Evaluating COVID-19 Lockdown and Business-Sector-Specific Reopening Policies for Three US States

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ABSTRACT

Background: The United States has been particularly hard-hit by COVID-19, accounting for approximately 30% of all global cases and deaths from the disease that have been reported as of May 20, 2020. We extended our agent-based model for COVID-19 transmission [1] to study the effect of alternative lockdown and reopening policies on disease dynamics in Georgia, Florida, and Mississippi. Specifically, for each state we simulated the spread of the disease had the state enforced its lockdown approximately one week earlier than it did. We also simulated Georgia's reopening plan under various levels of physical distancing if enacted in each state, making projections until June 15, 2020.

Methods: We used an agent-based SEIR model that uses population-specific age distribution, household structure, contact patterns, and comorbidity rates to perform tailored simulations for each region. The model was first calibrated to each state using publicly available COVID-19 death data as of April 23, then implemented to simulate given lockdown or reopening policies.

Results: Our model estimated that imposing lockdowns one week earlier could have resulted in hundreds fewer COVID-19-related deaths in the context of all three states. These estimates quantify the effect of early action, a key metric to weigh in developing prospective policies to combat a potential second wave of infection in each of these states. Further, when simulating Georgia's plan to reopen select businesses as of April 27, our model found that a reopening policy that includes physical distancing to ensure no more than 25% of pre-lockdown contact rates at reopened businesses could allow limited economic activity to resume in any of the three states, while also eventually flattening the curve of COVID-19-related deaths by June 15, 2020.

KEYWORDS

COVID-19, agent based model, SEIR, policy simulation

INTRODUCTION

SARS-CoV-2 – the virus responsible for the novel coronavirus disease 2019 (COVID-19) – has resulted in an estimated 5 million reported cases and an estimated 328,000 reported deaths worldwide as of May 20, 2020 [2]. The United States (U.S.) has been particularly hard-hit by the infection, accounting for approximately 30% of all cases and deaths worldwide that have been reported as of May 20, 2020 [2]. Recent evidence suggests that this is partly due to states' slow responses in acting to stop the spread of the virus, meaning eventual state lockdowns began weeks after the disease had likely already been spreading rapidly across the country [3]. Here, to quantify the effect of earlier policy action, we used an agent-based simulation to estimate how enacting state-wide lockdowns one week ahead of when they were actually enacted could have curbed transmission of SARS-CoV-2 in the contexts of Georgia, Florida, and Mississippi. Understanding the impact of early policy action will be critical for developing prospective plans for combating the disease in the event of a second wave of infection.

Second, despite having substantial numbers of active infections, as of the week of April 27, many states in the U.S. have already partially reopened businesses and/or let lockdown orders expire, with other states soon to follow [4–6]. In some states, these restrictions have been lifted in opposition to federal guidelines that recommended states achieve declines in reported COVID-19 case counts for two weeks before relaxing restrictions [2, 7]. We used our agent-based model to estimate both (1) the effect that reopening select businesses subject to distancing restrictions might have on the transmission of the virus and (2) the level of physical distancing that must be maintained as businesses reopen in order to prevent further widespread outbreaks of COVID-19. Specifically, we simulated Georgia's reopening policy which involved reopening certain businesses like bars, salons, and tattoo parlors, and also released the state-wide shelter in place order. For comparison, we simulated the scenario using approximate populations for Georgia as well as Florida and Mississippi, making projections through June 15, 2020.

MODEL DESCRIPTION

Our model, detailed in Fig. 1, is an agent-based Susceptible, Exposed, Infected, Recovered (SEIR) model. It simulates the contact of each individual with others at home, work, school, and in the community; tracks the exposure of each individual to the disease through these contacts; and simulates their progression through the disease course after becoming infected. For work contacts in particular, we associate each agent with a "sector", as defined by the Bureau of Economic Analysis (BEA) [8], depending on their sampled occupation. Agents within the same sector may have "work contacts" only with other agents in their sector. To instantiate the model for a new region, we use census data to create a simulated population matching the demographics of the state as well as the occupations held, combined with data on diabetes and hypertension prevalence for that state. To fit the model to a given state, we calibrate the model's internal parameters such that the number of coronavirus-related deaths produced by the simulation match what has been officially reported over the time period for which data are available. For fitting, daily data on reported deaths were collected from the Johns Hopkins Coronavirus Resource Center [2], as of April 23, 2020. Remaining data sources were collected at either the state-level or country-level, as noted in Table 1. Tuned model parameters for each state are listed in Appendix A. For more details about the model, please see [1].

