Estimating the Effectiveness of COVID-19 Mitigation Policy in Rhode Island

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BACKGROUND

When the first cases of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) were detected in Rhode Island in late February 2020, little was known about the disease, except that it was a coronavirus to which the entire human population was immunologically naive, that its basic reproduction number was between 1.4 and 2.5,[1] and that it had the potential of causing severe respiratory symptoms and death in sufficient proportions to overwhelm hospital systems quickly. At that moment, Rhode Island, like many other jurisdictions in the United States, had two significant vulnerabilities: tight limits on its ability to expand hospital bed capacity beyond existing demands, and a very limited stockpile of personal protective equipment for hospital personnel.[2,3] Given this situation, the state implemented strict mitigation interventions in real time to slow disease transmission.

Given all the unknowns posed by a novel virus, combined with daily reports of mounting disease burden in China[4] and the urgency inherent in the World Health Organization's official declaration of pandemic (March 11, 2020),[5] the only sure mitigative tool in public health's armamentarium to minimize disease exposure in the general population was a blunt one: reduction in the density of the general population by sheltering in place (what became known around the world colloquially as "lockdown"[6]). Accordingly, in a mere two weeks (March 9–22, 2020) the Governor of Rhode Island shut down most indoor public venues – schools, churches, sports events, theatrical events, bars and restaurants, densely populated workplaces, etc. – and limited the size of social gatherings in all settings to 25 people.[7] Other tweaks of Rhode Island's policy package would follow, such as an order for "employees at 'customer-facing' businesses to wear masks,"[7] 14-day quarantines for travelers entering the state, and temporary closures of outdoor public venues such as beaches and parks,[7] but by March 23, 2020, the density and mixing of the general public in Rhode Island was about as minimal as possible under the circumstances. Rhode Island would remain in this state for seven weeks, at which time restrictions on the size of social gatherings were eased slightly in what was called "Phase One of Reopening,"[7] beginning May 9, 2020. Phases 2 and 3 would follow on June 1 and 30, 2020, respectively, effectively allowing most businesses to reopen, subject to rules such as masking.[7] In September, most Rhode Island schools at all levels would reopen for in-person instruction.[7]

The closures and other restrictive policies of early 2020 produced undesirable effects, primarily on employment and schooling. Thousands of Rhode Island workers were laid off in March 2020 as workplaces shut down,[8] and Rhode Island students at all levels were transitioned from classroom to remote learning.[7] Most people became more socially isolated than they had ever been. It will require years of research to understand all the negative consequences of the blunt mitigative tools applied (worldwide) in early 2020. However, the positive consequences – reductions in potential morbidity and mortality – may be explored with epidemic models, and this is what we set out to do, using simple epidemic models to compare the results of two hypothetical scenarios with the observed burden of COVID-19 in Rhode Island during the first year of the pandemic.

METHODS

First, a simple S-I-R approach was used to model the first epidemic year of the Coronavirus Disease of 2019 (COVID-19) in Rhode Island, 1/27/2020–2/28/2021, using counts of hospital admissions as the primary basis of the models, supplemented by counts of positive tests and deaths when these data became available and were deemed reliable.

The S-I-R model, introduced to epidemiology a century ago,[9] models epidemics mechanistically, by describing them as the outcome of a stylized infection process on homogeneous groups of people. In the simplest form of this model, a susceptible group (S) may be infected upon contact with people in an infectious group (I), who will in turn recover or die and move to a "removed" group (R). The advantage of this stylized model is that it is easy to conceptualize, it is transparent, and it is easily replicable, because it is fully described by a set of simple algebraic (difference) equations. In its deterministic implementation, which ignores complicated descriptions of uncertainty, one can easily explore the impact of parameter changes on results.

To tailor an S-I-R model to Rhode Island, we used a total population size of 1,097,379 people, the 2020 U.S. Census count for Rhode Island,[10] a disease duration of $D = 10$ days, and a reproduction number at the beginning of the epidemic of $R(0) = 2.5$. The reproduction number, $R(t)$, where t refers to the "epidemic day" from 0 to N, the end of the epidemic, is the average number of new infections that each infectious person generates over the duration of their illness. R(0) is called the "basic reproduction number," while R(>0), e.g., R(1), R(2), R(3)…, is called the "effective reproduction number." The values we used for D and R(0) are within accepted ranges for the original strain of SARS-CoV-2.[11]

R(t) depends on many factors, including characteristics of the pathogen, the proportion of the population in the susceptible group, and how likely it is that an infectious and a susceptible person will interact closely enough for the latter to be infected. Infections are more likely to occur when there is a higher "density of interactions." Therefore, as a population becomes denser, R(t) increases; as it becomes less dense, R(t) decreases.

