

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

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### **Salient Findings:**

1. Each phase of nation-wide lockdown has contributed to the decline of effective reproduction number ( $R_t$ ) for India. However, the trends in the value of  $R_t$  varied considerably across the states.
2. Effective reproduction number was near to two during the pre-lockdown period and had started to decline and reached to the level of 1.04 on 9<sup>th</sup> May. Again, it has shown an increasing trend and attained the value of 1.14 on 17<sup>th</sup> May.
3. The value of the effective reproduction number increased in India at the end of April due to the sudden increase in cases in Punjab and Tamil Nadu.
4. The consistent decline in effective reproduction number was observed in the states of Andhra Pradesh, Karnataka and Kerala since 2<sup>nd</sup> April. However, a minor resurgence in  $R_t$  is observed in Kerala and Karnataka recently.
5. The major increase in the value of effective reproduction number was seen in the states of Bihar, Odisha, Rajasthan, and Uttar Pradesh after 9<sup>th</sup> May due to increasing numbers of migrant workers returning to their home.
6. Regression analysis suggests that higher testing rate was the most significant factor at the state-level that contributes to the decline of  $R_t$  during the lockdown period.
7. Return of migrant workers to their home, inefficient contact tracing and poor quality of quarantine centres are the responsible factors in spreading the infection.

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

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**Short Title:** Effective Reproduction Number for COVID-19 for India and its States

## Abstract

**Introduction:** WHO declared the outbreak of the novel Coronavirus, COVID-19, as a pandemic on 11<sup>th</sup> March. On 24<sup>th</sup> March, a three-week nation-wide lockdown has been announced, which is now extended till 31<sup>st</sup> May. Effective Reproduction Number ( $R_t$ ) helps in understanding how effective preventive measures have been in controlling an outbreak.

**Objective:** 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 that are responsible for the uneven distribution of effective reproduction number ( $R_t$ ) of COVID-19 across different states of India.

**Methods:** 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 ( $R_0$ ) of three.

**Results:** At the national level, India's  $R_t$  has been declined from 1.81 (90% HDI: 1.64, 2.00) on 1<sup>st</sup> April to  $R_t = 1.20$  (90% HDI: 1.08, 1.32) on 15<sup>th</sup> April but the slight increase was observed on 3<sup>rd</sup> May ( $R_t = 1.38$  (90% HDI: 1.30, 1.48)). The decline in the value of  $R_t = 1.04$  (90% HDI: 0.96, 1.13) was seen on 9<sup>th</sup> May after that an increase was observed on 17<sup>th</sup> May ( $R_t = 1.14$  (90% HDI: 1.06, 1.21)). The value of  $R_t$  at the state level has shown significant variations. Testing rate per million population had a significant impact in reducing the  $R_t$ .

**Conclusion:** 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 it plays an essential role in identifying the cases and isolating them at an early stage of infection

**Keywords:** Effective Reproduction Number; COVID-19; India; Government Interventions; Lockdown; Bayesian approach; State-level analysis.

## Introduction

The World Health Organization (WHO) has declared the outbreak of the novel Coronavirus, (COVID-19) as a pandemic on 11<sup>th</sup> March 2020. In India, the first positive case of COVID-19 was detected on 30<sup>th</sup> 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 18<sup>th</sup> 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 (Ferguson *et al.*, 2020). 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 systems (World Bank Database). 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 25<sup>th</sup> 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 (ILO, 2020). 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 offspring (Heesterbeek, 2002). 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 dynamics (Delamate *et al.*, 2019). 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 9<sup>th</sup> 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  $R_t$ .

## 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 14<sup>th</sup> March to 17<sup>th</sup> 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 1<sup>st</sup> 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 cases (Diekmann *et al.*, 1990).

Bettencourt & Ribeiro's approach has been used to calculate  $R_t$  (Bettencourt, 2008), as described in (Systrom, 2020) 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  $\lambda$  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  $\lambda$ .

