

# COVID-19 Epidemic in Mumbai: Projections, full economic opening, and containment zones versus contact tracing and testing: An Update

TIFR Covid-19 City-Scale Simulation Team

Prahladh Harsha, Sandeep Juneja, Daksh Mittal, Ramprasad Saptharishi

October 29, 2020

## I. SUMMARY

Mumbai, amongst the most crowded cities in the world, has witnessed the fourth largest number of cases and the largest number of deaths among all the cities in India. The first case in Mumbai was detected on 11 March 2020, and the first fatality was recorded on 17 March 2020. Currently, as of 26 October, 2020, Mumbai has reported 252,087 cases and 10,099 fatalities, thus contributing disproportionate share to India's tally of 7.94 million reported cases and 119,014 deaths. Mumbai, along with the rest of India has been in a lockdown since March 25, 2020. Initially imposed for three weeks, this lockdown was extended in Mumbai and other parts of India till May 17, 2020. Thereafter, Mumbai has seen gradual relaxations in population movement. In particular, in the "Mission Begin Again" order dated 31st August 2020 [1], the Government of Maharashtra has allowed 20% attendance in workplaces.

As per the release by the government, the Indian economy contracted by 23.9% in the first quarter of the fiscal year 2020-21. Given the large economic toll on the country from the lockdown and the related restrictions on mobility of people and goods, swift opening of the economy especially in a financial hub such as Mumbai becomes critical. However, opening up of Mumbai is crucially linked to opening its crowded public transit systems, especially the crowded suburban trains. Too swift an opening may lead to a sudden increase in the spread of the epidemic leading to a 'difficult to manage' second wave of hospitalisations.

Fortunately, the curve of medical indicators for Mumbai such as hospitalisations, critical patients, reported cases and fatalities at any time, had begun to stabilize or 'flatten' over the

months of June and July and further reduced in August. There was some increase in medical indicators from late August onwards which appears again to be stabilizing by mid-October. This was very likely due to the increased intermingling due to the Ganpati festival combined with the opening up of the economy. Mumbai Sero-Survey [2] indicated high prevalence in the city and particularly in the slums in early July. Given the increase in reported cases from the city especially from the non-slum areas since then, the overall prevalence in Mumbai is likely to be quite high, thus allowing the city room to further open up. In this report, we use our IISc-TIFR agent based simulator described in detail in [3] to develop long term projections for Mumbai under realistic scenarios related to Mumbai's opening of the workplaces, or equivalently, the economy, and the associated public transportation through local trains and buses.

These projections were developed taking into account a possible second wave if the economy and the local trains are fully opened either on November 1, 2020 or on January 1, 2021. The impact on infection spread in Mumbai if the schools and colleges open on January first week 2021 is also considered. We also capture the increased intermingling amongst the population during the Ganpati festival as well as around the Navratri/Dussehra and Diwali festival. Our conclusion, based on our simulations, is that the impact of fully opening up the economy on November 1 is manageable provided reasonable medical infrastructure is in place. Further, schools and colleges opening in January do not lead to excessive increase in infections. While Ganpati festival had a substantial impact on medical indicators, if the intermingling level during Navratri/Dussehra and Diwali festival is similar, then, since these festivals occur later when a larger fraction of the population has already been infected, the resulting infections are likely to be less, and thus the overall impact on city's medical infrastructure also relatively less. Though not explicitly modelled, we expect similar conclusions to hold for the Chat festival and Christmas later in the year. Of course, if there is a substantial increase in interaction amongst the population during the upcoming festivals and the social distancing/masks related precautions are relatively weakened, then one may again see a significant rise in infections.

*Changes from the earlier report [4].:* This report is an update of an earlier one we released in early September [4]. The key changes, and the explanation for the modifications, are given below:

- To improve the modelling of the infection in high-density areas (slums) to better match the observed prevalence data [2], we increase the high-density transmission rate (HD-FACTOR set to 3, instead of 2).

- We use the data from [5] for age distribution in high-density areas and low-density areas to capture the fact that the high-density areas have a younger population (see Figure 1). This results in a lower fatality rate per infection within the high-density areas, and also an increase in spread within the high-density areas since there are more individuals in the working age-group.
- The population of Mumbai is taken to be 12.8 million as opposed to 12.4 million. This is in consonance with mid-year estimated population 2019 data with MCGM that updates the 2011 census data [6], [7].
- The intervention modelling includes lower compliance and higher community level interactions during the festive seasons. The details of this are explained in subsection II-A.

The net result of these changes is that in our model slums see high infections early on largely during April to June. Infections thereafter are primarily from non-slums. This matches the Mumbai scenario much better. Later in this report we also conduct some rudimentary experiments to ball park gauge the benefits and the costs of introducing *perfect* vaccines amongst the older population of Mumbai.

Our simulations further suggest that by mid-January 2021, the prevalence (fraction of the population infected) can be seen to be stabilising close to 80% in slums and 55% in non-slums. This stabilisation and high prevalence indicates that Mumbai city may have more or less reached “herd immunity” by then. By this we mean that the new infections and related medical indicators in the city will be substantially reduced compared to their peak values in mid-May and June 2020.

In these simulations we also conduct counterfactual experiments where the containment efforts as well as the contact tracing and testing efforts are varied and their impact on the health indicators is measured. Our simulations suggest that containment efforts do a better job of slowing infection spread compared to increasing the contact tracing and testing efforts. Increase in the latter leads to only marginal improvement in slowing the infection.

Below, we list some policy recommendations for opening up the workplaces and schools and colleges in Mumbai that incorporates above considerations.

#### A. Policy Recommendations

- We had in the earlier version of this report [4], recommended gradual opening of the workplaces so that the increase in infections that may result from increased occupancy in local trains and other public transport is manageable. We continue to recommend

similar gradual opening up of the city and that the economy may be fully opened up by November 1 or soon thereafter, again with the opening up process carefully based on observed infections.

- Schools and colleges may be opened by first week of January 2021. As mentioned earlier, our simulations suggest that the resulting second wave from this opening up is minimal.
- Social distancing in public transport, staggering of office times, use of shifts to the extent feasible is recommended.
- Prevailing hygiene measures such as mandatory use of masks/face-covers, encouragement of regular hand-hygiene, regular disinfection of “high-touch surfaces” in trains and workplaces [8] etc. should continue as before.
- Our analysis of containment zones vis-a-vis contact tracing and testing suggests that wherever feasible and when the economic costs are not prohibitive, containment in regions where infection is seen to be present is a desirable option to slow the infection spread.

In addition to the various modeling assumptions listed in our previous reports [3], [9], our recommendations rely on two important assumptions.

- 1) Our first assumption is that the population, by and large, will continue to observe social distancing precautions including wearing of masks. This could change as public perception of risk changes over time. This may lead to increase in infections not accounted for in our projections.
- 2) Our second assumption is that the reinfection probability is sufficiently small for that population of Mumbai that it can be ignored in opening up of the city. We note that cases of reinfection have recently been reported. However, the number of such reports continues to be very few. If this changes and reinfection happens to a non-negligible proportion of the population, then our projections become less valid.

**Vaccines:** It is believed that a COVID-19 vaccine will become available sometime in 2021. Important decisions related to prioritising people to vaccinate and to manage the storage and distribution of vaccines would require careful analysis. This analysis would also include the cost and time taken in vaccine production, the effectiveness of the vaccines, the frequency of administering them to each person, the time that a vaccine takes to provide immunity, and the duration for which the immunity is provided. These are complex issues that require detailed analysis. Later in this report we conduct some very rudimentary simulation experiments

related to administering vaccines under simplified assumptions to get a ball park idea of the potential costs and benefits, in terms of number of fatalities and the load on medical facilities, of administering vaccines to relatively older population in Mumbai.

Our broad conclusions are that Greater Mumbai has an estimated 13.1 lakh people aged 60 and older. If these are all vaccinated by February 1 with a vaccine that provides instantaneous and perfect immunity, then the number of fatalities post February 1 will reduce by estimated 53% from around 950 to 450 in the next six months. The hospitalisations (including critical cases) will reduce by estimated 40% from around 8840 to 5340 in the next six months. Similarly, if estimated 29.3 lakh 50 years and older Greater Mumbai residents are vaccinated on February 1, then the number of fatalities post February 1 will reduce by estimated 64% from around 950 to 340 in the next six months. The hospitalisations (including critical cases) will reduce by estimated 67% from around 8840 to 2910 in the next six months.

There have been varying news-reports on the differences among the population in how the disease spreads with respect to age, especially among the younger population. In particular, the role of the younger population in the transmission of the disease is not well-understood. In our earlier report [4], we took a cautious view and recommended opening of schools and colleges only as late as January 1, 2021, several months after the opening of the economy. Recent studies in the Indian states of Andhra Pradesh and Tamil Nadu [10] suggest that children in the age group of 0–14 pose a significant transmission risk, corroborating our recommendation.

**Caveats:** We emphasize that our simulator is intended primarily as a tool for comparing the effectiveness of different non-medical interventions to assist decision making. In particular, the simulator, due to the inherent model uncertainty, is not intended as a tool for predicting absolute numerical values of COVID-19 cases. In our informal view (which is difficult to validate scientifically), a confidence interval of  $\pm 20\%$  to  $30\%$  around the projected numbers may be reasonable to capture the model uncertainty. This number may be larger when estimates with small values are considered. On the other hand, the statistical error due to the random noise in the simulations is much smaller and is easily controlled.

We also recognize that many of the non-pharmaceutical interventions considered in our study, especially when they remain implemented over a long duration, may lead to important social and economic concerns and consequences, beyond their effect on the evolution of the epidemic. Prolonged restrictions, besides economic concerns, may also lead to disruption of many essential supply chains and medical services. The World Health Organisation Pulse

report [11], based on responses from over 100 countries, show significant reductions in routine vaccinations, diagnosis and treatment of noncommunicable diseases, antenatal care, cancer diagnosis and treatment, and many others. These are important factors that must be taken into consideration when implementing any prolonged restrictions. However, we do not know how to quantitatively project many of the socio-economic effects of a non-pharmaceutical intervention. The scope of our simulator is to project purely COVID-19 related stresses on the medical infrastructure. The modelling of such socio-economic effects, though important, remains beyond the scope of our simulator.

Similar to our previous report, we emphasize that this report has been prepared to help researchers and public health officials understand the effectiveness of social distancing interventions related to COVID-19 in terms of the stresses on the medical infrastructure. The report should not be used for medical diagnostic, prognostic or treatment purposes or for guidance on personal travel plans.

## II. TOWARDS FULLY OPENING MUMBAI

Greater Mumbai (consisting of Mumbai and Suburban Mumbai) has a population of about 1.28 crores (12.8 million) and a population density of roughly 21,000 per km<sup>2</sup> making it one of the densest cities in the world<sup>1</sup>. Further, about 53% [12] of Mumbai lives in cramped dwellings with shared sanitation facilities where the population density may be 5 to 10 times larger than other parts of the city. In addition, crowded suburban trains are the lifeline of the city where the suburban railway system serves more than 80 lakh (8 million) passengers on a weekday, in normal times [13]. It is generally believed that the infection spreads faster in denser areas, due to increased contacts in these areas. Given these factors, the public health threat in Mumbai is particularly acute. The importance of modelling the effect of infection spread arising from the gradual opening and relaxation of lockdown measures, for a city like Mumbai, cannot then be over-emphasized. We model the spread of infection in the city using our IISc-TIFR agent-based city simulator [3]. For completeness, we briefly review it below.

**Agent-based city simulator (ABCS):** As described in detail in [3], our agent-based simulator creates a synthetic model of about 1.28 crore (12.8 million) residents of Mumbai that matches the city population ward-wise, and matches the numbers employed, numbers in schools, commute distances, etc. This is done by suitably populating households, schools, and workplaces with people. Several interaction spaces including households, local communities,

<sup>1</sup>Some of the discussion in the Introduction first appeared in [9]

schools, workplaces, trains, etc. are then modelled to realistically capture the spread of infection. The synthetic city is then seeded with infections to match the observed fatalities till April 10. The infective individuals expose the susceptible individuals to the disease through their interactions in the various interaction spaces. The disease then incrementally evolves in time. The tool helps keep track of the number infected in the city as well as the disease progression within an infected individual. A person infected by the disease may remain asymptomatic and recover, or may develop symptoms. A symptomatic person may recover or may develop severe symptoms and be hospitalised. A patient hospitalised may recover or may become critical. A critical patient may recover or may become deceased. The disease progression parameters are based on [14].

