

A Model Based Analysis for COVID-19 Pandemic in India: Implications for Health Systems and Policy for Low- and Middle-Income Countries

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Abstract

Background

Our analysis aims to model COVID-19 pandemic in India, potential impact of various measures, along with assessment of health system preparedness and cost to manage the epidemic.

Methods

We developed a susceptible-exposed-infectious-recovered (SEIR) mathematical model to predict the health outcomes under an unmitigated scenario which comprises of air travel restrictions alone, and the current scenario consisting of air travel restrictions along with 8-week lockdown. In addition, we also evaluate the effectiveness of 8-week lockdown along with intensified public health measures at varying level of effectiveness. We assessed the impact of these interventions on COVID-19 related health outcomes in comparison to the unmitigated scenario. Next, we ascertain the need for augmenting infrastructure and the costs of COVID-19 management in India.

Findings

In the event of a lockdown for 8 weeks, the peak of the epidemic shifts by 34-76 days, and the number of cases at the end of 8-week lockdown reduces by 69% to 97% with varying effectiveness of lockdown. However, the cumulative long-term cases remain the same. Intensification of public health surveillance measures with 60% effectiveness is estimated to reduce the cases at peak and cumulative number of infections by 70% and 26.6% respectively. The requirement of ICU beds and ventilators would reduce by 83% with intensified public health measures. The cost of managing COVID-19 in India is nearly 4.5% of the gross domestic product (GDP) in the absence of any intervention which increases to 6.2% with intensified public health measures for COVID-19 response.

Conclusion

Lockdown measures delay the onset of peak, and give much needed time to health system to prepare. Strengthening the public health system response in terms of testing, isolation treatment of cases, and contact tracing needs would lead to significant gains in terms of case load, and meeting health system needs.

Summary

What is already known?

A few studies have been carried out in Indian context to model the epidemic. These models explored the impact of lockdowns and social distancing measures focusing more on the course of the epidemic but none of these evaluated the impact on health system's response needed as well as the economic impact of COVID-19 management in India. The findings from these studies are limited in a sense that either these studies evaluated the hypothetical scenarios of strategies implemented or focusing to smaller geographical regions in India.

What are the new findings?

Evidence pertaining to health economic impact of COVID-19 management, in context to Low- and Middle-Income countries, is very limited. To address this, we used the susceptible-exposed-infectious-recovered (SEIR) model to assess:

- the health system preparedness challenge in terms of hospital beds for isolation, intensive care and ventilators which would be required to manage the epidemic and the economic implications of managing the COVID-19 pandemic in India.
- the incremental cost of intensified public health measures per infection and per death averted.

What do the new finding imply?

In India, measures such as lockdowns would certainly delays the onset of peak of COVID-19 epidemic. This would help delay the surge of cases, which would buy time for the health system to prepare. Strengthening the health system response in terms of enhanced testing, isolation of cases, treatment and contact tracing, as is being done currently, would have to be the mainstay to reduce the impact of the pandemic in terms of reduction in infected population and COVID-19 deaths in India until vaccine becomes available.

Introduction

The recent novel coronavirus disease (COVID-19), which originated in Wuhan in China, was declared a pandemic by the World Health Organization (WHO) on 11th March 2020. At the time of writing of this paper, more than 215 countries and territories globally have been affected by COVID-19, and a total of 6.6 million cases and 392,802 deaths due to the disease have been reported.¹ In India, as of June 7, a total of more than 246,662 cases have been reported, and 6946 persons have died.²

COVID-19 has multi-faceted implications, for the health sector in terms of initiating prevention and control measures as well as creating infrastructure to isolate and treat those detected positive and trace contacts, as well as non-health sector and the wider economy due to the nature of preventive actions being undertaken. Almost every country has introduced measures towards reducing transmission, which has ranged from self-initiated social-distancing to state enforced lockdowns and curfews. The Prime Minister of India also announced a nation-wide lockdown on 24th March as a measure towards reducing transmission. The lockdown was implemented nationally for 6 weeks, followed by another 2-weeks of graded lockdown in districts as per their risk assessment.

Several of these measures in different countries have been guided by mathematical models to help policy makers make evidence-informed decisions, especially in case of a disease where there are several uncertainties. Several studies have been carried out in Indian context to model the epidemic.³⁻⁵ These models explored the impact of lockdowns and social distancing measures focusing more on the course of the epidemic but none of these evaluated the impact on health system's response needed, as well as economic impact of the COVID-19 in India.³⁻⁵

In this paper, we developed a susceptible-exposed-infectious-recovered (SEIR) type mathematical model to predict the epidemic curve in India in the presence of the 8-week lockdown being imposed by the Government of India, under different scenarios of effectiveness of the lockdown and public health measures. Secondly, we ascertain the health system preparedness challenge in terms of hospital beds for isolation, intensive care facilities and ventilators which would be required to manage the epidemic. Importantly, we estimate the overall cost of managing the COVID-19 pandemic in India, considering all direct resource use.

Methods

Imported Risk of Infection

We used the data on the day-wise number of international air travellers, stratified by the country of their origin, from 1st December 2019 to 22nd March 2020, to populate a SEIR model (Figure 1, Supplementary file 1: Section 1.1 Box, S2) for predicting the total COVID-19 infections in India. The data on the international air travellers arriving in India was obtained from the Director General Civil Aviation on personal communication.⁶ Two set of criteria were chosen to select countries which could contribute to the epidemic in India – the top 20 countries with highest burden of COVID-19, and the top 20 countries in terms of incoming air traffic to India. Using these

2 criteria, since 8 countries were common, we finally chose 32 countries in our model to have contributed the incoming COVID-19 positive cases. We used the actual data of air travel for December 2019, and January 2020 (Supplementary file 2). For February and March 2020, we estimated the number of air traffic based on the data for similar months in 2016, 2017, 2018 and 2019, applying annual growth rates and the country distribution of the incoming passengers. Further, we assumed that the air traffic from China sector stopped from 5th February 2020, while the daily traffic in March 2020 was assumed to be reduced by a factor of 15%. Further, since the Government of India imposed travel embargo on air travel since 22nd March, we assumed the risk of imported infections beyond this date to be zero.

