Full Paper

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

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Introduction

The World Health Organization (WHO) has declared the novel Coronavirus (COVID-19) outbreak 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 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-19[1]. The absence of sufficient doses of the COVID-19 vaccine for the Indian population makes 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 system[2]. In the absence of sufficient vaccine, 'social distancing' is the optimal strategy to control novel Coronavirus spread.

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 crisis[3]. The housing conditions are relatively deplorable for one in six urban dwellers, and the 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 and scale up the testing production 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 disease's onset until the healthcare infrastructure can handle the surge in cases.

The concept of basic reproduction number (R_0) was first introduced in demography, where this metric was used to count offspring[4]. 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 one of the fundamental and most often used metrics for studying infectious disease dynamics[5]. In view of the current COVID-19 pandemic, the paper attempts 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, urbanization, good governance indicator, 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 I show the number of tests done per million population by different states of India as of 9th May. However, India has limited facilities due to which sufficient tests could not be conducted in some states; thus, they did poorly in stopping the spread of the virus. Rapid testing at an early stage has shown phenomenal results in most states, which is illustrated in Fig I.

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 a state government's social welfare program's effectiveness. It is expected that states placed with a high human development index will do far better in controlling the virus's spread than those having a lower HDI Index. It is also hypothesized that the 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 essential 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 that state's health infrastructure. It is conceptualized that these factors have a strong relationship with the decline of R_t.

Material & 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 of 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. Good Governance Index is a uniform tool across the States to assess the Status of Governance and the impact of various interventions taken up by the State Government and Union Territories (UTs). The Department of Administrative Reform and Public Grievances (DARPG), the Government of India, partnered with the Centre for Good Governance (CGG), Hyderabad, to design and develop the Good Governance Index. Urbanization is another factor that is a key correlate of total infections reported. Urban areas are a high-risk zone for infections, considering the nature of the spread of diseases. Urbanization percentage at the state level has been used from Census 2011. 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 Rt, the situation is more controllable. In general, $R_t < 1$ is the main goal of the policy planners working in epidemiology. Epidemiologists argue that tracking R_t is the only way to manage the transmission of communicable disease. More importantly, it is helpful 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, Rt, in terms of the probabilistic epidemiological model, given the time series for new cases[6].

Bettencourt & Ribeiro's approach has been used to calculate R_t[7], as described in[8] 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, today's Rt's value is related to the value of yesterday's R_{t-1} and every previous value of R_{t-m}. Bayes' rule updates the beliefs about R_t's true value based on how many new cases have been reported each day.

Bayes' Theorem suggests

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

$P(k \mid R_t)$: The likelihood of observing 'k' new cases given Rt, time points.

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

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

Choosing a Likelihood Function $P(k_t \mid R_t)$

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:

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

There exists a relationship between R_t and λ.

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

Where ɤ 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 findings[9]. Further, new cases are known; therefore, the likelihood function as a Poisson parameterized by fixing k and varying R_t can be reformulated[7].

$$P(k \mid Rt) = \frac{\lambda^{k} . e^{-\lambda}}{k!}$$

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 by [9] 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 mean incubation period's preliminary estimates (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 transmission[13]. 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 2:1[14]. In the present study, the mean value of the serial number is considered as four days.

Basic Reproduction Number (R_0)

The reproduction Number for COVID 19 at the initial stage is estimated between 2 and 3[15]. Using the raw CDC data, the basic reproduction number's estimated value is between 2.2 and 2.3. Another study[16] 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 effective reproduction number estimate using the current adopted Bayesian approach is independent of the initially assumed value of 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 Rt's value during the 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, Urbanization, HDI, PCHE and Good Governance Index as independent variables. All independent variables were normalized between 0 and 1 to bring all the independent variables in the dataset to a common scale.

Results

The effective reproduction number, R_t, changes over time because of the decrease in the fraction of susceptible. R_0= 3 considered as the initial value of R_t and Serial Interval (SI) of 4 days, have been taken for the present study. However, initial value of R_0 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 Rt 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.

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 the starting date from where lockdown policies will affect R_t's value.

Fig II shows the value for R_t for India. The value of R_t 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 the first lockdown period on 15th April, it reached the level of 1.20 (90% HDI 1.08, 1.32) and further declined to Rt = 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. India's R_t =1.07 (90% HDI: 1.01, 1.11) was observed on 21st January 2021, nearly after a year of onset of the pandemic.