#### A. Scenarios considered

In this work we report the following scenarios:

- **Long term forecasts:** We develop long term forecasts till March 15, 2021 under the following six scenarios:
  - Containment effort set at 75% and at 60%. Exact modelling of containment effort relies on the modelling feature ‘neighbourhood containment zones’ introduced in [3] and is discussed later in Section III.
  - Train infection levels are set at normal  $\beta_T = 0.19 \times \beta_H$  (see [9] for detailed calculations to arrive at this number; that report also discusses the household transmission parameter  $\beta_H$  and the rationale that relates it to  $\beta_T$ . The value of  $\beta_H$  used is calibrated primarily to fatality data, and is given in Figure 2.) as well as to the larger value of  $\beta_T = 0.30 \times \beta_H$  to account for the additional infections that may occur in trains through passengers coming to Greater Mumbai through the neighbouring areas in the Mumbai Metropolitan Region (MMR). We further consider a more pessimistic higher value of  $\beta_T = 0.40 \times \beta_H$  to account for the inherent uncertainty in estimating  $\beta_T$  without availability of relevant data on infection spread through trains.

The workplace attendance is a good measure of economic activity. It is set in our model as follows: Lockdown till May 17. Mobility to workplaces set at 5% from May 18 to May 31. In June this is set at 15% and it increases to 25% in July. It is set at level 33% in August. For September and October it is set at 50%. And thereafter it fully opens (100% attendance) from November onwards.



Festivals in Mumbai are a time for increased intermingling amongst the population, and during this time compliance on wearing masks, maintaining social distance, etc. is likely to be less. We account for this in our model as follows:

- To account for increased intermingling due to the Ganpati festival, from August 20 to September 1, we increase  $\beta$  for community by  $2/3$ , and we reduce compliance from 60% in non-slums and 40% in slums to 40% in non-slums and 20% in slums. With this adjustment we observe that the fatality data from the model is fairly close to the actual observed fatalities in months of September and October.
- We do a similar adjustments for Navaratri and Dussehra for the period October 19 to October 25. For Diwali we conduct similar adjustments for the period November 8 to November 14.

The developed model is validated by comparing the model projections with the observed health data, that is, observed number of fatalities, hospitalisations and critical cases.

As in [9], in all our simulations we continue to assume that outside the festival times, 60% of households are compliant in residential, relatively low density areas (non-slums), while 40% of households are compliant in slums or high density areas.

- **Fully operational economy:** We consider the following three scenarios:
  - 1) The workplaces fully operational on November 1 and school/colleges open on January 1,
  - 2) workplaces fully operational on November 1 and school/colleges remain closed,
  - 3) workplaces and school/colleges fully operational from January 1.

Fully opening workplaces or the economy implies that the trains are back to the capacity as in normal pre-covid times. To err on the side of caution, we keep the train beta at a high risk level, that is,  $\beta_T = 0.4 \times \beta_H$ , in these scenarios.

- **Containment zones and contact tracing and testing** are regarded as two important policy tools available to decision makers in slowing the epidemic spread. Our small network framework (introduced in [3]) through the neighbourhood cells allows us to model neighbourhood containment efforts with reasonable accuracy. Further, the small network framework with the introduction of the community of friends and neighbourhood community, allows us to plausibly model the contact tracing and testing efforts. The methodology to aid in measuring contract tracing and testing in our model is introduced in [3]. This modelling feature is further discussed in Section IV. Through our model we evaluate the performance of containment efforts by measuring the health indicators as a



Age Group	Slum age Distribution	Non Slum Age Distribution
Upto 10 yrs	15.82%	15.82%
11-20 yrs	18.38%	12.77%
21-30 yrs	18.51%	13.98%
31-40 yrs	17.70%	14.94%
41-50 yrs	11.35%	14.27%
51-60 yrs	11.35%	14.27%
61-70 yrs	5.48%	9.40%
71-80 yrs	1.17%	3.63%
81 yrs and above	0.21%	0.94%

Figure 1: Age Distribution for Greater Mumbai. Age distribution for slums and non-slums for 12 years and above is obtained from [5]. We combine this with [6] and [7], assuming that both slums and non-slums have the same percentage of population younger than 12 years, to arrive at the overall age distribution for Greater Mumbai.

function of varying containment efforts. We similarly evaluate the the impact of varying level of contact tracing and testing efforts on the health indicators. While containment zones are relatively easier to administer compared to contact tracing and testing, our simulations suggest that the former may also be more effective in slowing the spread of the infection in the city. A caveat to keep in mind is that containment zones lead to restricting movements of relatively large number of people, and so may come at a significant economic and social cost.

- **Impact of Vaccination:** We consider the following simplistic scenarios: Population above the age of 60 is vaccinated on February 1. The vaccine comes into effect immediately and is 100% effective so that the vaccinated population instantly becomes immune. We also consider the scenario where population above the age of 50 is vaccinated on February 1. Medical statistics under both these scenarios are compared to the statistics under the no vaccine setting.

### III. SMALL NETWORKS AND CONTAINMENT

#### A. *Smaller networks*

As detailed in our previous report, each of the interaction spaces is further broken down in subnetworks that corresponds to most of the interactions that an agent has within that

Subnetwork	Larger interaction space	Description
Project	Workplace	Clusters of size 3–10 (uniformly chosen)
Class	School	All students of a specific age
Neighbourhood	Community	Grid cells of side length 178 mts
Close friends	Community	2–5 households randomly chosen for each household

Interaction space	Comment	$\beta$ value
Home	(calibrated)	1.93651
Workplace	(calibrated)	0.26862
Community	(calibrated)	0.02152
School	$2 \cdot \beta_{\text{workplace}}$	0.53723
Project	$9 \cdot \beta_{\text{workplace}}$	2.41758
Class	$9 \cdot \beta_{\text{school}}$	4.83507
Neighbourhood	$9 \cdot \beta_{\text{community}}$	0.19368
Close friends	$9 \cdot \beta_{\text{community}}$	0.19368

Figure 2: Interaction spaces, subnetworks and contact rates

interaction space (for instance, 90% of an agent’s interactions in the workplaces are within their “project” subnetwork). The subnetworks are listed as follows.

As in the earlier report [3], the contact rates are calibrated to match the observed growth of fatalities, and to have roughly equal contribution of infections from the household, community and workplace networks (including the subnetworks) in the “no-intervention” scenario.

### B. Containment strategy

While in [9] the containment zones were modelled at the ward level for computational ease, in the current implementation we aim for more accuracy through a finer and more accurate model of containment. In particular, we model containment at a neighbourhood cell level. Recall that our synthetic city is divided into a grid of square cells where length of each cell is 178 meters. Containment effort is modeled as an increasing adaptive function of the active hospitalisations observed in the neighbourhood cell. Number of hospitalisations is taken as the decision variable since it is easily observable as compared to tracking the number of positive cases in a cell, which may be harder to estimate accurately without extensive testing, and the two are highly correlated. The cell is incrementally closed as more number of hospitalisations are observed in it.

Specifically, suppose that the containment effectiveness (CE) =75% and there are 3,000 residents in a neighbourhood cell. Then, first hospitalisation leads to movement restriction of 25% internally amongst the residents as well as to and fro from the cell; second hospitalisation leads 50% movement restriction, and third hospitalisation onwards leads to 75% movement restriction. If, on the other hand, the neighbours in the cell are less than a thousand, then as long as there exists a hospitalised person in the cell, movement of every resident within the cell, as well as movements into and out of the cell are restricted by 75%.

More precisely, If containment effectiveness is set to a fraction  $y$ , and the neighbours in a cell equal  $n$  thousand, then every hospitalisation leads to  $y/n$  restriction in movement, and total movement restriction is capped at  $y$ . Thus, percentage of activity restriction (internally as well as in entering and leaving the cell), or containment effectiveness, is our control and we set it to

$$\min(hy/n, y),$$

where  $h$  denotes the number of people in the neighbourhood cell that are hospitalised<sup>2</sup>.

#### IV. SIMULATION RESULTS

As in [9], in all our simulations, outside of festival times, we set the compliance levels to 60% in residential or non-slum areas, and at 40% in high density or slum areas. This level of compliance with additional measures such a mask usage, case-isolation and home quarantine post lock-down, restriction on those above 65 to stay home, closed school and colleges match reasonably well the observed data on fatalities.

Further, accounting for the results of the Mumbai SeroSurvey [2], and in deviation from our earlier analysis in [9], we reduce the proportion of symptomatic population amongst those exposed to the Covid-19 disease to 40% from the earlier 66.67%. In addition, in our earlier simulation runs for Mumbai in [3], [9], [4]  $\beta$  values for homes and communities in slums were kept at two times the values for non-slums. In the current simulations this factor is increased to 3. As mentioned earlier, this better matches the observed prevalence estimates for Mumbai. The model is recalibrated to data using these adjustments.

##### A. Long term projections

We first discuss the long term projections. As mentioned earlier, we consider these under the workplace attendance scenario where after lockdown till May 17, there is 5% attendance

<sup>2</sup>In our current implementation, the number of hospitalized cases *excludes* those who are currently in critical care facilities.

from May 18 to May 31st. This increases to 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully opens November onwards. In addition, as discussed earlier, we adjust for increase intermingling in population during the three festival times. These projections are developed till March 15, 2021 under the following six scenarios.

- The containment effectiveness kept at 75% as well as 60%.
- The infection rate from trains kept at base risk level  $\beta_T = 0.19 \times \beta_H$  (recall that  $\beta_H$  corresponds to the household transmission parameter). This was derived as a plausible rate of infection in trains in [9]. To account for the uncertainty in such calculations and population from outside Greater Mumbai using Mumbai locals, we also consider the more pessimistic medium risk setting of  $\beta_T = 0.30 \times \beta_H$  and high risk setting of  $\beta_T = 0.40 \times \beta_H$ .

As in Reports [3] and [9], in our simulations, a synthetic city is created that match the aggregate Mumbai demographic data. For this city we run 5 independent simulations. The reported results are the average of these five runs.

In Figures 3a and 3b, we show the daily as well as the cumulative number of infections under the six scenarios. These results suggest that the growth of infections in Mumbai started to slow down from June, with slight increase every time the economy opened further or due to the festival season. From January 1 onwards the number of new infections becomes very small indicating that by and large herd immunity has been reached by the city. Furthermore, this suggests that city will stabilize with close to 8-9 million residents infected.

In Figure 4, we map the prevalence for all of Mumbai suggested by the model when CE is set to 0.60 and  $\beta_T$  is set at  $0.4 \times \beta_H$ . We also separately plot the prevalence for slums and non-slums. The salient observations are that herd immunity is reached at different level of prevalence in slums and non-slums. In slums this is attained at around 85%, while in non-slums the number is closer to 60%. The Mumbai SeroSurvey [2] suggested around 55% prevalence in slums and 15% prevalence in non-slums of the three wards of Mumbai that were sampled around the first two weeks of July. Due to a typical gap of 1-2 weeks between the time the infection happens and it can be detected by a serological test, we compare this with our model output on July 1. Our respective numbers on July 1 of 55% and 15% are more or less identical to theirs.

Figure 5a shows the daily number of the hospitalised patients as per our model under the six scenarios. In Figure 5b, we compare our hospitalisation numbers to the hospitalisation numbers reported by BMC in their Dashboard [15]. The BMC dashboard reports Dedicated Covid Hospital (DCH) as well as Dedicated Covid Health Centre (DCHC) aggregated together

and these are reported as hospitalisations under DCH and DCHC. We make the following adjustments to the data series from our model as well as from the BMC Dashboard to make the comparison between them more apples to apples.

- 1) As per personal communication with BMC, from mid-July onwards many of the hospital beds are taken up by patients coming from outside of Greater Mumbai (Greater Mumbai denotes the area that comes under the jurisdiction of BMC). These include patients coming from other areas in Mumbai Metropolitan Region (MMR) including Thane, Navi Mumbai and Vasai-Virar as well as from somewhat further regions such as Nasik. These are roughly estimated to equal 30% (based on feedback from a BMC official). To account for these, we increase our hospital patient projections by 30%, with the understanding that this increase is reasonable for comparison with observed data beyond mid-July.
- 2) The DCH and DCHC numbers reported by the BMC Dashboard include patients under ICU. In our model we report patients under ICU (critical patients) separately. Thus, we remove the ICU patients in the Dashboard data from the DCH and DCHC data.
- 3) Further, based on the snapshot data provided by BMC on August 1 and August 20, we inferred that about 13% of patients in DCH and DCHC are asymptomatic. The disease progression data in our model is taken from [16] and [14], and here hospitalised patients correspond to those with serious symptoms. Thus, to compare our projections with the observed data, we further reduce the DCH and DCHC reported numbers by 13%.