The data on the number of air passengers arriving in India from these 32 countries, was used along with prevalence of COVID-19 on respective day, in the country of origin, to estimate the number of the travellers who are COVID-19 positive (Supplementary file 2). The risk of a passenger from a particular country to be COVID-19 positive was also adjusted for the possible extent of under-reporting in the number of cases in respective countries. In order to do so, we estimated the vulnerability factor and the correction for death rate in different countries, in reference to South Korea as the reference country, as proposed by Lachmann.⁷ This method corrects for mortality rates by age-standardizing the COVID-19 mortality assuming South Korean population as reference. The latter is assumed to be reference in view of relatively highest number of testing undertaken in South Korea. Further, we reviewed other empirical estimations of under-reporting of cases from China, Italy, Iceland and United States.⁸ We finally corrected for under-reporting in cases from respective countries by calibrating our model to the reported number of cases in India. The final correction factor was closer to what was derived using the Lachmann methods (Supplementary file 1: Section 1.1, Box S 3).

Modelling Local Transmission in Counterfactual (CF-1)

We developed a deterministic mathematical SEIR model to simulate the transmission of COVID-19. The model assumes a heterogeneous population with random mixing. We seed the model by assuming that the COVID-19 positive travellers coming to India would be in asymptomatic (and hence first enter the exposed compartment of model) and symptomatic (and hence move to infectious compartment of model) in a ratio of 2:1. The entire population of India, on the 1st December 2019, was considered as the susceptible population.¹¹ Standard methods were used to estimate the day-wise number of exposed in India, based on the risk of incoming air travellers and the local transmission based on contact between the infectious and the susceptible population.

For our analysis, we assumed the reproduction number to be 2.5 as reported in recent studies before the introduction of stringent lockdown.¹⁰⁻¹³ A recent analysis of Indian pandemic also reported an R0 of 2.38 in the initial unmitigated scenario¹⁴. In view of the wide range of reproduction numbers reported in literature,¹⁰⁻¹⁵ we validated the model output using actual reported data on infections, deaths, cases requiring ICU and ventilator care. The latent period of disease and the duration of infectiousness ranges between 4-6 and 3-10 days respectively.^{10-13,15-17} We used 4 and 6 days as the latent period and duration of infectiousness in our base case (Table 1). COVID-19 specific case fatality rate of 2.59%, as per Indian data available so far on number of cases and deaths, was used.¹⁸ Similarly, the all-cause crude mortality rate reported for the year 2018 by India's Sample Registration System was used to estimate the daily risk of dying due to all other causes.¹⁹

The model divides the population of infectious cases into those which are likely to be diagnosed and treated, and those which are likely to get unreported in the surveillance. The proportion of diagnosed and reported versus undiagnosed and not reported is based on the proportion of the reported (in surveillance data) and estimated modelled cases at different time points. This factor was found to be 18.5% as on 24th March. For those who are detected in each cycle, we assume the above case fatality rate (2.59%), while for 1% of the unreported infectious which we assume to be severe cases requiring intensive care, we applied the reported case fatality rate for respiratory ICU patients in India.²⁰ No risk of COVID-19 specific mortality was assumed for the remaining 99% of the unreported cases which were assumed to be mild and not requiring hospital care (Table 1). We also assumed an enhanced risk of mortality²¹ for those patients, who require ICU or ventilator care, but are unable to access the same. This was considered appropriate in case of surge of cases, where health system capacity could potentially run out to cater the demand for critical care. In order to do so, two compartments for hospitalized patients were created – those whose need for health services was met versus those with unmet need.

The unmitigated scenario before the onset of lockdown was considered as counterfactual. It considers no additional interventions to limit the contact between individuals such as social-distancing or lockdown, and includes the actual air travel restrictions imposed by the Government only. Within this scenario, we also assume the extent of public health measures such as testing, isolation and treatment as per its existing coverage, i.e. 18.5%. This assumption is justified based on the ratio of cases predicted by our model versus what is reported as a result of the surveillance as on 24th March. For those who are diagnosed, we assume that these are detected at an average 3 days after the end of their latent period, i.e. the infected person remains infectious for about 3 days before being detected positive.

Modelling the Intervention Scenarios (Lockdown and Strengthening Public Health Surveillance)

The intervention scenario was assumed to be a case of ‘lockdown’ to enhance social distancing, which was imposed for a period of 8 weeks beginning from 24th March 2020 (Int 1.1). This intervention was over and above the air traffic restrictions which were part of counterfactual. The lockdown was uniformly implemented nationally during the first 6 weeks, while a graded hotspot-based lockdown was imposed for the last 2 weeks.²² All the districts in India were stratified in red, orange and green zones based on cumulative cases reported and doubling time. Since there is no empirical evidence on the effectiveness of lockdown to limit social distancing, we assumed the base case effectiveness to be 60%, but alternate scenarios of effectiveness of 20%, 40% and 80% for 6 weeks were also modelled. A weighted effectiveness of lockdown computed for the last 2 weeks was found to be 39%. This was based on the population size of districts, and estimated effectiveness of social distancing as per expert opinion in red (60%), orange (40%) and green (20%) zones (Table 1). The population which practices social-distancing during lockdown was assumed to have full protection from transmission. During each of this scenario, we assume an effectiveness of public health measures which includes testing, isolation, treatment, contact tracing at a rate similar to the counterfactual (Table 2).

At the end of the first 3-week period of lockdown (i.e. lockdown 1.0), we considered an alternative additional scenario that includes intensification of public health measures during lockdown which includes detection of cases through enhanced capacity of testing the symptomatic cases *within 3 days* of developing symptoms, isolation of positive cases, contact tracing and their quarantine (Int 1.2). In the base case, effectiveness of public

health measures was assumed to be 60% which implies 60% of the COVID-19 infected population will be detected, isolated and treated. Additional scenarios were modelled, where we report results for 20%, 40% and 80% effectiveness level of public health measures with fixed effectiveness of lockdown at 60% (Int 1.3). In order to model the intensified public health measures following 8-week lockdown, we assumed similar level of infectiousness of cases within the first 3 days after the latent period, and no risk of transmission thereafter till they either recover or die. Also, we assumed that the intensification of public health measures would begin post 3-week lockdown i.e. from 15th April 2020 and not from the beginning of lockdown as the health system will require some degree of preparedness to address the given situation. Infectious persons move to separate compartments based on whether these are diagnosed (with zero risk of transmission beyond the day of isolation) or not diagnosed in which case they continue with the standard risk of transmission till period of infectiousness.

