

Impact of Vaccine Prioritization Strategies on Mitigating COVID-19: An Agent-Based Simulation Study using an Urban Region in the United States

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Impact of Vaccine Prioritization Strategies on Mitigating COVID-19: An Agent-Based
Simulation Study using an Urban Region in the United States

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ABSTRACT

Background

Approval of novel vaccines for COVID-19 has brought hope and expectations, but not without additional challenges. One central challenge is how to appropriately prioritize the use of limited supply of vaccines. This study evaluates various prioritization strategies and the efficacy of the vaccination campaign underway in the U.S.

Methods

The study develops a granular agent-based simulation model for mimicking community spread of COVID-19 under various social interventions including full and partial closures, isolation and quarantine, use of face mask and contact tracing, and vaccination. The model is populated with demographic and societal data for an urban community in the U.S. with 2.8 million residents as well as viral parameters. The model tracks daily numbers of infected, hospitalized, and deaths for all census age-groups. Model is calibrated using parameters for viral transmission and level of community circulation of individuals. Published data from the Florida COVID-19 dashboard is used to validate the model. Vaccination strategies are compared using hypothesis test for pairwise comparisons.

Results

Three prioritization strategies examined are: a close variant of the CDC recommendation, an age-stratified strategy, and a random strategy. The impact of vaccination is also contrasted with a no vaccination scenario. The comparison shows that the ongoing campaign in the U.S. using vaccines developed by Pfizer/BioNTech and Moderna is expected to 1) reduce the cumulative number of infection by 10% and 2) help the pandemic to subside below a small threshold of 100 daily new reported cases sooner by approximately a month. The prioritization strategies when compared with each other showed no significant difference in their impacts on pandemic mitigation.

Conclusions

Recent explosive growth of the number of new COVID-19 cases in the U.S. continues to shrink the susceptible population. This, we believe, will likely limit the expected number of people that could be prevented from getting infected due to vaccination. A shrinking susceptible pool may also be an attributable reason for the observed lack of statistical difference among the outcomes of the prioritization strategies. However, the invariance of the strategies should give more latitude for decision makers in COVID-19 vaccine distribution.

Keywords: Vaccination strategies, COVID-19, Agent-based simulation model, Vaccination policies, Vaccination prioritization

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LIST OF ABBREVIATIONS

- AB – Agent-based
- SEIR – Susceptible – exposed – infected – recovered/removed
- SARS-CoV-2 – Severe acute respiratory syndrome coronavirus 2
- COVID-19 – Coronavirus Disease 2019
- USFDA – United States Food and Drug Administration
- CDC – Centers for Disease Control
- NAESM – National Academy of Sciences, Engineering, and Medicine
- QALY – Quality of Life Years

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DECLARATIONS

82 **Ethics approval and consent to participate:** Individual human data was not used in our study. Only aggregate data
83 made available in Florida COVID-19 Dashboard was used.

84 **Consent for publication:** Not applicable

85 **Availability of data and materials:** The datasets used and/or analysed during the current study are available from
86 the corresponding author on reasonable request.

87 **Competing interests:** The authors declare that they have no competing interests

88 **Funding:** Not applicable

89 **Authors' contributions:**

90 Hanisha Tatapudi: Conceived and designed the model, Selection of model input parameters and data gathering, Coding
91 and testing of the model, Design and perform the experiments, Output analysis and review, Manuscript preparation
92 and review

93

94 Rachita Das: Selection of model input parameters and data gathering, Output analysis and review, Manuscript
95 preparation and review

96

97 Tapas K Das: Conceived and designed the model, Selection of model input parameters and data gathering, Coding
98 and testing of the model, Design and perform the experiments, Output analysis and review, Manuscript preparation
99 and review

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133 INTRODUCTION

134 SARS-CoV-2 and resulting COVID-19 disease has been raging world-wide since early 2020, killing over 2.0
135 million globally and nearly 450,000 in the United States by the end of January 2021 [12]. A significant winter swell
136 in cases is underway in the U.S. despite protective measures in place such as face mask usage, limited contact
137 tracing, travel restrictions, social distancing practices, and partial community closures. To combat this, many
138 promising novel vaccines have been under development, of which two (Pfizer/BioNTech and Moderna) have been
139 authorized for emergency use since mid-December 2020 by the U.S. Food and Drug Administration (USFDA) [26].
140 Data from initial trials of cohorts greater than 30,000 people showed that these vaccines, given in two doses, are safe
141 and have ~95% effectiveness in preventing COVID-19 [23]. Vaccine deployment in the U.S. began soon after
142 USFDA approval.

143

144 Implementing an effective vaccination campaign will be essential to dramatically reduce the infection,
145 hospitalization, and death rates, but it poses many unique challenges. Vaccine prioritization and allocation strategy
146 is at the forefront of the challenges to effectively vaccinate communities. Strategy is influenced by a number of key
147 factors: 1) limited initial vaccine supply in the months following release, 2) transmission and severity of COVID-19
148 varying by segment of the population, 3) vaccine approvals only for adults, and 4) acceptability and compliance in
149 the community for two dose vaccination [4].

150

151 U.S. Centers for Disease Control (CDC) has released an outline prioritizing healthcare personnel, first responders,
152 persons with high risk medical conditions for COVID-19, and older adults >65 years. These groups will be given
153 priority for vaccination in phase 1, defined as when vaccine supply is still limited. In phase 2 (supply increases to
154 begin to meet demand) and phase 3 (supply is greater than demand), other population groups begin to be vaccinated
155 based on age and availability [25]. Vaccine allocation structures with basic similarities and some key differences are
156 being used by countries around the world. For example, after healthcare workers, France's vaccine allocation is
157 scheduled to include other general workers regardless of age who they have determined to be at high risk of
158 contracting and spreading the virus due to contact with the general public. This includes retail, school,

159 transportation, and hospitality staff [17]. Such differences in vaccine prioritization structures are as of yet untested
160 and warrant modeling and examination.

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162 The goal of this paper is to investigate the impact of vaccination on the pandemic via outcome measures of numbers
163 of infected, hospitalized, and dead in the months following December 15, 2020, when vaccination began in the U.S.
164 Two specific objectives of our investigation are: 1) to assess the expected impact of the vaccination program that is
165 currently underway on mitigating COVID-19, and 2) to inform public health officials on the comparative benefits, if
166 any, of the different vaccine prioritization strategies. We conduct our investigation by using our agent-based (AB)
167 simulation model for COVID-19 that was presented recently in [19]. We first extended calibration of our model till
168 December 30, 2020 to ensure that our model appropriately tracks the explosive increase in cases that started with the
169 onset of winter and the year-end holiday period. We then enhanced the model by adding a framework for
170 vaccination. This included: vaccination priorities for people based on attributes including profession and age, use of
171 two different vaccines by Pfizer/BioNTech and Moderna with their contracted quantities and approximate delivery
172 timelines, acceptability of vaccines to prioritized cohorts (approximately 60% based on national survey data [3,18]),
173 transition period between each priority group, vaccination rate, and immunity growth for vaccinated starting with the
174 first dose.

175
176 As in [19], we implement our calibrated AB model, augmented with vaccination, for Miami-Dade County of the
177 U.S. with 2.8 million population, which has been an epicenter of COVID-19 in the U.S. We conduct our
178 investigation by implementing four different strategies (including no vaccination) and obtaining the corresponding
179 numbers of total infections, reported infections, hospitalizations, and deaths. We compare and contrast the numbers
180 to assess vaccination efficacy and relative performances of the priority strategies. The vaccination strategies that we
181 investigate are a close variant of the CDC recommended strategy, an age-stratified strategy, and finally a random
182 strategy. We make a number of key observations from the results, which we believe will help public health officials
183 around the world to choose effective vaccine prioritization strategies to mitigate the negative impacts of COVID-19.

184

185 LITERATURE REVIEW

186 Vaccine prioritization and allocation are among the key challenges to strategically vaccinate communities during a
187 pandemic outbreak. On a global scale, equitable and ethical distribution of vaccines for all (low, medium, and high-
188 income) countries is an important question. As the world leader in promoting global health, WHO released an
189 evidence-based framework for vaccine-specific recommendations [24]. WHO proposed vaccine prioritization for
190 three potential scenarios of transmission: community transmission, sporadic cases or cluster of cases, and no cases.
191 Each scenario has three stages and focuses on different risk groups. COVID-19 pandemic resembles “community
192 transmission.” For this, the first stage focuses on healthcare workers and older adults with highest risk; second stage
193 continues the focus on older adults and people with comorbidities, sociodemographic groups, and educational staff;
194 and the third stage focuses on essential workers and social/employment groups unable to physically distance
195 themselves.

196 National Academy of Sciences, Engineering, and Medicine (NAESM) developed a more comprehensive phased
197 framework for equitable allocation of COVID-19 vaccine [29]. The first phase prioritizes healthcare workers and
198 first responders, people with high risk comorbidities, and older adults in overcrowded living conditions; second
199 phase focuses on K-12 school staff and child care workers, essential workers, people with moderate risk
200 comorbidities, people living in shelters, physically and mentally disabled people and staff that provide care,
201 employment settings where social distancing is not possible, and remaining older adults; third phase prioritizes
202 young adults, children, and workers; and fourth phase includes everyone else. No specific studies have yet been
203 presented to the literature that evaluate the efficacy of the proposed vaccination priorities for mitigating COVID-19.