Fig III & Fig IV (A-E) reveals that almost all states show a decreasing pattern in R_t from the beginning to the end of a year to pandemic except for Kerala, R_t's value for Kerala is still high on 21st January 2021 at R_t= 1.20 (90% HDI: 1.12, 1.26). This indicates that nation-wide lockdown has had a positive effect in stopping the spread of the virus across most of the 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, urbanization, good governance index, and PCHE, tests conducted per million population during the lockdown period were the significant factor at the 5% level of significance. The regression coefficient for the number of test variable was 1.135, which indicates that as the number of tests increases, the decline in R_t was observed. Further, this regression coefficient implies that the increase in testing rates helped identify and isolate the infected people and reduce the R_t during the lockdown period.

Discussion

This study evaluates the impact of nation-wide lockdown on COVID-19 cases in fourteen states of India. The nation-wide lockdown was implemented from 24th March 2020. The effective reproduction number (R_t) in several states has come down due to the lockdown compared to what was estimated at the beginning of the epidemic. 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. The overall picture suggests the initial success of Indian states to stop the rise of the curve. However, as a whole, the effective reproduction numbers (as of 21st January 2021) were above the epidemic potential. But, every estimation like this has an element of natural variation grounded in the model's uncertainties and assumptions. With these cautions, this reduction can mainly be explained by the reduced number of contacts among people owing to movement restrictions. A similar study on the impact of lockdown in India also reported a reduction in reproduction number[17]. However, as mentioned earlier, the effective reproduction number (R_t) estimations are dynamic and may change over age structure, time and nature of the intervention. R_t is a measure of transmissibility or contagiousness at a given period, and its reduction should be interpreted with caution.

Findings show that nation-wide lockdown has brought a decline in the reproduction number of India. However, this decline was not uniform as India is a diverse country where some states are highly developed in health infrastructure and human development, while some of the states are lagging in these facilities. This disparity in the states is responsible because government interventions in India are not having the desired effect on stopping the spread of the virus. The possible reasons for this disparity among states are rapid testing rate, Good Governance and urbanization. Our regression analysis suggested that Testing Rate, which is used as a proxy for each state's health policies, has a significant positive association with the decline of R_t during the lockdown period. The state's testing rate plays a vital role in identifying and isolating the infected people and reducing the R_t during the lockdown period. However, when we relate R_t with the testing rate, there is an endogeneity problem as reported infections are closely associated with testing numbers across the states. So, their relationship should be interpreted with caution.

Initially, the reported cases and the confirmed cases of COVID-19 were low due to low testing. However, the number of cases picked-up due to an increase in testing. Due to these factors, it was difficult to estimate a reliable R_t at the pandemic's initial stage. As per this study[18], 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. To detect 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-19[19]. 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 contributing to the spread of the infection 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 aforementioned limitation, the present study attempts to study the causes of variation among states in controlling the spread of the COVID 19. The findings show that the lockdown strategy has contributed to slowing the virus's spread to a greater extent.

This study's results should be interpreted with certain caveats apart from the inherent limitations of the data's crowd-sourced nature. A crowd-sourced dataset's credibility may be viewed from the following views: under-reporting, duplicated information, incomplete information, differential lag in reporting the cases, missing initial cases, and the inclusion of imported cases as native cases. These may lead to overestimation or underestimation of reproduction numbers. However, as the cases in this particular instance (www.covid19india.org) are chiefly extracted from official government websites, the magnitude of discrepancy may remain the same in some dimensions irrespective of the nature of the data source. Secondly, the investigators also tried to minimize these discrepancies by rigorous data cleaning, as far as possible by triangulating with other sources and subsequent merging of the final dataset.

The current study shows that the epidemic curtailment strategies enforced by the Indian government have been effective in reducing the effective reproduction number R_t. However, the R_t remains to be above 1 in India. The reason being, there is a variation in the decrease of these transmission parameters across different Indian states. With the inevitability of ending a lockdown even after a year of pandemic, future mitigation measures may consider this information and develop tailored strategies as alert systems for the institution of Non-Pharmaceutical Interventions (NPIs) at the state level or even the district level.