As a sensitivity analysis, we also evaluated the overall duration of the lockdown, which when complemented with intensified public health measures after 8 weeks of current lockdown, which could potentially lead to mitigation (R_0 less than 1) or suppression of the epidemic (R_0 equal to 1). A comparison between the Int 1.1 and unmitigated scenario provides the effectiveness of currently imposed 8-week (or 8-weeks) lockdown. On the contrary, the comparison between Int 1.2, Int 1.3 and unmitigated scenario represents the contribution of public health measures beyond the period of lockdown if implemented effectively.

Health System Preparedness and Cost

Based on the number of cases in each of the above scenarios, we estimated the health system preparedness required for testing, isolation and treatment of positive cases, and contact tracing. In order to do so, we assumed the distribution of cases as mild, moderate, severe and critical among those diagnosed as 90.8%, 3.3%, 4.8% and 1.1%^{23,24} which is based on reported severity among Indian cases (Table 1). The estimated cases which are not currently being detected were assumed to be milder, and hence we assumed them to be mild, moderate, severe and critical in a ratio of 95.7%, 3.3% 0.7% and 0.3%. The mild and moderate cases being diagnosed were assumed to require supportive isolation treatment without and with oxygen respectively, while the undiagnosed mild cases were assumed to not report to facilities. For the severe and critical cases, whether diagnosed or undiagnosed, we assumed that these would require intensive care and artificial ventilation respectively. While ascertaining the health system resource requirement, we also estimated the period of unmet need when the number of COVID-19 cases rise beyond the health system capacity dedicated for COVID-19 response. We used the estimates of cost per bed-day for each of these settings as proposed for reimbursement by India's national insurance program in case of COVID-19 treatment.²⁵ These prices have been set based on analysis of the cost data from the nationally representative Cost of Health Services in India (CHSI) study, and the national health system cost database.^{25,26} Similarly, we used the national price for COVID-19 testing to estimate the diagnostic costs.²⁷ The cost of contact tracing was determined based on actual practice in program using expert opinion. (Detailed methods for determining cost are presented in supplementary material (Supplementary file 1: Section 1.1, Box S1).

There were no patients or public involvement in the design, or conduct, or reporting, or dissemination plans of our research.

Results

Model Validation

On 6th May 2020, after the end of 6-week lockdown, the reported cases in India were 52987² which were 47% of cases estimated by our model in a scenario of lockdown with 40% effectiveness. This implied the testing and detection capacity was more than double during the lockdown period as it was 18.5% before the lockdown. Similarly, at the end of 6-week lockdown, our model estimated 2539 and 582 COVID-19 patients needing ICU treatment and ventilator support, whereas on the same day the in actual, there were 2258 and 421 patients, respectively.²³

Findings

In the unmitigated scenario, COVID-19 epidemic in India is estimated to reach its peak in mid-July 2020. (Figures 3 and 4). Our model estimates that during the unmitigated scenario, 18.5% of the total estimated COVID-19 cases are being diagnosed and detected through surveillance during the early phase (Supplementary file 1: Section 1.2, Figure S2). Ten percent of the population is estimated to get infected within 158 days of introduction of first COVID-19 case, and the infected population doubles within next 8 days (Supplementary file 1: Section 1.2, Figure S3).

In the event of a lockdown for 8 weeks, the peak of the epidemic shifts by 34-76 days, and the number of cases at the end of lockdown period is reduced by 69% to 97% with effectiveness of lockdown varying from 20 to 80% respectively (Figure S1A). This is likely to allow time for health system to prepare any shortfall in resources and infrastructure.

Intensification of public health measures along with lockdown (Int 1.2) leads to triple effects – firstly, as with lockdown – the peak shifts later. Secondly, there is a significant reduction in infected population at peak of epidemic by 70%, and cumulative infections decline by 26.6% (Figure 3). Finally, in terms of COVID-19 mortality, approximately 60% deaths can be prevented. One-third of this mortality prevention is attributed to reduction in unmet need for critical care as a result of intervention. The estimated mortality rate of COVID-19 in India is 1.6 deaths per thousand per year. If the lockdown is continued beyond 8 weeks, along with intensified public health measures (60% effectiveness), the epidemic can be suppressed with less than 10 new infections at the end of 20-week lockdown. Further, if the effectiveness of public health measures can be enhanced to 80%, the epidemic could be suppressed by the end of lockdown (Figure 4).

The estimated requirement of isolation beds, ICU beds and ventilators at the peak of the epidemic in the unmitigated scenario is 1805, 394 and 69 per 1 million population, respectively. In the event of public health measures being strengthened with 60% effectiveness after lockdown, requirement of ICU beds as well as ventilators each will be reduced by 83% (Figure 5). However, majority of the mild cases would require isolation in a non-hospital setting. In the event of lockdown alone, the current dedicated resources in terms of isolation beds, ICU beds and ventilators are adequate to meet the necessity till 3rd week of September, 2020. Beyond this point there is a period of unmet need for approximately 3.3 months for isolation and ICU beds and 2.9 months

for ventilators given the current resources falling inadequate. Similarly, in the scenario of intensified public health measures with 60% effectiveness after lockdown, the demand can be met till 1st week of November, 2020 and afterwards it is inadequate for 5.4, 4.6 and 3.9 months to meet the demand for isolation beds, ICU beds and ventilators, respectively. However, the shortfall of resources in the unmet period is huge in the scenario of lockdown alone compared to public health measures along with lockdown (Figure 5).

The health system cost of managing COVID-19 in the scenarios of no-mitigation or 8-week lockdown is estimated to be ₹ 11,313 billion (US\$ 150 billion). This is nearly 4.5% of the gross domestic product (GDP) of India. These estimated costs increased by 2.25 times with an intervention of 8-week lockdown and public health measures with 60% effectiveness (Table 3). The incremental cost of intensified public health measures per infection and death prevented is estimated to be ₹ 43,867 and ₹ 3.84 million respectively.

Discussion

Overall, our study results show that the COVID-19 pandemic in India in the absence of any intervention is likely to affect a large proportion of India's population, which has huge implications for the health system in terms of scaling-up its capacity. Our results, in terms of proportion of total population likely to be eventually get infected, exposure rate at the peak of the epidemic,²⁸⁻³¹ effectiveness of lockdown to change the epidemic curve, and the effectiveness of public health measures^{4,32-35} is similar to the findings from elsewhere in some other countries, as well as from recent evidence emerging from other studies in India. Similarly, our estimate of cases which are likely to get detected is similar to the reported cases as part of surveillance.