Daily new hospital admissions (hospitalizations) were modeled by assuming ratios of hospitalizations to our model's estimates of daily underlying infections as follows: 5% from 2/27/2020 through 5/31/2020, during a period of nursing home outbreaks, a 45-day transition from 5% to 3% as nursing home outbreaks were brought under control, and 3% thereafter. These Rhode Island-specific ratios were estimated by the Rhode Island Pandemic Modeling Team (RIPMT) in 2020 and have been working well during the four continuous years of COVID-19 monitoring. (JF, TT, and JP have been core members of the RIPMT from its inception.)

Deaths were modeled by applying observed ratios of deaths to hospitalizations as follows: 50% from 2/27/2020 through 5/31/2020, a 10-day transition from 50% to 25%, and 25% thereafter.

The model was then conformed to empirical observations by scaling the daily effective reproduction number, R(t), by a factor representing daily relative population density, d(t), permitted to vary between 1 (normal density) and 0 (a theoretical impossibility in which all members of the population are isolated from one another) (**Figure 1**). A daily value of d(t) was estimated such that daily hospitalizations resulting from the S-I-R model conformed to observed daily hospitalizations within about ± 10%. (The resulting "fit" is plotted in **Figure 2**.)

By plotting d(t), we were able to see and interpret the effects of mitigative public health policy as applied to reduce population density (to retard disease transmission) or removed to permit a return to normal population density. d(t) also reveals periods in which population density is naturally reduced (e.g., during summer months) and naturally increased (e.g., return to school in late summer and the holiday season at year's end) (**Figure 1**).

Then, two hypothetical scenarios were run:

Scenario 1 (S1): laissez-faire policy, in which the initial reduction in d(t) is limited to half of the observed reduction, i.e., 25% vs. 50%, simulating voluntary reduction in population density, e.g., voluntary actions to shelter in place, followed by the same seasonal pattern in d(t) as the empirical model, followed by voluntary reductions in the number and size of holiday gatherings (**Figure 3**).

Scenario 2 (S2): absence of policy, in which observed reductions in d(t) are eliminated except for seasonal (summer and fall) variations in d(t), to simulate the full potential of an R(0) = 2.5 epidemic, i.e., a theoretical, disastrous extreme in which people do not self-quarantine or otherwise adjust their behavior during the epidemic (**Figure 4**).

Figure 1. Estimated Proportionate Population Density, *Derived* (Rhode Island, 2/27/2020–2/28/2021)

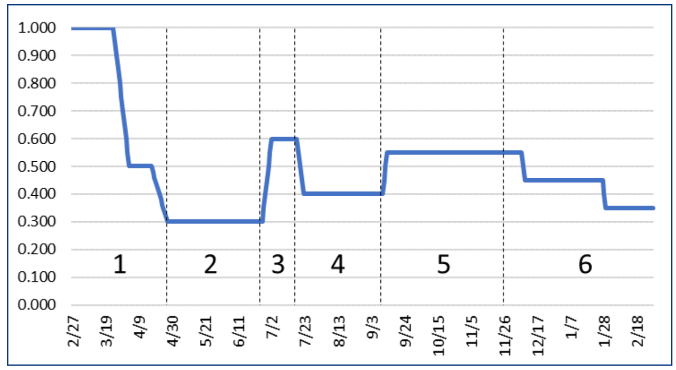


Figure 2. Hospital Admissions: Modeled and Observed (Rhode Island, 2/27/2020–2/28/2021)