204 A number of studies can be found in the literature on vaccination strategies for controlling outbreaks of other
205 viruses. The work presented in [8] analyzes the effect of both CDC guided targeted vaccination strategy as well as a
206 mass vaccination strategy for seasonal Influenza outbreaks in the U.S. The study found that a mass vaccination
207 policy reaped the most benefits both in terms of cost and quality-of-life years (QALYs) lost. Authors in [15] use a
208 genetic algorithm to find optimal vaccine distribution strategies that minimize illness and death for influenza
209 pandemics with age specific attack rates similar to the 1957–1958 A(H2N2) Asian influenza pandemic and the
210 1968–1969 A(H3N2) Hong Kong influenza pandemic. They consider coverage percentage under varying vaccine
211 availability and develop an optimal vaccination approach that is 84% more effective than random vaccination. A
212 study reported in [14] examined vaccination to prevent interpandemic influenza for high-risk groups and children,

213 and recommended concentrating on schoolchildren, most responsible for transmission, and then extend to high-risk
214 groups. A compartmental model in [13] was used to develop optimal strategies to reduce the morbidity and mortality
215 of the H7N9 pandemic. The study found that age specific vaccination schedules had the most beneficial impact on
216 mortality.

217 It can be concluded from the above review of relevant literature that there is no ‘one size fits all’ strategy for
218 vaccination to either prevent a pandemic outbreak or mitigate one. Virus epidemiology and corresponding disease
219 characteristics, as well as the efficacy and supply of the vaccine must be considered in developing an effective
220 vaccination prioritization strategy. Our paper aims to address this need by presenting a detailed AB simulation
221 modeling approach and using it to assess efficacy of vaccine prioritization strategies for COVID-19.

222

223 METHODOLOGY

224 Published COVID-19 modeling approaches are either data-driven models, as in [2, 5, 7, 9, 20], or variants of SEIR
225 type compartmental models as in [1, 11, 16, 21, 22]. Data driven models are very well suited for understanding the
226 past progression of a pandemic and also for estimating parameters characterizing virus epidemiology. However, these
227 models offer limited ability to predict the future progression of a pandemic that is dynamically evolving with regards
228 to virus epidemiology, disease manifestations, and sociological conditions. Compartmental models, on the other hand,
229 are aggregate in nature and do not adapt well to changing dynamics of disease transmission. An AB modeling approach
230 is considered to be more suitable for a detailed accounting of individual attributes, specific disease natural history,
231 and complex social interventions [6].

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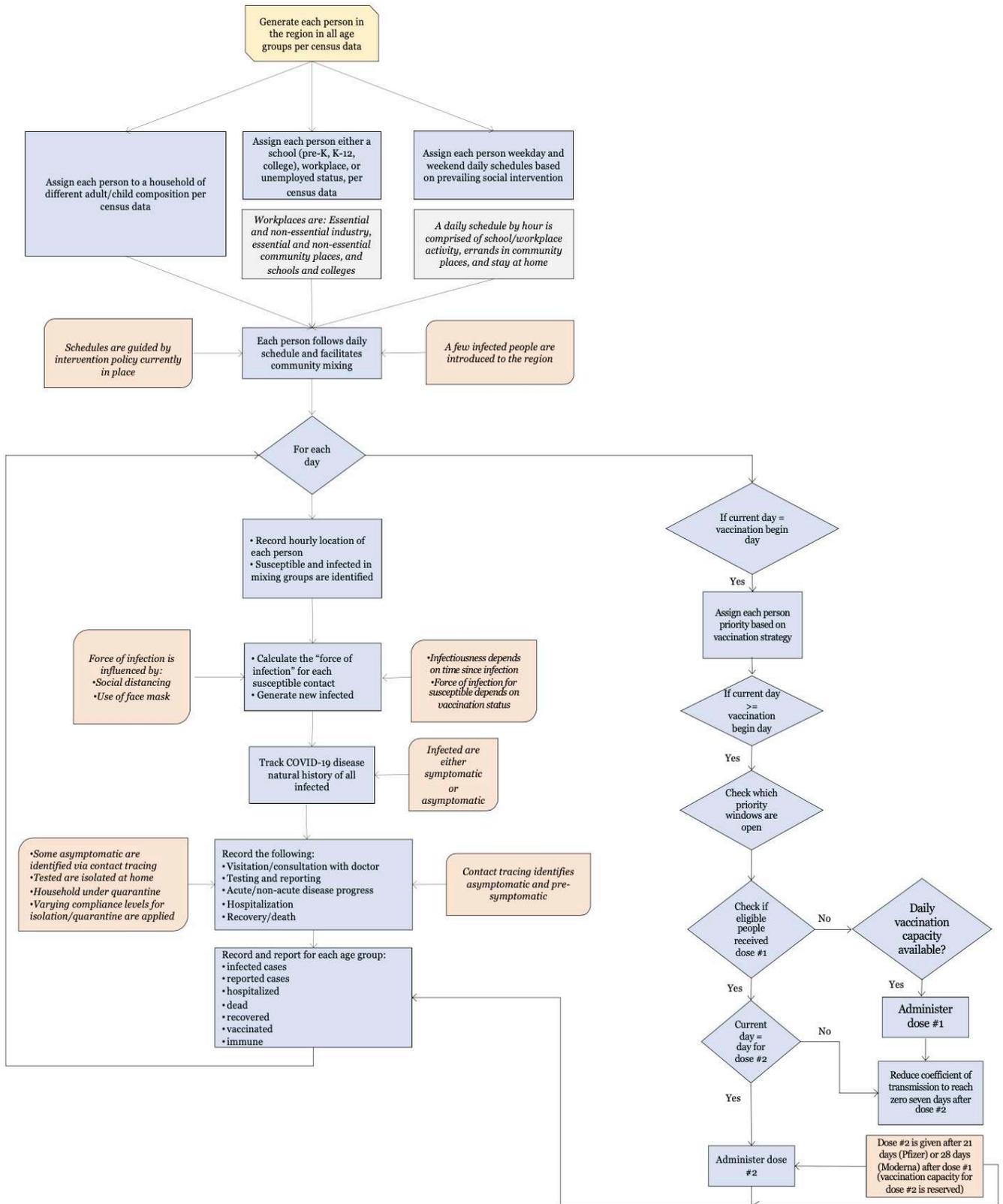
233 We use an enhanced version of our AB simulation model that was developed to examine various social intervention
234 strategies for COVID-19 [19]. The AB simulation model replicates the dynamics of the pandemic outbreak by
235 incorporating: 1) population demography of the outbreak region for all age groups and employment categories, 2)
236 numbers, sizes, and compositions of households, schools, workplaces, and community places, 3) daily schedules for
237 people of all age groups before and during the intervention orders (e.g., stay-at-home), 4) isolation of infected and
238 quarantine of household members, 5) closure and reopening of schools, workplaces, and community places, 6)
239 compliance to isolation and quarantine requirements, 7) face mask usage, 8) contact tracing, 9) prioritization of people

240 for vaccination, 10) vaccinating those willing to receive based on supply and priority windows, 11) epidemiological
241 parameters of the virus, 12) infection spread, and 13) disease natural history. The key epidemiological parameters
242 include: disease natural history with average lengths of latent, incubation, symptomatic, and recovery periods;
243 distribution of infectiousness; percent asymptomatic; and fatality rate.

244
245 As in the model presented in [19], each day our model tracks the following for each person: 1) hourly movements and
246 locations based on their daily schedules that depend on age, employment status, prevailing social intervention orders,
247 and quarantine/isolation status; 2) hourly contacts with other susceptible and infected; 3) vaccination status and
248 immunity, 4) force of infection accumulation; 5) start of infection; 6) visit/consult with a doctor (if symptomatic and
249 insured); 7) testing (if infected and visited/consulted a doctor or asymptomatic chosen for testing either randomly or
250 via contact tracing); 8) test reporting delay; 9) disease progression (if infected); 10) hospitalization (if infected and
251 acutely ill); and 11) recovery or death (if infected). The AB model reports daily and cumulative values of actual
252 infected, reported infections, hospitalized, and dead, for each age category. A schematic diagram depicting the
253 algorithmic sequence and parameter inputs for the AB simulation model is presented in Figure 1.

254
255 The AB simulation-based methodology is particularized using data for Miami Dade County of Florida, with 2.8
256 million population, an epicenter for COVID-19 spread in the South-Eastern United States. A step by step approach
257 for building such a model for another region can be found in [19]. The methodology begins by generating the
258 individual people according to the U.S. census data that gives population attributes including age (see Table A1 in
259 [19]) and occupational distribution (see Table A4 in [19]). Thereafter, it generates the households based on their
260 composition characterized by the number of adults and children (see Table A2 in [19]). The model also generates, per
261 census data, schools (see Table A3 in [19]) and the workplaces and other community locations (see Table A4 in [19]).
262 Each individual is assigned a household, while maintaining the average household composition, and, depending on
263 the age, either a school or a workplace (considering employment levels). A daily (hour by hour) schedule is assigned
264 to every individual, chosen from a set of alternative schedules, based on their attributes. The schedules vary between
265 weekdays and weekends and also depend on the prevailing social intervention orders (see Table A5 in [19]).