The recently released report by the mathematical modelling group at the Imperial College on COVID-19, estimates 7 billion population (89%) globally to be infected by the end of the current pandemic, which will lead to 40 million deaths. The Australian modelling study demonstrates that, with no intervention the epidemic would peak around mid-May and almost 50% of the population would be affected. In terms of impact of case isolation (1-week delay in peak), school closures (2-week delay in peak) and social distancing with a compliance of 70% or less, there is just a delay in peak achieved with no significant reduction in number of cases. If the compliance is more than 70%, there may be reduction in incidence and prevalence but the epidemic is expected to resurge once these measures are taken off.³⁵ We have also observed similar findings from our present study for India. Another recent study shows that lockdown for 3-weeks only delays the onset of peak rather than mitigating the epidemic.⁴

However, our study adds to the existing evidence in trying to clearly sync scenarios with emerging policy questions, as well as estimating the health system preparedness in terms of augmentation of infrastructure as well as cost. The Government of India has currently relaxed the lockdown after a period of 8-weeks, which ended on 17th May, 2020. The findings of our study also validate the steps taken by the Indian Government to use the lockdown to buy time for preparing the health system. The number of laboratories performing testing for COVID-19 has increased from 52 to 484 within a short period of 65 days.^{36,37} Strategies for pooling of samples is being adopted to enhance the geographical barriers. Also, India crossed its goal of 2 million tests which was

to be achieved by the end of May.³⁸ The testing rate has increased from 94.5 person per million population in late March to 1,973 people per million of the population as of now. The production of personal protective equipment (PPE) was also ramped up to about 4.5 lakh PPE kits per day, with nearly 600 domestic manufacturers.³⁹ As is the current policy direction, the lockdowns should be restricted to only hotspots to contain the spread rapidly in a short time. Together with strengthening public health measures, this is the most effective strategy which can not only flatten the curve by reducing the number of overall cases which would get infected, but also delay the onset of the peak which provides more time for the health services to respond. Worldwide, the vaccine development work is being done at an unprecedented pace but there are several challenges associated to it.⁴⁰

There are several other initiatives which the Government of India and State Governments have been undertaking to strengthen the response. Firstly, the criteria for testing have been relaxed.⁴¹ Secondly, the private sector facilities have also been accredited for provision of COVID-19 diagnostics. These two have increased the daily coverage of tests about 5-fold since the beginning of response. Thirdly, the Government has invoked the legislations for engaging with the private hospitals to the extent of taking control of the private hospital which would be designated as COVID hospitals for treatment.⁴² Till date, 970 hospitals and 2300 centres have been designated as COVID hospitals and COVID centres, respectively.²³ This includes 10% of private sector hospitals. The National Health Authority is guiding the States for provider payment models for reimbursing private hospitals whose facilities are being taken over by Government. However, the overall contributions of treatment and care of private sector has been much lesser than the public-sector share. This builds further advocacy for public sector strengthening to meet the challenges of such pandemics. Fourthly, the State Governments are ramping up the public health capacity for contact tracing. Community centres or *Panchayat* (local bodies) in rural areas are being utilised for quarantining the contacts. . Fifth, targeted strategies have been scheduled based on risk assessment of districts. However, the risk grading is an ever-changing factor and thus, strategies should also be of evolutionary nature. Finally, Government of India has announced a stimulus package on 12th May 2020 which is around 10% of India's GDP to revive the economy due to COVID-19 crisis,⁴³ out of which ₹ 150 billion (US\$ 2 billion) is dedicated for COVID-19 health system needs. However, given the findings of our study, cost of mitigating the pandemic would have to be increased manifold.

Our study is based on epidemiological evidence which is currently available, which is drawn from countries which have already experienced the pandemic. Thus, there are data limitations. Firstly, the reproduction number could vary across states in India, owing to different population density, movement of individuals, demographic composition, prevalence of co-morbidities which is likely to affect the severity of disease, as well as health system preparedness and governance structures. Hence, future research should focus on generating more epidemiological evidences, and carrying out such model-based analysis at the state level to inform local policies. There are also uncertainties in terms of how much is the transmissibility of COVID-19 in India, and its likely variation given the changes in temperature and humidity which will occur with changing season. Moreover, all intervention scenarios are assessed considering that air travel restrictions continue, which may not be the case indefinitely. Thirdly, there are other costs associated with the program management and expansion of health infrastructure which are not incorporated in our economic analysis. Finally, it is also getting widely recognised that the COVID-19 is negatively impacting the access to care for other services which has implications for

universal health coverage. The negative health consequences or externality of the COVID-19 pandemic also needs to be evaluated. Finally, we have not assessed the sector-wise macroeconomic implications of COVID-19 which would need to be measured. Our study findings should be viewed considering these limitations, and should be reviewed periodically with actual epidemiological data. However, the states should begin planning their strategies in short-term based on study findings. More model-based analysis with local data should be encouraged.

Overall, to conclude, management of COVID-19 will involve dynamic review of policies and significant strengthening of the health system. While lockdowns will delay the onset of peak and will give the very much needed time for health system to respond, strengthening the health system response in terms of testing, isolation of cases, treatment and contact tracing, as is being done currently, would have to be the mainstay to reduce the impact of the pandemic in India until vaccine becomes available.

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Table 1: List of Parameters for India COVID-19 model

PARAMETERS	BASE VALUE	SOURCE
Population parameters		
Total population size (in billion)	1.38	19
Crude Death Rate (per 1000 population)	7.21	19
Natural history of COVID 19		
Average latent period (days)	4	10-17
Average duration of infectiousness (days)	6	10-17
Incubation period (days)	5.8	10-17
Basic reproduction number	2.5	10-17
Parameters related to clinical severity of COVID 19		
Recovery period for mild cases (days)	14	45
Recovery period for moderate to severe cases (days)	30	45
Case Fatality Rate (percent) among reported COVID cases	2.59	18
Case fatality Rate (percent) among respiratory ICU patients in India (Assumed for unreported severe COVID case)	17.8%	20
Relative risk of fatality among critical care patients in case of non-ICU treatment	1.247	21
Parameter assumptions pertaining to different model scenarios		
Imported transmissions:		
Proportion of exposed among imported transmissions	0.67	Expert opinion
Proportion of infectious among imported transmissions	0.33	Expert opinion
Proportion of cases being reported	0.185	Authors' calculation
Proportion of mild cases among reported cases	0.908	23-24
Proportion of moderate cases among reported cases	0.033	23-24
Proportion of severe cases among reported cases	0.048	23-24
Proportion of critical cases among reported cases	0.011	23-24