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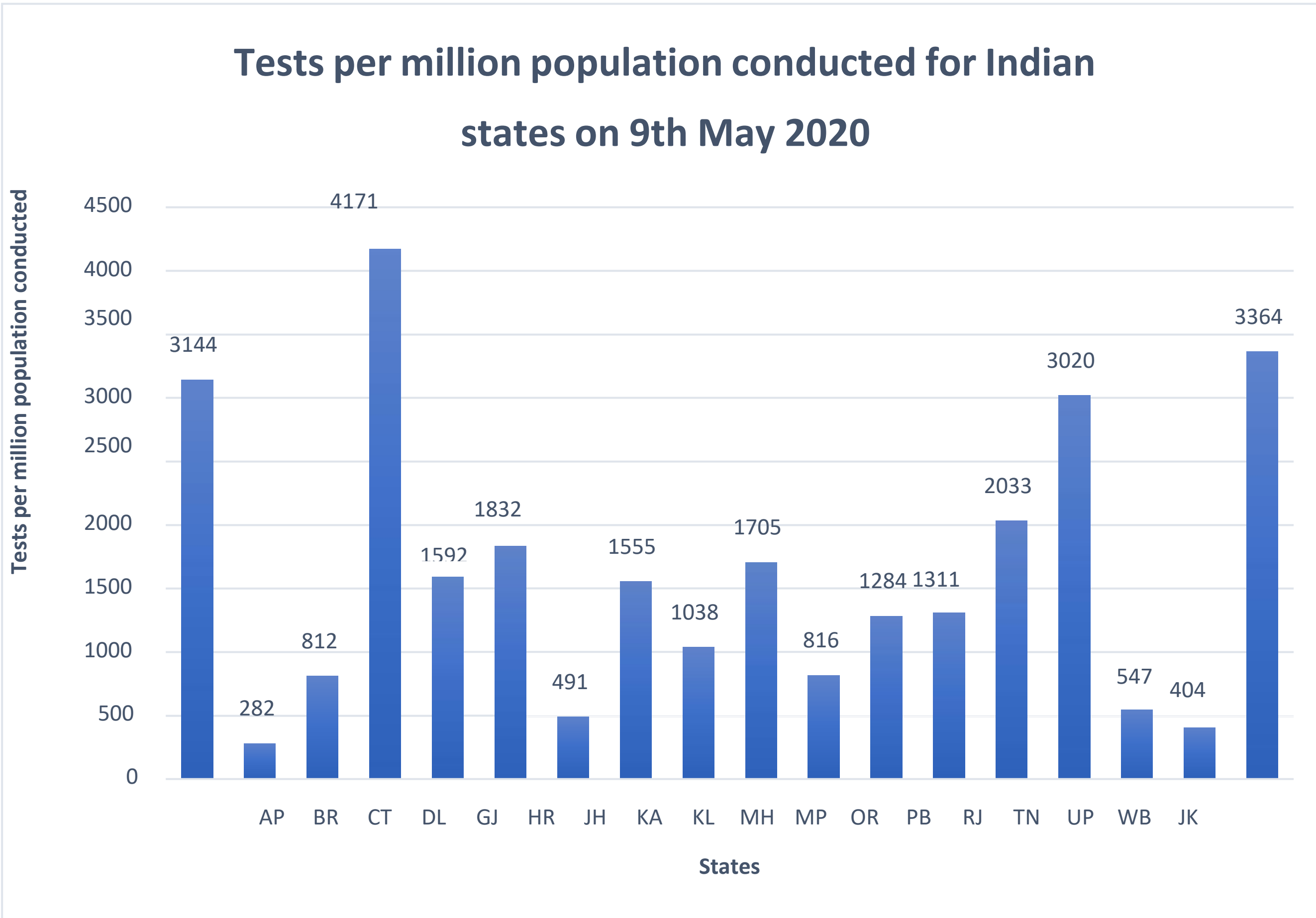
Tables and Figures

Fig I COVID-19 Testing Rate (test per million population) for states of India, 2020