It can be seen from Figure 5b that with the above corrections, post mid-July, our projections are reasonably close to the adjusted DCH and DCHC numbers.

In Figure 6a, the projected daily number of the critical cases under the six scenarios are shown. Again, to compare with the Mumbai ICU numbers as per the BMC Dashboard, we scale our numbers by 41% in Figure 6b. These again are based on a snapshot input provided by BMC where 41% of the critical beds used by the Mumbai population were in use by population from outside the city. Here too, the match between the adjusted model and data after mid-July appears reasonable. From May 27 to June 16 the occupancy of reported ICUs was seen to be above 98% as per the BMC Dashboard (except on May 29, when it was 97%). This may at least partially explain why the model numbers for critical cases in this period are much higher than the actual numbers.

Figure 7a shows the projected fatalities based on our model and compares them to the fatality data as reported by BMC through their Dashboard. Figure 7b shows cumulative number of fatalities as a function of time. As pointed out in earlier reports [3] and [9], in

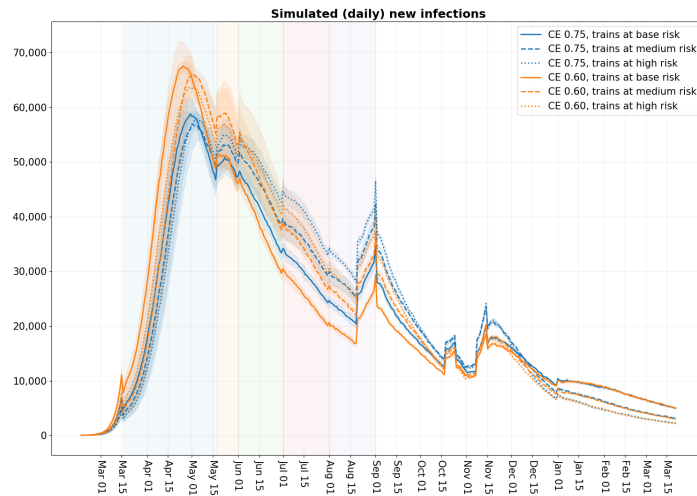
our model the key transmission rates are calibrated to primarily match the initial observed fatality data in Mumbai as well as in the rest of India. Further, the compliance parameters used in the model are fine tuned so that the model fatalities are close to the reported fatality data (as reported by BMC through their Dashboard [15]). As evident from the two figures, the match between the model generated fatality and the reported fatality data appears to be quite good. Few points are in order.

- BMC in mid-June had updated the reported deaths data. Figure 7b shows both the original and the updated reported fatality data. Observe, that our model (the data series corresponding to CE 0.60 and base or medium train risk  $\beta_T$  level) slightly underestimates this series from mid-May to mid-June. One reason for this may be that while in our model there is no limit on ICUs for critical patients, the city of Mumbai did observe this shortage around that period.
- Our model reports higher number of deaths (under CE 60%, and high train risk  $\beta_T$  value) compared to the reported from July onwards. This may be partially explained by the fact that around mid-June BMC stopped testing dead bodies for covid [17].

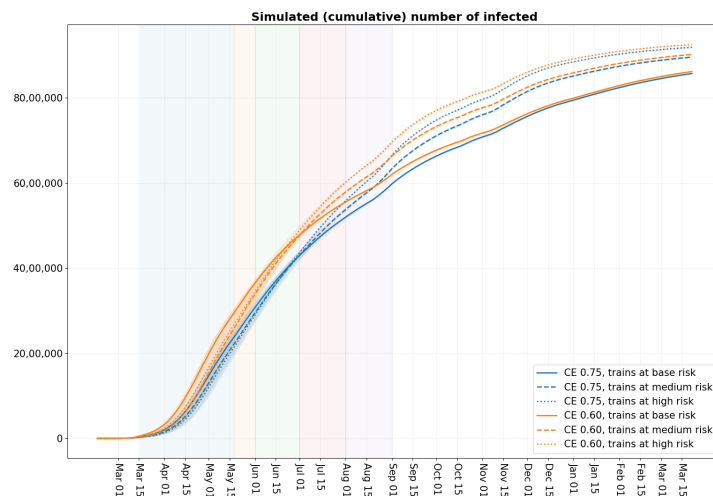
A broad conclusion suggested by our model is that the fatalities in the city will stabilize within 13,000 to 14,000 by March 2021.

In Figures 8a and 8b, we report the observed daily and the cumulative cases in Mumbai. In Figure 8a we also report the daily tests conducted to illustrate the correlation between these and the observed cases. This correlation is especially strong from September first week to mid-October. Since these numbers are a function of the testing strategy followed, they are difficult to estimate. Later, in Section VI, we discuss our contact testing and tracing strategy that was tailored to the case data from mid-May onwards until the last ten days of August. However, since then the amount of testing in Mumbai has significantly increased and we do not have an accurate model to estimate the number of positive cases thereafter.

In Figure 9 we report the time series of fatalities in slums and non-slums as per our model (the actual data is not available). The model result suggest that fatalities in slums peaked during the months of May and June. They plateau around their peak from July to October in non-slums.



(a) Daily new infections under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. Includes Ganpati, Navratri/Dussehra and Diwali relaxations.



(b) Cumulative infection growth under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. Includes Ganpati, Navratri/Dussehra and Diwali relaxations. Under this schedule as per simulations the city stabilizes with 8 to 9 million of the population infected.

Figure 3



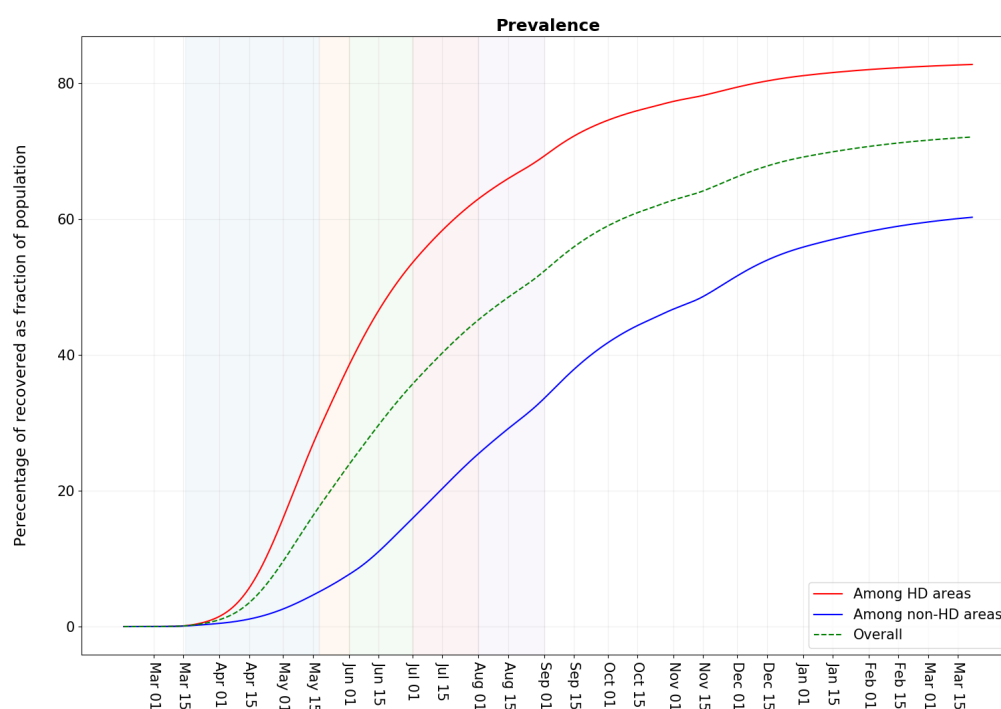
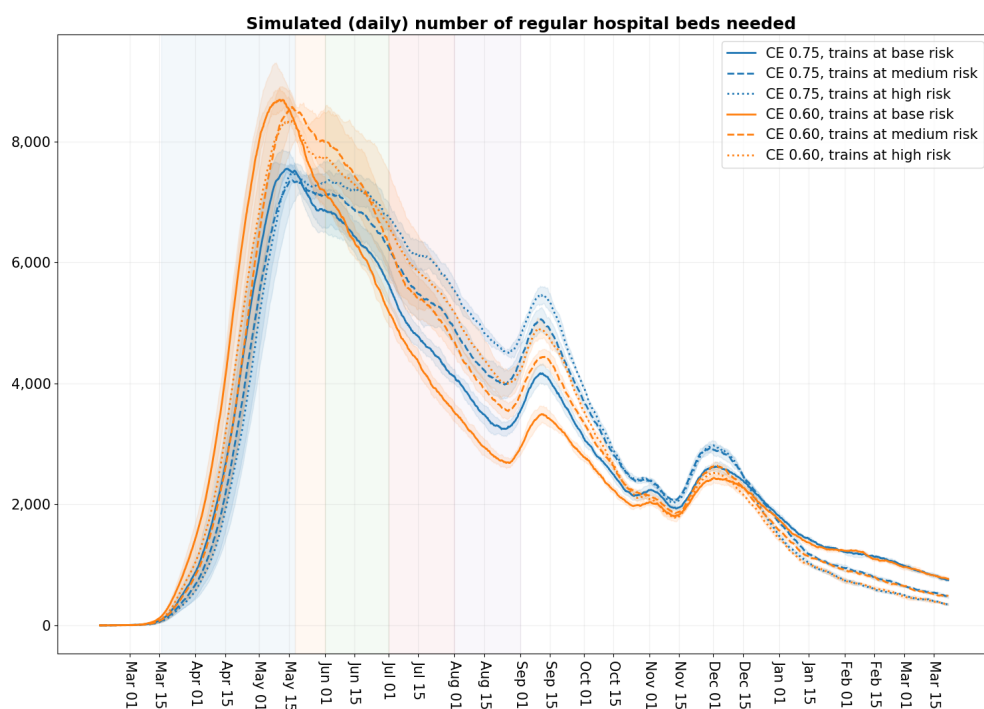
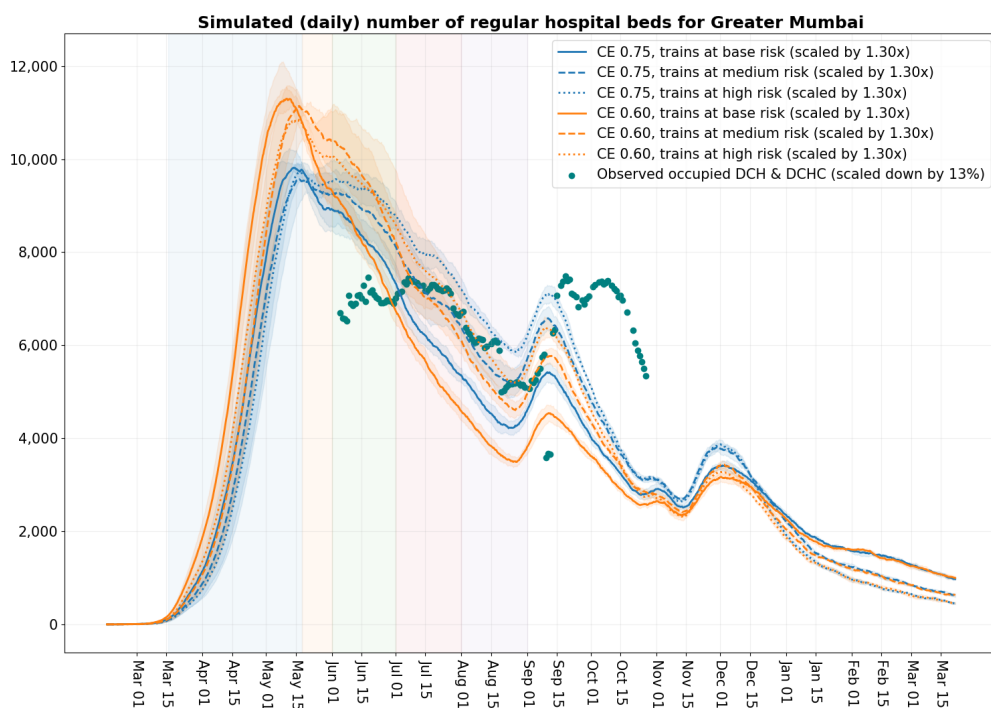


Figure 4: Simulated prevalence in Mumbai slums (HD areas) and non-slums under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. Includes Ganpati, Navratri/Dussehra and Diwali relaxations. The herd immunity in slums is attained at around 80%, while in non-slums it is attained at prevalence close to 55%.

