

Estimation of Effective Reproduction Numbers for COVID-19 using Real-Time Bayesian Method for India and its States

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Abstract

WHO declared the outbreak of the novel Coronavirus, COVID-19, as a pandemic on 11th March. On 24th March, a three-week nation-wide lockdown has been announced, which is now extended till 31st May. Effective Reproduction Number (Rt) helps in understanding how effective preventive measures have been in controlling an outbreak. This study assesses the impact of nation-wide lockdown in slowing down the spread of the COVID-19 at the national and state level. An attempt has also been made to examine the important state-level factors responsible for the uneven distribution of Rt of COVID-19 across different states of India. Bayesian approach based on the probabilistic formulation of standard SIR disease transmission models have been employed assuming serial interval of 4 days and basic reproduction number (R0) of three. India's Rt has declined from 1.81 (90% HDI: 1.64, 2.00) on 1st April to Rt =1.04 (90% HDI: 0.96, 1.13) on 9th May, after that it started increasing, and Rt =1.14 (90% HDI: 1.06, 1.21) was observed on 17th May. The value of Rt at the state level has shown significant variations. The testing rate had a significant impact in reducing the Rt at the state-level. The strategy of lockdown has contributed to containing the spread of the virus to some extent, but India still has a long way to go. Testing Rate is the most significant factor at state-level, as Testing and isolating patients sooner significantly reduces the disease spread.

Introduction

The World Health Organization (WHO) has declared the outbreak of the novel Coronavirus, (COVID-19) as a pandemic on 11th March 2020. In India, the first positive case of COVID-19 was detected on 30th January 2020, in Kerala. Cases started to increase from the first week of March 2020, and it reached to the level of 100,000 on 18th May 2020. A majority of patients initially identified had a travel history. These patients acted as primary cases and started infecting the general population. It is believed that it will take twelve to eighteen months to develop a vaccine for COVID-19¹. The absence of a vaccine for COVID 19 is making the situation even worse for the overstretched Indian health care systems. For example, the number of hospital beds per 1000 population is less than one - it is just one indicator to cite the vulnerable situation of India's health care system². In the absence of a vaccine, 'social distancing' is the optimal strategy to control the spread of novel Coronavirus.

A three-week nation-wide lockdown was imposed on 25th March 2020 to curtail the spread of the Coronavirus. This is a tough decision for any nation, particularly for a country with 22% of the population living below the poverty line and 90% of its workforce employed in the informal sector. About 400 million workers in the informal economy are at risk of falling deeper into poverty during the crisis³. The housing conditions are relatively deplorable for one in six urban dwellers, and density of slum areas is a serious concern and poses a challenge to maintain the social distancing among the population. The purpose of the nation-wide lockdown is to contain the spread of the Coronavirus so that the Government could take a multi-prong strategy: add more beds in its network of hospitals, scale up the production of the testing kits for COVID-19 and personal protection equipment (PPE) for the health workers. This lockdown helps to

break the chain of infections. It hopes to delay the onset of the disease until the healthcare infrastructure can handle the surge in cases.

It is evident that the concept of basic reproduction number (R_0) was first introduced in the field of demography, where this metric was used to count offspring⁴. The epidemiologists started to use this concept in the case of infective cases. This indicator aims to provide information about the contagiousness or transmissibility of infectious and parasitic agents. R_0 (Basic Reproduction number) has been described as being one of the fundamental and most often used metrics for the study of infectious disease dynamics⁵. In view of current COVID-19 pandemic, the paper makes an attempt to understand the effect of nation-wide lockdown on the reproduction number over different periods in India and its selected states. Further, the study also tries to understand the important factors associated with the decline in Effective Reproduction (R_t) at the state level.

There are a host of factors at the state level, which affect the decline in effective reproduction number (R_t). The present study considered several important factors at the state level, like the number of tests performed per million population, human development index, indicators of good governance and per capita health expenditure. Rapid testing at the beginning of transmission is one of the major responsible factors in declining the R_t as it helps in identifying and isolating the patients at an early stage. Fig 1 shows the number of tests done per million population by different states of India as on 9th May. However, India has limited facilities due to which sufficient tests could not be conducted in some states; as a result, they did poorly in stopping the spread of the virus. Rapid testing at an early stage has shown phenomenal results in most of the states, which is illustrated in Fig 1.

Apart from the nation-wide lockdown, social-welfare programs were implemented but not in a uniform way by all states. Human Development Index (HDI) at the state level is a good indicator of the effectiveness of a social welfare program implemented by the state government. It is expected that states placed with a high human development index will do far better in controlling the spread of the virus than those having a lower HDI Index. It is also hypothesized that Governance index at the state level assesses the Status of good Governance and it is also a summary measure of the impact of various interventions taken up by the State Government and Union Territories (UTs). Governance is an important factor at the state level for controlling the spread of infection as it tells us how efficient a government is in implementing policies and creating an impact through them. Health Infrastructure is also an important aspect for understanding the healthcare delivery provisions and welfare mechanisms. Per Capita Health Expenditure (PCHE) in a state is a good indicator of the health infrastructure of that state. It is conceptualized that these factors have a strong relationship with the decline of R_t .