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

Where  $\gamma$  is the reciprocal of the serial interval, and the value of the serial interval has been considered to be four days based on the findings of Du *et al.* (2020). Further, new cases are known; therefore, the likelihood function as a Poisson parameterized by fixing k and varying  $R_t$  can be reformulated (Bettencourt, 2008)

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

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](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 (14<sup>th</sup> 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 (Duet *et al.* (2020); Nishiura *et al.* (2020); Li *et al.* (2020); Linton *et al.* 2020). Recent analyses by Duet *et al.* (2020) 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) (Li *et al.*, 2020; Linton *et al.*, 2020). 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 (Fraser *et al.*, 2004). This is also confirmed by a report (Wei *et al.*, 2020) which states that investigation of all 243 cases of COVID-19 reported in Singapore during 23<sup>rd</sup> January–16<sup>th</sup> March identified seven clusters of cases in which pre-symptomatic transmission is the most likely explanation for the occurrence of secondary cases. This applies to India as well. 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. (The Times of India, 2020). 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 3 (White *et al.*, 2020). Using the raw CDC data, the estimated value of the basic reproduction number is between 2.2 and 2.3. Another study by Kucharski *et al.* (2020) 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 (14<sup>th</sup> 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 2<sup>nd</sup> April and 9<sup>th</sup> May) for states acts as the dependent variable, and state-level factors namely Tests Conducted (between 2<sup>nd</sup> April and 9<sup>th</sup> 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 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 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 1 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 White *et al.* (2009).

### **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 2** 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 1<sup>st</sup> April. The lockdown slowly started to show an impact as  $R_t$  has declined substantially, and by the end of first lockdown period on 15<sup>th</sup> 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 27<sup>th</sup> April, which shows that nation-wide lockdown has significantly lowered down the pace of transmission of COVID-19. An increase was observed on 3<sup>rd</sup> 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 9<sup>th</sup> May before increasing again to  $R_t=1.14$  (90% HDI: 1.06, 1.21) on 17 May.

**Fig 3 & Fig 4(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 2. 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.

## Discussions and Conclusions

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 15<sup>th</sup> 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 28<sup>th</sup> 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 3<sup>rd</sup> 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 drastically (India TV, 2020). 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 market (The Indian Express, 2020). So, such lapses on the Government's part takes away all the progress made due to the lockdown. Again, on 17<sup>th</sup> 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 9<sup>th</sup> 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, which is consistent with the findings of (Dwivedi *et al.*, 2020; Kumar *et al.*, 2020). 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 17<sup>th</sup> 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 the study by (Goli and James, 2020), 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-19 (Subramanian and James, 2020).

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.

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## References

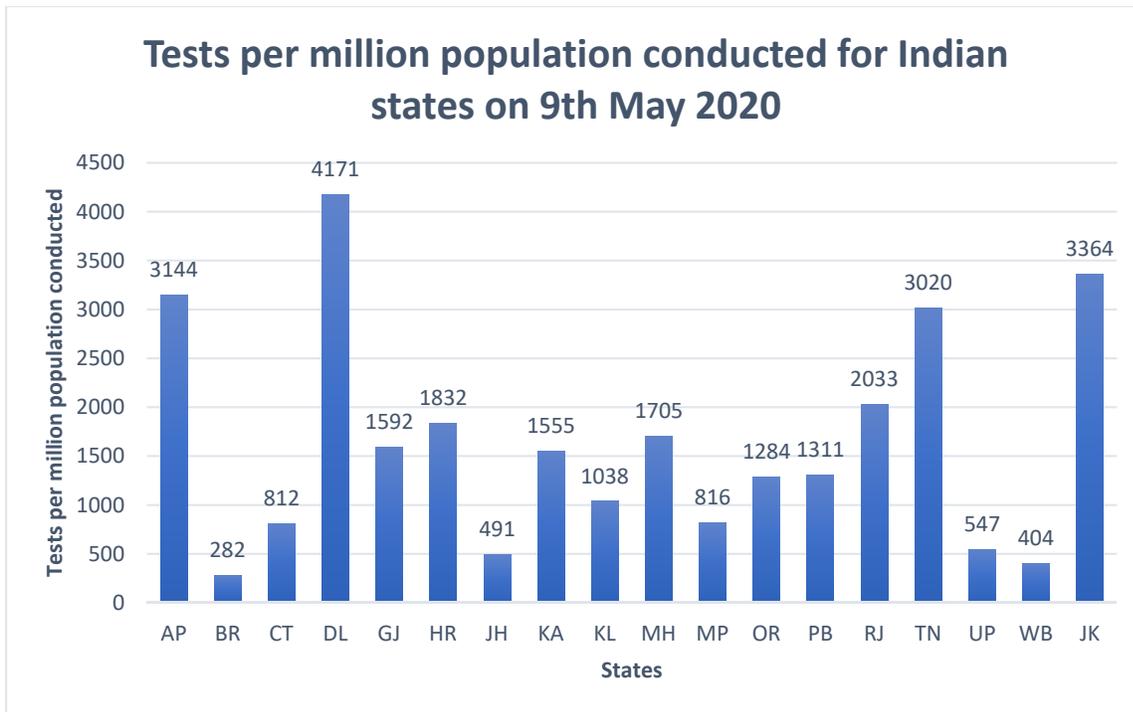
1. Bettencourt LMA, Ribeiro RM (2008) Real Time Bayesian Estimation of the Epidemic Potential of Emerging Infectious Diseases. PLoS ONE 3(5):e2185. <https://doi.org/10.1371/journal.pone.0002185>
2. Central Bureau of Health Intelligence, 2019. National Health Profile 2019 (14<sup>th</sup> Issue)
3. Delamater, P. L., Street, E. J., Leslie, T. F., Yang, Y. T., & Jacobsen, K. H. (2019). Complexity of the basic reproduction number (R<sub>0</sub>). *Emerging infectious diseases*, 25(1), 1.
4. Diekmann, O., Heesterbeek, J. A. P., & Metz, J. A. (1990). On the definition and the computation of the basic reproduction ratio R<sub>0</sub> in models for infectious diseases in heterogeneous populations. *Journal of mathematical biology*, 28(4), 365-382.
5. Du, Z., Xu, X., Wu, Y., Wang, L., Cowling, B. J., & Meyers, L. A. (2020). Serial Interval of COVID-19 among Publicly Reported Confirmed Cases. *Emerging Infectious Diseases*, 26(6), 1–7. <https://doi.org/10.3201/eid2606.200357>
6. Dwivedi, L. K., Rai, B., Shukla, A., Dey, T., Ram, U., Shekhar, C., . . . Unisa, S. (2020, 25<sup>th</sup> April, 2020). Assessing the Impact of Complete Lockdown on COVID-19 Infections in India and its Burden on Public Health Facilities. A Situational Analysis Paper for Policy Makers. Mumbai.
7. Ferguson, N. M., Laydon, D., Nedjati-Gilani, G., Imai, N., Ainslie, K., & Baguelin, M. (2020). Imperial College COVID-19 Response Team. *Report 9: Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand*.
8. Fraser, C., Riley, S., Anderson, R. M., & Ferguson, N. M. (2004). Factors that make an infectious disease outbreak controllable. *Proceedings of the National Academy of Sciences*, 101(16), 6146-6151.
9. Global Data Labs (2018). Subnational Human Development Index 4.0