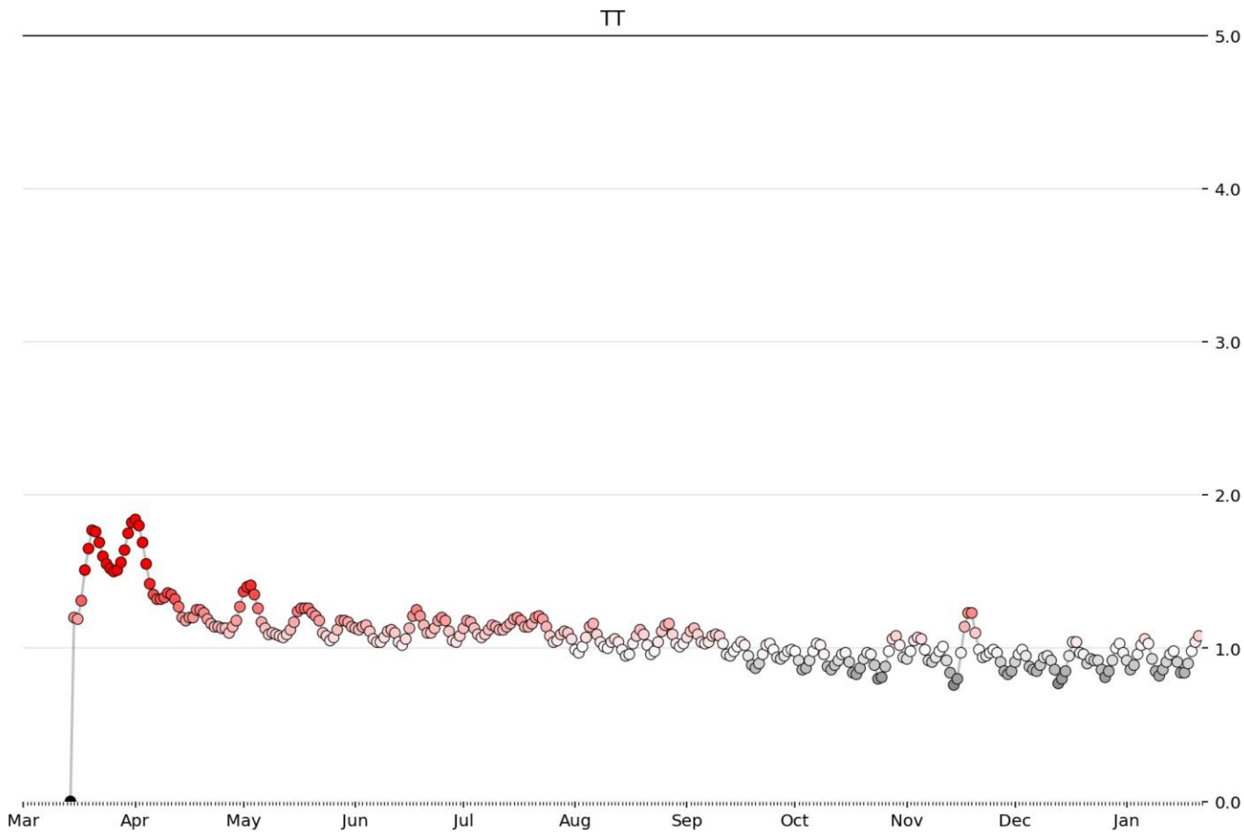
Source: Data repository of covid19india.org

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

				24th 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)
				2nd 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)
				28th 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)