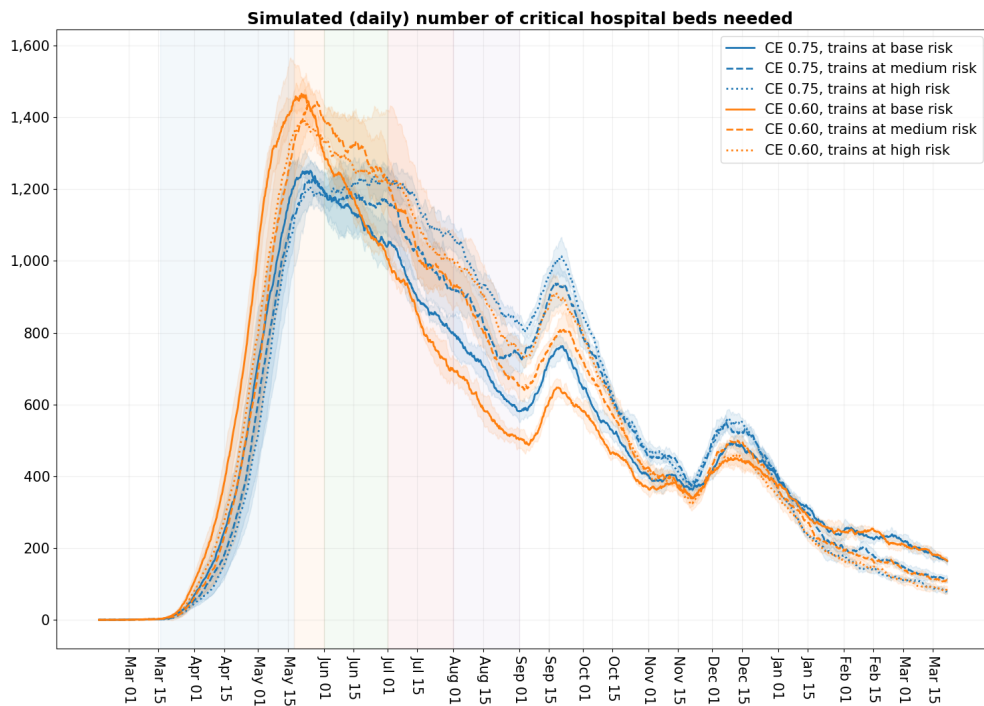


(a) Simulated daily hospitalised patients in the city under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% till October and 100% from Nov. Includes Ganpati, Navratri/Dussehra and Diwali relaxations.

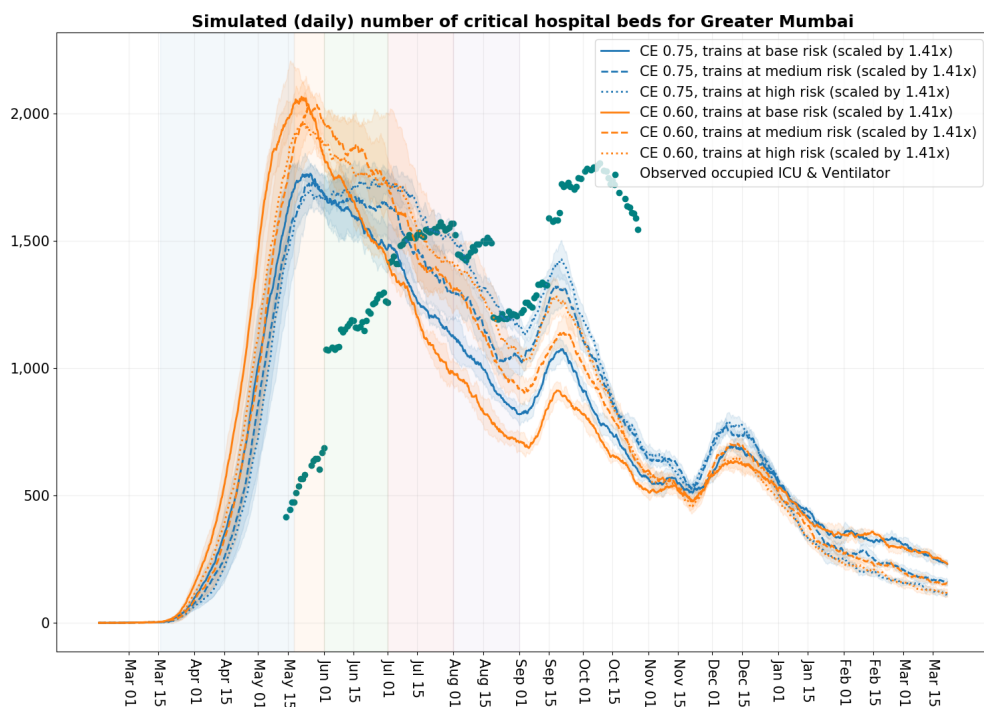


(b) Comparison of simulated daily hospitalised patients in the city with the DCH and DCHC numbers reported by BMC. The simulated numbers are increased by 30% to account for estimated patients coming from the other MMR areas. These cases came to Mumbai mainly from around mid-July. The ICU numbers are removed from the reported DCH and DCHC numbers. These numbers are further reduced by 13% to remove the estimated asymptomatic patients in DCH and DCHC to facilitate comparison.

Figure 5

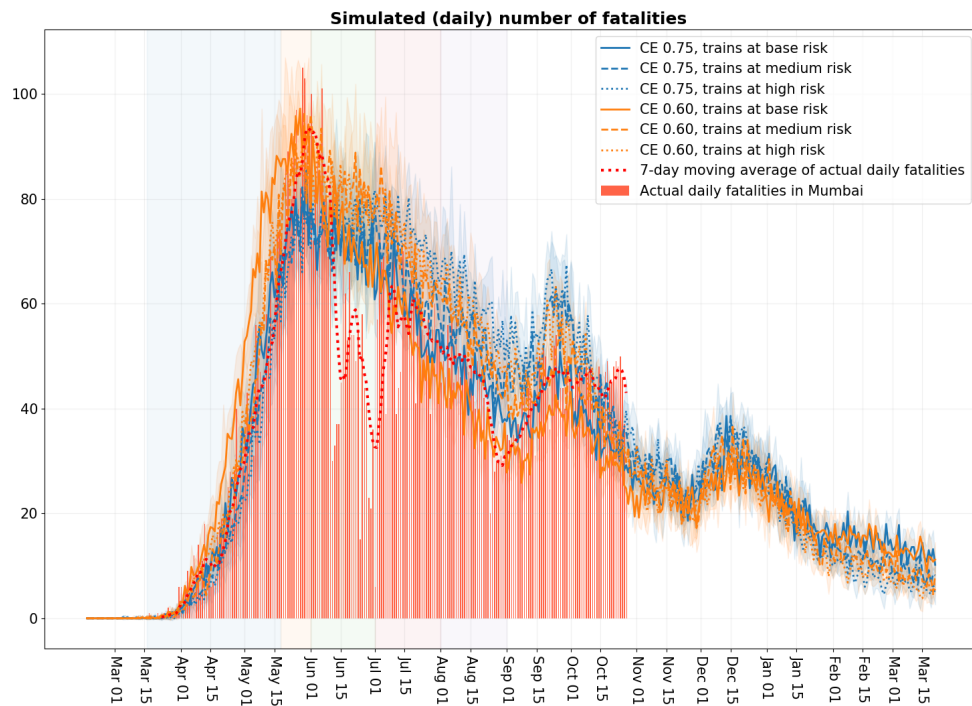


(a) Simulated daily critical patients in the city under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. Includes Ganpati, Navratri/Dussehra and Diwali relaxations.

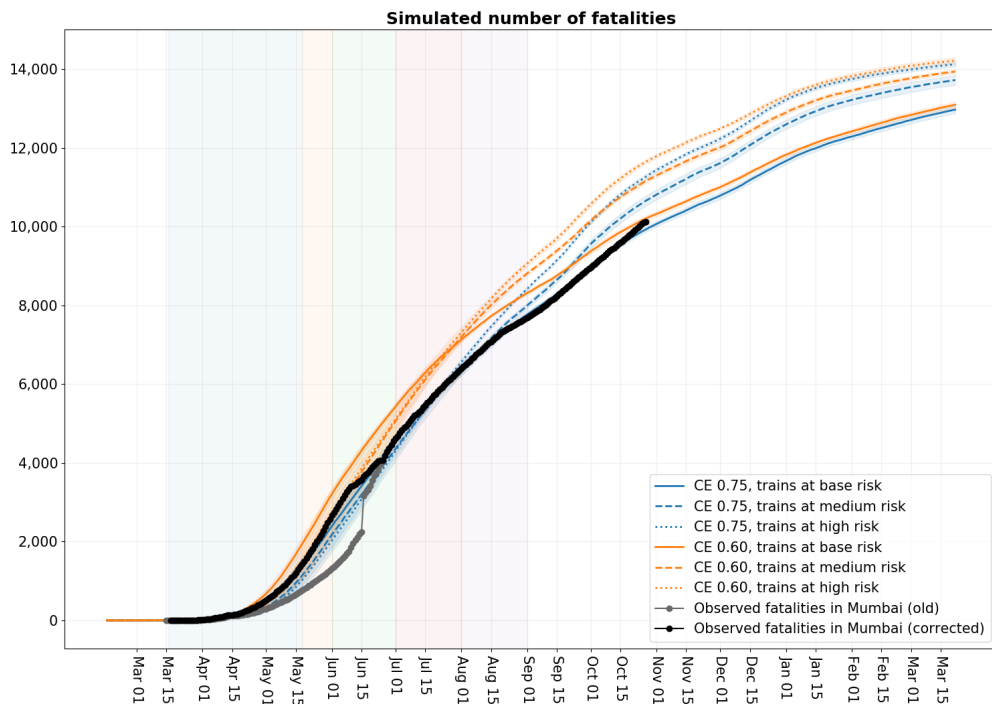


(b) Comparison of simulated daily critical patients in the city with the DCH and DCHC numbers reported by BMC. The simulated numbers increased by 41% to account for estimated patients coming from the other MMR areas. These cases came to Mumbai from around mid-July.

Figure 6

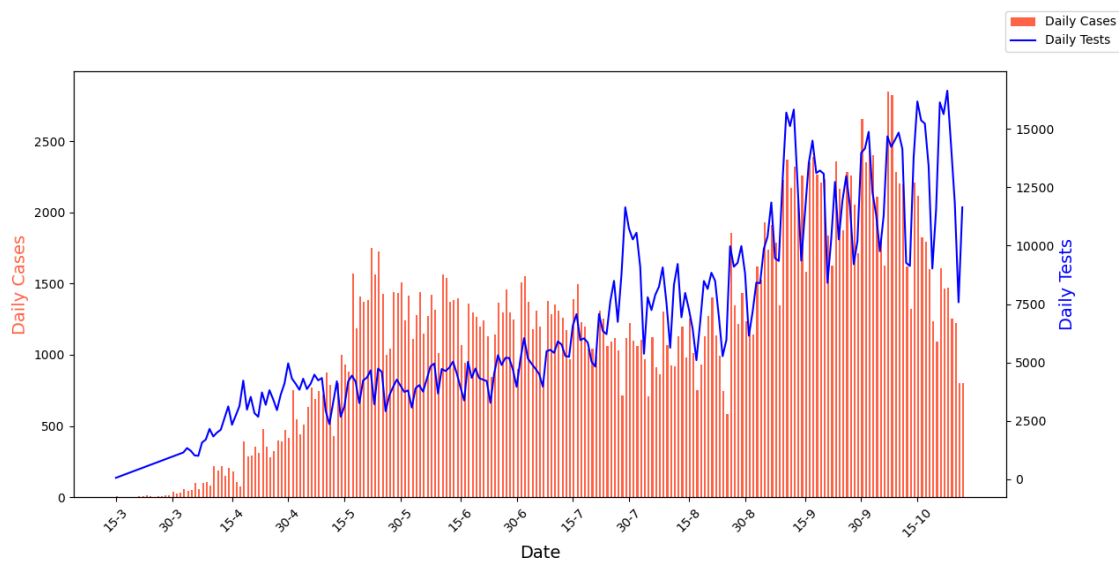


(a) Simulated daily deaths in the city under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. Includes Ganpati, Navratri/Dussehra and Diwali relaxations.