10. Goli, S and James, K.S. (2020) How much India detecting SARS-CoV-2 Infections? A model-based estimation. medRxiv Preprint <https://doi.org/10.1101/2020.04.09.20059014>.
11. Heesterbeek, J. A. P. (2002). A brief history of  $R_0$  and a recipe for its calculation. *Acta biotheoretica*, 50(3), 189-204.
12. ILO (2020). ILO Monitor: COVID-19 and the world of work. Second edition
13. India TV, 2020: 167 pilgrims, who returned to Punjab from Hazur Sahib in Maharashtra, test COVID-19 positive. Retrieved from <https://www.indiatvnews.com/news/india/maharashtra-hazur-sahib-nanded-76-pilgrims-test-covid19-positive-in-amritsar-punjab-612947>
14. Kucharski, A. J., Russell, T. W., Diamond, C., Liu, Y., Edmunds, J., Funk, S., ... Flasche, S. (2020). Early dynamics of transmission and control of COVID-19: a mathematical modelling study. *The Lancet Infectious Diseases*, 20(5), 553–558. [https://doi.org/10.1016/S1473-3099\(20\)30144-4](https://doi.org/10.1016/S1473-3099(20)30144-4)
15. Kumar, K., Meitei, W.B., Singh, A. (2020, 7<sup>th</sup> May 2020). Projecting the future trajectory of COVID-19 infections in India using the susceptible-infected-recovered (SIR) model
16. Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., ... Feng, Z. (2020). Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. *New England Journal of Medicine*, 382(13), 1199–1207. <https://doi.org/10.1056/NEJMoa2001316>
17. Linton, N. M., Kobayashi, T., Yang, Y., Hayashi, K., Akhmetzhanov, A. R., Jung, S., ... Nishiura, H. (2020). Incubation Period and Other Epidemiological Characteristics of 2019 Novel Coronavirus Infections with Right Truncation: A Statistical Analysis of Publicly Available Case Data. *Journal of Clinical Medicine*, 9(2), 538. <https://doi.org/10.3390/jcm9020538>
18. Ministry of Personnel, Public Grievances & Pensions (2019). Good Governance Index