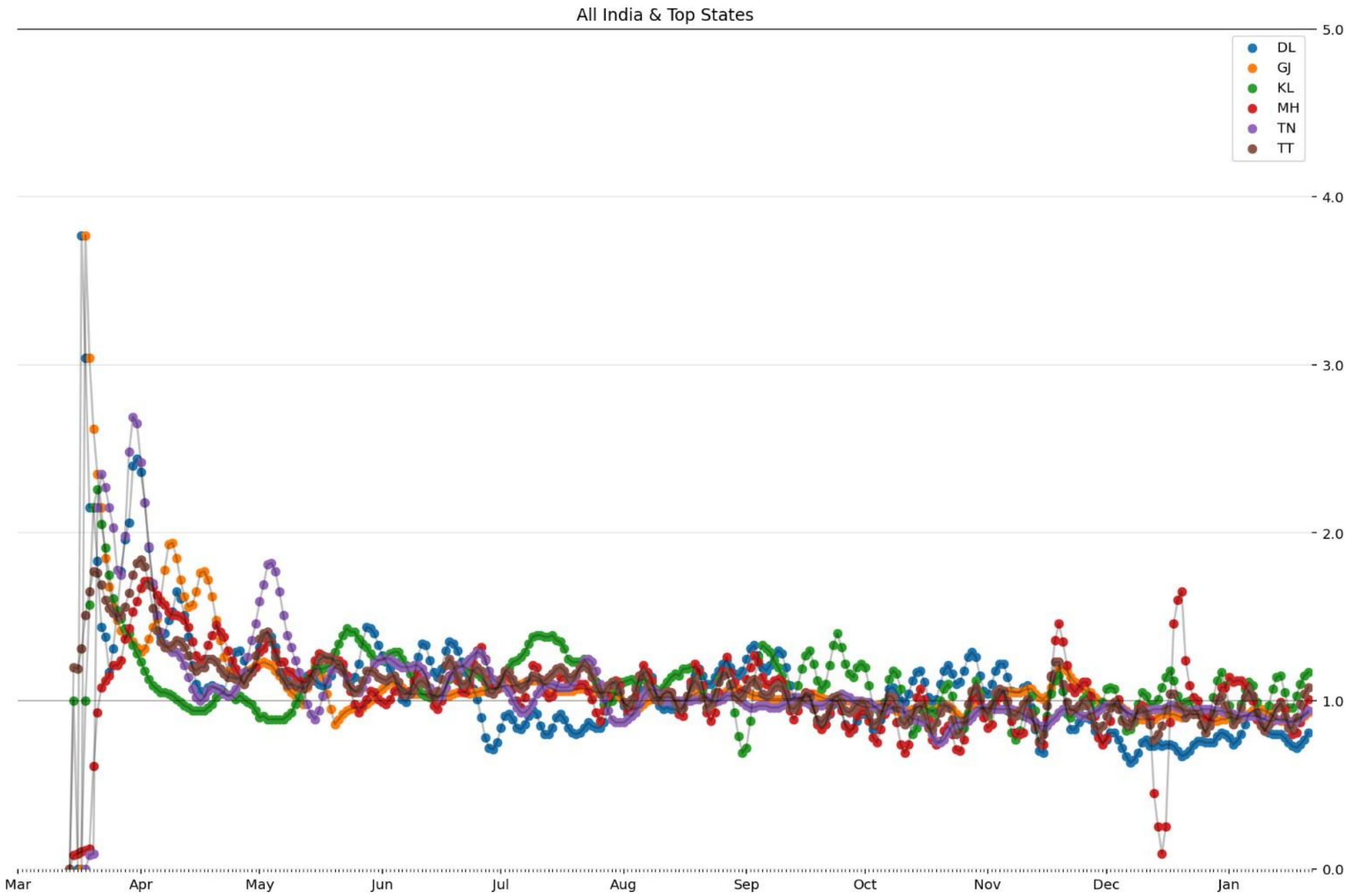
Source: Based on calculations of Jupyter Notebook https://sanzgiri.github.io/covid-19-dashboards/

Fig II: Real-time effective Reproduction number (R_t) for India for all lockdown periods, 21st Jan, 2021