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Figure 1: Schematic of the AB model for mimicking COVID-19 spread under social interventions and vaccination in the U.S.

270 Simulation begins on the day when one or more infected people are introduced to the region (referred to as simulation
271 day 1). Simulation model tracks hourly movements of each individual (susceptible and infected) every day, and
272 records for each susceptible the number of infected contacts and their identification at each location. Based on the
273 level of infectiousness of each infected contact (which depends on the day of his/her infectiousness period), the model
274 calculates the daily force of infection received by each susceptible from all infected contacts at all hours of the day
275 [10]. Since the exact immune response from vaccine is not known yet, we assume a linearly increasing partial
276 immunity for susceptibles after they receive the first dose, attaining full immunity after seven days after the second
277 dose; we have so far only considered vaccines made by Pfizer/BioNTech and Moderna. Following the assumption
278 made in [19], the daily force of infection is considered to accumulate. However, it is assumed that if a susceptible does
279 not gather any additional force of infection (i.e., does not come in contact with any infected) for two consecutive days,
280 the cumulative force of infection for the susceptible reduces to zero. At the end of each day, the model uses cumulative
281 force of infection to calculate the probability of infection for each susceptible. The model updates the infection status
282 of all individuals to account for new infections as well as disease progressions of infected individuals. A pseudo-code
283 in Figure 2 depicts the major elements and structure of the AB simulation program.

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Main

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1 for simulation_day = 0,...,max_day
2   if simulation_day = 0
3     generate_entities()
4     generate_businesses()
5     initialize_outbreak() // Introduces a small number of infected individuals who are contagious
6     begin_outbreak() // Begin interaction among infected and susceptible and start community spread
7     report (infected, tested, reported, hospitalized, death) // Keeps track of daily age specific numbers

```

Function: Generate entities

```

1 // Generates population in the region based on census and assigns them to household and
2 workplace/school (including those unemployed who stay at home)
3 for household = 1,...,total_household_types
4   n1 = number of adults
5   n2 = number of children
6   for i = 1,...,n1
7     assign_age_household_workplace()
8   for j = 1,...,n2
9     assign_age_household_school()

```

Function: Generate businesses

```

1 // Generates businesses in the region based on census data and
2 // classifies them as essential and non-essential industries and community places
3 for business = 0,...,total_business_types
4   initialize_mixing_groups() // Creates smaller mixing groups (departments) within each
5                               business and assigns employees

```

Function: Begin outbreak

```

1 // Assigns daily schedules based on prevailing social intervention, tracks hourly social mixing, accounts for
2 viral transmission, creates new infections, tests and reports infected, tracks disease progress for infected, monitors
3 stay at home/hospitalization, and records recovery and death
4 if simulation_day < lockdown_day
5   schedule = schedule_1 // Pre-pandemic schedule
6 if (simulation_day >= lockdown_day) and (simulation_day < Phase_I)
7   schedule = schedule_2 // Schedule after lockdown begins (closure of non-essential places and schools and
8 partial opening of essential places with limited capacity)
9 if (simulation_day >= Phase_I) and (simulation_day < Phase_II)
10  schedule = schedule_3 // Schedule during Phase I of reopening (schools remain closed, partial opening of
11 essential and non-essential with limited capacity)
12 if (simulation_day >= Phase_II) and (simulation_day < Full_reopening)
13  schedule = schedule_4 // Schedule during Phase II of reopening (schools remain closed, increased partial
14 opening of essential and non-essential places)
15 for hour = 1,...,24
16  disease_progress() // Monitors disease condition along disease natural history on an hourly basis for
17 each infected individual
18  tracking_individuals() // Tracks infected and susceptible in the same location (mixing group) by the hour and
19 calculates added force of infection for susceptible and tracks viral accumulation
20  infection_process () // At the end of each day, infection status of each susceptible with
21 any viral accumulation is determined
22  testing() // Tests symptomatic and some selected asymptomatic based on test availability and
23 reports outcome considering test sensitivity and reporting delay
24  hospitalization() // Tracks hospitalization of symptomatic developing acute condition
25
26 if (simulation_day = vaccination_begin_day)
27   assign_vaccination_willingess() // We assume 60% of the population is willing to be vaccinated
28   assign_vaccine_priority() // Vaccine priority is assigned by chosen criteria (age and profession)
29
30 if (simulation_day >= vaccination_begin_day)
31   for each willing and priority eligible individual
32     if (received first dose)
33       if (current_day = second_dose_day)
34         administer_dose_2() // Dose 2 is administered 21 days after first dose for Pfizer
35 vaccine and 28 days for Moderna vaccine
36     else
37       administer_dose_1()
38       reduce_transmission_coefficient() // Reduce coefficient of transmission to reach zero seven days
39 after dose #2
40
41 recovery() or death() // Tracks recovery or death for individuals in home/hospitals

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Figure 2: Pseudo-code for agent-based simulation model of COVID-19 with implementation of two-dose vaccines

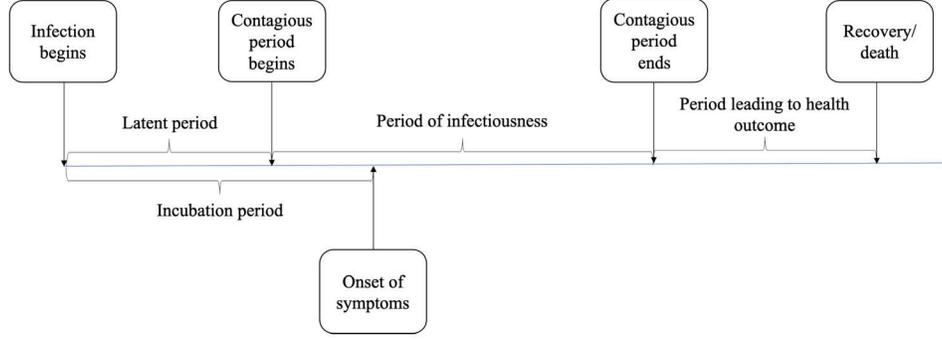


Figure 3: Disease natural history of COVID-19 [19]

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The infected people are considered to follow a disease natural history as shown in Figure 3, parameters of which can be found in Table A6 of [19]. The model assumes that the recovered cases become fully immune to further COVID-19 infections. However, since this assumption is not fully supported yet by data, people recovered from COVID-19 are also considered candidates for vaccination. The duration and intensity of infectiousness is considered to be guided by a lognormal density function (see Figure 4). The function is truncated at the average length of the infectiousness period (which is considered to be 9.5 days). Asymptomatic cases are assumed to follow a similar infectiousness intensity profile but scaled by a factor C_k in the force of infection calculation (1) (see Table A7 in [19]).

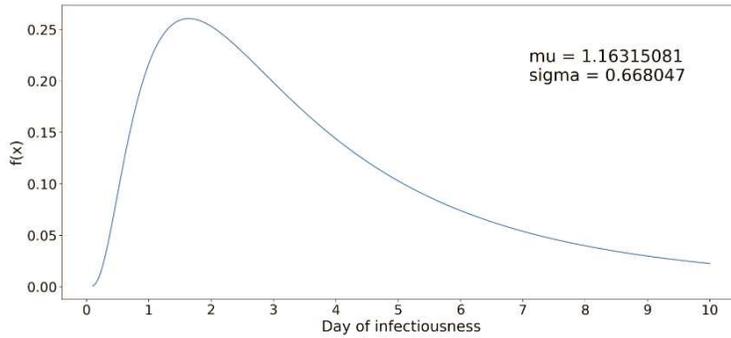


Figure 4: Lognormal distribution function for infectiousness profile of a COVID-19 case [19]

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The AB model estimates the probability of infection for a susceptible i using the accumulated value of *daily force of infection* (λ_i), which is calculated as follows.

$$\lambda_i = \sum_{k|h_k=h_i} \frac{I_k \beta_h \kappa (t - \tau_k) \rho_k [1 + C_k (\omega - 1)]}{n_i^\alpha} + \sum_{j,k|l_k^j=l_i^j} \frac{I_k \beta_p^j \kappa (t - \tau_k) \rho_k [1 + C_k (\omega - 1)]}{m_i^j}. \quad (1)$$

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Equation (1) is a modified version of the force of infection equation given in [10], parameters of which can be found in Table A7 of [19]. The force of infection is gathered by a susceptible individual each day from all infected contacts in his/her mixing groups (home, school/workplace, and community places). The cumulative value of λ_i is used at the end of each day to calculate the probability of infection as $1 - \exp^{-\lambda_i}$.