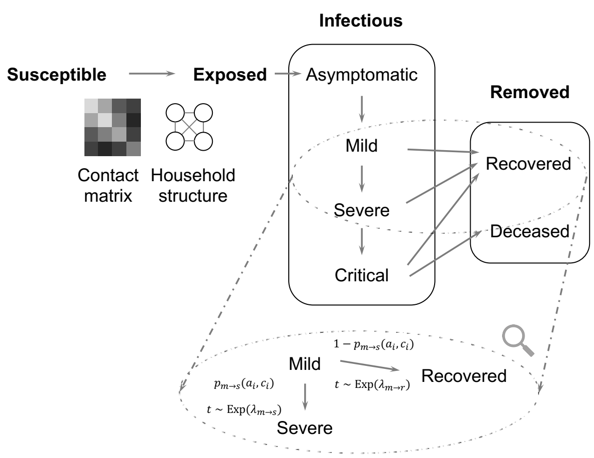

Figure 1: We use a modified SEIR model, where the infectious states are divided into levels of disease severity. The transitions are probabilistic, and there is a time lag for transitioning between states. E.g., the magnified section shows the details of transitions between mild, recovered, and severe states. Each arrow consists of the probability of transition (e.g., $p_{m\to s}(a_i,c_i)$ to progress from mild to severe), as well as the associated time lag for the transition (e.g., the time t to progress from mild to severe is drawn from an exponential distribution with mean $\lambda_{m\to s}$). In addition, a_i and c_i denote the age and set of comorbidities of the infected individual i, respectively.

Table 1: Demographic and comorbidity data sources. All data were collected at the state level except for the contact matrices which were estimated for the entire United States. *Centers for Disease Control and Prevention

Data	Source
Contact Matrices	Prem et al. [9]
Age, Household, Occupation	Census Microdata [10]
Diabetes Rates by Age	CDC* [11]
Hypertension by Age (GA, MS)	United Health Foundation [12]
Hypertension by Age (FL)	Smith et al. [13]

SCENARIOS SIMULATED FOR GEORGIA, FLORIDA, AND MISSISSIPPI

We simulated a total of six scenarios for the states of interest, Georgia (GA), Florida (FL) and Mississippi (MS).

Round One: Full Lockdowns or Release. To estimate the impact that locking down earlier might have had on the spread of the virus in each state, we considered three scenarios in which full state-wide shelter in place orders were varied.

(1) **Actual lockdown:** Lockdown was started on the actual date of the shelter-in-place state order and was maintained until the end of the simulation on June 15, 2020. The actual lockdown date for Georgia, Florida, and Mississippi was April 3, April 3, and April 1 respectively.
(2) **Earlier lockdown:** Lockdown was started on the shelter-in-place order date of New York City (March 23, 2020), and was maintained until the end of the simulation on June 15, 2020.
(3) **Early lift:** Lockdown was started on the actual date of the shelter-in-place state order, but was lifted on April, 23, though schools were kept closed.

Round 2: Georgia Reopening Plan. As of April 27, Georgia has allowed several businesses to reopen subject to employee distancing restrictions, including bars, restaurants, movie theaters, gyms, bowling alleys, salons, and beauty shops [4, 5]. All health centers were also allowed to reopen without distancing restrictions [4]. Further, the official state shelter in place order expired on April 30, 2020 [14]. We simulated this scenario by (1) sending back to work those agents who fell under BEA codes: 111CA, 22, 23, 311FT, 42, 445, 452, 485, 621, 622, 623, 624, 713, 722, and 81, matching the sectors that the governor allowed to reopen, and (2) allowing increased contact by the general population due to their visiting open businesses. However, due to the uncertainty about whether businesses would actually reopen, or whether the population would continue to physically distance themselves as diligently after lifting of the shelter in place order, we simulated three possible reopening scenarios with differing levels of post-lockdown contact increase. In all scenarios, the lockdown was started on the actual shelter-in-place order for the state, listed businesses were reopened on April 27, and lockdown was lifted on April 30, 2020 (though schools remain closed).

