The Future of Coronademic: Predicting the Trajectory of COVID-19 Epidemic in India

By

Ayushi Sharma

Dissertation submitted in partial fulfillment of the requirements of the degree
MBA Hospital and Health Management

Academic year, 2018-2020

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TO WHOMSOEVER MAY CONCERN

This is to certify that **Ayushi Sharma**, student of MBA Hospital and Health Management from The IIHMR University, Jaipur has undergone internship training at **IQVIA Consulting and Information Services India Pvt. Ltd.** from **February 3, 2020** to **June 12, 2020**.

The Candidate has successfully carried out the study designated to him during internship training and his approach to the study has been sincere, scientific and analytical.

The Internship is in fulfillment of the course requirements.

I wish him all success in all his future endeavors.

Dean, Academics and Student Affairs
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June 19, 2020

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This certificate is issued in recognition of successful completion of 4 months and 10 days of **her Project** in the department of **Public Health.**

We wish her all the best for future endeavors.

For IQVIA Consulting and Information Service India Pvt. Ltd.

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Sr. Director HR, AMESA

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CERTIFICATE BY SCHOLAR

This is to certify that the dissertation titled "**The Future of Coronademic: Predicting the Trajectory of COVID-19 Epidemic in India"** and submitted by **Ayushi Sharma** Enrollment No. **0729** under the supervision of **Dr. Piyusha Majumdar** for award of MBA in Hospital and Health Management of the University carried out during the period from February 3, 2020 to June 12, 2020 embodies my original work and has not formed the basis for the award of any degree, diploma associate ship, fellowship, titles in this or any other institute or other similar institution of higher learning.

Ayushi Sharma

Signature

Abstract

Background: WHO on 30th January 2020 declared the COVID-19 outbreak a Public Health Emergency of International Concern. India is grappling with the recent COVID-19 outbreak that has affected many states till now. The government along with public health workers is actively making efforts in reducing the impact of the outbreak and eventually bringing it to an end. Mathematical modelling counters the unpredictable nature of the COVID-19 outbreak and can considerably help the government in planning and evaluating through informed decisions.

Methodology: A Predictive study design using deterministic mathematical modelling approach (SEIRD Model) is used to predict the course of COVID-19 Epidemic in India for next one year. The study is also reflective of the effect of lockdown on the trajectory and the predicted data is compared against actual data. Data is extracted from MoHFW and Our World in Data to make the predictions. The model is run using MATLAB function to solve the differential equations.

Key Results: The graph is plotted for Susceptible, Exposed, Infected, Recovered and Dead population over the next one year. Two different graphs, one depicting the uninterrupted course of the disease and other, considering the change in dynamics of transmission due to lockdown are plotted. The overall impact predicted in both the graphs is same except the lockdown will cause a delay in reaching the peak as per the projections. The graphs are plotted against actual data available at the time of study which alludes to deficiency in testing in the initial stages of the outbreak.

Conclusion: SEIRD model has provided insights into the transmission dynamics of COVID-19 outbreak in India and used to make predictions on the trajectory of COVID-19 outbreak in India over the next year. The effect of lockdown in slowing the growth rate of the epidemic is seen with the help of this study. The study is useful in identifying key parameters, focusing on which the public health measures to control the epidemic can be devised by the government.

Acknowledgement

The dissertation opportunity I had at IQVIA, Delhi was a great experience of learning and professional development in the healthcare industry. During my dissertation period, I received unstinting help from various people who I would like to thank with deep gratitude.

I express my sincere and deepest gratitude to my organization mentor Mr. Kapil Dev Singh, Engagement Manager, IQVIA, Delhi, who despite his busy schedule, took time out to hear, guide and keep me on the correct path during my dissertation and allowed me to carry out my project. I convey my heartfelt gratitude to Mr. Vinayak Saroliya, Consultant, IQVIA, Delhi, for his constant guidance and encouragement through each stage of the project.

I would also like to thank Mr. Varindra B, Associate Director- HR, IQVIA, for giving me this incredible opportunity and helping me at each and every step.

My team members and the IQVIA staff has been extremely supportive throughout, I'd like to thank them for their wonderful collaboration and constant willingness to support me in all my endeavors.

I express my sincere thanks to my internal guide, Dr. Piyusha Majumdar, for her valuable guidance and timely suggestions whenever I sought them.

I extend my gratitude to Dr Pankaj Gupta, Dr. P R Sodani & his team to make this wonderful experience possible.

In addition, I would like to thank my parents for their wise counsel and sympathetic ear and for always giving me the best advice.

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List of Abbreviations

SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
COVID-19	Coronavirus Disease 2019
WHO	World Health Organization
RNA	Ribonucleic Acid
MoHFW	Ministry of Health & Family Welfare
GoI	Government of India
SIR	Susceptible-Infected-Recovered
SEIRD	Susceptible-Exposed-Infected-Recovered-Dead

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Introduction

In early December 2019, a cluster of cases similar to viral pneumonia of an undetectable cause, associated with a point source of origin from a fish market in Wuhan, Hubei, China raised wide concern and investigation on the etiological agent of the impending outbreak began. The novel coronavirus, known to cross species and affect humans, responsible for the infection was later named as SARS CoV-2 and the disease caused by it was labelled COVID-19. The disease was first reported to WHO on 31st December 2019. In no time, the outbreak crossed geographical boundaries and took off to several other countries. WHO later on 30th January 2020 declared the outbreak a Public Health Emergency of International Concern.

SARS CoV-2, a positive-sense single-stranded RNA virus is believed to have zoonotic origins. It shares genetic similarity with bat coronavirus. The virus presents as a respiratory illness with symptoms such as cough, fever and difficulty in breathing. In severe cases, it causes pneumonia and even death. SARS CoV-2 is contagious and spreads primarily through close contact and respiratory droplets. Indirect transmission through inanimate surfaces is also a possible mode of infection. The symptoms may start to appear in as few as 2 days or as long as 14 (estimated ranges vary from 2-10 days, 2-14 days, and 10-14 days), during which the virus is contagious, but the infected person does not display any symptom (asymptomatic transmission).