Materials And Methods

Data on COVID-19 was obtained from the data-sharing portal covid19india.org. Information is collected on daily confirmed cases and daily testing numbers at the state level from 14th March to 17th May 2020.

For calculating the test per million population at the state level, the testing numbers were extracted at the state level from the data-sharing portal covid19india.org. The figures of the population for the selected states as on 1st March 2020 has been taken from the report “Population Projection for India and States (2011–2036)” provided by National Commission for Population (NCP). HDI Index 2018 at the state level is taken from the Global Data Lab, which provides the HDI Index at the state level for all countries from 1990-2018. Per Capita Health Expenditure (PCHE) data from the National Health Profile (NHP 2019) has also been used. All the calculations for estimating R_t are done using Jupyter notebook with Python 3.

Effective reproduction Number (R_t)

Effective reproduction number (R_t) is the mean number of infections generated during the infectious period from a single infected person at time t . The effective reproduction number may vary across locations because contact rates among people may differ due to differences in population density, cultural differences, level of immunity and restrictions imposed on the movement of the people. When $R_t > 1$, the pandemic will spread through a large part of the population. If $R_t < 1$, the pandemic will slow quickly before it has a chance to infect many people. Lower the value of R_t , the situation is more controllable. In general, $R_t < 1$ is the main goal of the policy planners working in the field of epidemiology. Epidemiologists argue that tracking R_t is the only way to manage the transmission of the communicable disease. More importantly, it is useful to understand R_t at the sub-national level to manage the transmission effectively.

Bayesian estimation of R_t with quantified uncertainty

Parameter estimation with quantified uncertainty can be achieved using the Bayesian approach in the context of probabilistic epidemiological models. Bayes’ theorem expresses the full probability distribution for model parameters, such as the effective reproduction number, R_t , in terms of the probabilistic epidemiological model, given the time series for new cases⁶.

Bettencourt & Ribeiro’s approach⁷ has been used to calculate R_t ⁷, as described in⁸ as well. The data is available on how many new people have COVID-19 based on daily new cases. This new case count gives us information about the current value of R_t . Further, the value of today’s R_t is related to the value of yesterday’s R_t and every previous value of R_{t-m} . Bayes’ rule updates the beliefs about the true value of R_t based on the information of how many new cases have been reported each day.

Bayes' Theorem suggests

$$P(R_t | k) = \frac{P(k | R_t) \cdot P(R_t)}{P(k)}$$

$P(k | R_t)$: The likelihood of observing ‘ k ’ new cases given R_t time points.

$P(R_t)$: The prior beliefs of the value of $P(R_t)$ at the beginning of the study period

$P(k)$: The probability of observing 'k' new cases for a given day

Choosing a Likelihood Function $P(k_t | R_t)$

Given an average arrival rate of λ new cases per day, the probability of observing 'k' new cases is distributed according to the Poisson distribution:

$$P(k | \lambda) = \frac{\lambda^k \cdot e^{-\lambda}}{k!}$$

There exists a relationship between R_t and λ .

$$\lambda = k_{t-1} \cdot e^{\frac{1}{\tau}(R_t - 1)}$$

Where $\frac{1}{\tau}$ is the reciprocal of the serial interval, and the value of the serial interval has been considered to be four days based on the most reliable findings⁹. Further, new cases are known; therefore, the likelihood function as a Poisson parameterized by fixing k and varying R_t can be reformulated⁷.

$$P(k | R_t) = \frac{\lambda^k \cdot e^{-\lambda}}{k!}$$

Input variables required for its calculation are-

1. Daily number of confirmed cases at the state and national level which is taken from http://api.covid19india.org/states_daily_csv/confirmed.csv
2. Serial Interval for COVID -19 is required
3. Basic Reproduction Number at the initial time (14th March) (R_0) is required.

Serial Interval and Incubation Period for COVID 19

Literature suggests the mean serial interval for COVID-19 ranges from 4 to 8 days⁽⁹⁻¹²⁾. Recent analyses by⁹ used a much larger sample that includes up to 468 pairs, making their estimates of between 4 and 5 days which are more statistically reliable. The estimated mean serial interval is shorter than the preliminary estimates of the mean incubation period (approximately 5 days)^(11,12). When the serial interval is shorter than the incubation period for infectious disease, the pre-symptomatic transmission is likely to have taken place and may occur even more frequently than symptomatic transmission¹³. The Indian Council of Medical Research (ICMR) also confirmed that as much as 80% of all cases could be asymptomatic based on the fact that COVID-19 tests that delivered positive results in India show that

69% of positive cases were asymptomatic, whereas 31% are symptomatic representing a ratio of 2:1¹⁴. In the present study, the mean value of the serial number is considered as four days.