19. National Commission for Population, 2019. Population Projection for India and States (2011 – 2036)
20. Nishiura, H., Linton, N. M., & Akhmetzhanov, A. R. (2020). Serial interval of novel coronavirus (COVID-19) infections. *International journal of infectious diseases*.
21. Subramanian, S. V., & James, K. S. (2020). Use of the Demographic and Health Survey framework as a population surveillance strategy for COVID-19. *The Lancet Global Health*.
22. Systemrom, Kevin, <http://systemrom.com/blog/the-metric-we-need-to-manage-covid-19/>
23. The Indian Express. (2020). Over 35% Tamil Nadu coronavirus cases linked to Koyambedu market in Chennai. Retrieved from <https://indianexpress.com/article/india/over-35-tn-cases-linked-to-a-market-in-chennai-6408861/>
24. The Times of India. (2020). How asymptomatic cases fuelled spread of Coronavirus. Retrieved from <https://timesofindia.indiatimes.com/india/how-asymptomatic-cases-fuelled-spread-of-coronavirus/articleshow/75292506.cms>
25. White, L. F., Wallinga, J., Finelli, L., Reed, C., Riley, S., Lipsitch, M., & Pagano, M. (2009). Estimation of the reproductive number and the serial interval in early phase of the 2009 influenza A/H1N1 pandemic in the USA. *Influenza and Other Respiratory Viruses*, 3(6), 267–276. <https://doi.org/10.1111/j.1750-2659.2009.00106.x>
26. World-Bank. Hospital beds (per 1,000 people). The World Bank Data Base -Retrieved from [https://data.worldbank.org/indicator/SH.MED.BEDS.ZS?end=2015&name\\_desc=false&start=2015&view=bar](https://data.worldbank.org/indicator/SH.MED.BEDS.ZS?end=2015&name_desc=false&start=2015&view=bar).

## Appendix

**Fig 1** COVID-19 Testing Rate (test per million population) for states of India, 2020



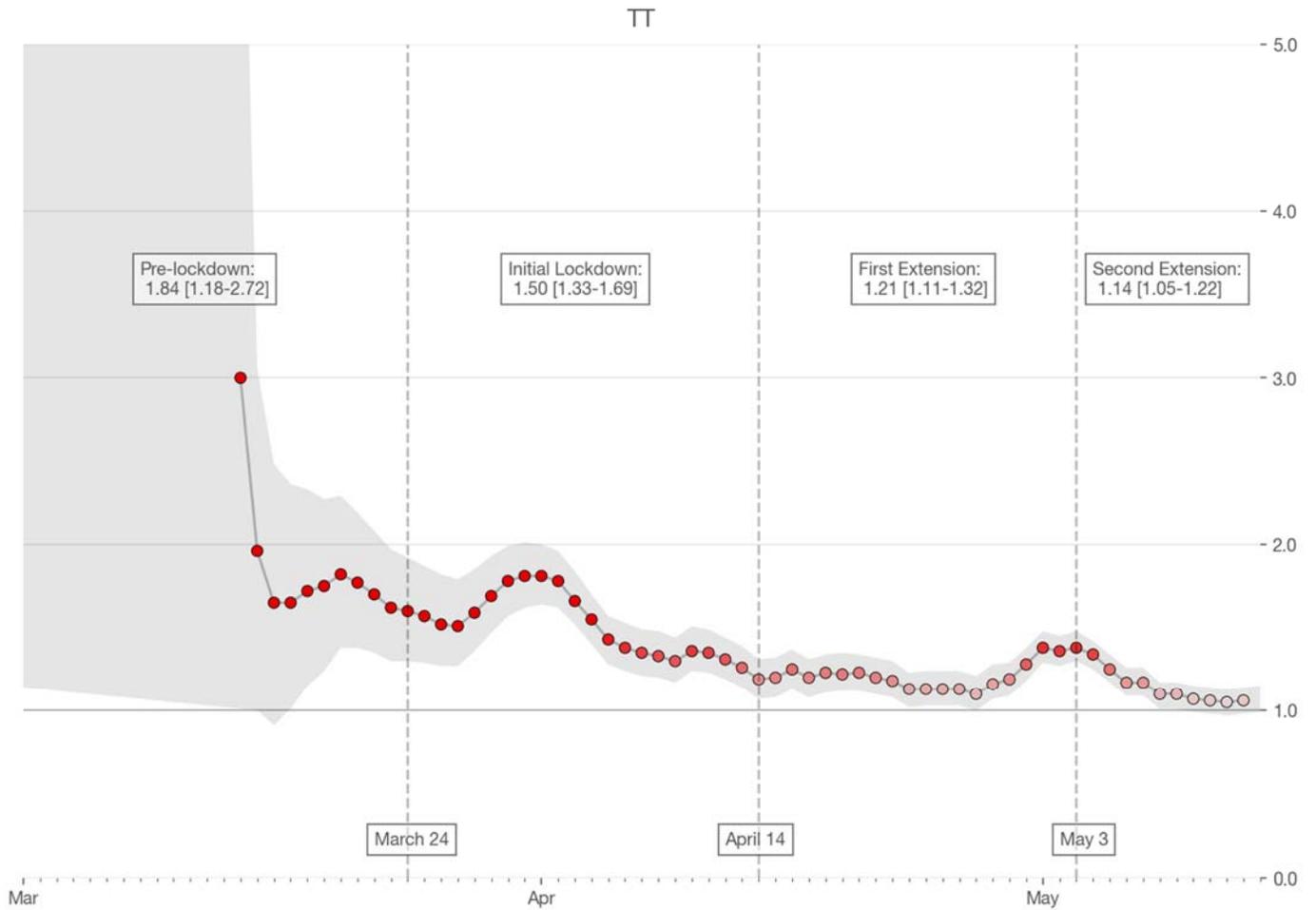
**Source:** Data repository of covid19india.org