(4) **Low increase in contact:** When listed businesses were reopened on April 27, those employees had 25% of their pre-lockdown contact with other employees. When lockdown was lifted on April 30, the general population had 20% of their pre-lockdown contact.
(5) **Medium increase in contact:** When listed businesses were reopened on April 27, those employees had 50% of their pre-lockdown contact with other employees. When lockdown was lifted on April 30, the general population has 50% of their pre-lockdown contact.
(6) **High increase in contact:** When listed businesses were reopened on April 27, those employees had 100% of their pre-lockdown contact. When lockdown was lifted on April 30, the general population had 100% of their pre-lockdown contact.

PRIMARY RESULTS

Round One

Figs. 2, 3, and 4 show the trajectories for each scenario in Round One. In each graph, we show both the median trajectory (over 500 simulations), and the 25th and 75th percentiles. Thus, the shaded area represents our projected interquartile range for the cumulative number of documented deaths per state. We found that, in our simulation, lifting lockdowns early resulted in a rapid increase in documented deaths, while an early start to the lockdown averted a substantial number of documented deaths compared to the "Actual lockdown" scenario. The projected number of documented deaths in each scenario and for each state are shown in Table 2.

Table 2: Projected number of documented deaths by June 15, 2020 (median value over 500 runs), in the earlier lockdown (LD) scenario, as compared to actual reported deaths, and in early lockdown lift scenario, as compared to an extended shelter-in-place. For all three states, earlier lockdown and early lockdown lift were simulated to occur on March 23 and April 23, respectively. The numbers reported in parentheses represent the interquartile range.

	Georgia	Florida	Mississippi
(1)	1,838 (1,004–2,922)	1,919 (988–3,014)	397 (212–639)
(2)	378 (206–591)	312 (147–525)	94 (52–160)
(3)	13,149 (7,953–17,935)	20,485 (13,206–28,455)	3,971 (2,723–5,159)

Table 3 provides a comparison between the number of projected documented deaths under the earlier lockdown scenario and the most recently available actual COVID-19 death data [2] in Georgia, Florida, and Mississippi. In all three states, our model found that enacting lockdown just one week earlier could have prevented hundreds, if not thousands, of COVID-19 related deaths as of May 20.

Table 3: Projected number of documented deaths by May 20 (median value over 500 runs) in the earlier lockdown scenario, as compared to actual reported deaths. For all three states, the earlier lockdown start date was set to March 23, 2020. The numbers reported in parentheses represent the interquartile range.

	Georgia	Florida	Mississippi
Actual	1,697	2096	570
Early LD simulation	367 (199–574)	299 (142–510)	91 (50–155)

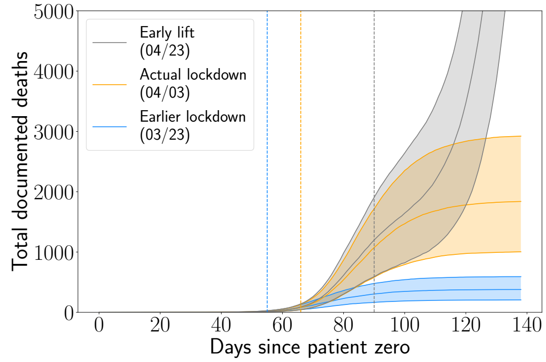

Figure 2: Cumulative documented deaths in each scenario for GA. The blue dashed line indicates the start of the "Earlier lockdown" on March 23. The yellow dashed line indicates the start of the lockdown (April 3) for the "Actual lockdown" and "Early lift" scenarios. The grey dashed line indicates the simulated "Early lift" date on April 23.

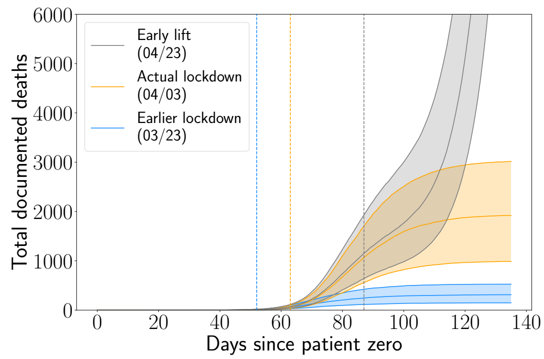

Figure 3: Cumulative documented deaths in each scenario for FL. "Earlier lockdown" date was set to March 23, "Actual lockdown" was April 3, and "Early lift" date was April 23.