The first case of COVID-19 dates to 17th November 2019 or 1st December 2019 later to which it spread to all provinces of China and has now affected more than 180 countries. WHO declared COVID-19 outbreak a pandemic on 11th March 2020. As of 31st May 2020, there have been total 5,934,936 cases and 367,166 deaths attributed to COVID-19. (Source: ourworldindata.org)

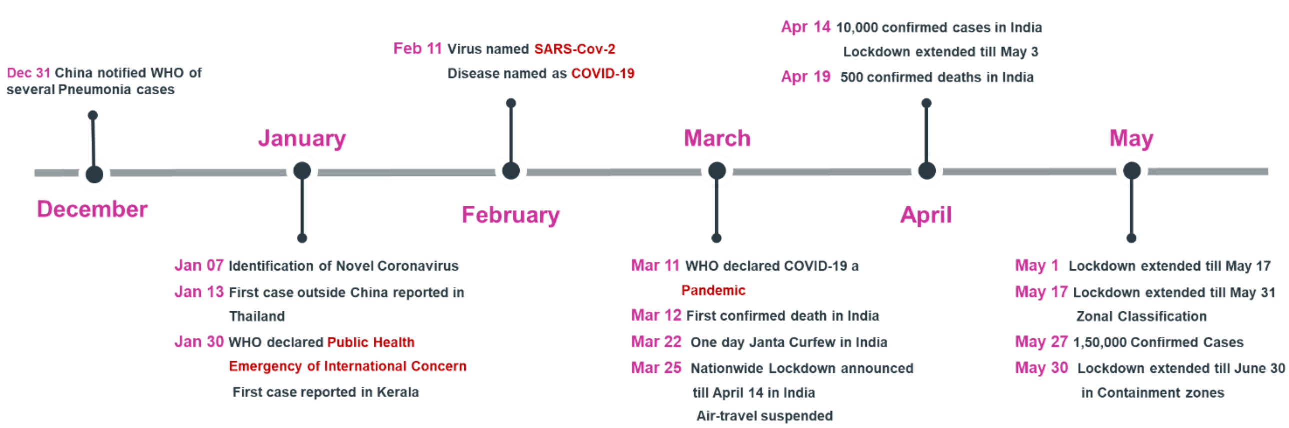

Figure 1 A Timeline of COVID-19 Major Events

The attack rate or transmissibility of the virus in terms of Reproduction Number (R0) is estimated to be between 1.4-2.5 by WHO. (Source: WHO.int) This indicates that a single infected person can spread the disease to people within the mentioned range. R0 greater than one suggests that the outbreak will not die out on its own. However, many other studies have estimated a higher R0 between 3.6-4.0. The Case Fatality Rate was calculated to be 6.12% across the world. (Source: ourworldindata.org)

India saw its first COVID-19 positive case on 30th January 2020 in Kerala. The infected person was a student who had returned from Wuhan, China. As of 31st May 2020, MoHFW has confirmed 182,143 cases, 86984 recoveries and 5164 deaths. (Source:MoHFW) No new cases were reported in February however later in March and since, the transmission escalated and spread across the country

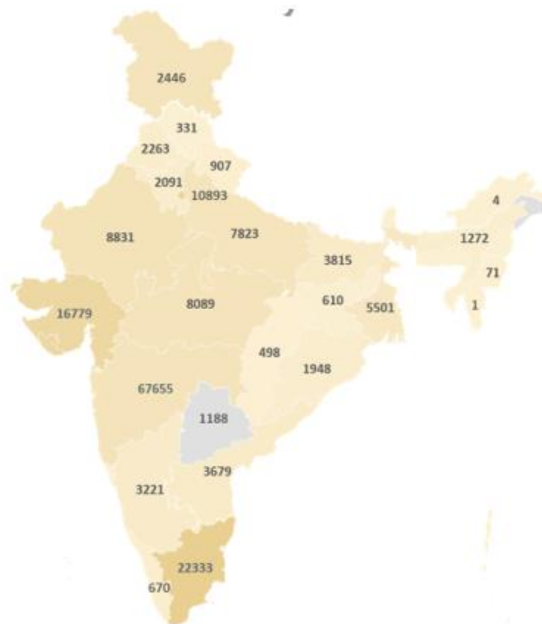

Figure 2 State-wise Total Confirmed cases as of 31st May 2020 (Source: MoHFW)

India currently has the highest load of confirmed cases in Asia. However, India's Case Fatality Rate is relatively lower at 2.83% compared to the global 6.12%. The doubling rate of cases stood at 13 days by the end of May. India's recovery rate has improved astonishingly from 11.42% in mid-April to 48% in May end. The reproduction number has taken a dip from to 2.25 to 1.5 by end of May. In the beginning, testing of only those who has a travel history of 12 high-risk countries or had come in contact with positive cases were being conducted as per the government guidelines. However, later in March, in response to sharp increase in cases, testing was scaled up where revised guidelines were released by ICMR wherein all suspected individuals were being tested in both government and private labs. As of 31st May 2020, India has tested 38,37,207 samples. The test positivity rate stands at 4.7%.

By the end of May, 13 cities account for 70% of the case load in India. These cities include Mumbai, Chennai, New Delhi, Ahmedabad, Thane, Pune, Hyderabad, Kolkata, Indore, Jaipur, Jodhpur, Chengalpattu and Thiruvallur.

India began thermal screening of international passengers at airport on 6th March 2020. States and several ministries worked together to set up quarantine facilities and additional infrastructure required to deal with the outbreak. GoI issued an advisory on 17th March 2020 to all states regarding implementation of social distancing as a preventive strategy. Several states started to close schools, colleges and movie halls to contain the spread of virus. The government stopped issuing new visas from 3rd March 2020 and previously issued visas to high-risk countries were suspended.

The first phase of nationwide lockdown was announced by PM Narendra Modi, starting from 25th March for a period of 21 days. The lockdown was extended till phase four that ended on 31st May 2020. The zonal classification of the nation into Red, Orange and Green zones was done by the government to allow relaxations accordingly. The Ministry of Electronics and Information Technology launched ‘Arogya Setu’, a smart phone application that aids in "contact tracing and containing the spread" of COVID-19 pandemic in the nation.

The concealed and unpredictable nature of infectious diseases makes the processes of systematic modelling and estimating crucial parameters invaluable in uncovering mechanisms giving rise to the observed patterns.