Basic Reproduction Number (R_0)

Reproduction Number for COVID 19 at the initial stage is estimated between 2 and 3¹⁵. Using the raw CDC data, the estimated value of the basic reproduction number is between 2.2 and 2.3. Another study¹⁶ estimated that the median daily reproduction number (R_t) in Wuhan had declined from 2.35 (95% CI 1.15–4.77) at one week before travel restrictions were introduced on 23rd January 2020, to 1.05 (0.41–2.39) one week after. So, a basic reproduction number (R_0) of 3 at the initial stage of infection (14th March in our case) will yield good results for the present study. However, the estimate of the effective reproduction number using the current adopted Bayesian approach is independent of the initial assumed basic reproduction number.

Multiple Linear Regression

Multiple linear regression analysis was carried out to quantify the impact that state-level factors made in the decline of R_t . The difference created in the value of R_t during lockdown phase (between 2nd April and 9th May) for states acts as the dependent variable, and state-level factors namely Tests Conducted (between 2nd April and 9th May) per million, HDI, PCHE and Good Governance Index as independent variables. All independent variables were normalized between 0 and 1 to bring all the values of independent variables in the dataset to a common scale¹⁵.

Results

The effective reproduction number, R_t , changes over time, because of the decrease in the fraction of susceptible. $R_0 = 3$ considered as initial prior and Serial Interval (SI) of 4 days have been taken for the present study. However, initial prior does not affect the estimates as it converges to a similar R_t after a few days regardless of which value of R_0 was considered in the permissible range. Table I illustrates that with different values of R_0 , the estimated value of R_t is almost remained unchanged. The width of the Highest Density Interval (HDI) is almost the same for a given SI. Regardless of different values of R_0 , in all instances, uncertainty was reduced as more cases were reported over time. It is also observed that the value of R_t increases with an increase in the serial interval, which is consistent with the findings of.

Impact of lockdown on R_t at national and state level for India

The value of R_t at the state level helps in understanding the spread of disease in two ways. First, to understand how effective the measures have been imposed in controlling the outbreak and secondly, it gives us vital information about whether Government should increase or reduce the restrictions based on the competing goals of economic prosperity and human safety. It is expected that nation-wide lockdown

would be efficient in bringing down the value of R_t . In this study, 2nd April is considered as the starting date from where lockdown policies will affect the value of R_t .

Fig II shows the mean value for R_t for different lockdown periods. The mean value of R_t for each lockdown period has declined continuously, which shows that lockdown has helped in reducing R_t . It is observed that India attained a maximum value of 1.81 (90% HDI 1.64, 2.00) on 1st April. The lockdown slowly started to show an impact as R_t has declined substantially, and by the end of first lockdown period on 15th April, it reached to the level of 1.20 (90% HDI 1.08, 1.32) and further declined to $R_t = 1.10$ (90% HDI 1.00, 1.21) on 27th April, which shows that nation-wide lockdown has significantly lowered down the pace of transmission of COVID-19. An increase was observed on 3rd May ($R_t = 1.38$ (90% HDI 1.30, 1.48)), which declined to $R_t = 1.04$ (90% HDI: 0.96, 1.13) as on 9th May before increasing again to $R_t = 1.14$ (90% HDI: 1.06, 1.21) on 17 May.

Fig III & Fig IV (A-D) reveals that almost all states show a decreasing pattern in R_t from the beginning to the end of April, thereafter daily cases started to rise in the starting of May and R_t increased for almost all states, but gets stabilized later. This indicates that nation-wide lockdown has had a positive effect in stopping the spread of the virus across all states. However, the quantity of decline in the value of R_t varied considerably among the states.

Role of state-level factors in explaining the disparity in the values of R_t

Multiple linear regression analysis was carried out to examine the impact of selected covariates on the decline in ERN, and results are presented in Table II. The table clearly shows that after controlling the HDI, index of governance and PCHE, tests conducted per million population during the lockdown period was the significant factor at the 5% level of significance. The regression coefficient for the number of test variable was 1.018, which indicates that as the number of tests increases, the declined in R_t was observed. Further, this regression coefficient implies that the increase in testing rates helped in identifying and isolating the infected people and which facilitated in reducing the R_t during the lockdown period.