**Table 1:** Most Likely (ML) values of  $R_t$  and Highest Density Interval (HDI) based on different Serial Interval (SI) &  $R_0$ , 24<sup>th</sup> March, 2<sup>nd</sup> April & 28<sup>th</sup> April 2020

<b>24<sup>th</sup> March</b>										
	<b>SI=3</b>	<b>90% HDI</b>	<b>SI=4</b>	<b>90% HDI</b>	<b>SI=5</b>	<b>90% HDI</b>	<b>SI=6</b>	<b>90% HDI</b>	<b>SI=7</b>	<b>90% HDI</b>
<b><math>R_0=1.5</math></b>	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)
<b><math>R_0=2.0</math></b>	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)
<b><math>R_0=2.5</math></b>	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)
<b><math>R_0=3.0</math></b>	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)
<b><math>R_0=3.5</math></b>	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)
<b>2<sup>nd</sup> April</b>										
	<b>SI=3</b>	<b>90% HDI</b>	<b>SI=4</b>	<b>90% HDI</b>	<b>SI=5</b>	<b>90% HDI</b>	<b>SI=6</b>	<b>90% HDI</b>	<b>SI=7</b>	<b>90% HDI</b>
<b><math>R_0=1.5</math></b>	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)
<b><math>R_0=2.0</math></b>	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)
<b><math>R_0=2.5</math></b>	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)
<b><math>R_0=3.0</math></b>	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)
<b><math>R_0=3.5</math></b>	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)
<b>28<sup>th</sup> April</b>										
	<b>SI=3</b>	<b>90% HDI</b>	<b>SI=4</b>	<b>90% HDI</b>	<b>SI=5</b>	<b>90% HDI</b>	<b>SI=6</b>	<b>90% HDI</b>	<b>SI=7</b>	<b>90% HDI</b>
<b><math>R_0=1.5</math></b>	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)
<b><math>R_0=2.0</math></b>	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)
<b><math>R_0=2.5</math></b>	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)
<b><math>R_0=3.0</math></b>	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)
<b><math>R_0=3.5</math></b>	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)