Mathematical theories heavily influence epidemiology, which is essentially a public health population biology discipline. Mathematical modelling of epidemic dynamics is now ubiquitous. Many mathematical models are used to understand how a virus spreads within the host population, both in time and space. Such models play an important role nowadays in quantifying possible infectious disease control and mitigation strategies.

The essence of mathematical modelling lies in developing a set of mathematical equations that simulate reality. These equations are solved for certain values of the parameters within the equations. The solutions can be refined with the use of information that is already known about the virus spread, for example, available data on confirmed number of infections, the confirmed number of recoveries or the reported number of deaths due to the infection. (Griffiths et al, 2020)

The history of mathematical modelling of spread of disease goes down to 1760 when Daniel Bernoulli, a trained physician, formulated a mathematical model to evaluate the impact of variolation on life expectancy.

Mathematical models of epidemics are essentially of two types; stochastic and deterministic. Stochastic models are useful in estimating probability distributions of potential outcomes by allowing for chance variations in risk of exposure, disease and other illness dynamics. Deterministic/Compartmental models, on the other hand, do not entail any element of chance or any uncertainty. (Source: Wikipedia)

The Kermack-McKendrick model is an SIR model, developed by W. O. Kermack and A. G. McKendrick in 1927. The model has been widely applied to various infectious diseases such as Rubella, Measles, Plague etc. Three-time dependent compartments; Susceptible, S(t); Infected, I(t) and Recovered, R(t) underpin the SIR Model. The model is governed by a set of coupled nonlinear ordinary differential equations. The SIR model has various modifications, one of them is SEIRD model. (Choisy et al, 2007)

India is grappling with the recent COVID-19 outbreak that has affected many states till now. The government along with public health workers is actively making efforts in reducing the impact of the outbreak and eventually bringing it to an end. Predictive modelling counters the unpredictable nature of the COVID-19 outbreak and can considerably help the government in planning and evaluating through informed decisions. This study sets out to understand the behavior of COVID-19 outbreak in India using a deterministic modelling approach.

Aim: To understand the growth trajectory of the COVID-19 outbreak in India by forecasting the impact of the outbreak using a deterministic modelling approach

Objectives:

- To understand the transmission dynamics of COVID-19 Epidemic in India using SEIRD Model
- To forecast the trajectory of COVID-19 Epidemic in India for the next one year using SEIRD Model
- To compare the estimated trajectory with Actual data
- To explore a way forward in terms of public health preparedness with the help of SEIRD model

Literature Review

Recent events have drawn the prime focus of health systems towards infectious disease threats. The world continues to face longstanding, emerging and reemerging infectious disease outbreaks. The track record indicates that these threats are detrimental not only to human health, but social and economic well-being as well.

Epidemic forecasting using predictive modelling plays a crucial role in studying patterns, planning and evaluating public health response measures. Researchers have been increasingly applying mathematical models to project the progress of an outbreak, its possible outcomes and thus help inform public health interventions. (1)

There have been many studies on the COVID-19 outbreak that has become a global concern recently. A lot of them cover various mathematical models and their role in studying the epidemiology of the outbreak especially in capturing spread of the disease and estimating impact of the pandemic. All manner of recent literature relevant to the objectives of this research are reviewed below:

Title	**Author/s**	**Year**	**Key features**
A time series method to analyze incidence pattern and estimate reproductio n number of COVID-19	Soudeep Deb Manidipa Majumdar	March 2020	The study aimed at identifying the rate of growth of infection, identify the time of significant change in growth pattern of the outbreak and estimated the reproduction number. This was done for various provinces of China and six other countries including India. The statistical analysis was done using Auto-Regressive Integrated Moving Average method with time dependent parameters. The model provided insights on time dependence pattern and the time trend of the disease-incidence. The model also provided insights on the prevalent epidemiological stage of outbreak in the study regions out of the four described stages of COVID-19 spread.

			The study also suggests the importance of depicting realistic growth predictions for proactive public response measures and continuous assessment of interventions and regulations. (2)
COVID-19 in India: Predictions, Reproduction Number and Public Health Preparedness.	Balram Rai, Anandi Shukla, Laxmi Kant Dwivedi	April 2020	The data of 21 days on confirmed, recovered and dead cases in India was fed into an exponential growth model to predict these three components till 30th April'20. Average reproduction number and herd immunity data was calculated using mathematical model. The data was collected from 14th March to 3rd April. The estimated number of active cases came out to be 2,49,635 and confirmed cases to be 2,84,709 by the end of April. The Reproduction Number was estimated at 2.56 for the period of 21 days. The Herd Immunity was predicted to be 61% for the elimination of infection from the country. The study mentioned the low rate of testing in India and implied how the cases will shoot up if the testing rate is improved. The study also analyzed the Public health capacity of India and indicated an alarming situation in terms of public health preparedness in due to community outbreak. (3)
CoronaTracker: World-wide COVID-19 Outbreak Data Analysis and Prediction	Fairoza Amira Binti Hamzaha , Cher Han Laub , Hafeez Nazric , Dominic Vincent Ligotd , Guanhua Leee ,Cheng Liang	March 2020	Coronatracker community developed an online platform that provides news, statistics and analysis on COVID-19. Coronatracker aims at predicting and forecasting COVID-19 associated deaths, cases and recoveries for several nations using predictive modelling. The data for SEIR Model was captured trough Coronatracker website. The study predicted that more than 76000 cases would be present around March 2020 and that the outbreak would reach its peak around May 2020 and would start to decline around early July 2020. The average Infected-suspected ratio came out to be 2.399. The paper also pointed at the 'infodemic' i.e abundance of

	Tanf , Mohammad Khursani Bin Mohd Shaibg , Ummi Hasanah Binti Zaidonh , Adina Binti Abdullahi , Ming Hong Chungj , Chin Hwee Ongk , Pei Ying Chewl and Roland Emmanuel Salunga		information regarding COVID-19 from various sources including the ones with less reliability and hence the idea of Coronatracker was born. (4)
Prudent public health intervention strategies to control the coronavirus disease 2019 transmission in India: A mathematical model-based approach	Sandip Mandal, Tarun Bhatnagar, Nimalan Arinaminpathy, Anup Agarwal, Amartya Chowdhury, Manoj Murhekar, Raman R. Gangakhedkar	February 2020	The study aimed at exploring the possibility of delaying or preventing the local outbreaks of COVID-19 through international travel restrictions in context of India. The study made use of SEIR model to analyze the natural history and transmission dynamics of the disease. The study assumed that quarantine of symptomatic cases would be able to identify and quarantine 50 per cent of symptomatic individuals within three days of onset of symptoms. In a rather optimistic scenario, the reproduction number (R0) of 1.5, and asymptomatic infections lacking any infectiousness, the measures of mitigation would reduce the cumulative incidence by 62 per cent. In the pessimistic scenario of R0 =4, and asymptomatic infections being half as