Discussion

The world is going through a pandemic, and almost every country is affected by it. In India, proactive measures like nation-wide lockdown and social distancing had been followed at an early stage of infection. India's R_t hit its peak on 1st April with $R_t = 1.81$ (90% HDI: 1.64, 2.00) but declined to $R_t = 1.20$ (90% HDI: 1.08, 1.32) on 15th April, which shows that the nation-wide lockdown has slowed the reproduction rate of COVID-19. Just when control of deadly virus seems to be going on the right track, daily confirmed cases started rising from 28th April, and it has not slowed down yet. It increased the value of R_t to the level of 1.38 (90% HDI 1.30, 1.48) on 3rd May due to the sudden spike in daily confirmed cases of Punjab and Tamil Nadu. The reason for this sudden spike in Punjab is pilgrimage returnees from

Maharashtra's Hazur Sahib in Nanded, which increased the R_t value for Punjab drastically¹⁷. While in Tamil Nadu, this sudden spike in daily cases is linked to Koyambedu Market, a wholesale vegetable and fruit market in Chennai. In fact, over 35 per cent of the cases reported in Tamil Nadu so far have been traced to the Koyambedu market¹⁸. So, such lapses on the Government's part takes away all the progress made due to the lockdown. Again, on 17th May, the value of the effective reproductive number has again increased slightly to $R_t = 1.14$ (90% HDI: 1.06, 1.21) from $R_t = 1.04$ (90% HDI: 0.96, 1.13) on 9th May. The reason being, there is a sudden spike in the number of cases in almost all states last week, as the migrant workers are returning back to their homes. Findings show that all phases of lockdown have brought a decline in the reproduction number of India. However, these interventions could not completely work as India is a diverse country where some states are highly developed in terms of health infrastructure and human development, while some of the states are lagging in these facilities. This disparity in the states is responsible for the fact that government interventions in India are not having the desired effect on stopping the spread of the virus. Further, states like Punjab ($R_t = 0.69$, 90% HDI: 0.42, 1.00), Tamil Nadu ($R_t = 0.94$, 90% HDI: 0.79, 1.08) and Andhra Pradesh ($R_t = 0.99$, 90% HDI: 0.74, 1.27) are able to bring down daily new cases by converging R_t to less than 1, less developed states like Jammu & Kashmir ($R_t = 1.26$, 90% HDI: 0.97, 1.56), Odisha ($R_t = 1.29$, 90% HDI: 1.03, 1.58) and Bihar ($R_t = 1.33$, 90% HDI: 1.09, 1.59) still have higher infection rates even at the end of Phase-3 lockdown as on 17th May. The possible reasons for this disparity among states are rapid testing rate, Good Governance and social welfare. Our regression analysis suggested that Testing Rate is the most significant factor that contributed to the decline of R_t during the lockdown period. The testing rate in the state plays a vital role in identifying and isolating the infected people and helped in reducing the R_t during the lockdown period. As per this study¹⁹, India is detecting just 3.6% of the total number of infections of COVID-19 with a huge variation across its states. They also suggest that India must increase its testing capacity and go for widespread testing, as late detection of virus puts patients in greater need of ventilation and ICU care, which imposes greater costs on the health systems. India should also adopt population-level random testing to assess the prevalence of the infection. For detection of the true prevalence of COVID-19 infections in the country, India can adopt the well-established National Family Health Survey (NFHS) framework as a solution to ascertain the true prevalence of COVID-19²⁰.

However, there might be other factors at the state level like lapses of state governments, the return of migrant workers to their home, efficient contact tracing and quality of quarantine centres, which are contributing in the spread of the infection but could not be quantified in the study. So, apart from the factors considered here, these factors should also be accounted for in the studies to get a clearer picture. Despite the afore-mentioned limitation, the present study is the first attempt to study the causes of variation among states in controlling the spread of the COVID 19. The findings show that the strategy of lockdown has contributed to slowing the spread of the virus to a greater extent. However, still, India has a long way to go to control the spread of the virus and to maintain its effective reproduction number (R_t) below one. In the wake of the current situation, complete lockdown is recommended as only three states are able to maintain its effective reproduction number (R_t) below one. In the coming weeks, it is expected

that daily confirmed cases will rise in India as migrants are returning home in large numbers. So, the number of isolation beds, ICU beds and ventilator beds should be increased in all states. This needs to be done to accommodate a large number of cases for the coming weeks when the daily confirmed cases will be at its peak, as health infrastructure is not up to the mark even in the developed states to handle a pandemic of this magnitude.

Declarations

Funding Statement

No external funding was received in carrying out this study.

Conflicts of interest

The authors have declared no conflicts of interest.

Availability of Data

Data is open access and available at http://api.covid19india.org/states_daily_csv/confirmed.csv

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Tables

Table I: Most Likely (ML) values of R_t and Highest Density Interval (HDI) based on different Serial Interval (SI) & R_0 , 24th March, 2nd April & 28th April 2020