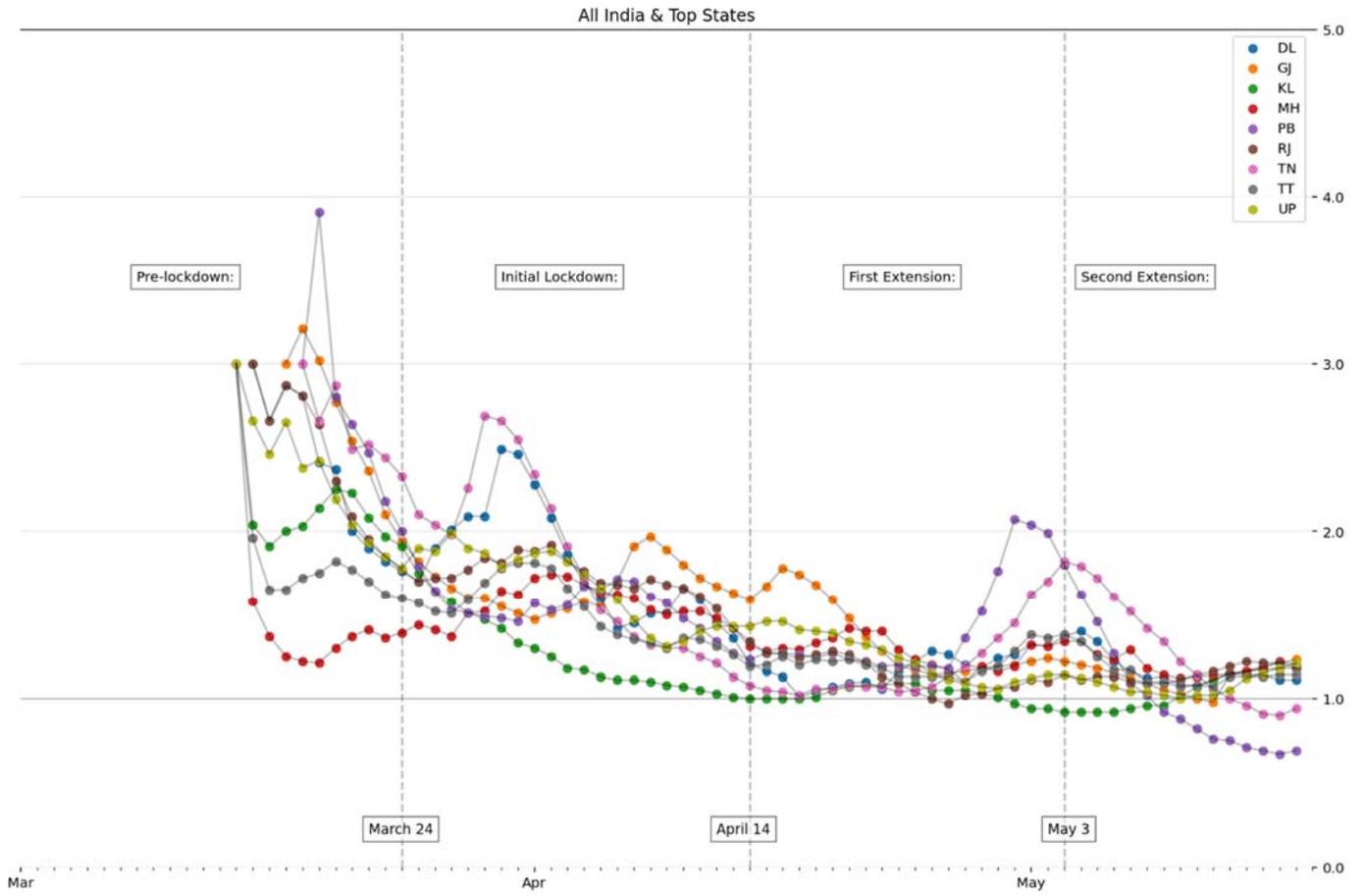
**Source:** Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/>

**Fig 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/>

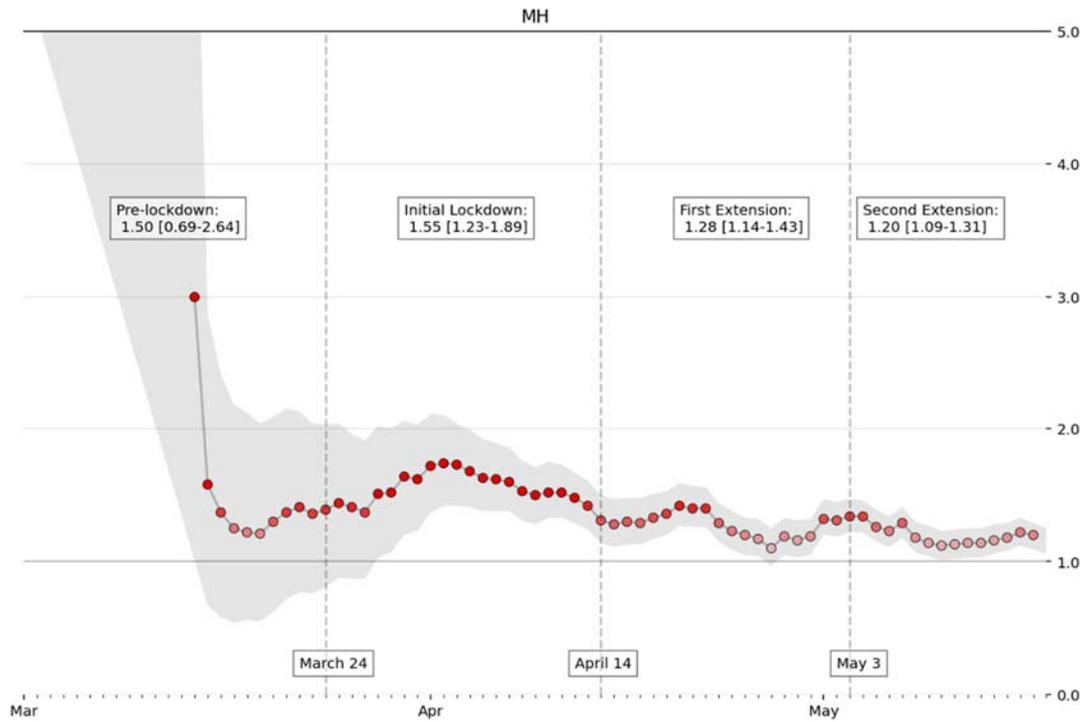
**Fig 3:** Real-time effective Reproduction number ( $R_t$ ) for India and states for all lockdown periods, 2020