	& Swarup Sarkar		infectious as symptomatic, this projected impact falls to two per cent. (5)
Forecasting COVID 19 growth in India using Susceptible-Infected-Recovered (S.I.R) model	Jay Naresh Dhanwant and V. Ramanathan		The study intended to forecast and analyze the growth of COVID-19 in India, focusing on the main feature of the i.e. beta, that governs the spread through social-contact structure. The results were compared against actual data and the model proved to be reasonably accurate. Beta reduced from 0.3536 to 0.2627 upon imposition of nationwide lockdown. However, this value is yet not expected to be sufficient in stopping the growth of the outbreak. (6)
What will be the economic impact of COVID-19 in the US? rough estimates of disease scenarios.	Andrew Atkeson	March 2020	This modelling study of progression of COVID-19 outbreak in US using SIR model endeavors to investigate the outcomes of extreme mitigation efforts temporarily and then being relaxed. The model suggested that the disease would restart with a rapid progression and spread across the nation within 18 months and would reach the peak of infection within next 450 days. The study concludes that a sustained mitigation effort is necessary to curb the spread of infection. (7)
Model studies on the COVID-19 pandemic in Sweden	Chong Qi and Daniel Karlsson, Karl Sallmen, Ramon Wyss	April 2020	The study captures infections and deaths in Sweden due to COVID-19 using multiple models beginning with an analytical susceptible-infected (SI) model and the standard susceptible-infected-recovered (SIR) model followed by investigation of susceptible-infected-deceased (SID) correlations using SIR framework. The models reproduce well the number of infected cases and provide similar predictions. The model shows a huge gap in reported and predicted cases which alludes to inadequate testing rate. (8)

Analysis and forecast of COVID-19 spreading in China, Italy and France	Duccio Fanelli, Francesco Piazza		The study analyzes the dynamics of COVID-19 outbreak in China, France & Italy with the time period of 22nd Jan-15th Mar 2020. Application of SIR model on data of this time period shows that the recovery rate is seemingly same whereas infection rate and death rate differ in the countries which could be attributed to diverse health conditions of the vulnerable population. (9)
A simple Stochastic SIR model for COVID-19 Infection Dynamics for Karnataka after interventions – Learning from European Trends	Ashutosh Simha, R. Venkatesha Prasad, Sujay Narayana	April 2020	SIR model was applied to project the growth of COVID-19 outbreak in India as well as in Karnataka. The parameters were optimized based on infection trends in European countries and India. Various curves were plotted to find the most effective lockdown schedule, the results indicated that any lockdown schedule would only shift the peak and not bring the spread of the disease to an end. (10)
Why is it difficult to accurately predict the COVID-19epidemic?	Weston C. Roda, Marie B. Varughese, Donglin Han, Michael Y. Li	March 2020	The wide range of variations in different model predictions can be attributed to unidentifiability in model calibrations using confirmed cases. Using the Akaike Information Criterion (AIC) for model selection, it has been concluded that simpler the model, more accurate the result. (11)
Projecting the future	Kaushalendra Kumar,	May 2020	SIR model was used to predict the future trajectory of COVID-19 outbreak in India at national level and of worst-hit

trajectory of COVID-19 infections in India using the susceptible-infected-recovered (SIR) model	Wahengbam Bigyananda Meitei, and Abhishek Singh		states, Delhi, Maharashtra & Gujarat. The results indicated a dip in Reproduction number during first and second lockdown. (12)
A Time-Dependent SEIRD Model for Forecasting the COVID-19 Transmission Dynamics	Taarak Rapolu, Brahmani Nutakk, T. Sobha Rani, S. Durga Bhavani4	May 2020	SEIRD model was applied to forecast the number of cases in Maharashtra and Gujarat and further in various districts of the two states. The predictions made for Maharashtra were satisfactory however Gujarat predictions showed a high error rate. (13)
Prediction of Pandemic COVID-19 situation in Maharashtra, India	Sunny Kumar	April 2020	The study explains the spreading of COVID 19 in the Maharashtra region. The outbreak is studied by the SIR model. The model predicted that the maximum infected population will be almost ~ 3000 after 40 days at the peak point. After reaching the peak point the recovery will be more and the virus infection will be high for R ~ 2.66. (14)
Prediction of COVID-19 Disease Progression in India	Sourish Das	April 2020	SIR model was implemented to estimate the basic reproduction number R0 at national and state level. The analysis indicated that the early disease progression of India is similar to that of

			to China. Therefore, with lockdown in place, India should expect as many as cases if not more like China. The study states that if the lockdown works, less than 66,224 cases by May 01,2020 should be expected. (15)

Methodology

Research Question: What is the trajectory of COVID-19 epidemic growth in India as per transmission dynamics modelled through SEIRD Model?

Research Design: A non-experimental, predictive study design on secondary data is adopted for the purpose of this study.

Data Source: Data on number of confirmed cases, deaths and recoveries is extracted from MoHFW and Our World In Data for the time period of 31st January 2020 to 31st May 2020.

Material & Tools: MATLAB software is used to execute the model

Model

SIR Model divides the host population into three compartments based on their epidemiological status. These are: Susceptible, Infected and Recovered. (16)

Figure explains that the three categories form a cascade in which people move from one category to next one in an irreversible manner.