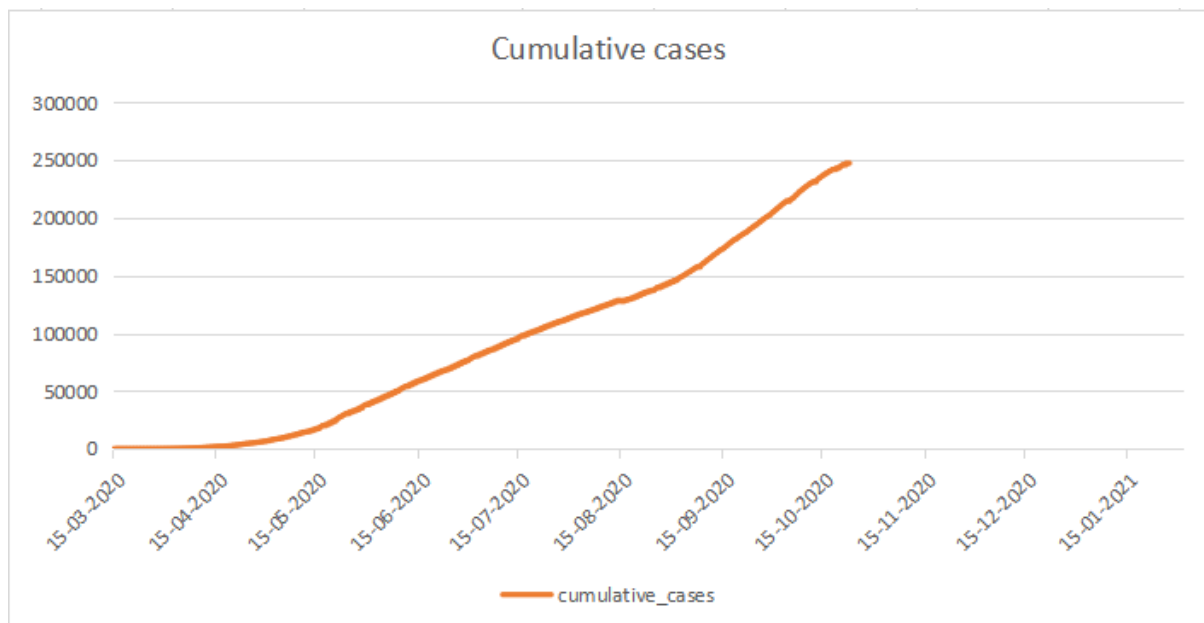


(b) Simulated cumulative fatalities in the city under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. Includes Ganpati, Navratri/Dussehra and Diwali relaxations. As per the simulations, the fatalities in the city stabilize around 14,000 by March, 2021.

Figure 7



(a) Daily reported cases and tests in the city.



(b) Cumulative reported cases in the city.

Figure 8

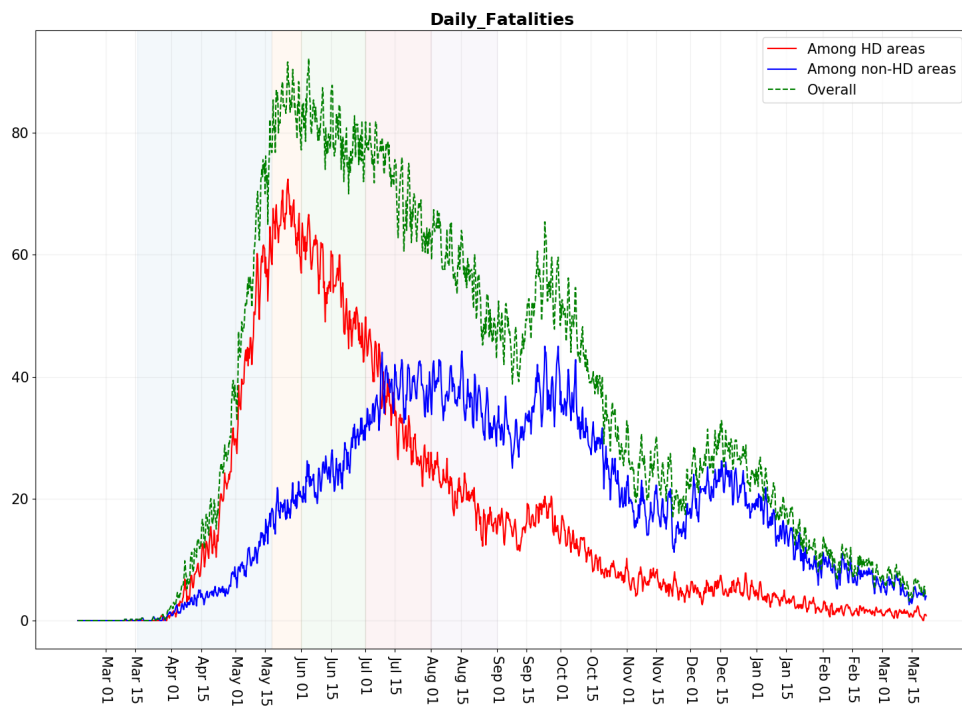


Figure 9: Simulated fatalities in Mumbai slums (HD areas) and non-slums under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. Includes Ganpati, Navratri/Dussehra and Diwali relaxations.

## V. FULLY OPERATIONAL OF ECONOMIC ACTIVITY

In Figure 10, we plot the simulated hospitalisations as well as critical cases where we compare the following three scenarios

- Workplaces fully open on November 1 and School/Colleges open from January 1.
- Both Workplaces and School/Colleges fully open on January 1.
- Workplaces fully open on November 1 and School/Colleges remains closed.

All the scenarios include Ganpati, Navratri/Dussehra and Diwali relaxations. The simulated hospitalised numbers and critical numbers are increased by 30% and 41%, respectively, to account for estimated patients coming from the other MMR areas. The ICU numbers are removed from the reported DCH and DCHC numbers. These numbers are further reduced by 13% to remove the estimated asymptomatic patients in DCH and DCHC. The train  $\beta_T$  is set at high risk, that is  $\beta_T = 0.4 \times \beta_H$ .

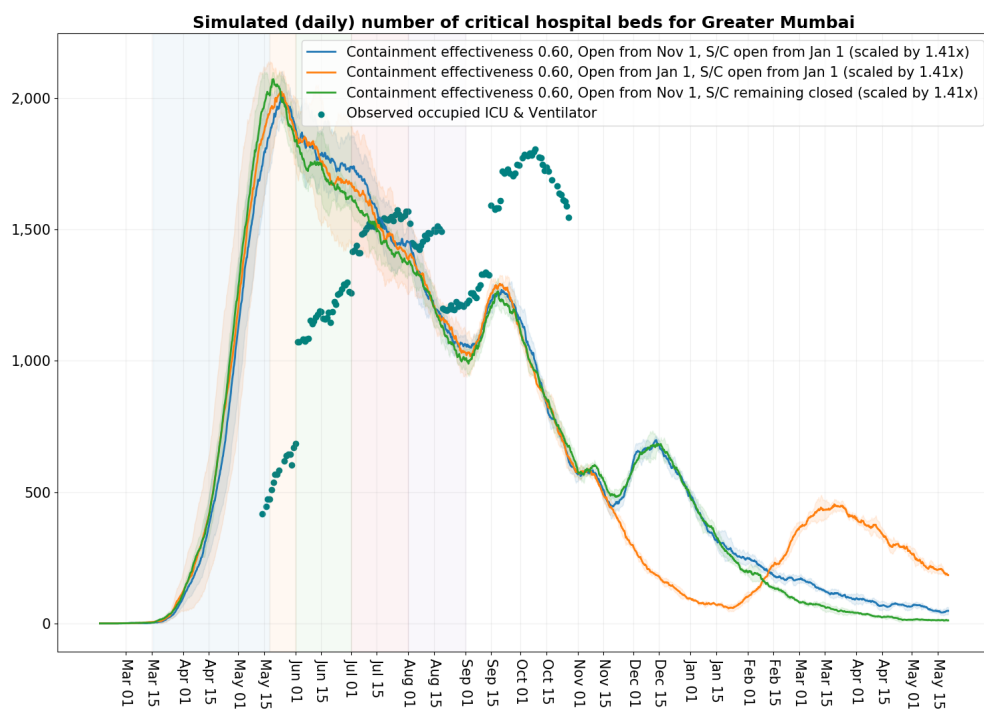
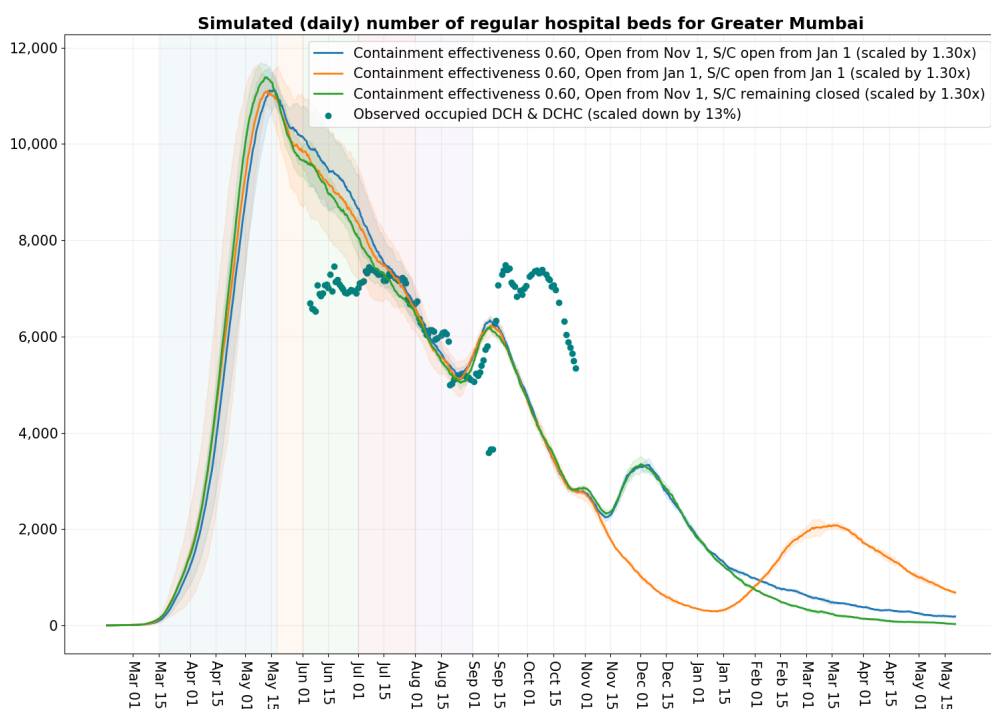
Our key observations are that the second wave of hospitalisations and critical cases is much higher with the November 1 opening compared to the January 1 opening. While the projected hospitalisations increase from around 2,300 a day to a peak of about 3,200 a day with the November 1 opening, the increase is from about 200 a day to around 2,000 a day on January 1 opening. Further, the opening of the schools on January 1 lead to only a small increase in hospitalisations and critical cases.

Under the November 1 opening the daily critical cases peak at around 700 in mid-December under November 1 opening. These peak at around 400 in mid-March after January 1 opening.

Figure 11 reflects a similar pattern in fatalities observed under these fully operational scenarios. While the projected daily fatalities increase from around 20 a day to a peak of about 30 a day with the November 1 opening, the increase is from about 4 a day to a peak of around 20 a day on January 1 opening.

Figure 12 show a similar pattern in number infected observed under these fully operational workplace scenarios.





**Figure 10:** Simulated number of daily hospitalized patients and daily critical cases under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards with School/Colleges opening from January 1. This schedule is overlaid with scenarios of 1) workplace and s/c opening from January 1, 2) Workplace open from November 1 and s/c remaining closed. All the scenarios include the three festival relaxations. The simulated hospitalised numbers and critical numbers are increased by 30% and 41% respectively to account for estimated patients coming from other MMR areas. The ICU numbers are removed from the reported DCH and DCHC numbers. These numbers are further reduced by 13% to remove the estimated asymptomatic patients in DCH and DCHC.