The AB model incorporates all applicable intervention orders like stay-at-home, school and workplace closure and reopening, isolation of symptomatic cases at home, and quarantine of household members of those who are infected. The model also considers: varying levels of compliances for isolation and quarantine, lower on-site staffing levels of essential work and community places during stay-at-home order, restricted daily schedule of people during various social intervention periods, phased lifting of interventions, use of face masks, contact tracing with different target levels to identify asymptomatic and pre-symptomatic cases, and vaccination. The timeline for social interventions implemented in the model are summarized in Table 1. For many other salient features of our AB simulation model, such as percentages of asymptomatic and uninsured with no access to doctor referral needed for testing during early days of the pandemic, CDC’s changing testing guidelines, test sensitivity and specificity, test result reporting delay, etc., readers are referred to [19].

Intervention policy implemented at Miami-Dade County, Florida, U.S.	Date of implementation	Day of Simulation
<i>Stay at home policy</i>	March 17 2020	35
<i>Phase I reopening</i>	May 18 2020	97
<i>Phase II reopening</i>	June 5 2020	115
<i>Mandatory usage of Face mask</i>	June 25 2020	135
<i>Contact tracing (assumed to begin)</i>	June 30 2020	140
<i>Phase III reopening</i>	September 25 2020	227
<i>School reopening</i>	September 30 2020	232
<i>Vaccination begin day</i>	December 15 2020	308

Table 1: Social intervention order timeline for Miami-Dade County [27]

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As observed in [19] , though it is implemented for a specific region, our model is quite general in its usability for other urban regions with similar demography, societal characteristics, and intervention measures. In our model, demographic inputs (age and household distribution, number of schools for various age groups, and number of workplaces of various types and sizes) are curated from both national and local census records. Social interventions vary from region to region and the related parameters can be easily updated. Similarly, the data related to epidemiology

340 of COVID-19 are unlikely to be significantly vary from one region to another, though some adjustments of these based
341 on population demographics may be needed.

342

343 **Model Calibration**

344 The AB model utilizes a large number of parameters, which are *demographic, epidemiological, and social intervention*
345 *parameters*. We kept almost all of the above parameters fixed at their respective chosen values and calibrated the
346 model by changing values for only a few. The calibrated parameters include the transmission coefficients used in
347 calculating force of infection at home, work, school, and community places (β_h and β_p^j). The choice of the values of
348 transmission coefficients was initially guided by [10] and thereafter adjusted at different points in time during the
349 calibration period (until December 30, 2020). The only other parameters that were calibrated are the number of errands
350 in the daily schedules under various intervention conditions and the percentage of workers in essential (e.g., healthcare,
351 utility services, and grocery stores) and non-essential (e.g., offices and restaurants) workplaces who physically
352 reported to work during different intervention periods. Calibration of the above parameters was done so that the daily
353 cumulative numbers of reported infected cases from the AB simulation model closely match the values published in
354 the Florida COVID-19 dashboard until December 30, 2020. Figure 5 shows the daily cumulative average values (with
355 95% confidence intervals) for the reported infected cases, hospitalizations, and deaths as obtained from the simulation
356 model. The dotted lines represent the actual numbers reported in the Florida COVID-19 dashboard for Miami-Dade
357 County [28].

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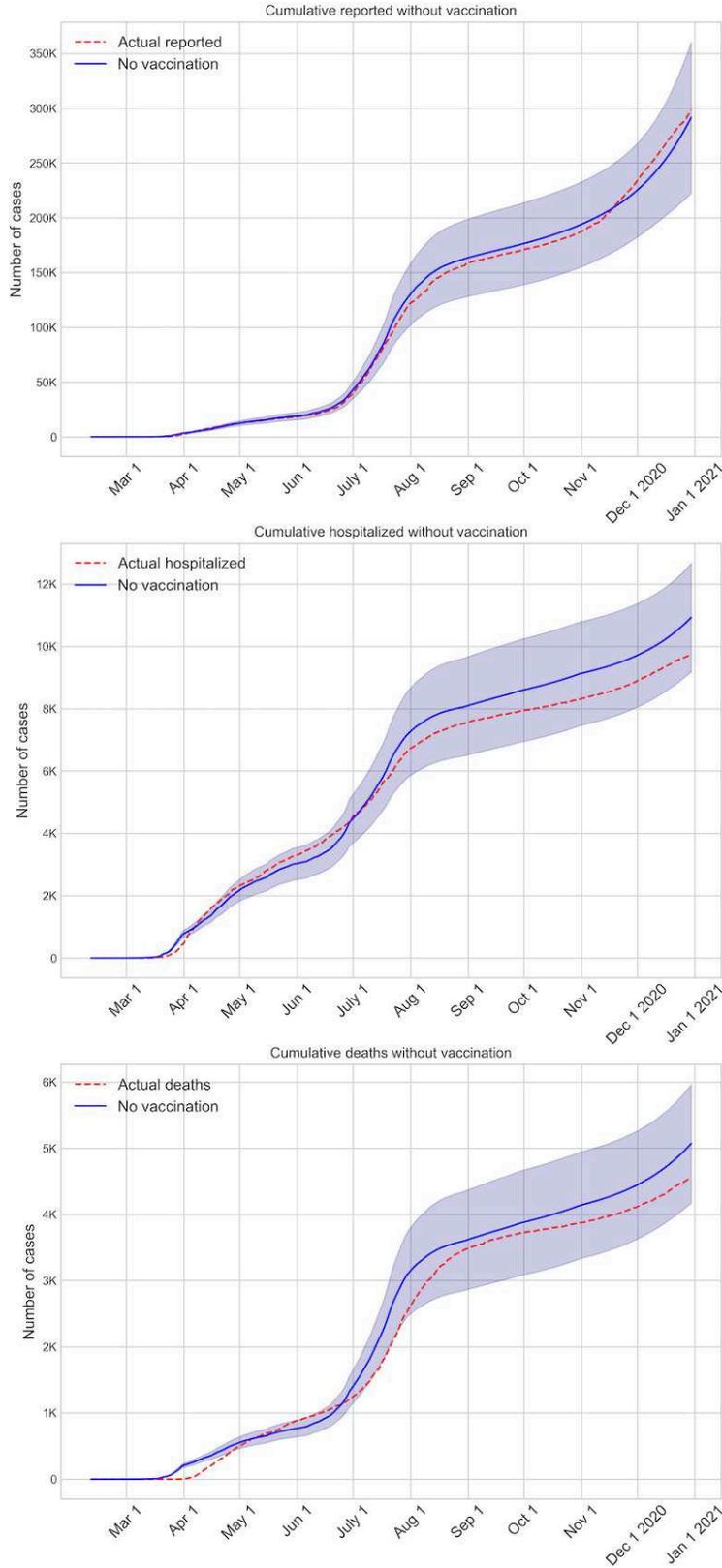


Figure 5: Validation graphs with average daily cumulative values of infected, reported, and death calibrated until Dec 30, 2020

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VACCINE PRIORITIZATION STRATEGIES

We used our AB model to examine the expected benefits of the ongoing vaccination in the U.S. using the limited supply of two types of vaccines developed by Pfizer/BioNTech and Moderna, which currently have the emergency approvals for distribution. We considered the number of vaccine doses that the two companies are contracted by the U.S. government to supply, which include the initial contracts for 100 million doses from each company and the more recent contract for an additional 100 million doses from Pfizer/BoiNTech. That makes it a total of 300 million doses which can inoculate 150 million people, as both vaccines require two doses to be administered 21 days and 28 days apart, respectively for Pfizer/BioNTech and Moderna. To our knowledge, the total supply is being apportioned among the states and the counties depending on the population. Florida has approximately 6.5% of the U.S. population and the Miami Dade County has 13% of Florida’s population. Hence, we assumed that Miami Dade County will receive approximately 2.54 million doses and be able to vaccinate 1.27 million people out of the total 2.8 million population. We also assumed that the vaccine deliveries will occur in batches starting in late December 2020 till late June 2021. Our study goal was to first determine the extent of reduction in the number of infections, hospitalizations, and deaths that we can expect to realize from the vaccination process in comparison with if no vaccines were available. Thereafter, we conducted a comparative study between three different vaccination priority schemes to determine if the outcomes (number of reported cases, hospitalized, and dead) from those are statistically significant.

	Priority 1	Priority 2	Priority 3	Priority 4	Priority 5
Age stratified strategy	<ul style="list-style-type: none"> Healthcare providers Nursing home residents Dec 15, 2020 – Jan 13, 2021 	<ul style="list-style-type: none"> People of ages 65 and over Jan 14 – Feb 12 2021 	<ul style="list-style-type: none"> People of ages 55 to 64 Feb 13 – Mar 14 2021 	<ul style="list-style-type: none"> People of ages 45 to 54 Mar 15 – Apr 13, 2021 	<ul style="list-style-type: none"> People of ages 16 to 44 Apr 14 – Jul 15, 2021
Minor CDC variant strategy	<ul style="list-style-type: none"> Healthcare providers Nursing home residents Dec 15, 2020 – Jan 13, 2021 	<ul style="list-style-type: none"> First responders Educators People of ages 75 and over Jan 14 – Feb 12, 2021 	<ul style="list-style-type: none"> People of ages 65 to 74 Feb 13 – Mar 30, 2021 	<ul style="list-style-type: none"> People of ages 16 to 64 Apr 1 – Jul 15, 2021 	<ul style="list-style-type: none"> NA
Random strategy	<ul style="list-style-type: none"> Healthcare providers and nursing home residents Dec 15 2020 – Jan 13, 2020 	<ul style="list-style-type: none"> All people of ages 16 and over Jan 14 – Jul 15, 2021 	<ul style="list-style-type: none"> NA 	<ul style="list-style-type: none"> NA 	<ul style="list-style-type: none"> NA

452 Figure 6: Vaccine prioritization strategies examined using AB simulation model for COVID-19 in the U.S.
 453 The priority strategies that were examined are broadly described here; a more complete description is presented in
 454 Figure 6.