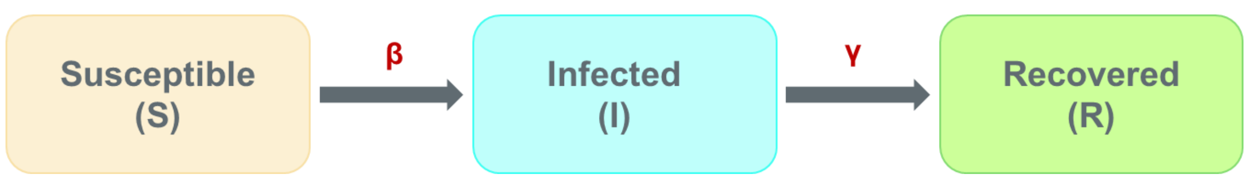

Figure 3 Diagrammatic Representation of SIR Model

Susceptible (**S**) population consists of people vulnerable of contracting an infection. In infection such as COVID-19, entire population falls under the susceptible category in the beginning.

Infected (**I**)population includes the people who leave the susceptible category upon getting infected and are capable of transmitting the infection to others.

Recovered (R)Population are the people who move out of the infected category after recuperation.

Therefore, N= S+I+R

Assumptions:

- The Fatality rate is assumed to be small compared to recovery rate, therefore S, I and R accounts for the entire population (N)
- The model assumes a closed population, that the population remain the same for the time period and nor birth or death take place.
- There is no immunity against the infection amongst the population

Initial Conditions

At time = 0,

Susceptible population is very large since everyone is susceptible to the infection at the beginning.

$$S(0)= S0$$

Infected population is small in the beginning as only few people have the infection

$$I(0)= I0$$

Recovered population is zero at the beginning as it marks the onset of infection and convalescence period is longer.

$$R(0)= 0$$

Equations

The SIR model is governed by nonlinear ordinary differential equations for each of these categories. These equations outline the rate of change of each compartment with respect to time.

$$\partial S \ \partial t = -\beta \ SI \ N$$

- Where, β, controls the transmissibility or rate of spread, which represents the probability of transmitting disease between a susceptible and an infectious individual. The Basic R0 used in this study is 2.25 and R0 during lockdown is taken to be 1.5. The multiplicative operation between S and I suggest that interaction between these two categories increase the likelihood of infection depending upon the probability of an infected person to transfer infection to an individual upon close contact. The negative sign alludes to the decreasing trend of susceptible population with time.

$$\partial I\ \partial t = \beta\ SI\ N - \gamma I$$

- Recovery rate $\gamma = 1/D$, is determined by the average duration of recovery D, of infection. After this period, they enter the removed phase. The Duration used in this study is 7. This equation entails the population moving out of the susceptible category minus those transitioning to the recovered category, hence, the negative sign

$$\partial R\ \partial t = \gamma I.$$

- This equation governs the number of people getting added to the recovered category

The following graph (Figure 4) is plotted for a disease that can infect everybody and no intervention or immunity against the infection is developed so far.

The downward slope of S(t) indicates that as time goes on, the number of susceptibles gets lesser. And given that everyone is capable of getting infected, at some point towards the end the infection would sweep through the population.

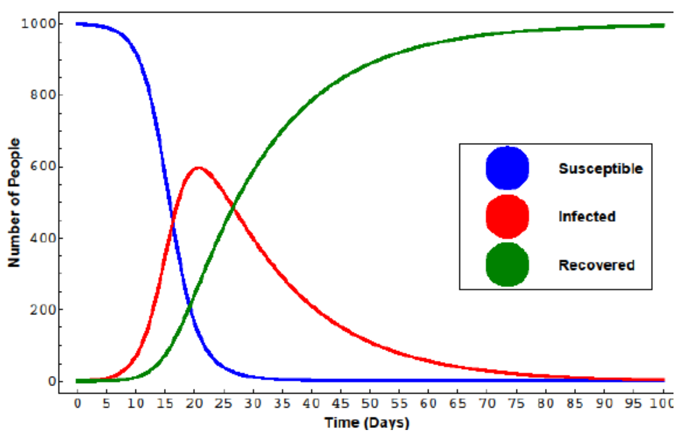

Figure 4 An Illustrative Graph of SIR Model (Source: Mathematical association of America)

R(t) has an upward slope as the recovered population that is initially zero, increases with time as more and more people will recover from the infection.

I(t) has a bell-curve curve indicating that the number of infected people would increase with time as more and more people leave the susceptible category until a point of time when rate of recovery is more than rate of infection, where the curve starts dropping to the point where every person who acquired the infection is recovered.

SEIRD Model

It is one of the variations of the SIR model used to accurately predict the count of Susceptible, Exposed, Infected, Recovered and Infected persons.

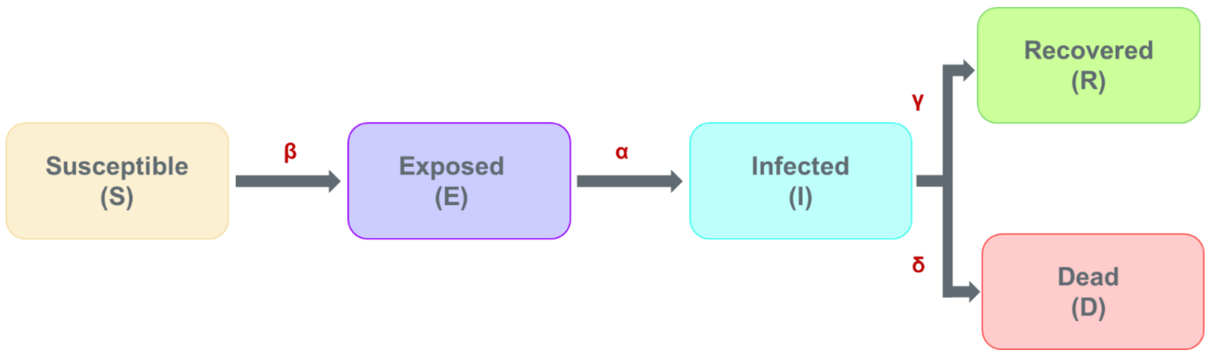

Figure 5 Diagrammatic Representation of SEIRD Model

The equations governing the SEIRD Model are:

$$\Delta S = -\beta(t)S(t)I(t)\ N$$

$$\Delta E = \beta(t)S(t)I(t)\ N - \alpha(t)E(t)$$

- Incubation rate σ, is the rate of latent individuals becoming infectious. The incubation period used in this study is 5.2 days.

$$\Delta I = \alpha(t)E(t) - \gamma(t)I(t) - \delta(t)I(t)$$

- δ represents the death rate associated with the disease. The death rate used in this study is 2.83%.

$$\Delta R = \gamma(t)I(t)$$

$$\Delta D = \delta(t)I(t)$$

Result

COVID-19 Outbreak Trend in India

In India, after the first case was reported on 30th January in Kerala, no significant growth in the cases was observed in February. The infection was confined to Kerala, where a state calamity was declared on 4th February 2020. The first confirmed case tested negative on February 19, 2020.