24 th March										
	SI=3	90% HDI	SI=4	90% HDI	SI=5	90% HDI	SI=6	90% HDI	SI=7	90% HDI
$R_0=1.5$	1.43	(1.19,1.68)	1.58	(1.28, 1.91)	1.72	(1.34,2.10)	1.86	(1.42,2.32)	2	(1.49,2.53)
$R_0=2.0$	1.43	(1.20,1.69)	1.58	(1.28, 1.90)	1.73	(1.37,2.13)	1.88	(1.45,2.35)	2.02	(1.50,2.53)
$R_0=2.5$	1.44	(1.21,1.70)	1.59	(1.29,1.91)	1.74	(1.39,2.15)	1.89	(1.46,2.35)	2.04	(1.55,2.58)
$R_0=3.0$	1.44	(1.21,1.70)	1.6	(1.30,1.92)	1.76	(1.38,2.13)	1.91	(1.49,2.38)	2.06	(1.56,2.58)
$R_0=3.5$	1.45	(1.22,1.71)	1.61	(1.31,1.93)	1.77	(1.41,2.16)	1.93	(1.49,2.37)	2.08	(1.60,2.62)
2 nd April										
	SI=3	90% HDI	SI=4	90% HDI	SI=5	90% HDI	SI=6	90% HDI	SI=7	90% HDI
$R_0=1.5$	1.58	(1.45,1.72)	1.77	(1.60,1.93)	1.96	(1.76,2.15)	2.14	(1.92,2.37)	2.33	(2.14,2.59)
$R_0=2.0$	1.58	(1.45,1.72)	1.77	(1.60, 1.93)	1.96	(1.76,2.15)	2.15	(1.92,2.37)	2.33	(2.08,2.59)
$R_0=2.5$	1.59	(1.45,1.72)	1.78	(1.62, 1.96)	1.96	(1.77,2.16)	2.15	(1.93,2.38)	2.33	(2.08,2.59)
$R_0=3.0$	1.59	(1.45,1.72)	1.78	(1.62, 1.96)	1.96	(1.77, 2.16)	2.15	(1.93,2.38)	2.34	(2.09,2.60)
$R_0=3.5$	1.59	(1.45,1.72)	1.78	(1.61,1.94)	1.97	(1.77,2.16)	2.15	(1.93,2.38)	2.34	(2.09,2.60)
28 th April										
	SI=3	90% HDI	SI=4	90% HDI	SI=5	90% HDI	SI=6	90% HDI	SI=7	90% HDI
$R_0=1.5$	1.13	(1.04,1.21)	1.16	(1.07, 1.28)	1.2	(1.09,1.33)	1.23	(1.10,1.36)	1.27	(1.14,1.43)
$R_0=2.0$	1.13	(1.04,1.21)	1.16	(1.06, 1.26)	1.2	(1.09,1.33)	1.23	(1.10,1.36)	1.27	(1.14,1.43)
$R_0=2.5$	1.13	(1.04,1.21)	1.16	(1.07,1.28)	1.2	(1.09,1.33)	1.23	(1.10,1.36)	1.27	(1.14,1.43)
$R_0=3.0$	1.13	(1.04,1.21)	1.16	(1.07, 1.28)	1.2	(1.09,1.33)	1.23	(1.10,1.36)	1.27	(1.14,1.43)
$R_0=3.5$	1.13	(1.04,1.21)	1.16	(1.07,1.28)	1.2	(1.09,1.33)	1.23	(1.10,1.36)	1.27	(1.14,1.43)

Source: Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/>

Table II: Multiple Linear Regression with Difference in R_t (between 2nd April and 9th May) as the dependent variable, India, 2020.

Difference in R_t	Coefficient	Std. Error	t	P>t	95% Confidence Interval
Tests conducted**	1.018	0.3241	3.14	0.012	0.2849 1.7512
HDI Index	-0.109	0.3888	-0.28	0.785	-0.9888 0.7703
Governance index	-0.288	0.2911	-0.99	0.349	-0.9462 0.3708
PCHE	-0.955	0.7156	-1.33	0.215	-2.5735 0.6643
constant	-0.126	0.6547	-0.19	0.851	-1.6072 1.3549

R-squared 0.6042

Adjusted R-squared 0.4283

Source: Based on indicator values from various sources mentioned above and R_t value from Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/>