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

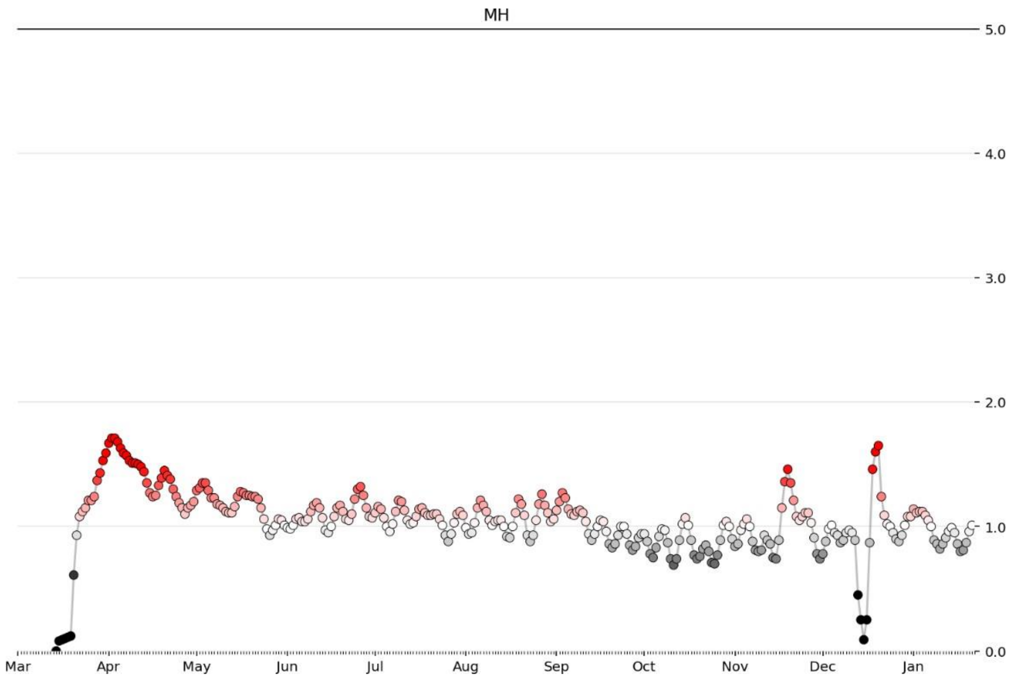
Fig III: Real-time effective Reproduction number (R_t) for India and states for all lockdown periods, 21st Jan, 2021



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

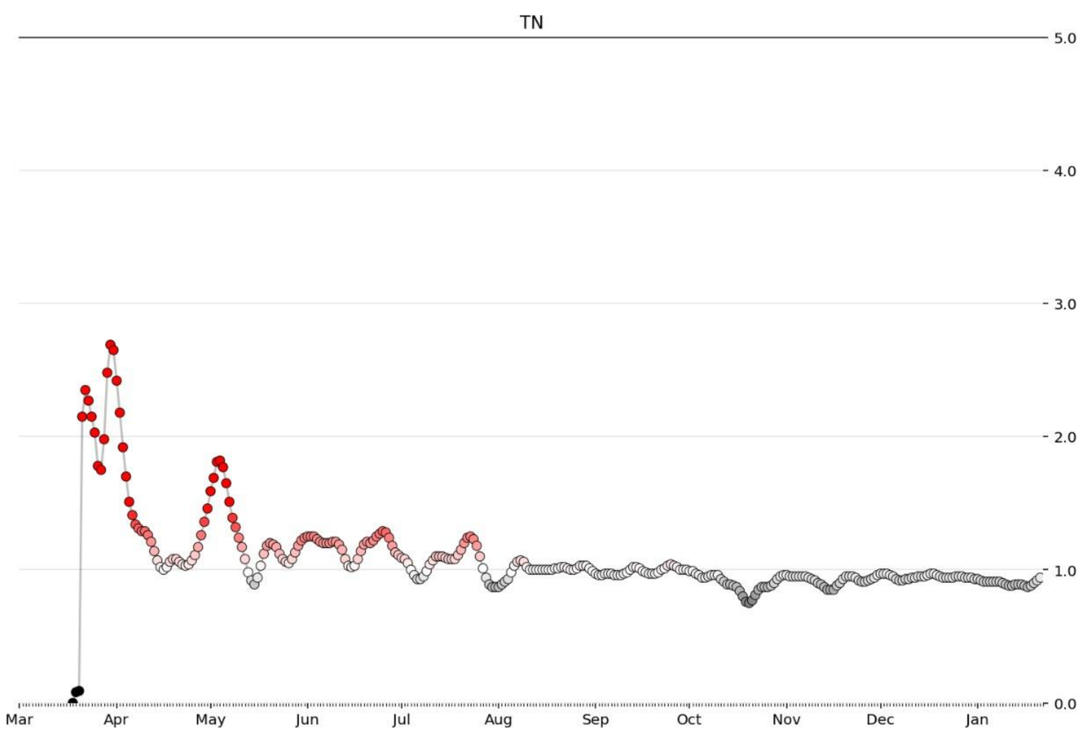
Note: TT represents India

Fig IV (A): Real-time effective Reproduction number (R_t) for Maharashtra on 21st Jan, 2021