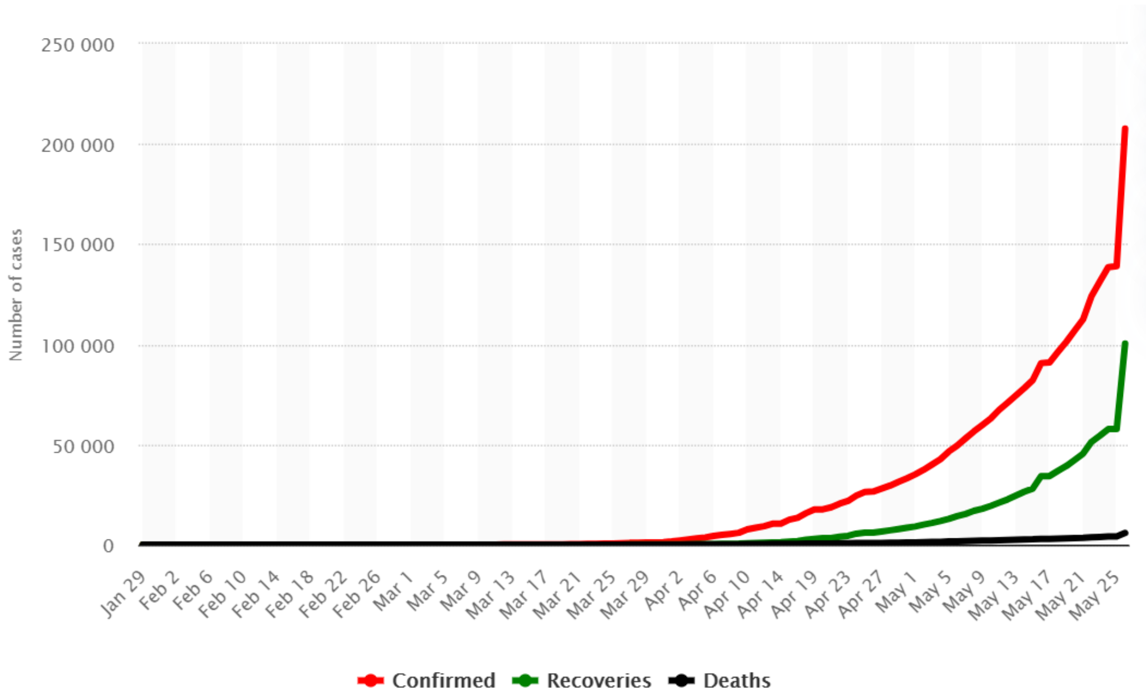

Figure 6 Daily Cumulative Confirmed Cases, Recoveries and Deaths recorded in India from January to May 2020 (Source: Statista)

It was only after 5th March 2020 that a consistent surge in the number of reported cases was observed in many parts of the country. India's first Covid-19 death was confirmed in the state of Karnataka on 12th March'2020. India declared COVID-19 a notified disaster on 14th March 2020 after the number of cases grew continuously. India crossed 100 and confirmed cases on 16th March and 28th March respectively. In view of this sudden growth of cases, Government of India imposed a nation-wide lockdown from 25th March 2020 which was extended till 31st May 2020. Therefore, the lockdown went on for a period of 68 days. The transmissibility of COVID-19 reduced considerably along with lockdown as indicated by the lowering of R0.

Estimating the Trajectory of COVID-19 in India

Using the data of reported cases, deaths and recoveries on 5th March 2020, SEIRD model was implemented using MATLAB function to solve the differential equations for S, E, I, R and D to predict the spread of COVID-19 for next one year. In one model, exponential growth of the disease as per its natural uninterrupted course i.e. without lockdown was estimated. Figure 8 In the second model, lockdown period was considered in estimating the figures for next one year. Figure 9.

```
function dydt = ode_fun_simple(t, y,beta)

Death = 0.0283;  % Death rate of COVID-19 (March, 2020)%0.0283
Pre_infec = 5.2;
alpha = 1/Pre_infec;
%Duration = 14;
Duration = 7;
gamma = 1/Duration;
S = y(1);
E= y(2);
I = y(3);

dS = -beta*I.*S;
dE = beta*I.*S -  alpha.*E;
dI = alpha*E - gamma*I;
dR = gamma*(1-Death)*I;
dD = (Death)*gamma*I;

dydt = [dS; dE; dI; dR; dD];
end
```

Figure 7 A code snippet from MATLAB software used to run the model

The graph below (Figure 8) shows the uninterrupted projections of population trends in S, E, I, R and D categories for the next 365 days i.e. till 5th March 2021.

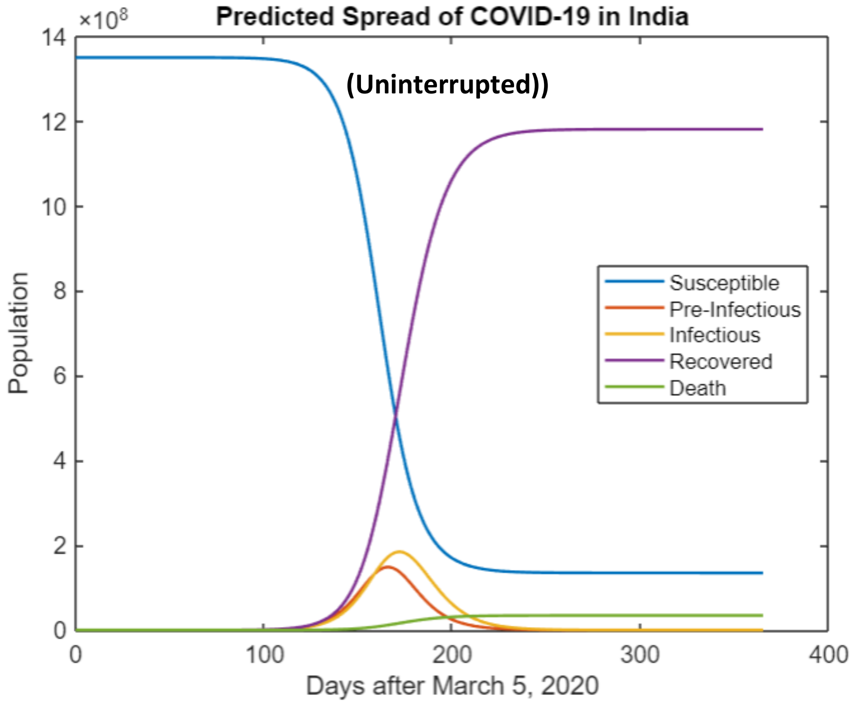

Figure 8 Predicted Spread of COVID-19 in India without considering the effect of lockdown