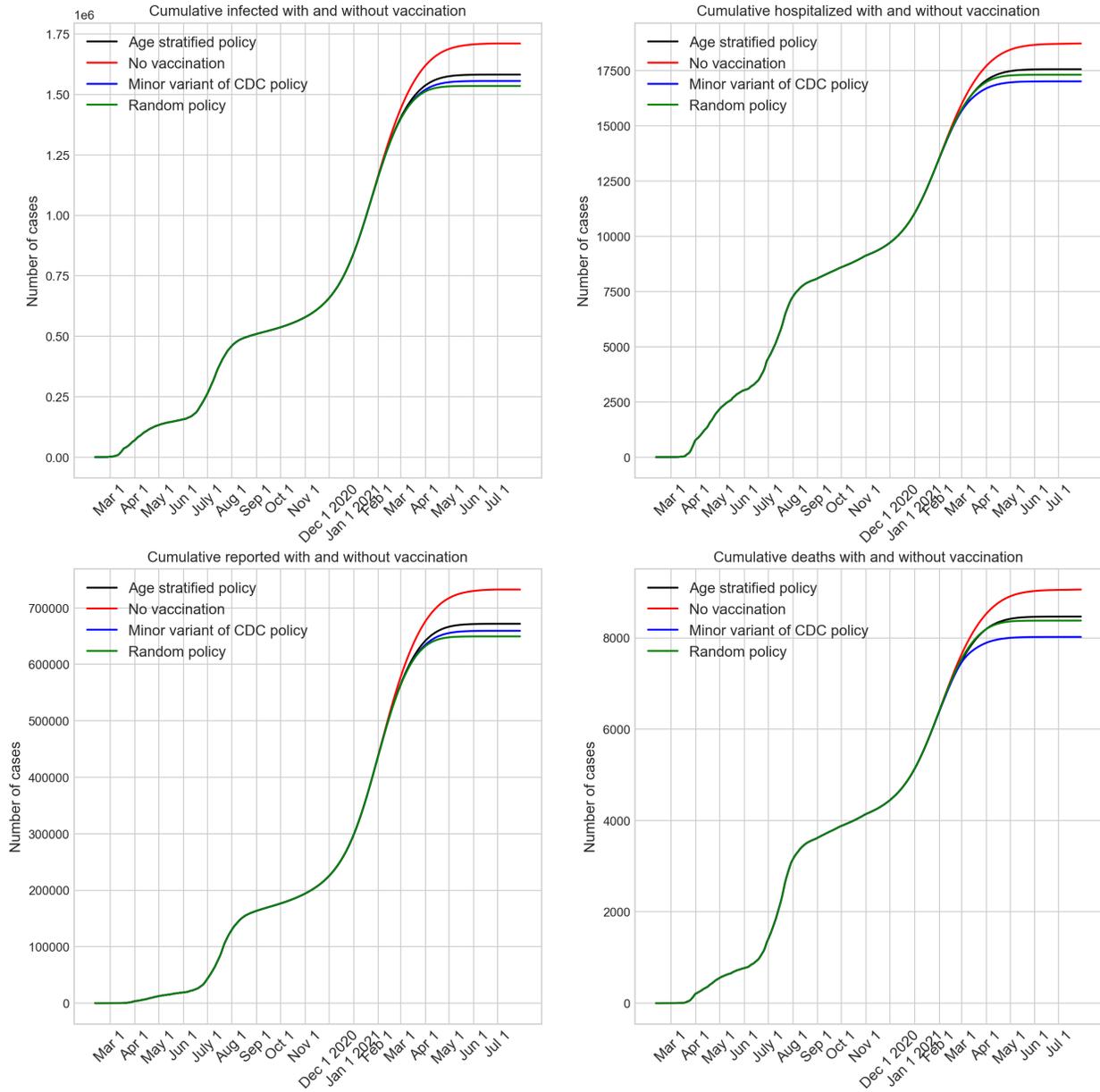
455 In the absence of a declared timeline for transition of eligibility from one priority group to the next, we
 456 assumed 30 days between transition. This period was extended to allow all eligible and willing to be vaccinated when
 457 the phased vaccine supply fell short of the number of people in the eligible priority group. The first strategy that we
 458 implemented is a close *variant of the CDC recommended strategy*: Priority 1: healthcare providers and nursing home
 459 residents; Priority 2: first responders, educators, and people of ages 75 and over; Priority 3: people of ages 65 to 74;
 460 Priority 4: people of ages 16 to 64. The CDC recommended strategy also includes in priority 3 people of ages 16 to
 461 64 with specific health conditions. Since we did not track health conditions in our AB model, we limited our priority
 462 3 to people of ages 65 and above only. The second strategy that we implemented is an *age-stratified strategy*: Priority
 463 1: healthcare providers and nursing home residents; Priority 2: people of ages 65 and over; Priority 3: people of ages
 464 55 to 64; Priority 4: people of ages 45 to 54; Priority 5: people of ages 16 to 44. The third strategy that we implemented
 465 is a *random strategy*: Priority 1: healthcare providers and nursing home residents; Priority 2: all people of ages 16 and
 466 over. People with prior COVID-19 history were not excluded and 60% of the people were considered willing to
 467 vaccinate [3, 18].

468

469 RESULTS

470 The strategy based on of the CDC recommendation achieves a reduction of 9%, 10%, 9%, and 11% for total infected,
471 reported cases, hospitalized, and dead, respectively, compared to the outcomes with no vaccination. According to our
472 model, with the close variant of CDC strategy the pandemic is likely to subside below a small threshold (100) of new
473 reported cases by May 16, 2021 compared to June 12, 2021 if no vaccines were available (see Figure 7). Hence the
474 likely net impact of vaccination in the urban Miami-Dade County of Florida will include sparing approximately 5.6%
475 of the population from infection and achieving normalcy about a month sooner. This seemingly low impact of
476 vaccination may be attributed to the fact that the trend of explosive growth of new cases in the winter months will
477 have significantly reduced the pool of susceptible people by late spring, possibly approaching the ‘herd immunity’
478 state. Figure 7 presents the plots of AB model predicted outcomes for four scenarios: no vaccination and the three
479 vaccine prioritization strategies. The plots show the average cumulative cases for infected (actual number of infected,
480 which is not observed and can only be assessed through a model), reported cases, hospitalizations, and deaths. As can
481 be seen, vaccination, irrespective of the strategy for prioritization, yields a significant reduction in the pandemic
482 impact. Per our model, with no vaccination, the percentage of infected population will reach nearly 61% by mid-June
483 of 2021.

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Figure 7: Impact of vaccination strategies on cumulative numbers of infected, reported, hospitalized, and dead from COVID-19

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The performances of the three vaccine prioritization strategies, as seen in Figure 7 are comparable. Simple pairwise

503

comparisons of the reported number of cases using a test of hypothesis showed that the variant of the CDC policy

504

produces a statistically significant lower number of reported cases than the no vaccination (p-value 0.0204). Age-

505

stratified and random strategies also yield statistically significantly lower numbers of reported cases compared to no

506

vaccination. However, comparison among the three vaccine prioritization strategies showed no significant statistical

507 difference for reported cases between strategies (p-values near 0.4). The numbers for hospitalizations and deaths also
508 had a similar trend. The model predicted values of the cumulative numbers of infected cases, reported cases,
509 hospitalized, and dead from the three policies and their 95% confidence intervals are presented in Table 2. The table
510 also provides the time frame when the pandemic falls below the threshold of 100 new reported cases. We observed
511 from the Florida COVID-19 dashboard that reported numbers of deaths are the most inconsistent of all reported data
512 due to reasons like: the timeline for deaths occurring from COVID-19 is highly variable, and deaths occur at homes,
513 hospitals, long term care facilities for which the reporting mechanism is perhaps not as streamlined. Hence, we applied
514 the percentages of deaths of those hospitalized in various age groups in the month of November 2020 to all the
515 subsequent months of our simulation study (till end of July 2021). As expected, CDC variant strategy produced
516 statistically significant lower numbers of hospitalized and deaths compared to no vaccination (p-values 0.0014 and
517 0.0015, respectively). The differences among the three vaccination strategies, however, are not statistically significant
518 (p-values range from 0.08 to 0.3).
519

Outcome Prioritization Strategy	Infected Cases	Reported Cases	Hospitalized	Deaths	Date when new reported cases fall below 100
No vaccination	1.71M (1.66M – 1.76 M)	732K (695K – 770K)	18.7K (18.3K – 19.1K)	9K (8.8K – 9.3K)	June 12, 2021
Minor variant of CDC	1.55M (1.38M – 1.73 M)	659K (567K – 752K)	17K (15.7k – 18.3k)	8K (7.2K – 8.8K)	May 17, 2021
Age stratified	1.58M (1.43M – 1.73M)	672K (589K – 754K)	17.6K (16.6k – 18.5k)	8.5K (7.9k – 8.9k)	May 22, 2021
Random	1.54M (1.32M – 1.75M)	649K (538K – 761K)	17.3K (15.9K – 18.7K)	8.4K (7.6K – 9.1K)	May 7, 2021

520

521 Table 2. Summary of expected cumulative values (with 95% confidence intervals) on July 31, 2021 obtained by the
522 AB model for the vaccine prioritization strategies
523

524 CONCLUDING REMARKS

525 We have developed a detailed AB simulation model for mimicking the spread of COVID-19 in an urban region
526 (Miami-Dade County, Florida) of the of the U.S. The model is calibrated using transmission coefficients and daily
527 schedules of the people and validated using the data reported in the Florida COVID-19 dashboard till December 30,
528 2020 (see Figure 5). On this validated model we have incorporated the vaccination process that started in the U.S. on
529 December 15, 2020 using two different vaccines developed by Pfizer/BioNTech and Moderna with an estimated 2.54
530 million doses for Miami-Dade county to inoculate 1.27 million people on a 2 dose regimen, based on government
531 contracts at the time of study.