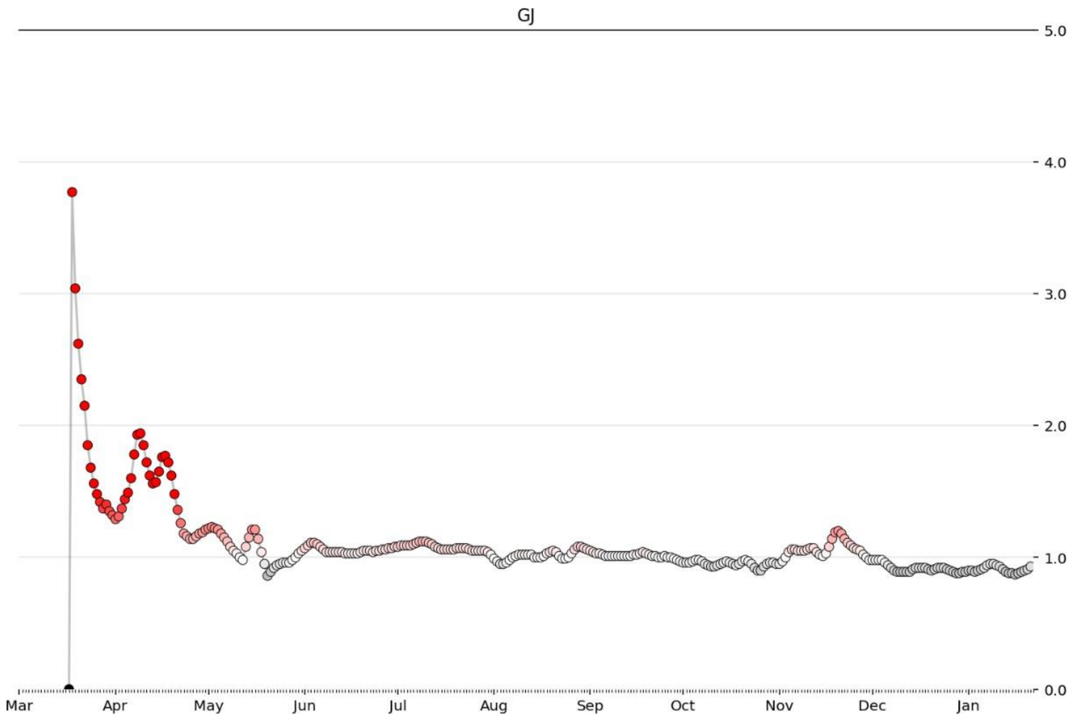
Source: Based on calculations of Jupyter Notebook **https://sanzgiri.github.io/covid-19-dashboards/**

Fig IV (B): Real-time effective Reproduction number (R_t) for Tamil Nadu on 21st Jan, 2021



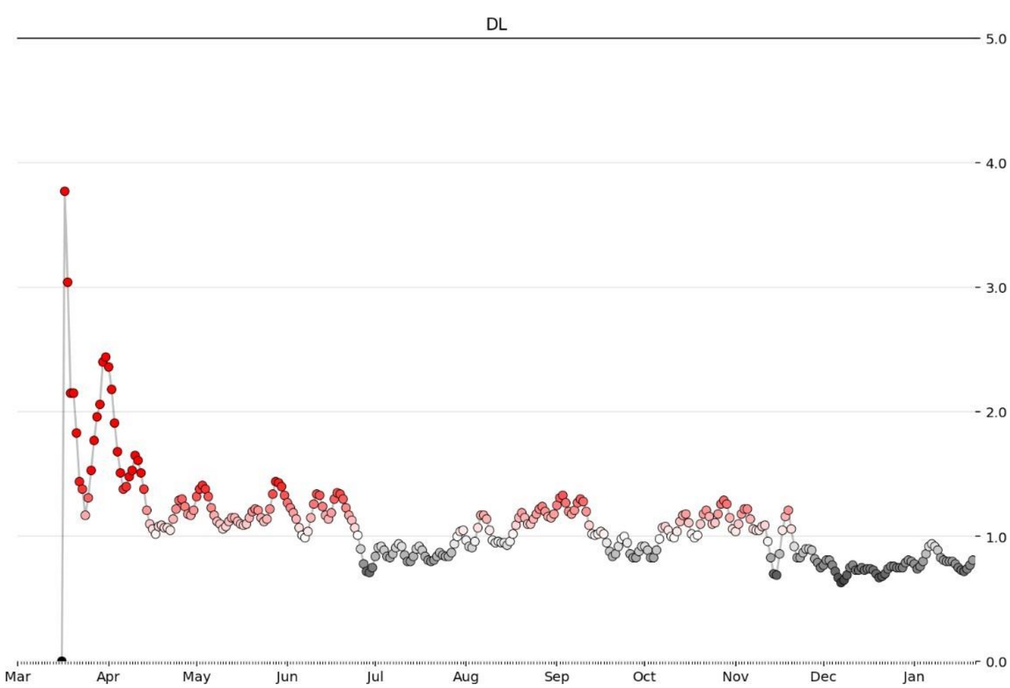
Source: Based on calculations of Jupyter Notebook **https://sanzgiri.github.io/covid-19-dashboards/**