This graph illustrates the natural uninterrupted trajectory of COVID-19 in India using the R0 value 2.3. Figure 9 Predicted Spread of COVID-19 in India considering the nationwide lockdownAs seen in the graph, entire population is susceptible in the beginning. With the S curve having a downward slope, almost 50% population will remain susceptible by the first week of September 2020. The curve begins to flatten around October 2020 as per the graph.

According to the model, the peak of pre-infectious state will be observed on 20th July 2020 at a population of 148 million. The E (Pre-infectious) curve begins to decline post 20th July 2020.

The bell shaped I (Infected) curve represents the number of infected persons i.e. number of people having the infection at a point of time which is also called as active cases. The peak of I curve is estimated at 184,500,000 near to mid-August 2020. The curve tends to decline after that as the number of active cases reduces as more people move to Recovered or Death category and less people are left in the Susceptible category.

The R (Recovered) curve shows an upward trend as more people will recover from COVID-19 and leave the infected stage. In next one year, a total of 1,168,900,000 people will recover from the infection if the transmission is allowed to follow its natural course.

According to the estimation made in this model, when no public health intervention is introduced, nearly 30 million people would succumb to the disease in one year, i.e. by March 2021.

The second model (Figure 9) takes into account the effect of nationwide lockdown that was imposed for a period of 68 days i.e. from 25th March 2020 to 31st May 2020. The predictions are made using different rates of infection (beta) during lockdown and without lockdown.

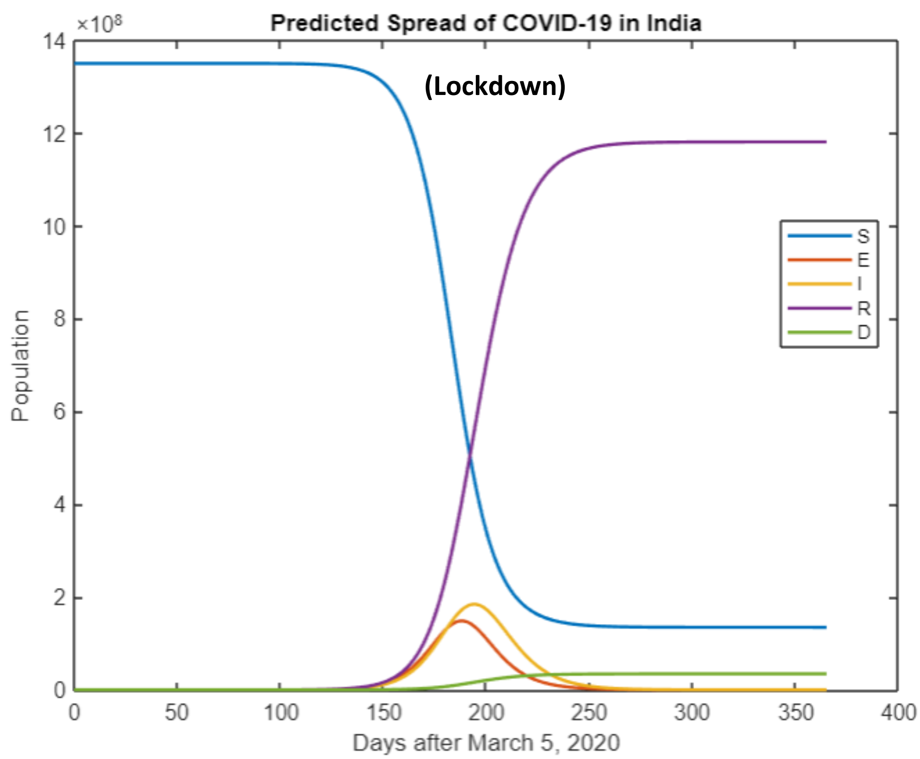

Figure 9 Predicted Spread of COVID-19 in India considering the nationwide lockdown

According to the above graph, the susceptible population will reduce to 50% by last week of September. The S curve is flattening around 13th November 2020.

The E curve has a peak at 104 million people around 23rd September 2020 post which the curve begins to decline.

The peak of I curve is estimated at 184,450,000 on 197th day of the graph i.e. mid-September 2020. The I curve begins to flatten around first week of November 2020.

According to the projection made in this graph, a total of 1,168,900,000 people will recover from COVID-19 in the next on year. The estimation is similar to when there is no lockdown, i.e. the outbreak grows naturally.

According to the number of deaths forecasted using this method, nearly 30 million would become the victim of COVID-19 in the next one year. The D curve is beginning to flatten around first week of November according to this graph.

Predicted Trajectories of COVID-19 in India with & without the effect of Lockdown: A Comparison

	Projections without Considering Lockdown	*Projections considering the 68 days lockdown*
Total Confirmed Cases	1.19 Billion	1.19 Billion
Total Recovered Population in one year	1,168,900,000	1,168,900,000
Total Deaths in one year	30 million	30 million

Actual and Predicted Impact: A Comparison

The predicted data of confirmed cases of both the graphs was plotted against actual data till 31st May 2020. A comparison was made for both the models, with and without lockdown.