532
533 Model results indicate that the use of the available vaccines can reduce the spread of the virus and help the pandemic
534 to subside below a small threshold of daily new cases by mid-May 2021, approximately a month sooner than if no
535 vaccines were available. Also, the vaccination is expected to reduce number of infections by approximately 10%
536 compared to no vaccination, which translates to sparing 5.6% of the total population from being infected.

537 We note that, even though the vaccines were developed and approved for human use at a much faster rate than ever
538 accomplished before, the accelerated growth of the infections, especially with the onset of the winter in the northern
539 hemisphere, reduced the opportunities for benefits that the vaccines could have delivered. For example, by end of
540 January 2021 a large proportion (over 41%) of the Miami-Dade population is expected to be infected, significantly
541 reducing the pool of susceptible for vaccines to work on.

542
543 Another noteworthy finding of this study was that there was no statistical difference in number of reported cases
544 between vaccination prioritization strategies tested: CDC recommendation based strategy, strictly age-based strategy,
545 and random strategy. This information can help give more latitude for decision makers in COVID-19 vaccine
546 distribution, as this research suggests that adhering strictly to priority groups may not be as paramount to vaccination
547 campaign success as simply distributing the vaccines.

548
549 Though our AB model is well suited to study future progression of COVID-19, it has some limitations. As mentioned
550 under vaccination strategies, our model did not include health conditions that are relevant to COVID-19 (like
551 pulmonary disease, obesity, heart problems) as attributes for people. Hence, we were not able to implement one
552 element of the CDC recommended prioritization strategy that includes people aged 16-64 years with underlying

553 medical conditions in priority 3. Also, we did not consider any vaccine wastage due to complexities associated with
554 refrigeration, distribution, and human error. We also assumed that vaccination of all priority groups will occur
555 uniformly over the eligibility periods considered, which may not reflect the reality. Also, since, to our knowledge,
556 there is little available literature on the rate of immunity growth each day from the two dose vaccines, we assumed a
557 linear growth starting with the first dose and culminating (full immunity) seven days after the second dose. Lastly, as
558 the pandemic progresses, new strains of the virus are being identified with slightly different viral parameters that may
559 not receive full coverage from the vaccine. It is unclear how this will impact the pandemic projection presented in this
560 model, though latest research shows that those vaccinated are likely to be protected from the new strains.

561
562 Unlike highly aggregated compartmental models that are relatively easy to apply to multiple regions/countries, agent-
563 based models are highly granular and require extensive data collection for the application region. The data include
564 population in all age groups, household compositions of adults and children, essential and non-essential businesses
565 and factories of different sizes as places for employment, schools and colleges of different sizes for different age
566 groups, peoples schedule on weekdays and weekends during different social intervention phases, intervention
567 timelines, testing availability and reporting delays, quarantine, isolation, and mask usage compliance, and level of
568 contact tracing. Hence, implementing the AB model to another region is a major task (see [19] for a step-by-step
569 approach).

570
571 As vaccination is ramping up in earnest in the U.S. at the time of our study, we believe that our results will provide
572 useful information for the healthcare policy makers not only for Miami-Dade County but for similar urban regions in
573 the U.S. and perhaps elsewhere in the world with a similar demography.