Proportion of cases unreported	0.815	Authors' calculation
Proportion of mild cases among unreported cases	0.957	Expert opinion
Proportion of moderate cases among unreported cases	0.033	23-24
Proportion of severe cases among unreported cases	0.007	Expert opinion
Proportion of critical cases among unreported cases	0.003	Expert opinion
Proportion of cases reported with intensified public Health Measures	0.6	Expert opinion
- Base case	0.2-0.8	
- Range		
Effectiveness of lockdown (6 weeks)		Author assumption
- Base case	60%	
- Range	20-80%	
Effectiveness of lockdown (7-8 week or Lockdown 3.0)	39%	Authors' calculation
Parameters related to COVID testing and treatment		
Specificity of screening test (Rapid test)	0.90	44
Number of tests done to detect one COVID positive case (Rapid test)	24.4	2
Number of tests done to detect one COVID positive case (RT-PCR)	1.18	46
Cost of screening test (□)	1500	27
Cost of confirmatory test (□)	3000	27
Cost of contact tracing (□)	1041	Authors' calculation
Unit cost per bed day of isolation (□): Mild cases	307	25-26
Unit cost per bed day of isolation (□): Moderate cases	591	47,26
Unit cost per bed day of ICU: without ventilator (□)	2914	25-26
Unit cost per bed day of ICU: with ventilator (□)	3097	25-26
Conversion rate □ to USD	75.44	48

Table 2: Summary of Model Scenarios

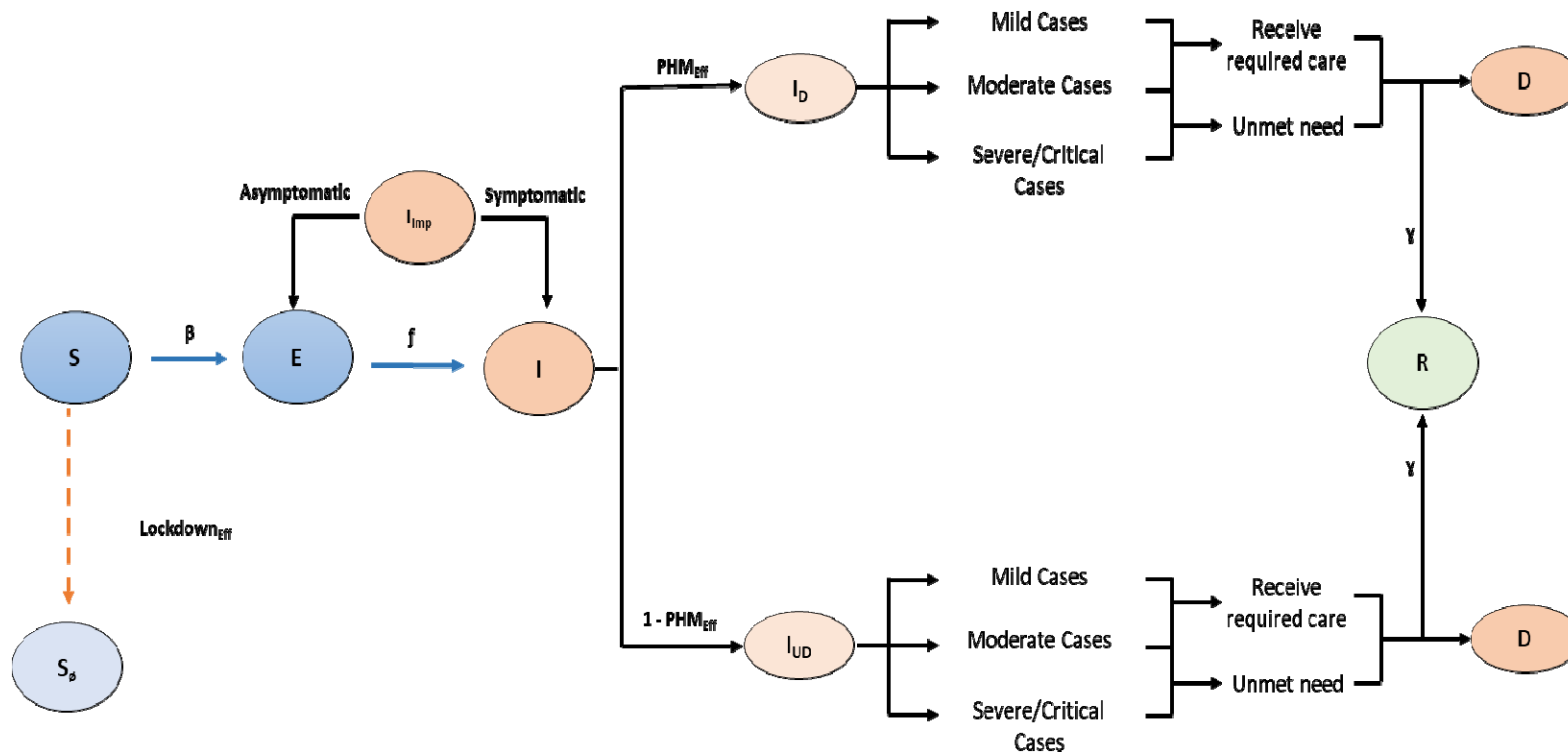
Abbreviated Notation	Expanded Notation	Description
CF-1	Unmitigated scenario (air travel restriction)	COVID transmission in India with usual rate of air traffic with actual Government of India restrictions put in place. In terms of effectiveness of public health measures, we assume that 18.5% ⁹ of the total cases are getting detected at an average 3 days following the latent period.
Int 1.1	Intervention 1: 6-weeks uniform +2-weeks graded hotspot-based lockdown* (Variable effectiveness)	COVID transmission in India with usual rate of air traffic with actual Government of India restrictions put in place, plus the imposition of 6-weeks national lockdown since 24 th March 2020 with varying levels of its effectiveness (20%, 40%, 60% and 80%) + 2-weeks graded hotspot-based lockdown.
Int 1.2	Intervention 2: 6-weeks uniform +2-weeks graded hotspot-based lockdown* (Variable effectiveness) + intensification of public health measures (Fixed effectiveness)	COVID transmission in India with usual rate of air traffic with actual Government of India restrictions put in place, plus the imposition of 6-weeks national lockdown since 24 th March 2020 with varying levels of its effectiveness (20%, 40%, 60% and 80%) + 2-weeks graded hot-spot based lockdown. In terms of effectiveness of Public health measures, we will assume 60% of the total cases are getting detected at an average 3 days following the latent period.
Int 1.3	Intervention 3: 6-weeks uniform +2-weeks graded hot spot-based lockdown* (Fixed effectiveness) + intensification of public health measures (Variable effectiveness)	COVID transmission in India with usual rate of air traffic with actual Government of India restrictions put in place, plus the imposition of 6-weeks national lockdown since 24 th March 2020 with 60% effectiveness + 2-weeks graded hot-spot based lockdown. Herein, we will vary the effectiveness of public health measures such that, in different scenarios, 20%, 40%, 60% and 80% of the total cases are getting detected at an average 3 days following the latent period.