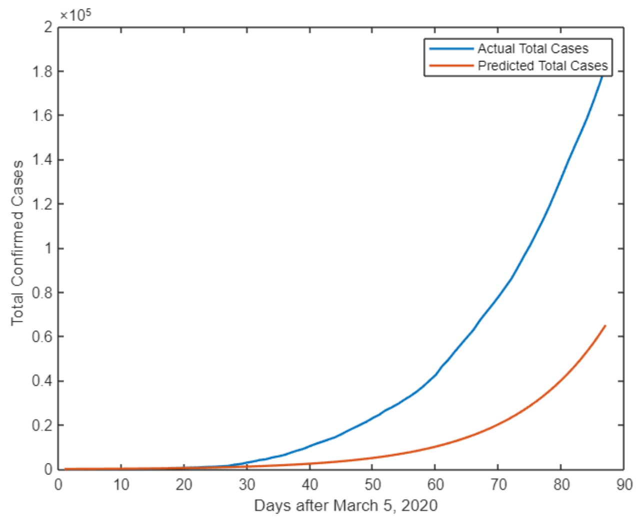

Figure 11 Actual VS Predicted Spread considering Lockdown of COVID-19 in India

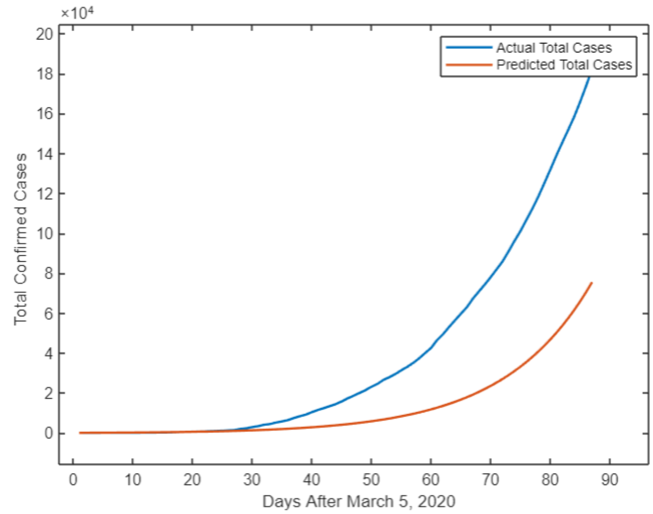

Figure 10 Actual VS Predicted (Uninterrupted) Spread of COVID-19 in India

The actual and predicted curves of total confirmed cases for the time period of 5th March 2020 to 31st May 2020 show a significant gap in both the graphs. The curve depicting the actual confirmed cases is steeper and shows faster growth than the curve depicting the predicted number of confirmed cases for the same time period in both the figures. This indicated that the predictions made in the study are not coherent with the actual data. The results are further discussed in the next section. However, the graph depicting the uninterrupted growth of COVID-19 (Figure 10) shows a lesser gap and is closer to the actual total confirmed cases as the curve depicting the predicted cases in the uninterrupted spread scenario shows a faster growth in the number of confirmed cases than in the graph that takes into account the effect of lockdown on the growth of cases.

Discussion

As of 31st May 2020, the COVID-19 epidemic has grown to 182,143 cases, 86984 recoveries and 5164 deaths. This is an alarming situation for the nation as along with the health of the population, the economic and social ramifications will be enormous. Five months into the epidemic, there is still less achieved in finding a vaccine or any curative medicine for the disease. If the number of cases continue to grow exponentially in this manner, it will be a never-seen-before public health disaster for India.

According to the estimations made in the study, unchecked, the epidemic will infect almost 70-80% of the population. The most astonishing characteristic of the virus is that it can infect everyone. Therefore, necessitating an immediate public health intervention.

The study has modelled the potential impact of mitigation strategies, such as nationwide lockdown of 68 days, travel restrictions, social distancing etc. The results are suggestive that the lockdown is able to interrupt the transmission of COVID-19. However, in order to achieve appreciable effects in long run, sustainable strategies need to be devised. As shown in the graph, the epidemic is estimated to grow at a sharper rate after the lockdown is lifted. Since government has planned on loosening the restrictions through it's three-phased Unlock plan, measures like social distancing, use of PPE, hand hygiene need to be strictly followed to avoid the surge in cases.

The lockdown has resulted in shifting of the peak of the infected cases by almost a month. The overall impact however, remains approximately the same in both the cases. Therefore, it can be inferred that lockdown is not a permanent solution but only a measure to slow down the growth for a stipulated period of time. Prolonged lockdown is not a feasible and sustainable strategy as it greatly threatens the economy of the country. The vulnerable population is extremely large and the factors such as poverty, hunger etc. only make the disaster even more deadly. To avoid the explosive growth of cases post lockdown, the government has to plan stringent epidemiological solutions meanwhile promoting research for curative interventions.

The plot of actual vs predicted cases reveals a gap between actual and predicted data. The gap could be attributed to the lack of testing in the beginning of the outbreak. India was only testing international passengers with a travel history of 12 high-risk countries until 20th March 2020. The testing rate increased gradually and is now increased multifold. Therefore, in the graph depicting the comparison of actual and predicted cases, the gap could be explained by low testing rate, which increased later in April when the number cases started to explode when the testing rate was significantly higher. This alludes to the possibility that the infection was sprawling across the nation, undetected.

The SEIRD model endeavors to explain the transmission dynamics of COVID-19. The coefficients that govern the course of epidemic as per the model can be used to devise mitigation strategies as elucidated below:

- Increasing the recovery rate, γ, by discovering curative medicines such as anti-viral drugs and therapies
- Decreasing the rate of infection, β, by implementing social distancing measures, isolation of suspected persons, which invariably requires robust testing and hence detecting the cases.

The predictions of the course of an epidemic are of great importance as they not only provide estimates of numbers of cases but aid in informed decision making. The GoI has taken various measures to contain the disease and is dedicated towards flattening the curve. To revive the halted operations and subsequently the economy, prudent decision-making and planning is imperative.

Conclusion

In this study, SEIRD model is used to understand the transmission dynamics of COVID-19 outbreak in India and also make predictions on the trajectory of COVID-19 outbreak in India over the next year. The effect of lockdown in slowing the growth rate of the epidemic is seen with the help of this study. The study suggests that lockdown is effective in slowing down the growth of cases but however it is not a permanent solution. The study has also made efforts to compare the estimated results with actual data. The model leverages the time dependent nature of disease growth in the population and suggests methods to plan future mitigation strategies.

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