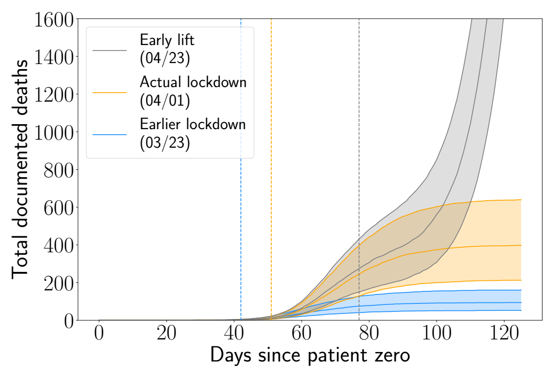

Figure 4: Cumulative documented deaths in each scenario for MS. "Earlier lockdown" date was set to March 23, "Actual lockdown" was April 1, and "Early lift" date was April 23.

Round Two

Figs. 5, 6, and 7 show the trajectories for simulating Georgia's reopening plan for each of the three states. In each graph, we show both the median trajectory (over 500 simulations), as well as the 25th and 75th percentiles. Thus, the shaded area represents our projected interquartile range for the cumulative number of documented deaths per state. We found that under all scenarios, there was risk of causing hundreds more deaths than if lockdowns were maintained. However, also notable is that under the "low increase in contact" scenario in which physical distancing ensured no more than 25% pre-lockdown contact, the number of new daily deaths approached 0 by June 15. This is in contrast to both the medium increase scenario (in which the number of new daily deaths were either near constant, or still slowly climbing) and the high increase scenario (in which deaths were increasing exponentially). The projected number of documented deaths in each scenario and for each state are shown in Table 4.

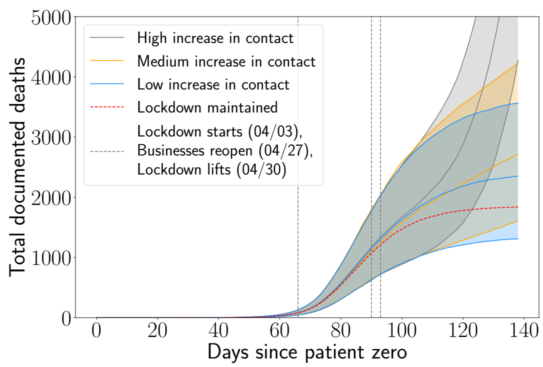

Figure 5: Cumulative documented deaths for Georgia's reopening plan scenarios simulated for GA. Lockdown started April 3, businesses reopened April 27 and lockdown lifted April 30. The red line shows the median projection when businesses stayed closed and lockdown was maintained.

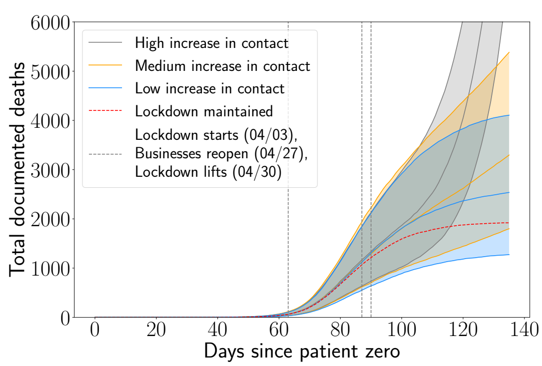

Figure 6: Cumulative documented deaths for Georgia's reopening plan scenarios simulated for FL. Lockdown started April 3, businesses reopened April 27 and lockdown lifted April 30. The red line shows the median projection when businesses stayed closed and lockdown was maintained.