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

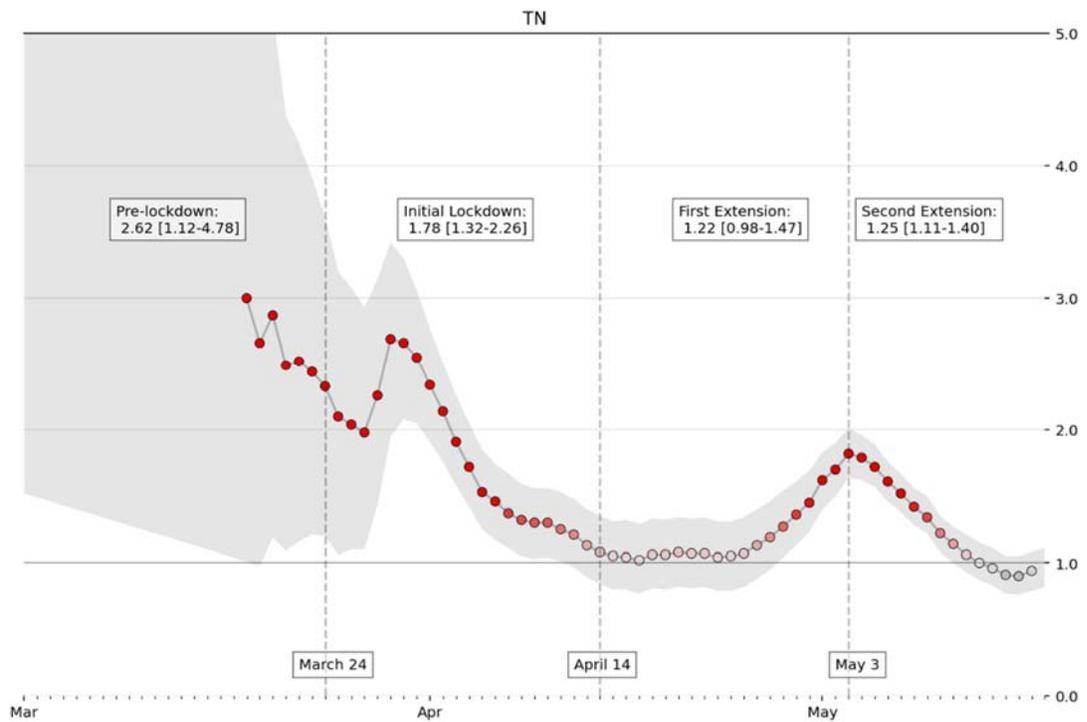
**Note:** TT represents India

**Fig 4(a):** Real-time effective Reproduction number ( $R_t$ ) for Maharashtra on 17<sup>th</sup> May 2020



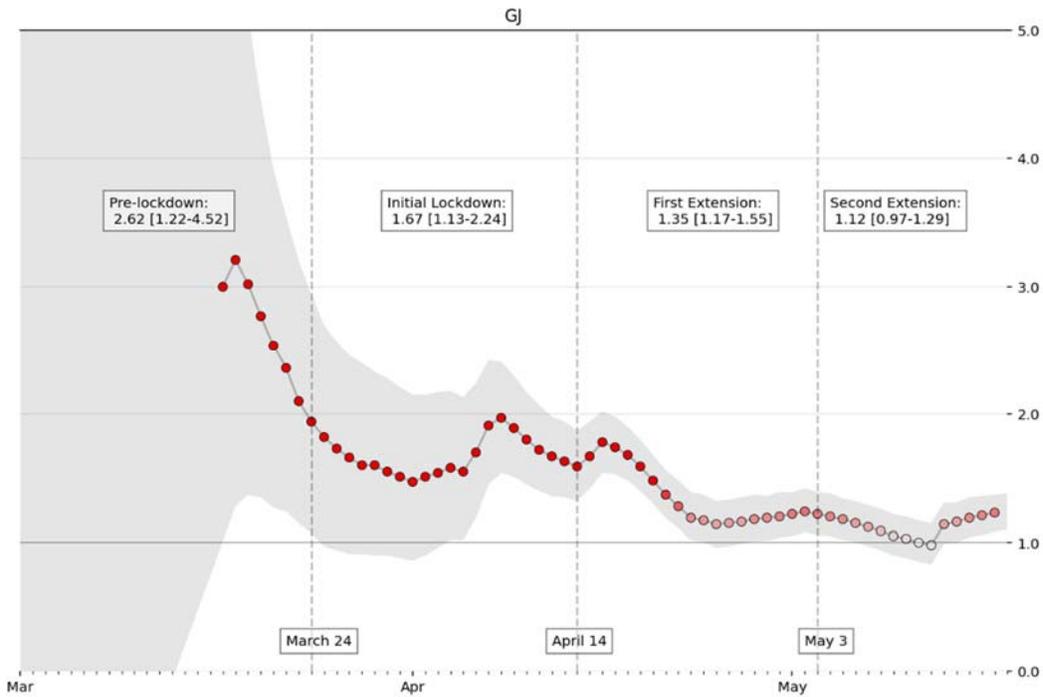
**Source:** Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/>

**Fig 4(b):** Real-time effective Reproduction number ( $R_t$ ) for Tamil Nadu on 17<sup>th</sup> May 2020



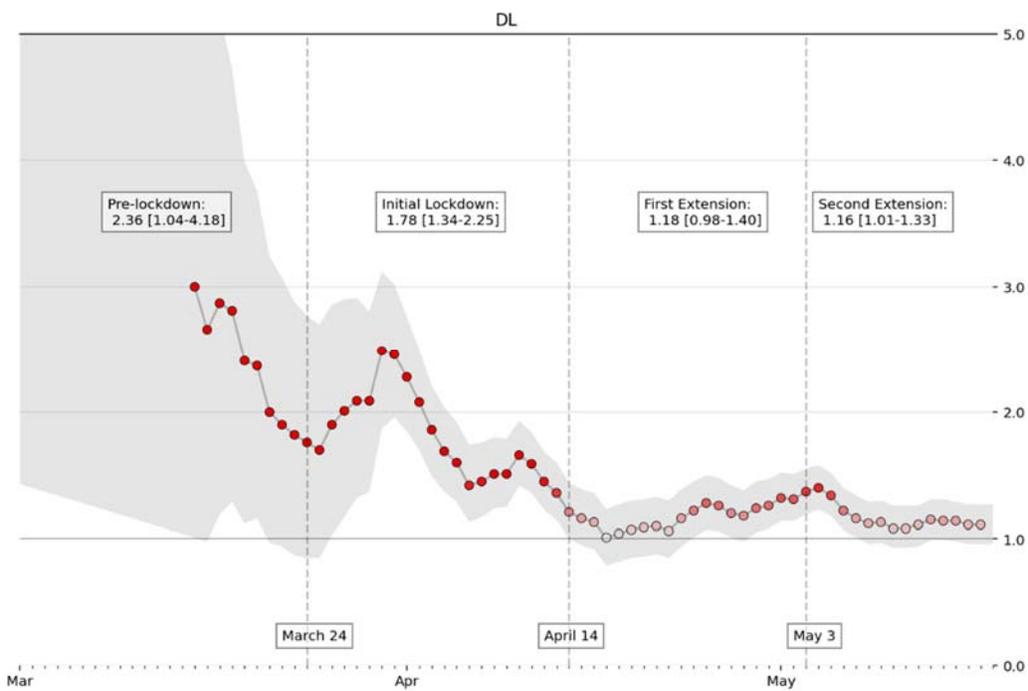
**Source:** Based on calculations of Jupyter Notebook <https://sanzgiri.github.io/covid-19-dashboards/>

**Fig 4(c):** Real-time effective Reproduction number ( $R_t$ ) for Gujarat on 17<sup>th</sup> May 2020



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

**Fig 4(d):** Real-time effective Reproduction number ( $R_t$ ) for Delhi on 17<sup>th</sup> May 2020



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

**Table 2:** Multiple Linear Regression with Difference in  $R_t$  (between 2<sup>nd</sup> April and 9<sup>th</sup> May) as the dependent variable, India, 2020.

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