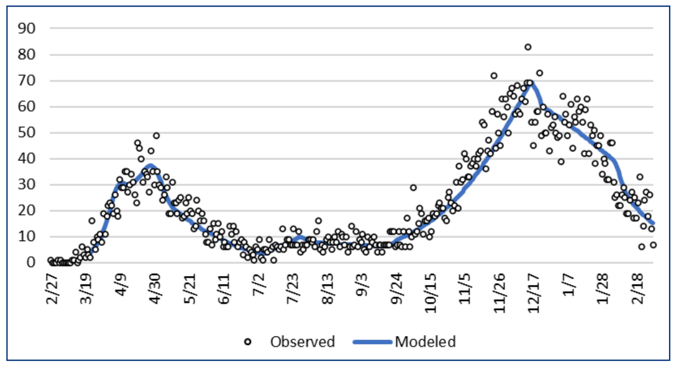


Figure 3. Modeled Proportionate Population Density, *Scenario 1* (Rhode Island, 2/27/2020–2/28/2021)

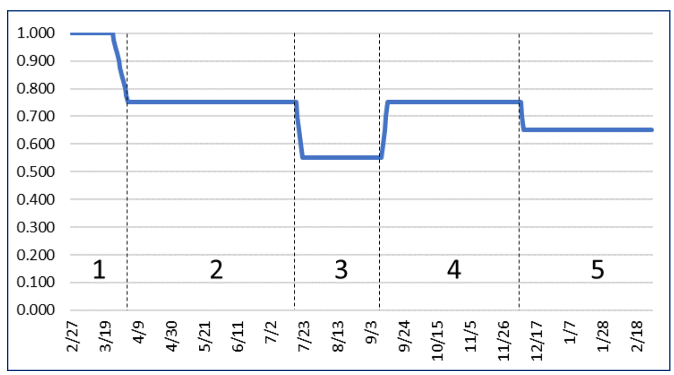


Figure 4. Estimated Proportionate Population Density, *Scenario 2* (Rhode Island, 2/27/2020–2/28/2021)

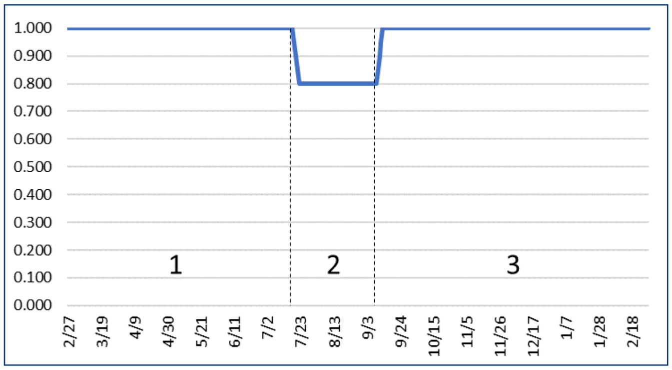


Figure 5. Hospital Admissions: Observed and Scenarios (Rhode Island, 2/27/2020–2/28/2021)

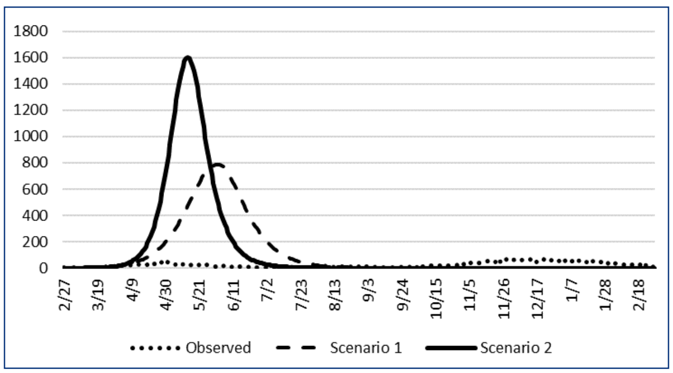
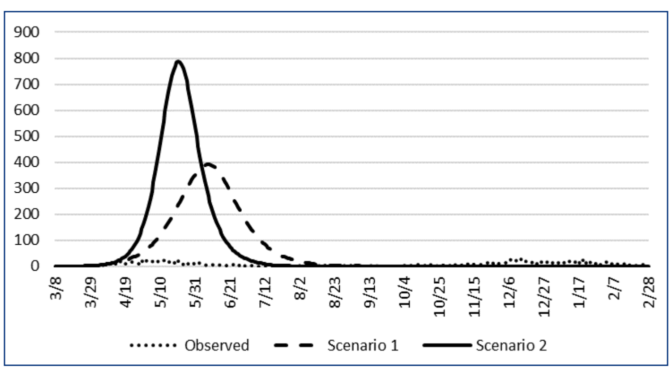


Figure 6. Deaths: Observed and Scenarios (Rhode Island, 2/27/2020–2/28/2021)



RESULTS

When the model is conformed to empirical reality, the revealed trend in d(t) has six distinct periods (**Figure 1**) related to pandemic policy and seasonal rhythms in population density: (1) lockdown; (2) stasis; (3) mitigative loosening; (4) reduction in the size of gatherings and summer's population decompression; (5) fall's recompression (return to school, work); (6) mitigative tightening in response to surging cases.[7] **Figure 2** reveals a good fit between observed and modeled hospitalizations when d(t) is derived in this way.