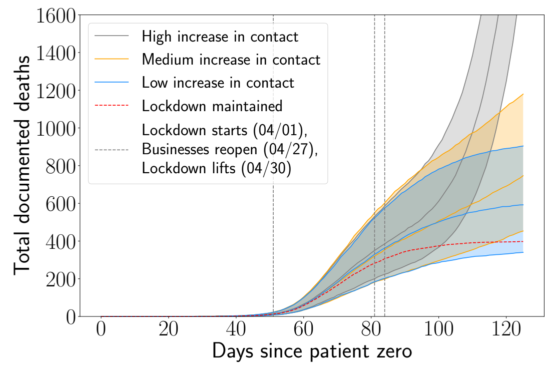

Figure 7: Cumulative documented deaths for Georgia's reopening plan scenarios simulated for MS. Lockdown started on April 1, businesses reopened on April 27 and lockdown was lifted on April 30. The red dashed line shows the median projected documented deaths under the scenario in which businesses stayed closed and the lockdown was maintained.

DISCUSSION

Our simulations provide estimates about the relative impact of different policy decisions on the projected number of COVID-19 related deaths. First, our results suggest that locking down even one week earlier in any of the three states could have saved on the order of hundreds of lives. This is a critical insight for developing contingency policies for a potential "second wave" of infections, something that epidemiologists warn could happen even without full relaxations of physical distancing given the expected low prevalence of immunity in the population [15, 16]. That is, should early warning signs indicate that a second wave of infection is starting, imposing strict distancing or lockdown measures as soon as possible will be key to quickly controlling the new outbreak and saving lives.

Second, our simulations of partial business reopening scenarios under various levels of contact increase provide multiple insights. Importantly, our model found that if businesses strictly enforced physical distancing rules *and* the general public practiced their own strict physical distancing, such that the population's effective contact was reduced to 20–25% of their pre-lockdown rate, then the number of daily new documented deaths could substantially decrease by June 15, 2020. In contrast, if this effective contact was 50% of its pre-lockdown rate, our simulations showed constant or increasing daily new deaths by June 15, and at 100% contact, deaths increased exponentially. This suggests that in order to safely reopen even limited sectors of the economy, as outlined in [4, 5], it will be critical to adopt a temporary new normal in which the population's contact is greatly reduced (20–25% of pre-lockdown rate) by means such as wearing personal protective equipment and practicing strict physical distancing.

Additionally, our results suggests that greater testing capacity could assist in determining an appropriate date for releasing the lockdown. More specifically, our model still estimated that even the low increase in contact scenario (20–25% pre-lockdown rate) could result in hundreds more documented deaths than if the lockdown was maintained. This is because whenever the reopening occurred in our model, some asymptomatic carriers inevitably returned to

Table 4: Projected number of documented deaths by June 15 (median value over 500 runs), under various reopening scenarios, in comparison of an extended shelter-in-place policy. For all three states, business were reopened on April 27 and lockdown was lifted was on April 30 in the simulation. The numbers reported in parentheses represent the interquartile range.

Scenario	Georgia	Florida	Mississippi
Lockdown maintained	1,838 (1,004–2,922)	1,919 (998–3,014)	213 (398–640)
Low increase in contact	2,350 (1,310–3,563)	2,537 (1,273–4,106)	592 (340–904)
Medium increase in contact	2,712 (1,604–4,236)	3,296 (1,799–5,382)	747 (453–1,180)
High increase in contact	7,154 (4,279–9,748)	11,418 (7,106–15,523)	2,738 (1,865–3,463)

the public, spread the infection, and ultimately caused more documented deaths. The number of asymptomatic carriers that return to the public is directly related to the number of new daily infections occurring when the lockdown is released. In our simulations, that number of new daily infections was still large (i.e., on a steep part of the curve) when the lockdown was released, leading eventually to a larger number of documented deaths than in extended lockdown scenarios. This suggests that having sufficient testing capacity at the time of reopening would be highly beneficial for two reasons: (1) it would allow policymakers to more accurately estimate how many asymptomatic carriers they expect to return to the population *before* making a reopening decision, and (2) *after* reopening, it would allow those asymptomatic carriers to be detected and isolated quickly.