574

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Figures

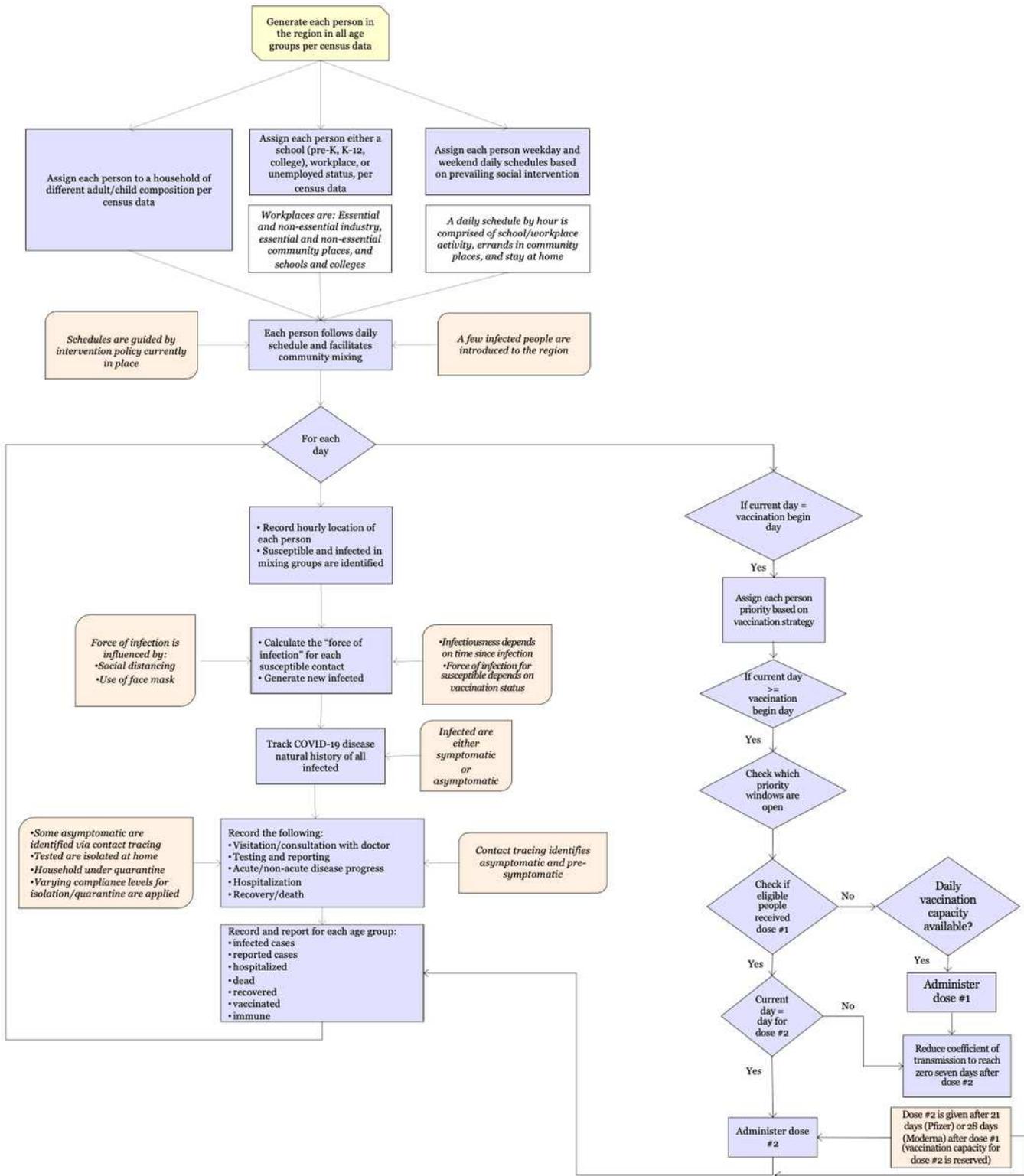


Figure 1

Schematic of the AB model for mimicking COVID-19 spread under social interventions and vaccination in the U.S.

```

Main
1 for simulation_day = 0,...,max_day
2   if simulation_day = 0
3     generate_entities()
4     generate_businesses()
5     initialize_outbreak() // Introduces a small number of infected individuals who are contagious
6     begin_outbreak() // Begin interaction among infected and susceptible and start community spread
7     report (infected, tested, reported, hospitalized, death) // Keeps track of daily age specific numbers

Function: Generate entities
1 // Generates population in the region based on census and assigns them to household and
2 workplace/school (including those unemployed who stay at home)
3 for household = 1,...,total_household_types
4   n1 = number of adults
5   n2 = number of children
6   for i = 1,...,n1
7     assign_age_household_workplace()
8   for j = 1,...,n2
9     assign_age_household_school()

Function: Generate businesses
1 // Generates businesses in the region based on census data and
2 // classifies them as essential and non-essential industries and community places
3 for business = 0,...,total_business_types
4   initialize_mixing_groups() // Creates smaller mixing groups (departments) within each
5   business and assigns employees

Function: Begin outbreak
1 // Assigns daily schedules based on prevailing social intervention, tracks hourly social mixing, accounts for
2 viral transmission, creates new infections, tests and reports infected, tracks disease progress for infected, monitors
3 stay at home/hospitalization, and records recovery and death
4 if simulation_day < lockdown_day
5   schedule = schedule_1 // Pre-pandemic schedule
6 if (simulation_day >= lockdown_day) and (simulation_day < Phase_I)
7   schedule = schedule_2 // Schedule after lockdown begins (closure of non-essential places and schools and
8   partial opening of essential places with limited capacity)
9 if (simulation_day >= Phase_I) and (simulation_day < Phase_II)
10  schedule = schedule_3 // Schedule during Phase I of reopening (schools remain closed, partial opening of
11  essential and non-essential with limited capacity)
12 if (simulation_day >= Phase_II) and (simulation_day < Full_reopening)
13  schedule = schedule_4 // Schedule during Phase II of reopening (schools remain closed, increased partial
14  opening of essential and non-essential places)
15 for hour = 1,...,24
16  disease_progress() // Monitors disease condition along disease natural history on an hourly basis for
17  each infected individual
18  tracking_individuals() // Tracks infected and susceptible in the same location (mixing group) by the hour and
19  calculates added force of infection for susceptible and tracks viral accumulation
20  infection_process() // At the end of each day, infection status of each susceptible with
21  any viral accumulation is determined
22  testing() // Tests symptomatic and some selected asymptomatic based on test availability and
23  reports outcome considering test sensitivity and reporting delay
24  hospitalization() // Tracks hospitalization of symptomatic developing acute condition
25
26 if (simulation_day = vaccination_begin_day)
27   assign_vaccination_willingness() // We assume 60% of the population is willing to be vaccinated
28   assign_vaccine_priority() // Vaccine priority is assigned by chosen criteria (age and profession)
29
30 if (simulation_day >= vaccination_begin_day)
31   for each willing and priority eligible individual
32     if (received first dose)
33       if (current_day = second_dose_day)
34         administer_dose_2() // Dose 2 is administered 21 days after first dose for Pfizer
35         vaccine and 28 days for Moderna vaccine
36     else
37       administer_dose_1()
38       reduce_transmission_coefficient() // Reduce coefficient of transmission to reach zero seven days
39       after dose #2
40
41  recovery() or death() // Tracks recovery or death for individuals in home/hospitals

```

Figure 2

Pseudo-code for agent-based simulation model of COVID-19 with implementation of two-dose vaccines

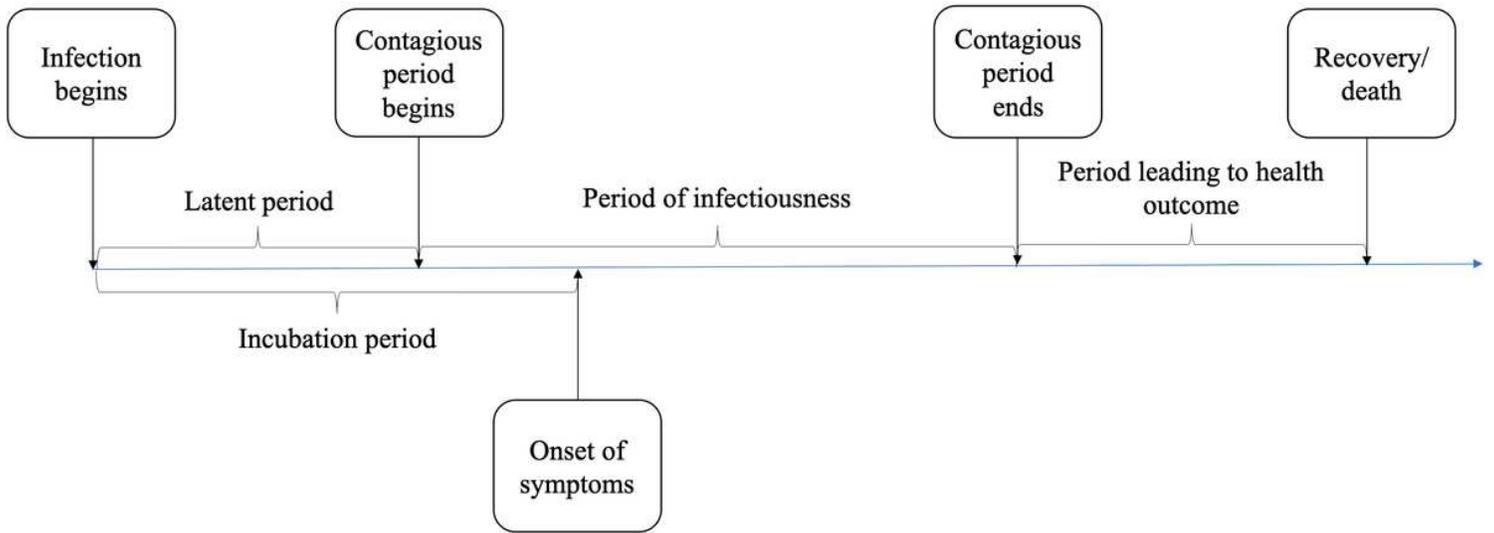


Figure 3

Disease natural history of COVID-19 [19]

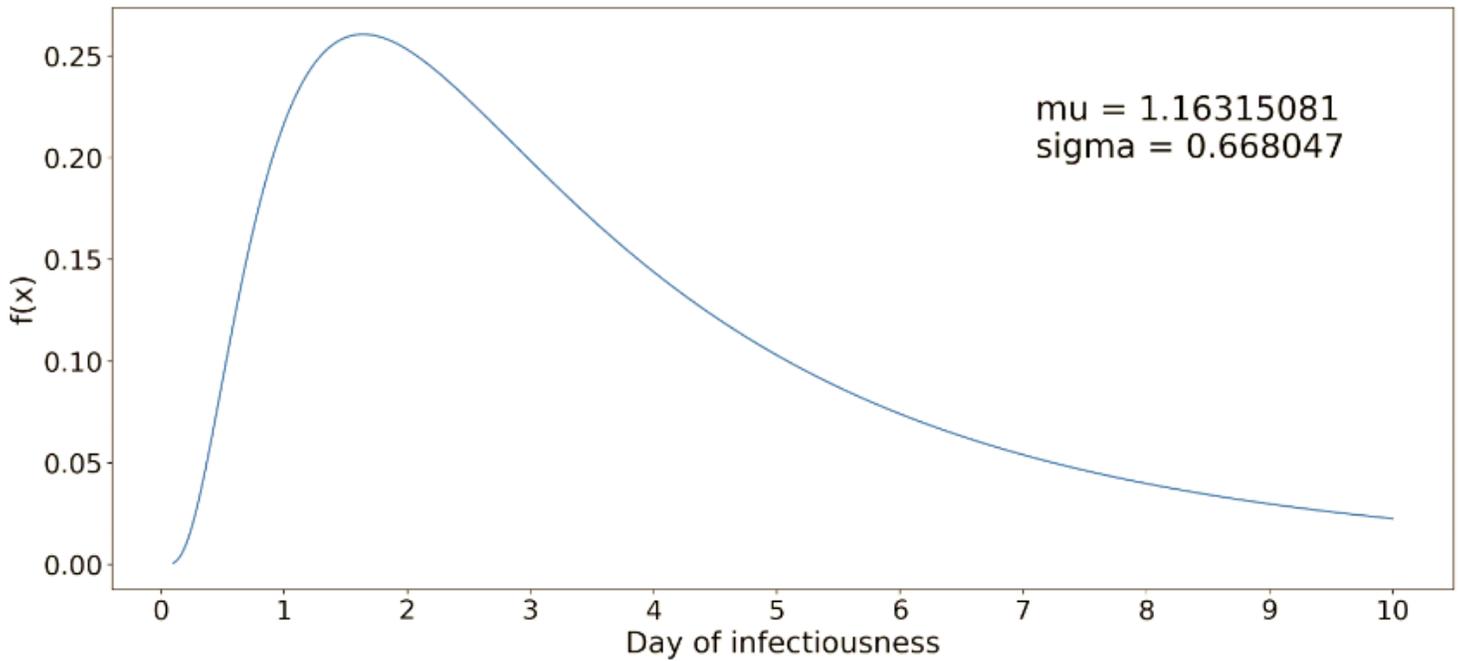


Figure 4

Lognormal distribution function for infectiousness profile of a COVID-19 case [19]

