Susceptible, Exposed, symptomatic Infectious, asymptomatic Infectious, Hospitalised, Recovered, and Dead individuals for the i^{th} age group. In addition, ρ denotes the probability that a contact results in infection, $C(ij)$ denotes the number of contacts of individuals in age group j with individuals in age group i, $N(i)$ is the population size of New Jersey in each of the age groups, $1/\gamma$ is the mean exposure time, $f(i)$ is the fraction of infected individuals who become symptomatic, $1/\sigma_{\text{symp}}$ and $1/\sigma_{\text{asymp}}$ respectively represent the mean symptomatic and asymptomatic time, $h(i)$ is the fraction of symptomatic infectious individuals who must be hospitalised, $1/\alpha_h$ is the mean hospitalisation time, $d(i)$ is the fraction of symptomatic infectious (non-hospitalised) individuals who die, and $d_h(i)$ is the fraction of hospitalised individuals who die. Parameter values that do not depend on age can be found in Table 2 while age-specific parameter values are given in Table 3. The social contact matrices are provided in [2]. The probability that a contact results in infection, ρ, was derived using empirically determined time-dependent values of New Jersey's reproduction numbers [4] compared to the model reproduction numbers computed using the next generation matrix approach [6].

Parameter	**Description**	**Value**
$1/\gamma$	mean exposure time (incubation period)	5 days [7]
$1/\sigma_{symp}$	mean symptomatic time	10 days [8]
$1/\sigma_{asymp}$	mean asymptomatic time	4 days [8]
$1/\alpha_h$	mean (standard) hospitalisation time	10.4 days [8]

Table 2: Description of the various parameter values in the mathematical model.

Age	N[9]	f [10]	h [11]	d_h [12]	d [13]
0-5	12%	11.1%	18.2%	0.2%	0.1%
6-9			5.5%	0%	0%
10-15	13%	12.1%	5.5%	0%	0%
16-19					
20-25	13%	12.1%	6.8%	0.2%	0.1%
26-29					
30-35	13%	12.1%	13.9%	0.9%	0.4%
36-39					
40-45	13%	12.1%	13.9%	0.9%	0.4%
46-49					
50-55	14%	17.5%	25.1%	3.6%	1.4%
56-59					
60-65	12%	28.7%	25.1%	3.6%	1.4%
66-69			51.2%	14.9%	5.9%
70-75	7%	28.7%	51.2%	14.9%	5.9%
76-79					
80+	4%	28.7%	61.7%	32.8%	12.9%

Table 3: Description of the various age-specific parameter values in the mathematical model.

References

[1] E. Forgoston and M. A. S. Thorne, "Strategies for controlling the spread of COVID-19," *in preparation*, 2020.

[2] K. Prem, A. R. Cook, and M. Jit, "Projecting social contact matrices in 152 countries using contact surveys and demographic data," *PLoS Computational Biology*, vol. 13, no. 9, p. e1005697, 2017.

[3] *New Jersey Department of Health*, 2020 (accessed May 23, 2020). `www.nj.gov/health/`.

[4] K. Systrom, *R_t: Effective Reproduction Number*, 2020 (accessed May 23, 2020). `rt.live`.

[5] *New Jersey Department of Health COVID-19 Confirmed Case Summary*, 2020 (accessed May 23, 2020). `www.nj.gov/health/cd/documents/topics/NCOV/COVID_Confirmed_Case_Summary.pdf`.

[6] P. Van den Driessche and J. Watmough, "Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission," *Mathematical Biosciences*, vol. 180, no. 1-2, pp. 29–48, 2002.

[7] S. A. Lauer, K. H. Grantz, Q. Bi, F. K. Jones, Q. Zheng, H. R. Meredith, A. S. Azman, N. G. Reich, and J. Lessler, "The incubation period of coronavirus disease 2019 (COVID-19) from publicly reported confirmed cases: estimation and application," *Annals of Internal Medicine*, vol. 172, no. 9, pp. 577–582, 2020.

[8] N. Ferguson, D. Laydon, G. Nedjati-Gilani, N. Imai, K. Ainslie, M. Baguelin, S. Bhatia, A. Boonyasiri, Z. Cucunubá, G. Cuomo-Dannenburg, A. Dighe, I. Dorigatti, H. Fu, K. Gaythorpe, W. Green, A. Hamlet, W. Hinsley, L. Okell, S. van Elsland, H. Thompson, R. Verity, E. Volz, H. Wang, Y. Wang, P. Walker, C. Walters, P. Winskill, C. Whittaker, C. Donnelly, S. Riley, and C. Ghani, "Report 9: Impact of non-pharmaceutical interventions (NPIs) to reduce covid-19 mortality and healthcare demand," 2020. `https://www.imperial.ac.uk/mrc-global-infectious-disease-analysis/covid-19/report-9-impact-of-npis-on-covid-19/`.

[9] *Census Reporter*, 2020 (accessed May 23, 2020). `censusreporter.org/profiles/04000US34-new-jersey`.

[10] M. Makhoul, H. Ayoub, H. Chemaitelly, S. Seedat, G. Mumtaz, S. Al-Omari, and L. Abu-Raddad, "Epidemiological impact of SARS-CoV-2 vaccination: mathematical modeling analyses," *MedRxiv*, 2020.

[11] Breakdown of hospitalisation by age from [5] as of May 10, 2020.

[12] The case fatality rates were derived from [5] as of May 10, 2020.

[13] Proportions for number of deaths in hospital and number of deaths outside of hospital of the total number of deaths were taken from the UK's Office for National Statistics (`www.ons.gov.uk`) on April 24, 2020. The non-hospital death rates were applied as a ratio derived from the d_h values.