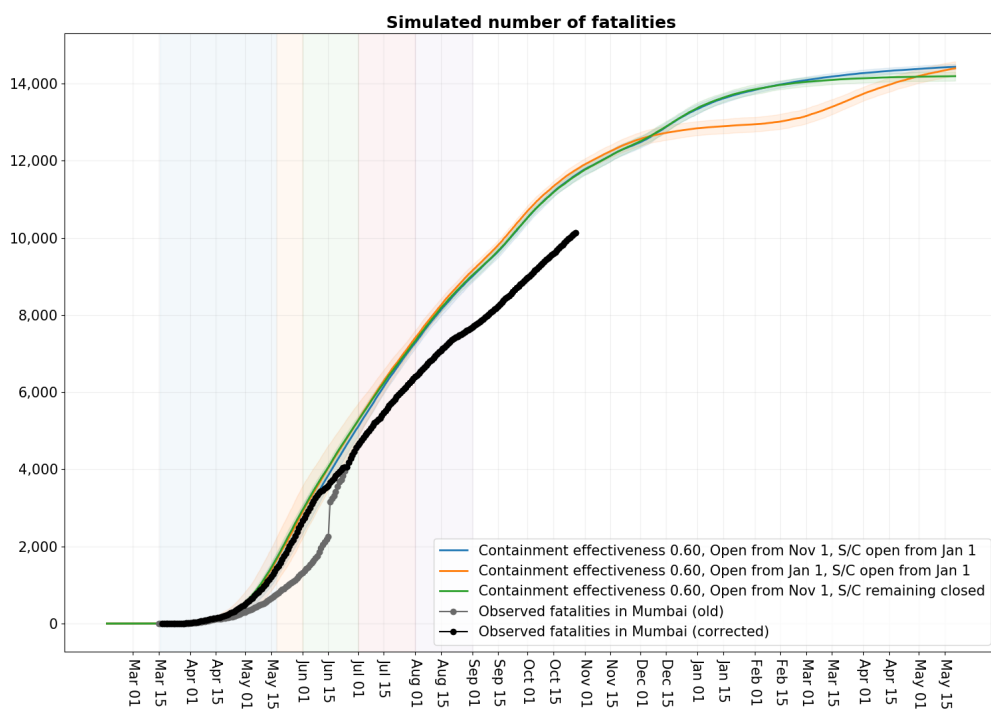
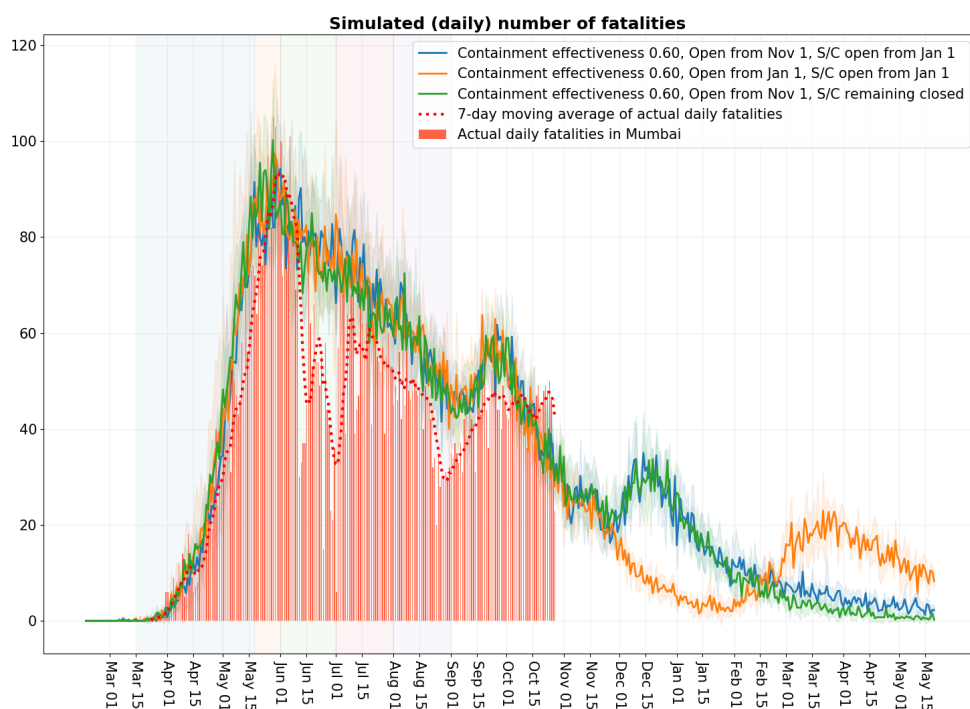


Figure 11: Simulated number of daily and cumulative fatalities under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards with School/Colleges opening from January 1. This schedule is overlaid with scenarios of 1) workplace attendance of 100% and school/colleges opening from January 1, 2) Workplace fully open from November 1 and school/colleges remaining closed. All the scenarios include the three festival relaxations.

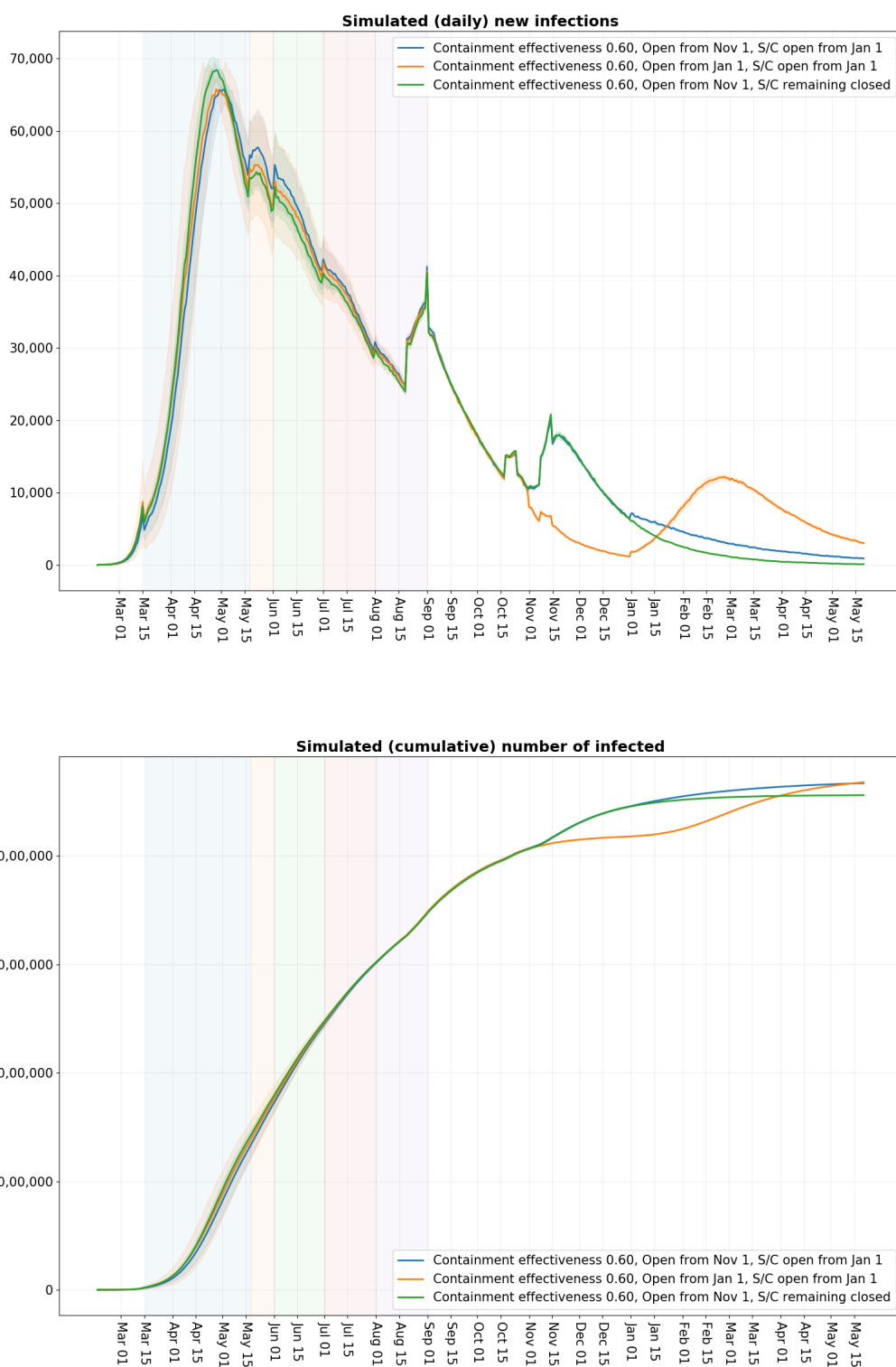


Figure 12: Simulated number of daily and cumulative infections under the workplace opening schedule 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards with School/Colleges opening from January 1. This schedule is overlaid with scenarios of 1) workplace attendance of 100% and school/colleges opening from January 1, 2) Workplace fully open from November 1 and school/colleges remaining closed. All the scenarios include the three festival relaxations.

## VI. COMPARING CONTAINMENT ZONES WITH CONTACT TRACING AND TESTING

For the comparison between the two strategies, containment zones are implemented as explained in Section III, while contact tracing and testing strategy designed to reflect the testing strategy and data from mid-May to mid-August is explained below.

### A. Contact tracing and testing

The contact tracing machinery can be briefly described as follows:

- 1) An individual that the simulator deems as a *hospitalised* case undergoes a COVID-19 test with some probability (specified by the protocol given in Figure 13). If the test turns out to be positive, this agent is deemed as a *hospitalised index case*. This hospitalised case is typically tested with probability 1, although later in Section VI when we evaluate medical statistics under different testing protocols, we allow this probability to take lower values of 0.66 and 0.8 as well.
- 2) When an *index case* is identified, a fraction of agents from their subnetworks (specified by the protocol) are quarantined and marked as *primary contacts*.
- 3) Each primary contact is tested with some probability (specified by the protocol). If the test is positive, then such agents are marked as *positive index cases*. The newly discovered *positive index cases* would additionally initiate contact trace around this agent like in the *hospitalised index cases*.

In the current implementation, 0.5% of the neighbourhood cell (which is 5 agents on average) and 100% of all other subnetworks are deemed as the agent's primary contacts. Furthermore, the testing probabilities in our current implementation are set to match a rough test positivity rate of 30% to 40%, which is the observed test positivity rate during the months of June and July in Mumbai [15].

Figures 14 and 15 show the impact of increasing containment effort on the resulting city medical statistics. Recall that containment efforts reduce the movement of individuals within the neighbourhood containment cell as well as those going out from or coming into the containment cell. The graphs indicate that containment efforts go a long way in slowing the infection. Thus, containment is an effective tool available to policy makers for slowing down the infection spread.

Figures 16 and 17 show the impact of increasing contact tracing and testing on the resulting city medical statistics. To test the intensity of contact tracing and testing, we consider three scenarios where the hospital index probability (the probability with which a hospitalised case is tested) takes values 0.66, 0.80 and 1.0.

Subnetwork	Type of index case	Status of primary contact	Test probability
Household	Hospitalised	Symptomatic	1
	Hospitalised	Asymptomatic	0.45
	Positive	Symptomatic	1
	Positive	Asymptomatic	0.45
Project	Hospitalised	Symptomatic	0.5
	Hospitalised	Asymptomatic	0.225
	Positive	Symptomatic	0.25
	Positive	Asymptomatic	0.1125
Close friends	Hospitalised	Symptomatic	0.25
	Hospitalised	Asymptomatic	0.2
	Positive	Symptomatic	0.125
	Positive	Asymptomatic	0.06
Neighbourhood cell	Hospitalised	Symptomatic	0.25
	Hospitalised	Asymptomatic	0.2
	Positive	Symptomatic	0.125
	Positive	Asymptomatic	0.06

Figure 13: Testing protocol

In these comparisons we have set the train transmission parameter  $\beta_T$  to  $0.3 * \beta_H$ . Further the relaxations due to the festivals are not considered.

The conclusion is that while contact tracing and testing does help in slowing the spread of the infection, the amount of reduction appears much less compared to that achieved through containment efforts, particularly since the latter appears to be cheaper and easier to implement.

The comparison between benefits of containment vis-a-vis contact tracing and testing is crystallised in Figure 18 where we plot the peak of moving ten day average of daily hospitalised patients as a function of these efforts. The contact tracing and testing effort measured on the x axis of the right hand figure corresponds to the hospital index probability for values 0.66, 0.80 and 1.0. We also consider the two higher contact tracing and testing cases where the hospital index probability is kept fixed at 1 but the remaining testing probabilities in the protocol are increased by 25% in one case and 50% in the other. These cases correspond to x-axis values of 1.25 and 1.5 in Figure 18.