Figures

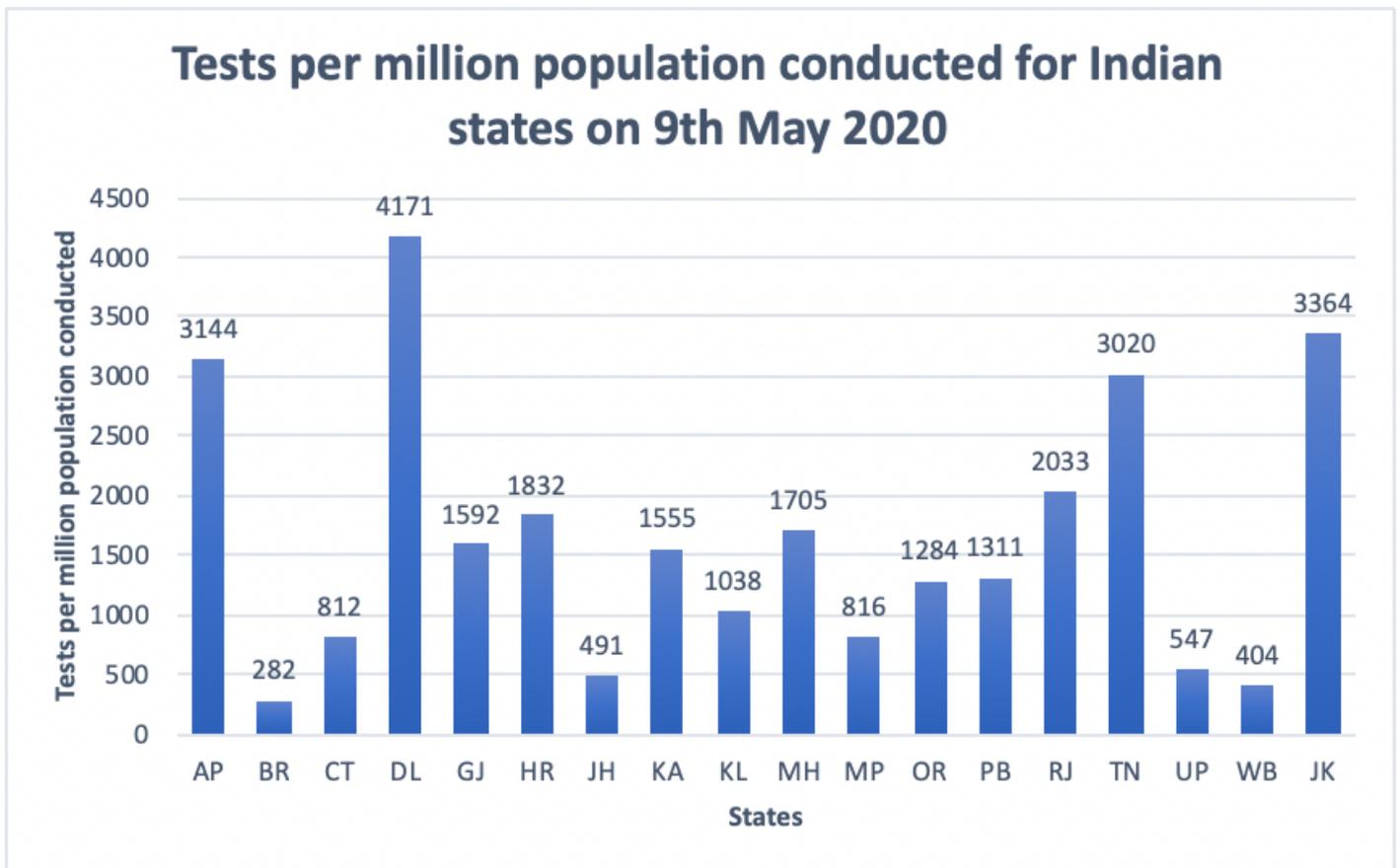


Figure 1

COVID-19 Testing Rate (test per million population) for states of India, 2020. Source: Data repository of covid19india.org