In S1 (**Figure 3**), the proposed trend in d(t) has five periods: (1) initial recommendations; (2) stasis; (3) summer's population decompression; (4) fall's population recompression; (5) holiday recommendations. In S2 (**Figure 4**), the proposed trend in d(t) has three periods: (1) normal population density; (2) summer's population decompression; (3) fall's population recompression.

S1 and S2 yield many more hospitalizations (H's) and deaths (D's) than observed in reality from 1/27/2020 through 2/28/2021. Voluntary mitigation (hypothetical scenario S1 – **Figure 5**) yields 30,361 (353%) more hospitalizations and 16,879 (648%) more deaths than enforced mitigation as implemented in Rhode Island. No mitigation (hypothetical scenario S2 – **Figure 6**) yields 40,367 (648%) more hospitalizations and 21,837 (839%) more deaths than enforced mitigation.

DISCUSSION

Despite being formulated during an intense public-health emergency, it is quite clear that improvised policies worked "to flatten the curve" in Rhode Island. Two possible "what ifs" reveal stark differences between what actually occurred in Rhode Island during the first year of COVID-19, what might have occurred with a hypothetical laissez-faire policy (S1), and the theoretical limits of epidemic morbidity and mortality without mitigation (S2).

Simple, transparent, and easily replicable S-I-R models suggest that SARS-CoV-2 hospitalizations might have been four to five times higher and deaths seven to eight times higher under the hypothetical laissez-faire policy we have characterized (S1) than observed under lockdown. Furthermore, the S1 hospitalization curve observed in **Figure 5** – together with what we know of the average length of stay of SARS-CoV-2 patients (10+ days well into July)[12] – suggests that Rhode Island's hospital system, whose maximum bed capacity at the time was 2,740,[13] would have been inundated with SARS-CoV-2 patients sometime in April, if not before. Just such a situation was playing out at the time in Italy,[14] whose COVID-19 epidemic surged well beyond the Rhode Island experience before the Italian government imposed a lockdown, as well. An even more sobering thought is that our S1 estimates of deaths (based on the empirical ratio of deaths to hospitalizations observed at the time) are clearly underestimates, for had the hospital system become dysfunctional, the death rate from other diseases and conditions requiring hospital care most likely would have increased as well.[15]

By flattening the curve of COVID-19 in Rhode Island, the state's enforced mitigative policies also reduced disease transmission before FDA emergency-use authorizations (EUAs) for remdesivir (antiviral) in May 2020,[16] of bamlanivimab (monoclonal antibody) in November,[17] and of Pfizer-BioNTech COVID-19 vaccine in December.[18] Together, these advancements saved many lives by preventing or reducing the severity of SARS-CoV-2 infection. Others (e.g., casirivimab + imdevimab[19]) would follow in short order.

Variations of the S-I-R model were in common use during the COVID-19 pandemic. A simple search of publications with the terms "S-I-R model" and "COVID 19" yields thousands of references. The model has strengths and weaknesses,[20-22] but its venerable history, simplicity, transparency, and replicability render it useful in conducting hypothetical exercises such as the one we have conducted.

Similar exercises have been undertaken to assess the effects of policies designed "to flatten the curve" of COVID-19,[23-26] but none to date for Rhode Island. Our results, which clearly suggest the effectiveness of the state's enforced mitigative policies, provide a basis for a more detailed analysis of the effectiveness of individual policies employed at the time.

CONCLUSIONS

The closure of Rhode Island's schools and many Rhode Island businesses in 2020, despite untoward side effects, probably prevented upwards of 30,000 hospitalizations and 16,000 deaths (compared to a hypothetical laissez-faire policy), saved its hospital system from dysfunction, and pushed the epidemic forward in time, when antivirals, monoclonal antibodies, and vaccines became available to prevent disease and blunt its severity.

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