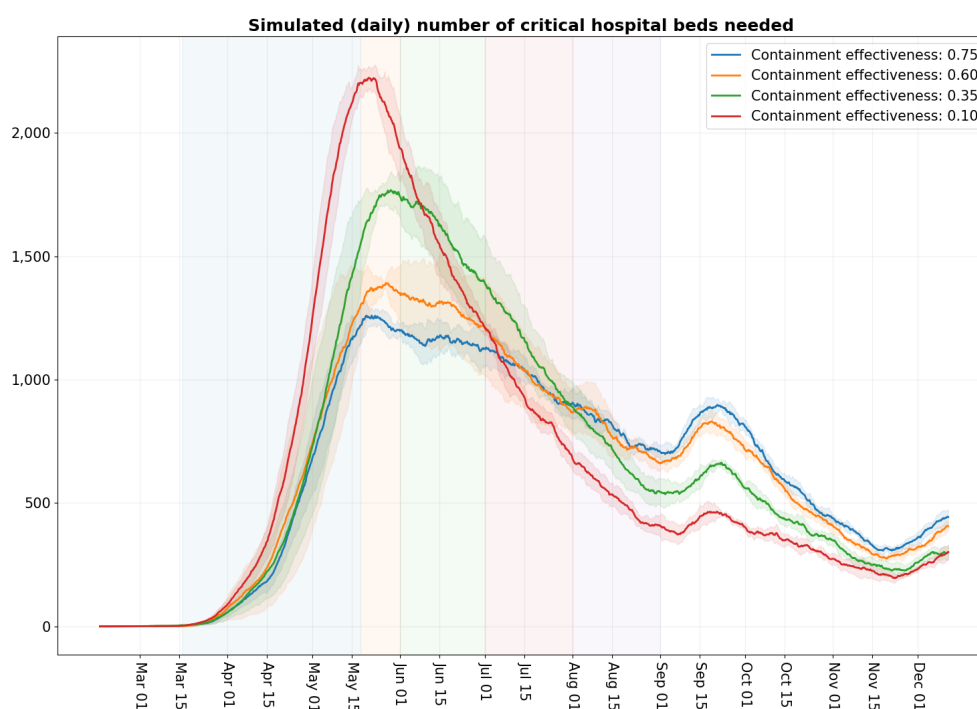
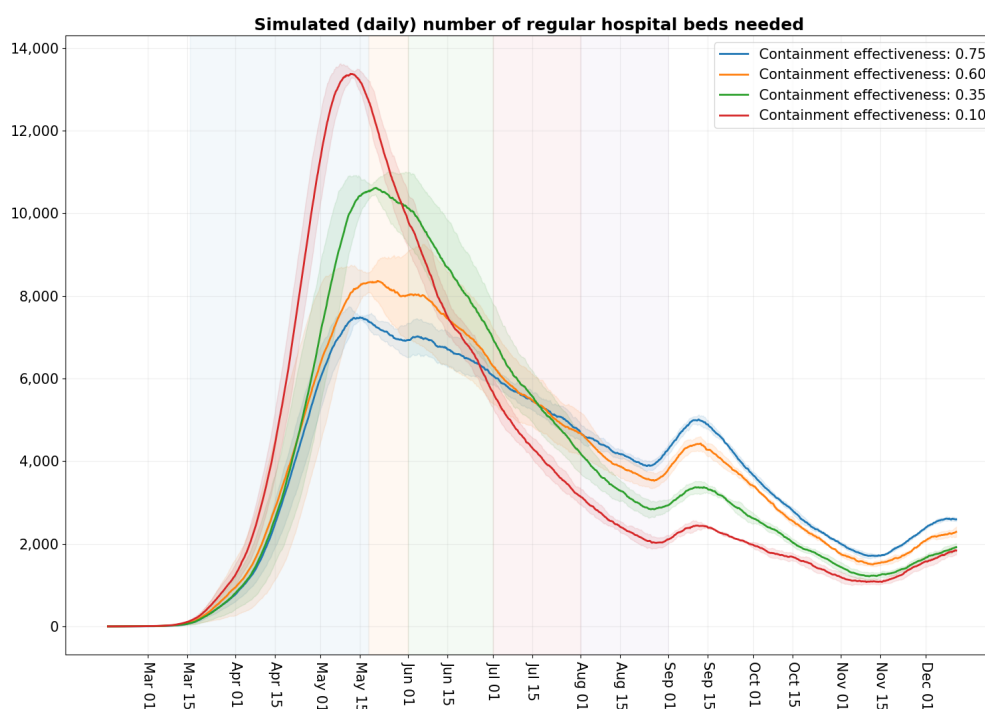


Figure 14: Simulated number of daily hospitalised patients and critical patients under varying level of containment efforts. Workplace opening schedule is set at 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards.

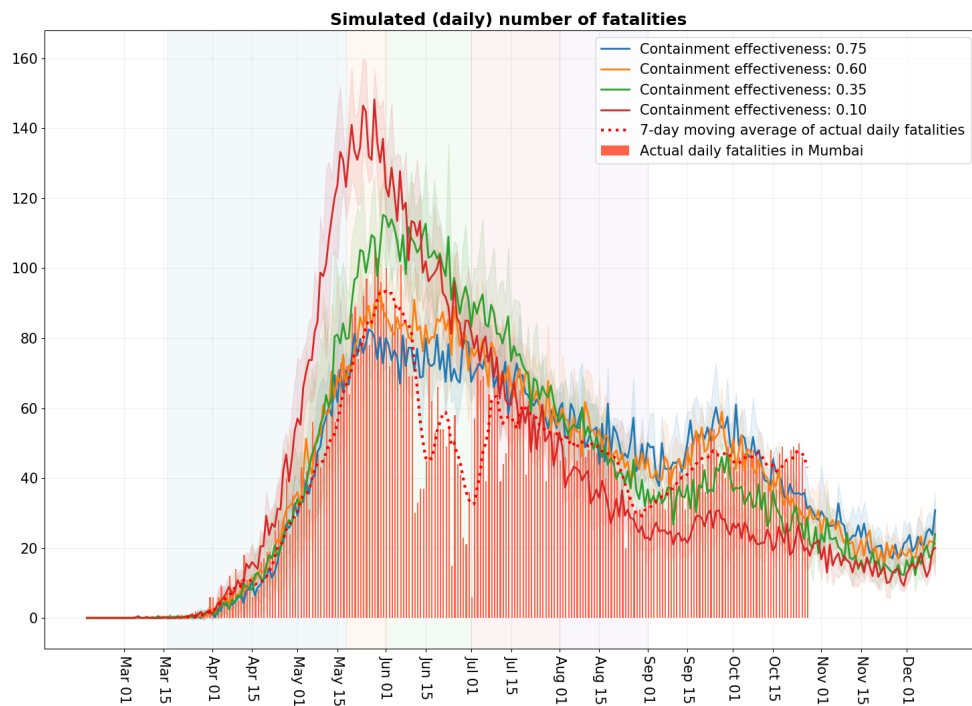


Figure 15: Simulated number of daily fatalities under varying level of containment efforts. Workplace opening schedule is set at 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards.



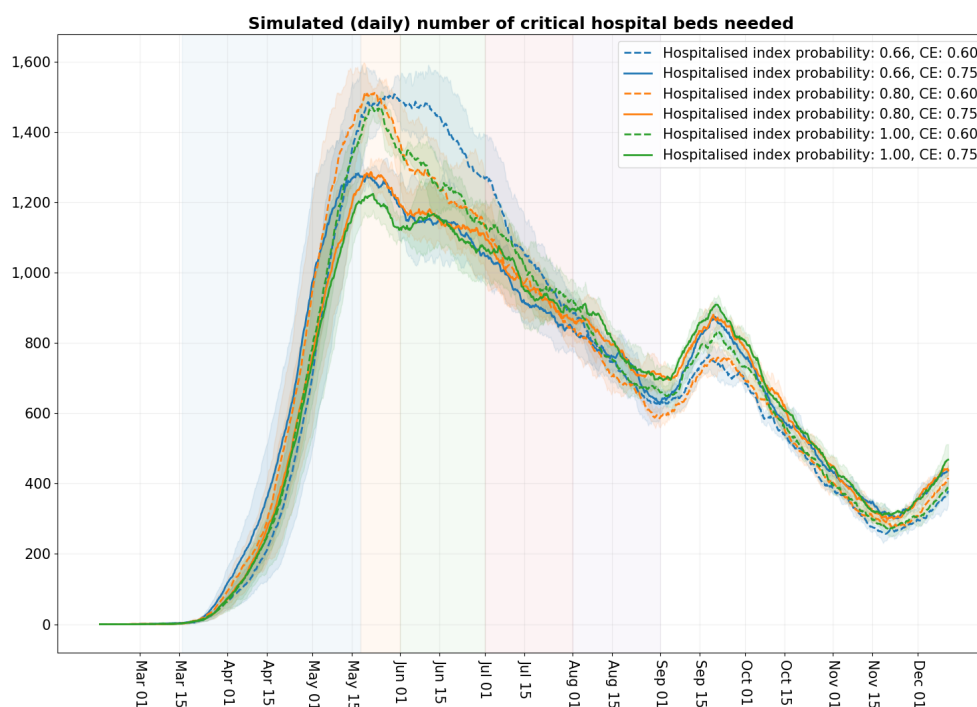
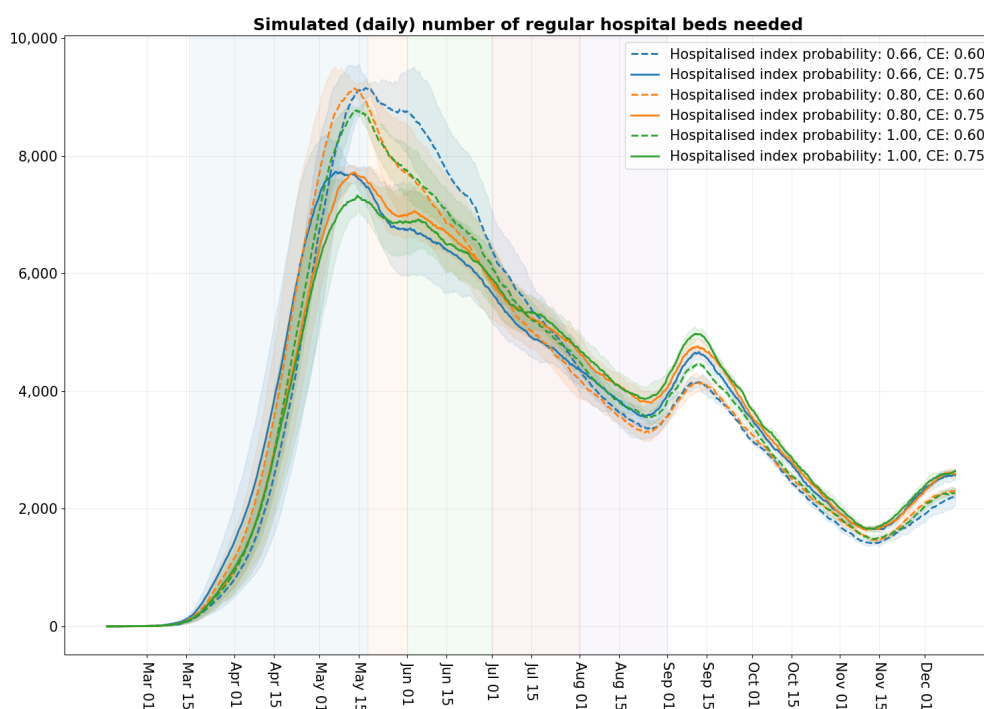


Figure 16: Simulated number of daily hospitalised patients and critical patients under varying level of contact tracing and testing strategies. Workplace opening schedule is set at 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards.