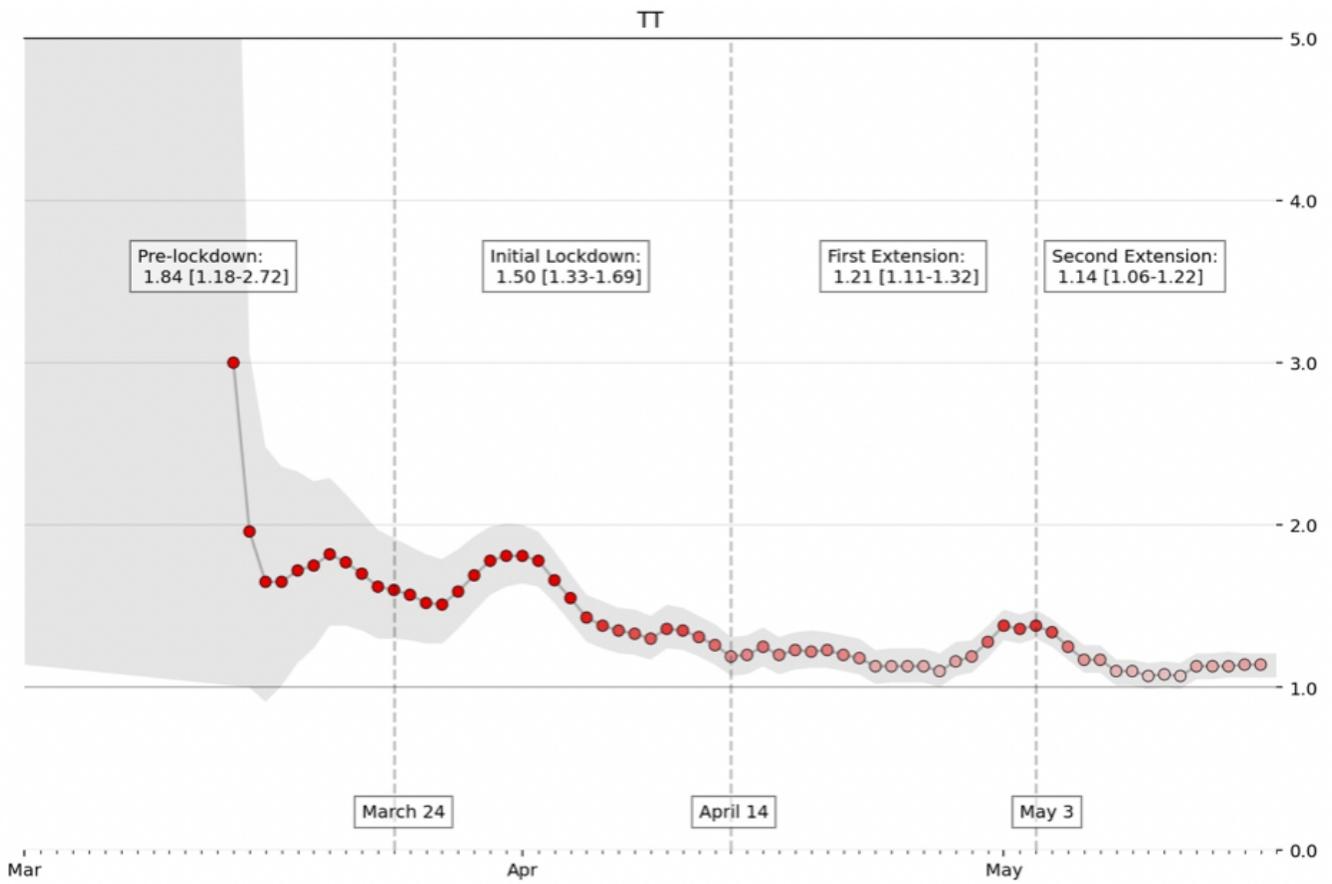


Figure 2

Real-time effective Reproduction number (R_t) for India for all lockdown periods, 2020. Source: Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/>

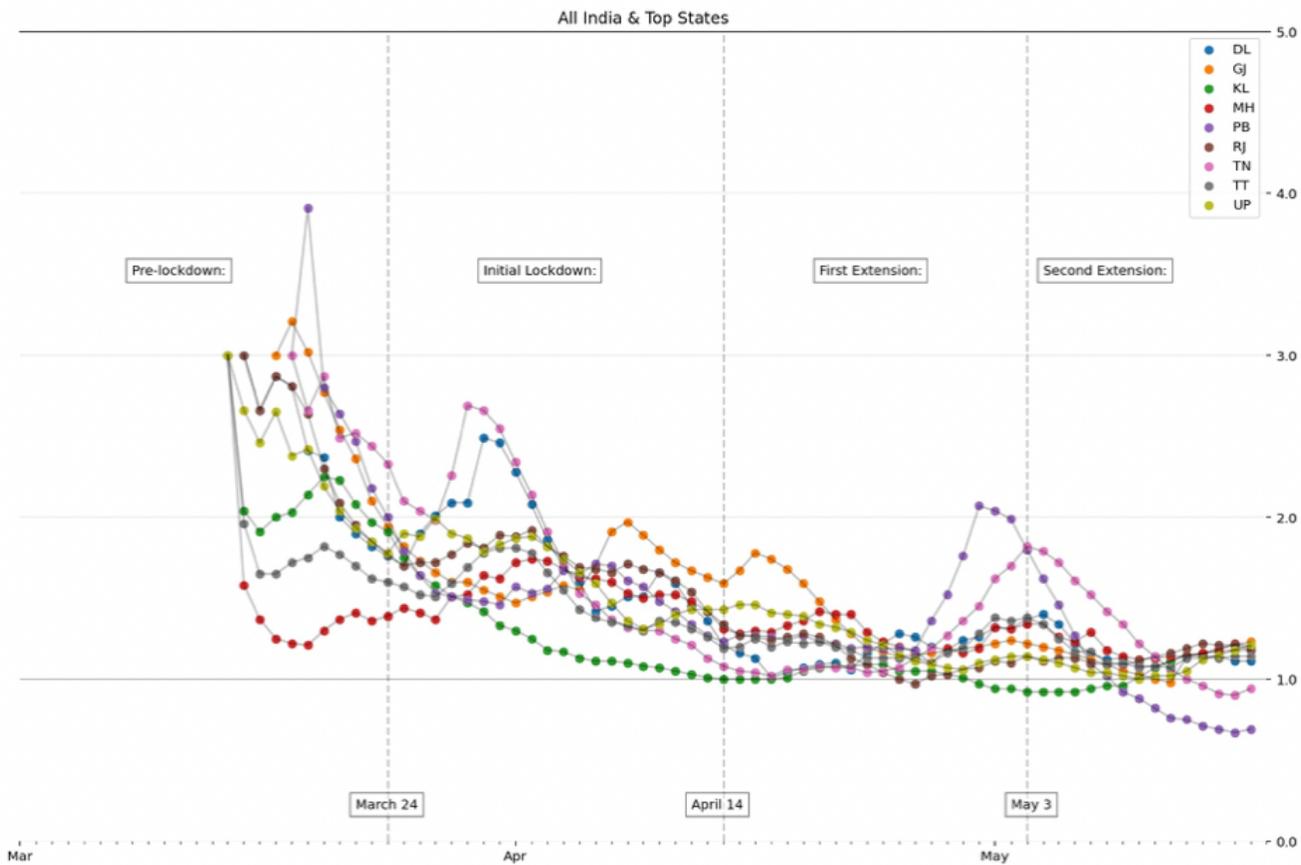


Figure 3

Real-time effective Reproduction number (Rt) for India and states for all lockdown periods, 2020. Source: Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/>. Note: TT represents India