LIMITATIONS AND CONCLUSION

Our approach has some limitations that present avenues for future work or reflect the current availability of data. For instance, agent heterogeneity is currently based on age, two comorbidity types, occupation, and household structure. However, other comorbidities that may be relevant to the progression or severity of COVID-19, such as smoking or chronic pulmonary disease [17], could easily be included as more data are made available about their interaction with the disease. Gender, which may have both biological and behavioral implications relevant to the contraction or progression of the disease [18], could also be included as studies are conducted and data is made available. Other limitations, such as the assumption that workers mix well within each BEA coded sector but not across sectors (which may be important for, e.g., janitorial services that cut across industries), will be more difficult to address without significant new surveys or data sources. However, the business-specific contact patterns modeled herein present a reasonable first step to estimating this important epidemiological mechanism of disease spread.

The model we develop also excludes geographic factors that may be important at the state level. For instance, contact patterns in a major metropolitan area may differ significantly from those in a rural community in the same state. Further, in reality, agents may visit other states with varying degrees that depend on occupation or current travel restrictions. Building a model to account for geographic heterogeneities in contact rates as well as interstate travel is an interesting avenue for future work. Leveraging agent-agent encounter data recorded on mobile devices presents a potential avenue for implementing these components [19, 20].

Despite the above limitations, these results provide useful insights about how decisions to enact lockdowns or reopen businesses could affect the health of the populations of Georgia, Florida, and Mississippi. However, like all simulations, our results should be considered as one input of many when making complex policy decisions.

Regarding the choice of timing for our simulated lockdown lifts, we used the latest information available in the press at the time the simulations were run. As more announcements are made by public officials across all states, our simulations can be updated to reflect, in each locality, the current evolution of the outbreak/local infection profile, the timing of reopening decisions, and the types of policies that are recommended in the post-lockdown phase.

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APPENDIX

A MODEL FITTING

The three parameters which must be tuned are: (1) p_{inf}, the probability of transmission given contact between an infected and susceptible individual; (2) t_0, "day zero" of the infection, which is not exactly known in most regions but must be tuned since it exerts a large impact on the trajectory of cases and deaths, due to rapid doubling times; (3) d_{mult}, which addresses remaining differences in the rate of mortality between locations of interest that are *not* captured by demographic factors in the model (e.g., the impact of greater pollution rates, or availability of hospital beds). $d_{\text{mult}} = 1$ corresponds to the COVID-19 mortality rate in New York since the model's age- and comorbidity-specific COVID-19 mortality rates were calibrated using data from that region [21, 22]. The parameters for each state were established via grid search using as a criterion the goodness-of-fit of the median trajectory over 100 random simulations. The best-fitting parameters for each state are shown in Table 5.

Table 5: Well-fitting parameters used to simulate the infection in each state.

State	p_{inf}	t_0	d_{mult}
Georgia	0.0229	Jan. 29	2.0
Florida	0.0210	Feb. 1	1.5
Mississippi	0.0240	Feb. 11	1.5

B VALIDATION

Our model closely matched the actual number of documented deaths, up to the most recent data available at the time of calibration (April 23, 2020). Moreover, we cross-referenced in Table 6 our projections for the "actual lockdown" scenario, by comparing against the cumulative number of documented deaths projected by three other models (as of April 23, 2020).

Thus, in the baseline scenario, all of the interquartile ranges projected by our model are aligned with the confidence intervals and point estimates of other publicly available and widely referenced models.

Table 6: Projected number of documented deaths in Georgia, Florida, and Mississippi, in the scenario where lockdown is maintained, in comparison with three other models. The projection is by May 12, 2020 for UT Austin, and by June 15, 2020 for IHME and MIT ORC. For UT Austin, the provided range of values is determined over 10 distinct runs. For IHME, the numbers reported in parentheses represent the 95% confidence interval. In our model, the numbers reported in parentheses represent the interquartile range. Finally, the publicly available MIT ORC output does not include any measure of uncertainty in death estimates.

Model	Georgia	Florida	Mississippi
UT Austin	(930-1723)	(993-1,644)	(203-434)
Us (May 12)	1,575 (852-2,513)	1,619 (834-2,553)	348 (185-556)
IHME	2,253 (990-6,252)	1,620 (999-3,381)	400 (208-1,014)
MIT ORC	1280	2144	777
Us (June 15)	1,838 (1,004-2,922)	1,919 (988-3,014)	397 (212-639)