* Lockdown 1.0 (3-weeks)- 25th Mar 2020 to 14th Apr 2020; Lockdown 2.0 (19 days)- 15th Apr 2020 to 3rd May 2020; Lockdown 3.0- Graded based on Zonal classification (2-weeks)- 4th May 2020 to 17th May 2020

Table 3: Cost of COVID epidemic management at varying effectiveness levels of lockdown and public health measure interventions in India

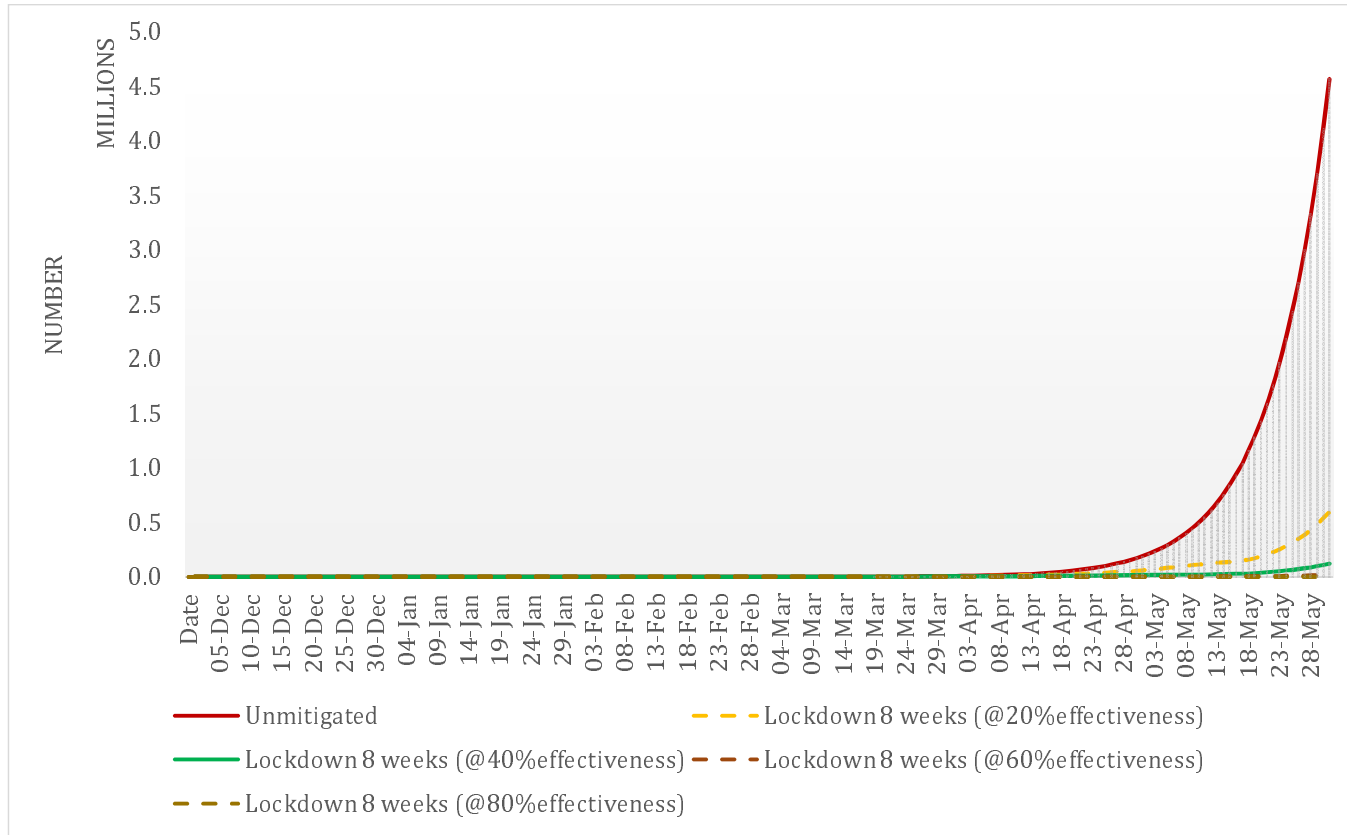
Cost, in billion ₹ (billion US\$)	Unmitigated	Lockdown 8 weeks (@20%effectiveness) + public health measures	Lockdown 8 weeks (@40%effectiveness) + public health measures	Lockdown 8 weeks (@60%effectiveness) + public health measures	Lockdown 8 weeks (@80%effectiveness) + public health measures
		Testing	9,240 (122)	21,913 (290)	21,888 (290)
Contact Tracing	234 (3.1)	556 (7.4)	555 (7.4)	554 (7.4)	553 (7.4)
Total Treatment Costs	1,839 (24.4)	3,180 (42)	3,176 (42)	3,167 (42)	3,166 (42)
Total Cost of COVID cases management	11,313 (150)	25,649 (340)	25,620 (340)	25,543 (339)	25,533 (338)
Cost, in billion ₹ (billion US\$)	Unmitigated	Lockdown 8 weeks + public health measures (@20%effectiveness)	Lockdown 8 weeks + public health measures (@40%effectiveness)	Lockdown 8 weeks + public health measures (@60%effectiveness)	Lockdown 8 weeks + public health measures (@80%effectiveness)
		Testing	9,240 (122)	9,905 (131)	18,609 (247)
Contact Tracing	234 (3.1)	251 (3.3)	472 (6.3)	554 (7.4)	0 (0)
Total Treatment Costs	1,839 (24.4)	1,911 (25.3)	2,923 (38.7)	3,167 (42)	0 (0)
Total Cost of COVID cases management	11,313 (150)	12067 (160)	22,004 (292)	25,543 (339)	3 (0.03)