Fig IV (C): Real-time effective Reproduction number (R_t) for Gujarat on 21st Jan, 2021



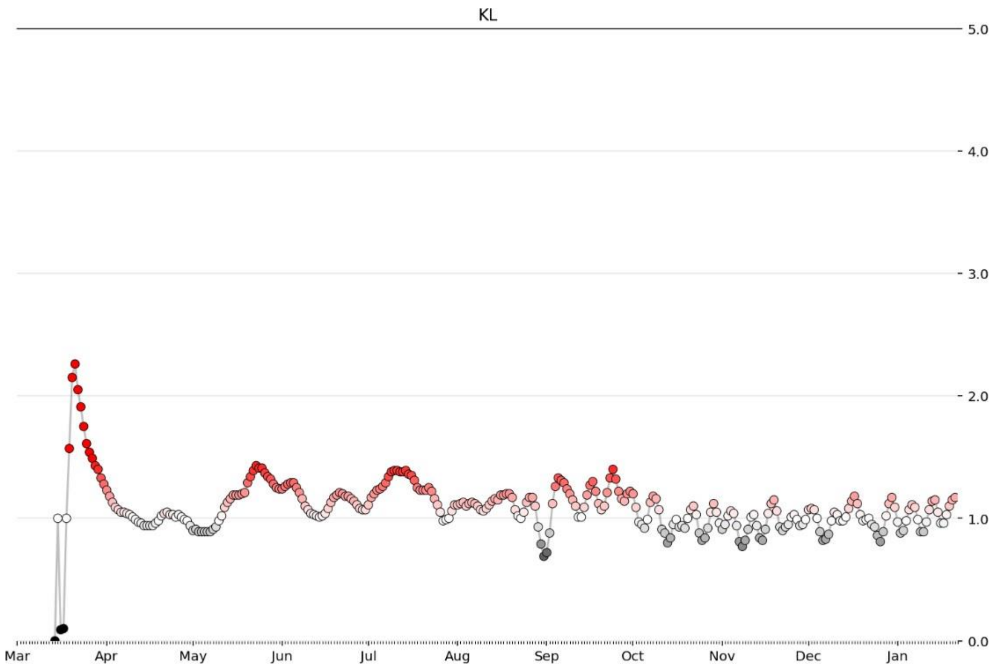
Source: Based on calculations of Jupyter Notebook **https://sanzgiri.github.io/covid-19-dashboards/**

Fig IV (D): Real-time effective Reproduction number (R_t) for Delhi on 21st Jan, 2021



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

Fig IV (E): Real-time effective Reproduction number (R_t) for Kerala on 21st Jan, 2021



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*	1.135	0.4287	2.65	0.029	0.1468	2.1240
HDI Index	-0.064	0.4590	-0.14	0.892	-1.1229	0.9941
Governance index	-0.258	0.3204	-0.8	0.445	-0.9965	0.4812
PCHE	-0.725	0.6391	-1.13	0.29	-2.1986	0.7489
Urbanization	0.223	0.6094	0.37	0.724	-1.1820	1.6284
constant	0.609	0.6036	1.01	0.342	-0.7825	2.0012

R-squared **0.5945**

Adjusted R-squared **0.3411**

***** significant at 5% level

N = 14 (Number of observations in the regression model, here N denotes the number of state's whose data is been used for regression).

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