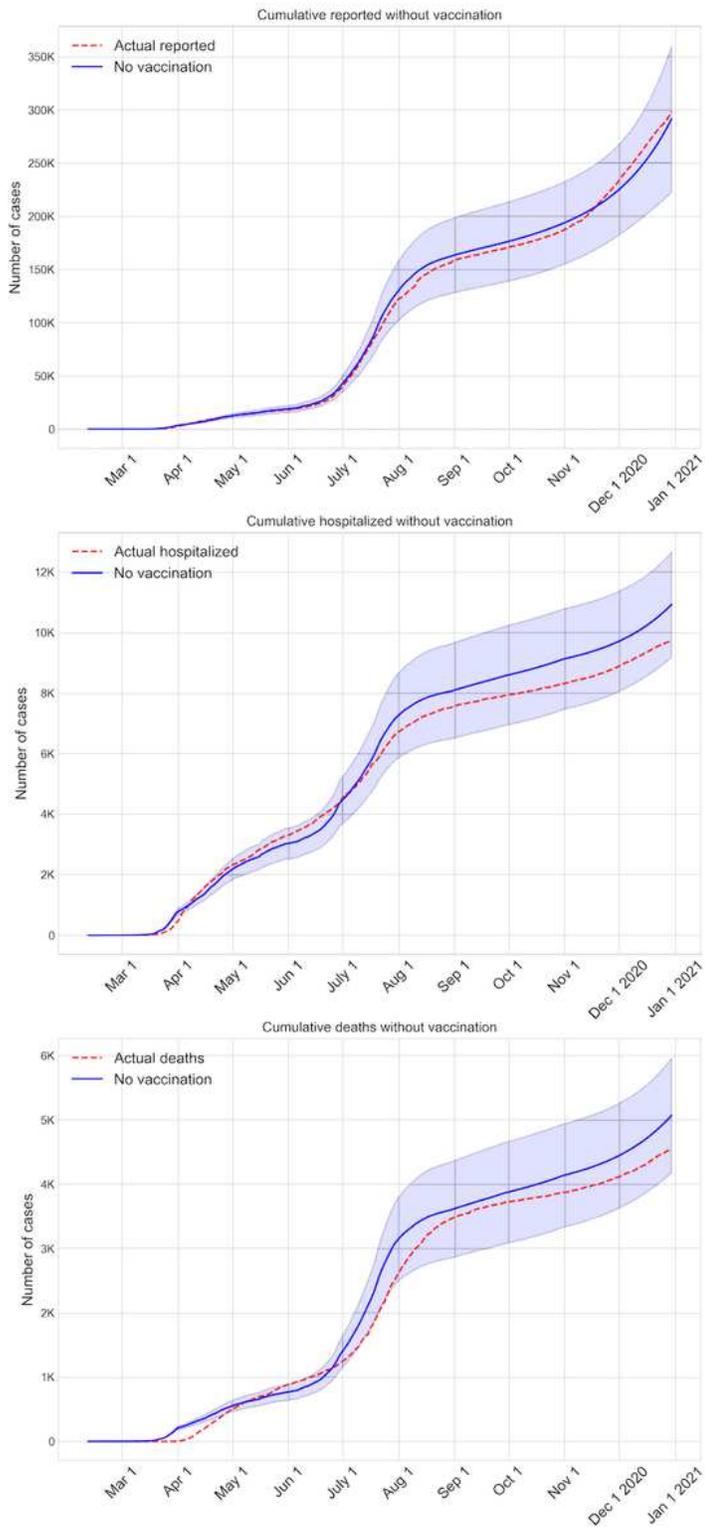


Figure 5

Validation graphs with average daily cumulative values of infected, reported, and death calibrated until Dec 30, 2020

	Priority 1	Priority 2	Priority 3	Priority 4	Priority 5
Age stratified strategy	<ul style="list-style-type: none"> Healthcare providers Nursing home residents <i>Dec 15, 2020 – Jan 13, 2021</i> 	<ul style="list-style-type: none"> People of ages 65 and over <i>Jan 14 – Feb 12 2021</i> 	<ul style="list-style-type: none"> People of ages 55 to 64 <i>Feb 13 – Mar 14 2021</i> 	<ul style="list-style-type: none"> People of ages 45 to 54 <i>Mar 15 – Apr 13, 2021</i> 	<ul style="list-style-type: none"> People of ages 16 to 44 <i>Apr 14 – Jul 15, 2021</i>
Minor CDC variant strategy	<ul style="list-style-type: none"> Healthcare providers Nursing home residents <i>Dec 15, 2020 – Jan 13, 2021</i> 	<ul style="list-style-type: none"> First responders Educators People of ages 75 and over <i>Jan 14 – Feb 12, 2021</i> 	<ul style="list-style-type: none"> People of ages 65 to 74 <i>Feb 13 – Mar 30, 2021</i> 	<ul style="list-style-type: none"> People of ages 16 to 64 <i>Apr 1 – Jul 15, 2021</i> 	<ul style="list-style-type: none"> NA
Random strategy	<ul style="list-style-type: none"> Healthcare providers and nursing home residents <i>Dec 15 2020 – Jan 13, 2020</i> 	<ul style="list-style-type: none"> All people of ages 16 and over <i>Jan 14 – Jul 15, 2021</i> 	<ul style="list-style-type: none"> NA 	<ul style="list-style-type: none"> NA 	<ul style="list-style-type: none"> NA

Figure 6

Vaccine prioritization strategies examined using AB simulation model for COVID-19 in the U.S.

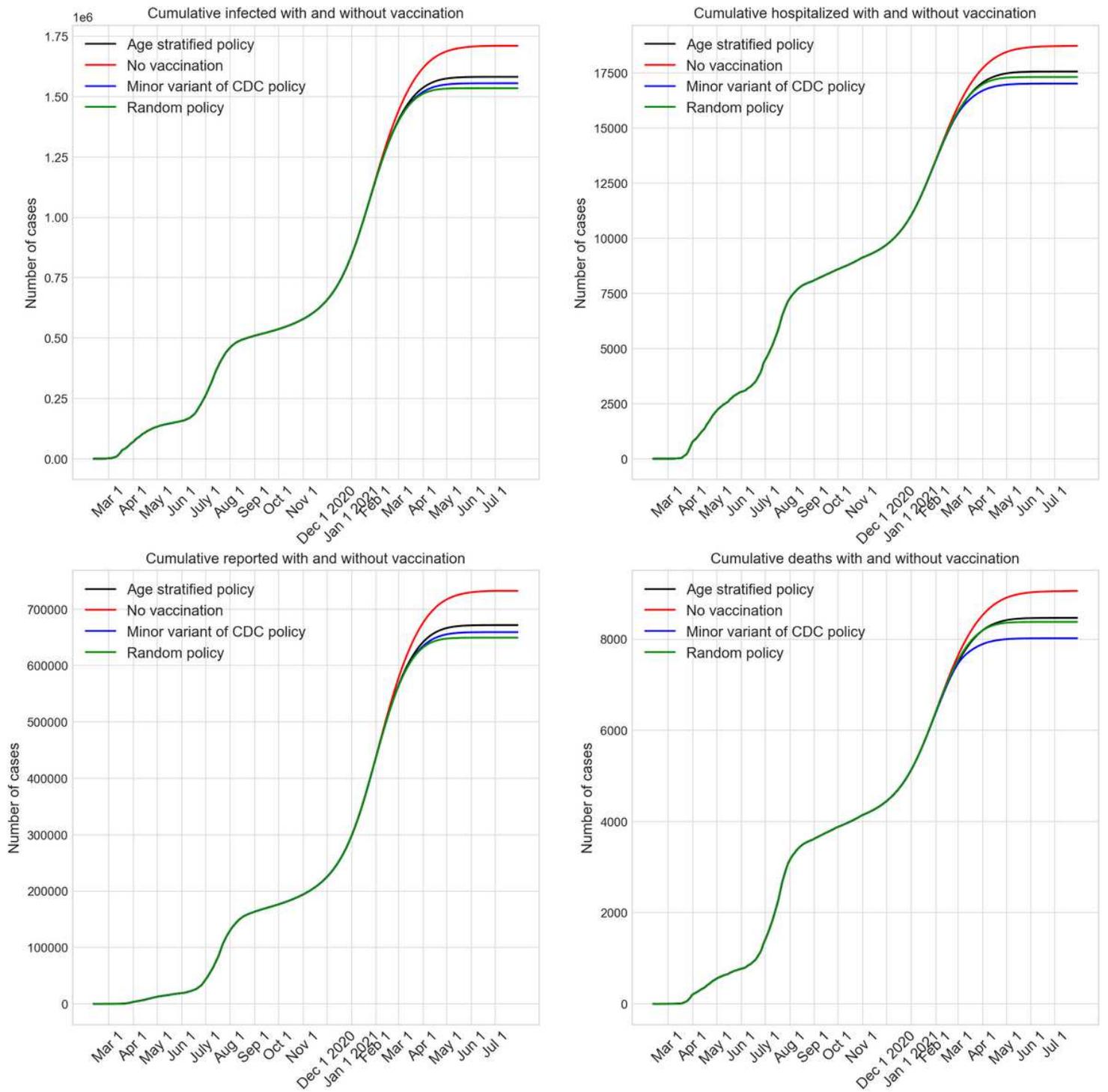


Figure 7

Impact of vaccination strategies on cumulative numbers of infected, reported, hospitalized, and dead from COVID-19