Figure 1: SEIR Schematic Model for COVID transmission in India



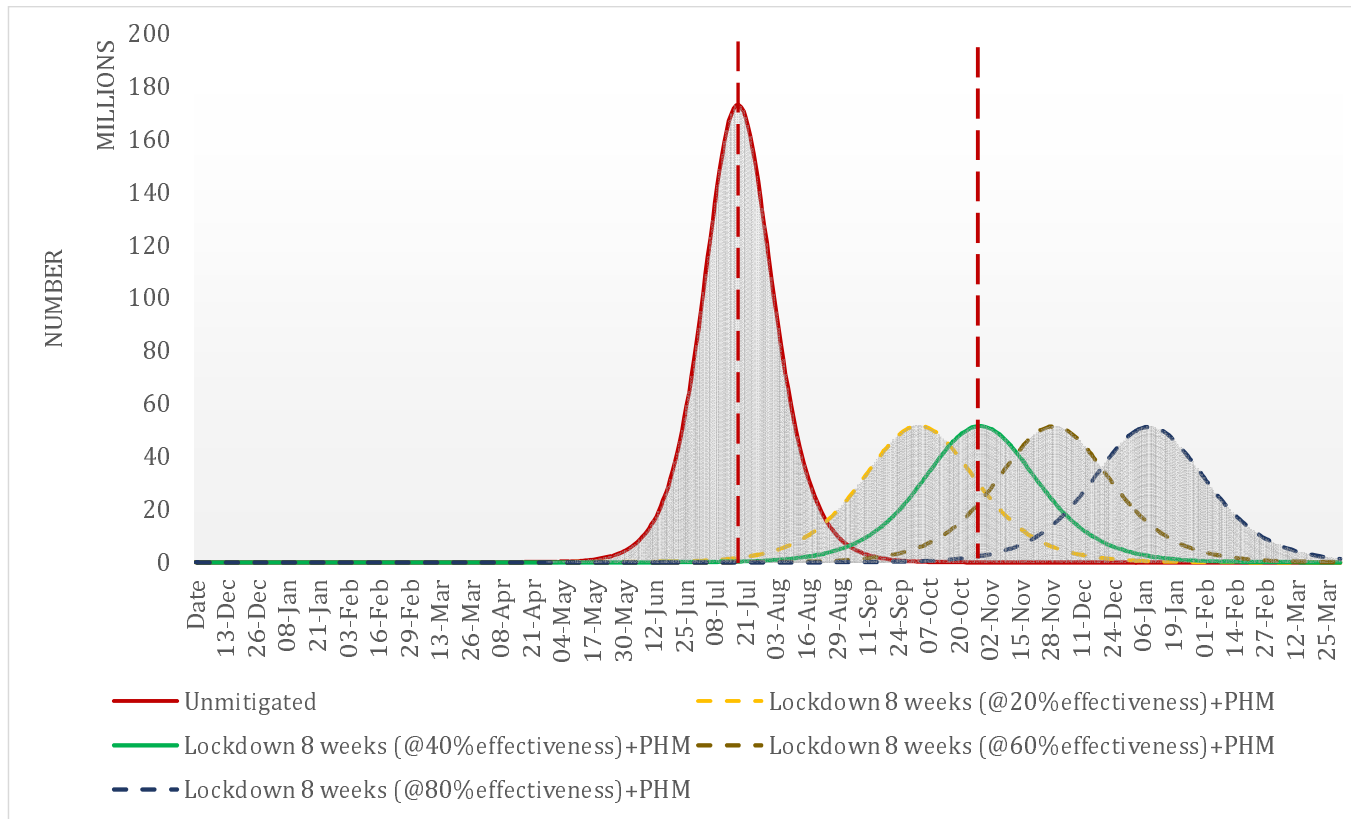
S = Susceptible, S₀ = Population no more susceptible as a result of lockdown, E = Exposed, I = Infectious, I_{imp} = Imported infections, I_{UD} = Undiagnosed infections, I_D = Diagnosed infections due to Public Health Measures (PHM), PHM_{Eff} = Enhances testing, diagnosis, contact tracing, upscaled health infrastructure in terms of isolation beds, ICU beds and Ventilators, R=Recovered, D=Deaths, β = Probability of transmission, f = Rate at which infected individuals become infectious per unit time, γ = Rate at which infectious individuals recover (become immune) per unit time.

Figure 2: Estimated COVID-19 Infected Population in Unmitigated and Potential Lockdown Scenarios, India