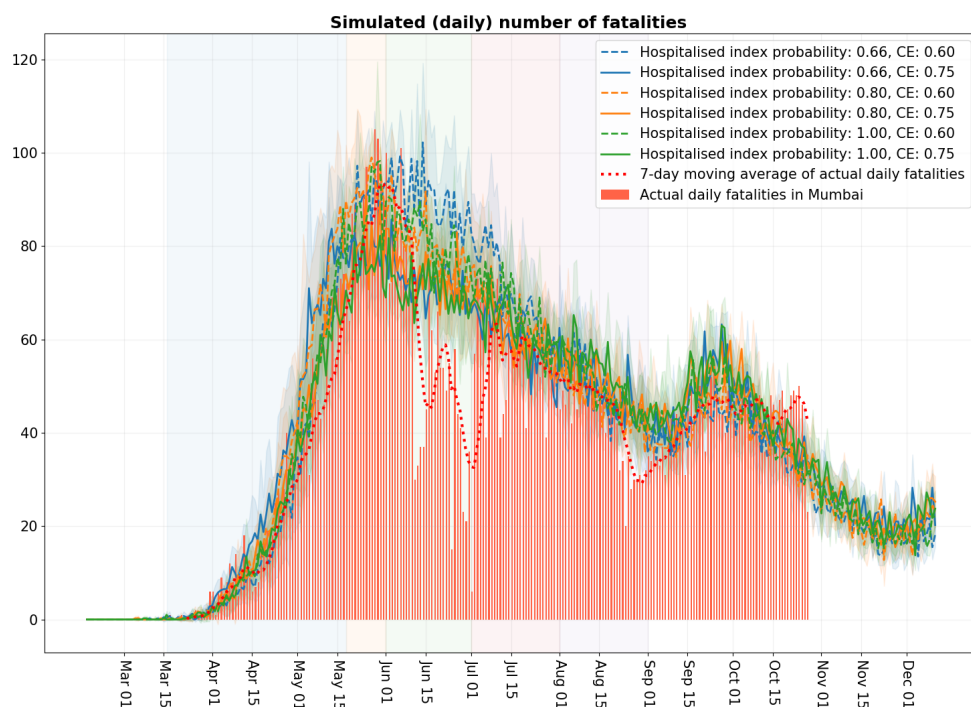


Figure 17: Simulated number of daily fatalities under varying level of contact tracing and testing strategies. Workplace opening schedule is set at 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards.

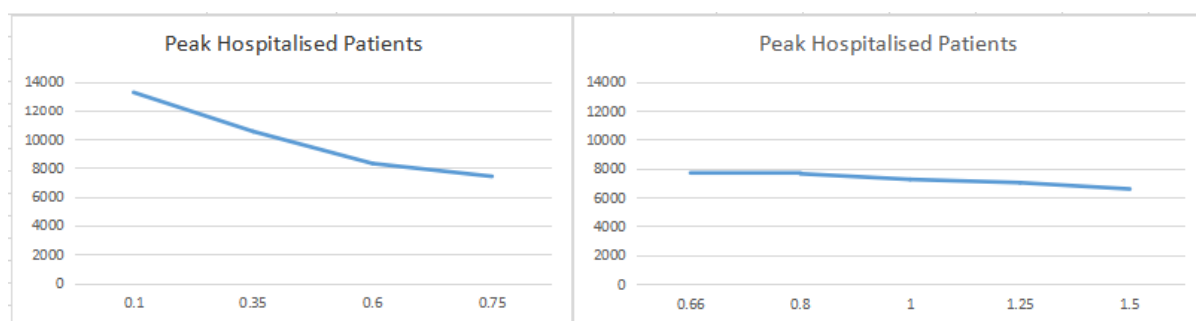


Figure 18: Comparison between benefits of containment effort vis-a-vis contact tracing and testing. The left figure reports the peak of moving ten day average of daily hospitalised patients as a function of containment effort. The right figure reports the same peak as a function of contact tracing and testing efforts.

## VII. IMPACT OF VACCINATION

Figures 19 and 21 show the impact of introducing vaccination on the resulting city medical statistics. The three festival relaxations are included in these simulations. The train transmission parameter  $\beta_T$  is set to its medium value  $0.3 * \beta_H$ . As mentioned earlier, to keep the discussion simple, we assume vaccines are administered to the specified population on February 1. They work instantly and provide complete immunity at least for the next six months.

Figure 20 suggests that by vaccinating people aged 60 years and above on Feb 1, 2021, around 498 lives (appx. 53%) can be saved in the next six months whereas vaccinating people aged 50 years above saves around 607 lives (appx. 64%) over the same period. It can also be seen from the simulation results that introducing vaccination significantly reduces the load on medical facilities. By vaccinating people aged 60 years and above on Feb 1, 2021, the hospitalisations (including critical cases) reduces to 5342 (from 8840 in the no vaccination case) which amounts to appx. 39.6% reduction. Similarly, by vaccinating people aged 50 years and above, the hospitalisations (including critical cases) reduces to 2908 (appx. 67% reduction).

The demographics of Greater Mumbai as estimated from Figure 1 suggests that approximately 13.1 lac Mumbai residents are aged 60 years or above. According to our simulations, out of these 13.1 lac, approximately 5.6 lac will be susceptible on Feb 1. Similarly, the total number of residents aged 50 and above is 29.4 lac whereas around 10.3 lac will be susceptible on Feb 1. Since, we may not be able to, or it may not even be desirable to, separate the susceptibles from the recovered population from vaccination viewpoint, we may have to vaccinate everyone in the respective age group to provide them immunity.

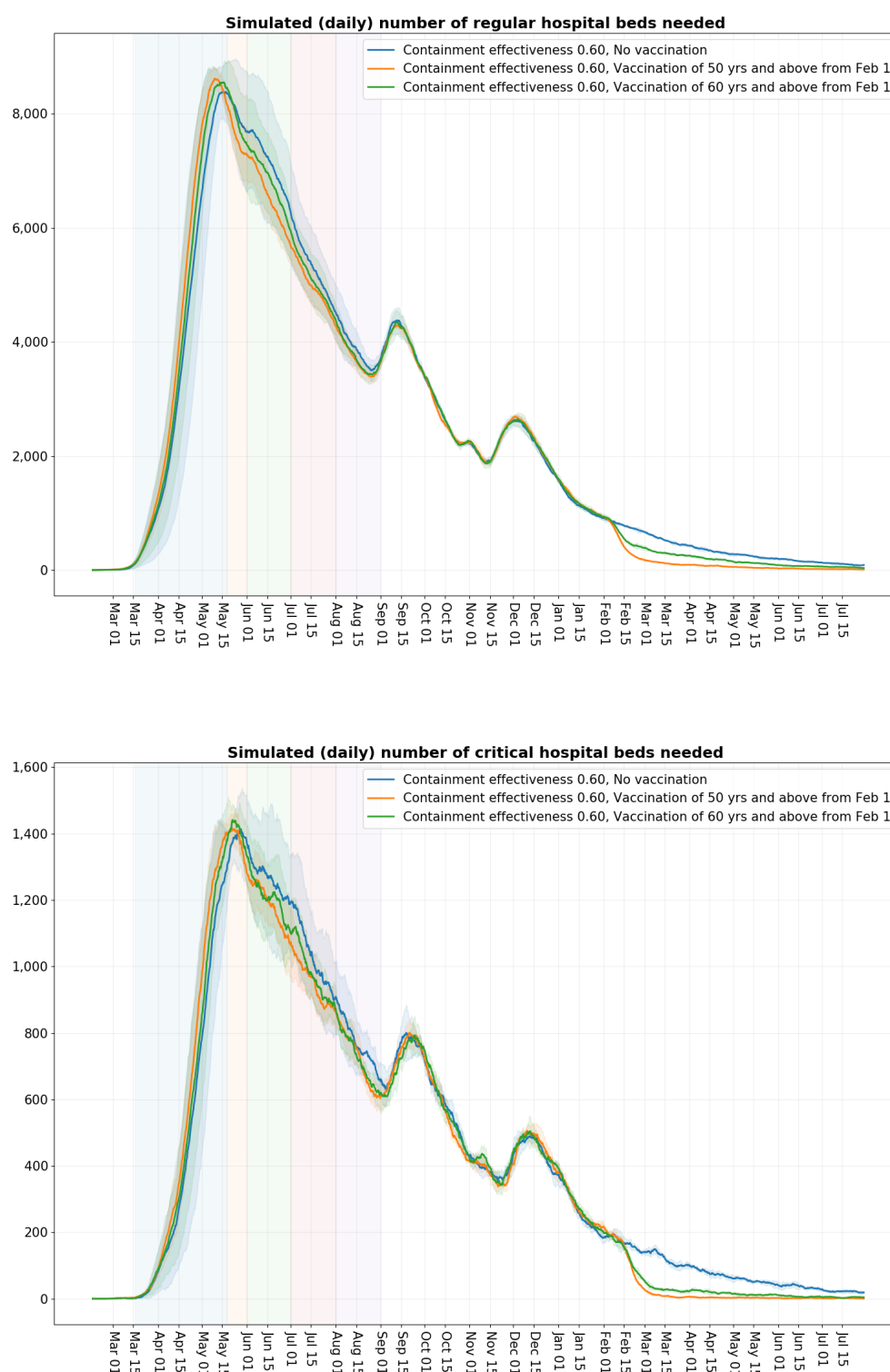


Figure 19: Simulated number of daily hospitalised patients and critical patients under scenarios of no vaccination, vaccinating people aged 50 years and above 60 years and above on Feb 1. Workplace opening schedule is set at 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. All the scenarios include the three festival relaxations.

Scenario	Fatalities	Hospitalisations (including critical cases)
No Vaccination	947	8840
Vaccination of people aged 50 yrs and above	340	2908
Vaccination of people aged 60 yrs and above	449	5342

Figure 20: Fatalities and hospitalisations (including critical cases) under scenarios of no vaccination, vaccination of people 50 years and above from Feb 1 and vaccination of people 60 years and above from Feb 1. Numbers shown are for a period of 6 months after Feb 1.

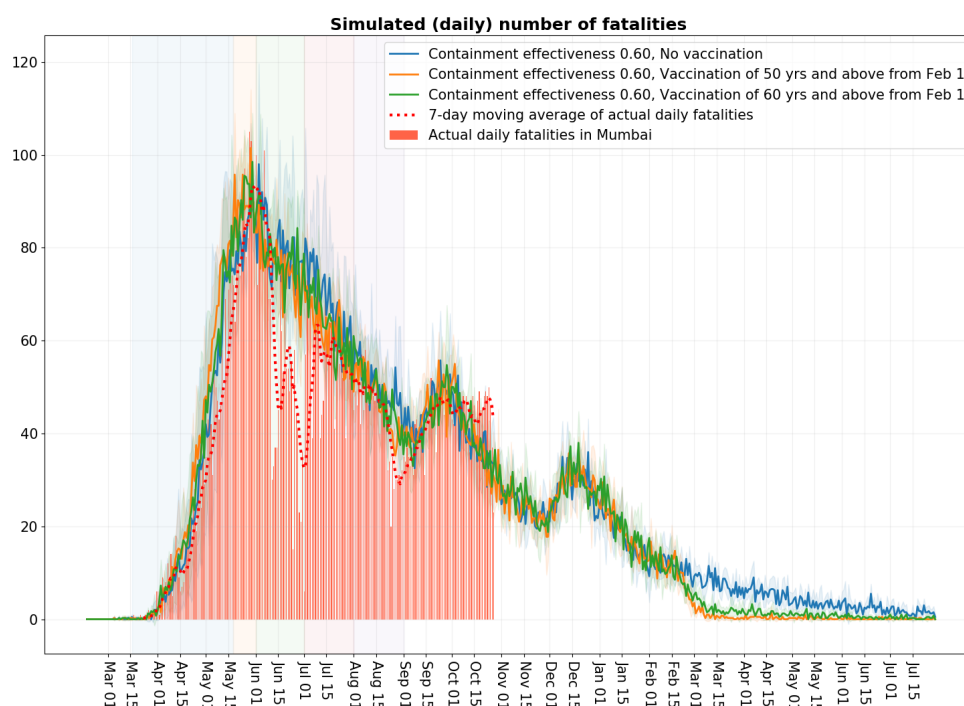


Figure 21: Simulated number of daily fatalities under scenarios of no vaccination, vaccinating people aged 50 years and above, and 60 years and above on Feb 1. Workplace opening schedule is set at 5% attendance, May 18 to May 31st, 15% attendance in June, 25% in July, 33% in August, 50% in September and October and fully open November onwards. All the scenarios include the three festival relaxations.

## ACKNOWLEDGMENTS

We thank our colleague Piyush Srivastava for many useful suggestions that helped our analysis. We thank Piyush as well as our IISc collaborators R. Sundaresan, P. Patil, N. Rathod, A. Sarath, S. Sriram, and N. Vaidhiyan for their tireless efforts in developing the IISc-TIFR Simulation model [3] and their key role in our earlier report on Mumbai [9].

We thank Mrs. Ashwini Bhide, AMC, MCGM for her insights and for her crucial data inputs. We also thank Bhaskaran Raman for his critical inputs on the socio-economic effects of prolonged non-pharmaceutical interventions. We thank Siddarth Raman, a volunteer at BMC, for his help with data.

Authors acknowledge support of the Department of Atomic Energy, Government of India, to TIFR under project no. 12-R&D-TFR-5.01-0500. RS is also supported by the Ramanujan Fellowship of DST. We also acknowledge the support of A.T.E. Chandra Foundation for this research.

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