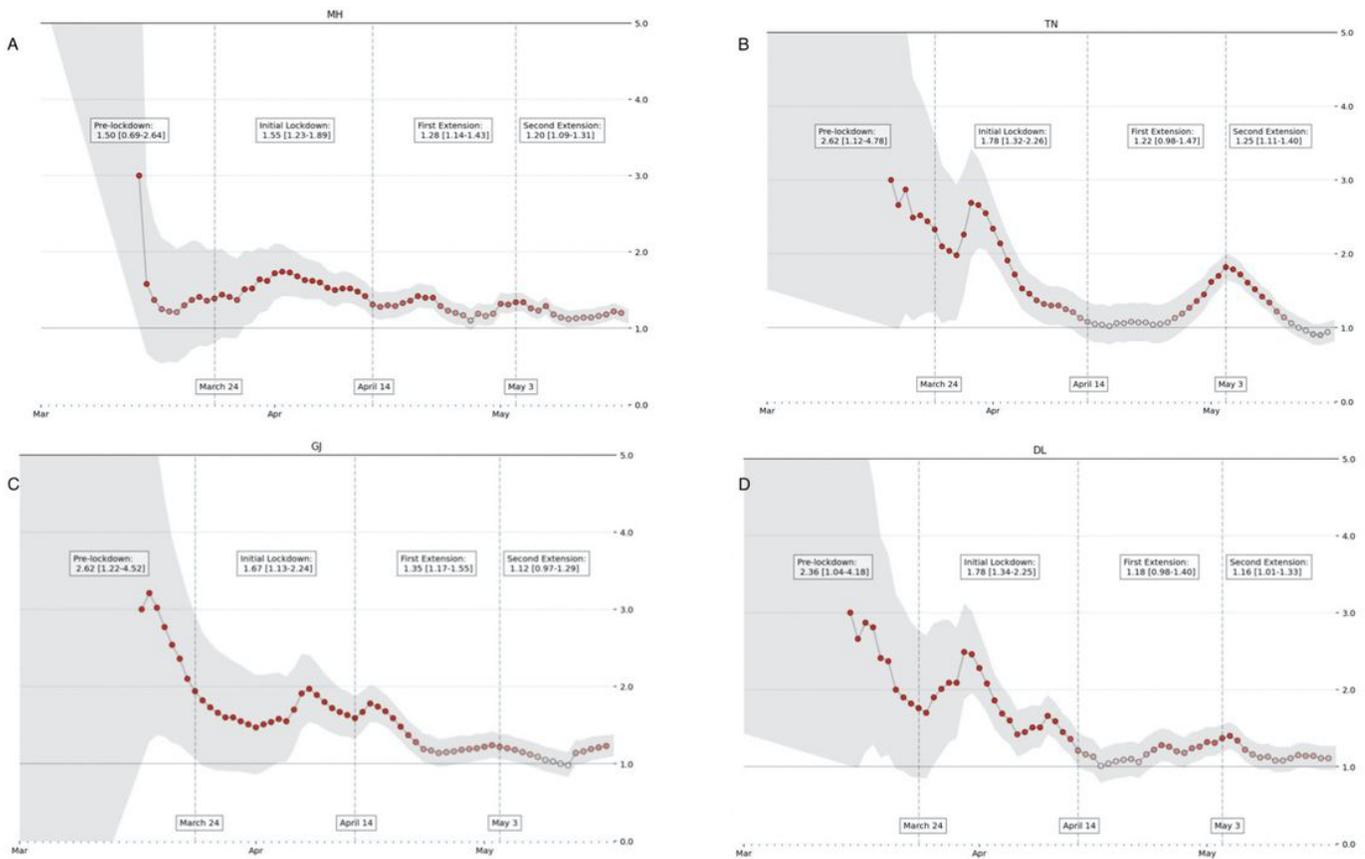


Figure 4

(A): Real-time effective Reproduction number (Rt) for Maharashtra on 17th May 2020. Source: Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/> (B): Real-time effective Reproduction number (Rt) for Tamil Nadu on 17th May 2020. Source: Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/> (C): Real-time effective Reproduction number (Rt) for Gujarat on 17th May 2020. Source: Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/> (D): Real-time effective Reproduction number (Rt) for Delhi on 17th May 2020. Source: Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/>