Note: Model cycle starts from Dec 1, 2019

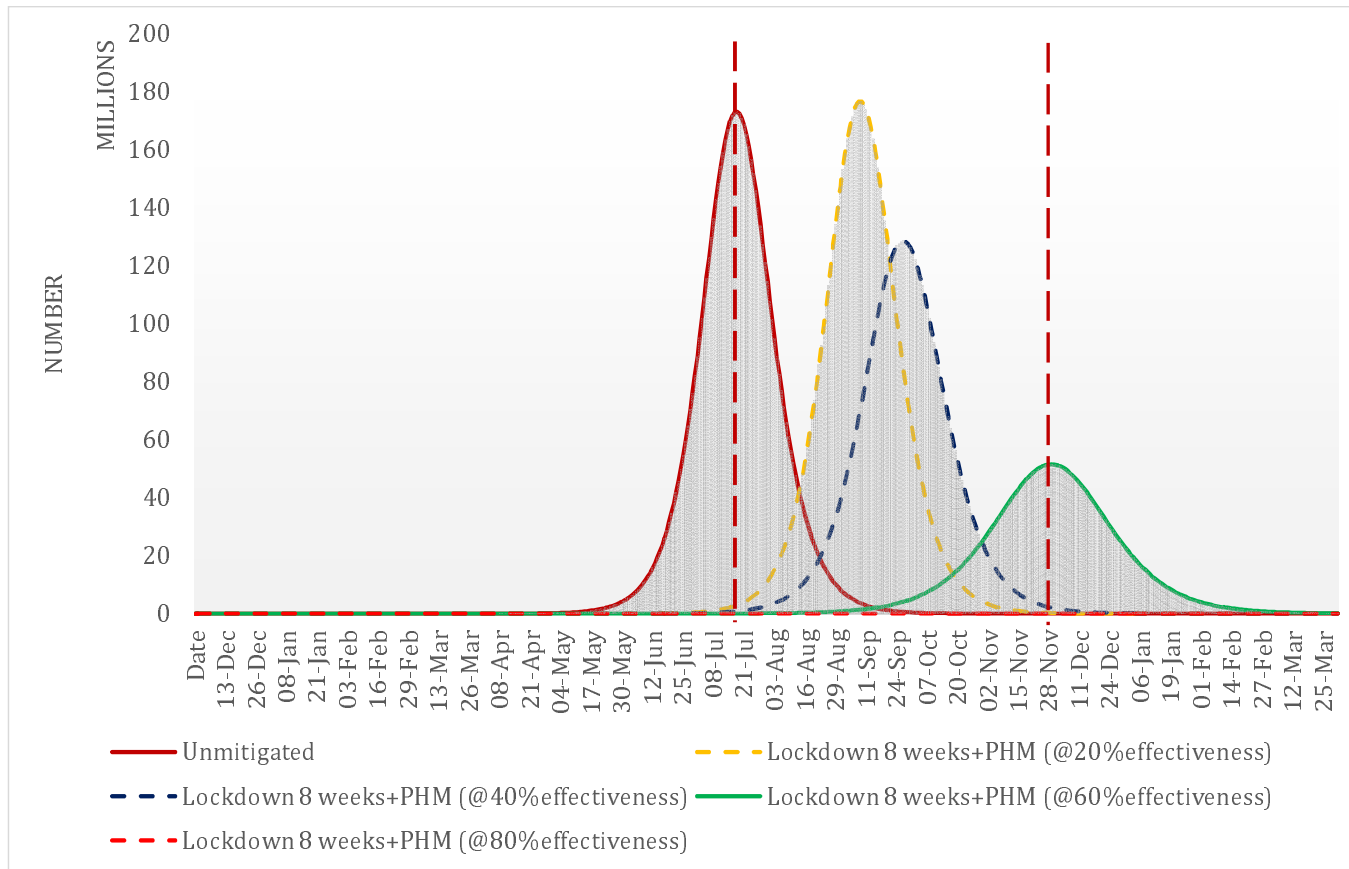
Figure 3: Estimated COVID-19 Infected Population in Potential Scenarios of Lockdown with Varying Effectiveness and Public Health Measures, India



Note: Model cycle starts from Dec 1, 2019; Lockdown effectiveness varied @20%, 40%, 60% and 80%

PHM= Public Health Measures (Includes intensified testing, isolation, treatment for 60% COVID Positive population)

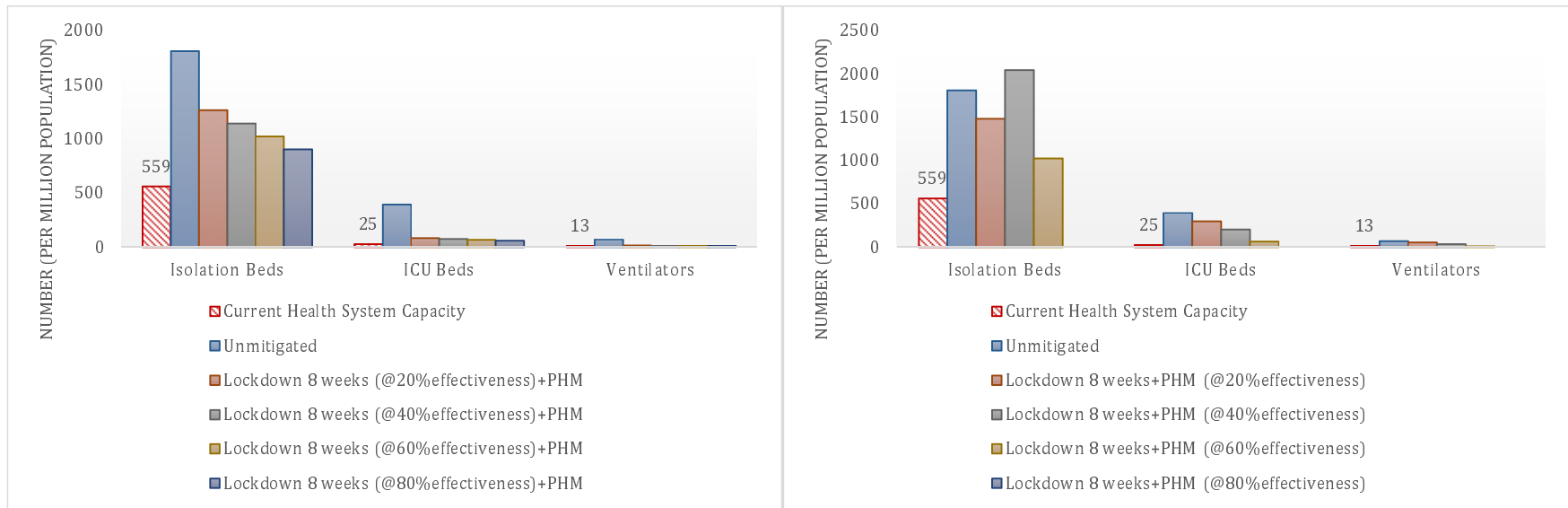
Figure 4: Estimated COVID-19 Infected Population in Potential Scenarios of Lockdown and Public Health Measures with Varying Effectiveness, India



Note: Model cycle starts from Dec 1, 2019; Lockdown effectiveness fixed @60%

PHM= Public Health Measures (Includes intensified testing, isolation, treatment for 20%, 40%, 60% and 80% COVID Positive population)

Figure 5: Estimated requirement for Isolation Beds, ICU beds and ventilators for COVID-19 Infected Population at peak in different scenarios compared to Current Health System Capacity, India



Note: In first figure, Lockdown effectiveness varied @20%, 40%, 60% and 80% and Public Health Measures (PHM) effectiveness fixed @60%
 In second figure, Lockdown effectiveness fixed @60% and Public Health Measures (PHM) varied @20%, 40%, 60% and 80%

