Prediction of the transition from sub-exponential to the exponential transmission of SARS-CoV-2 and epidemic nowcasting for metro-zones: Experiences from Chennai-Metro-Merge, India

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Abstract

Background: Several countries adopted lockdown to slowdown the exponential transmission of the COVID-19 epidemic. Disease transmission models and the epidemic forecasts at national level steer the policy to implement appropriate intervention strategies and budgeting. However, it is critical to design a data-driven reliable model for nowcasting for the small population, in particular metro cities.

Objective: The objective of this work is to analyze the transition of the epidemic from sub-exponential to exponential transmission in Chennai metro-zone and to analyze the probability of SARS-CoV-2 secondary infections while availing the public transport systems in the city.

Methods: A single geographical zone “Chennai-Metro-Merge” was constructed by combing Chennai district with three bordering districts. Sub-exponential and exponential models were developed to analyze and predict the progression of COVID-19 epidemic. Probabilistic models were applied to assess the probability of secondary infections while availing the public transport after the release of the lockdown.

Results: The model predicted that transition from sub-exponential to exponential transmission occurs around eighth week after the reporting a cluster of cases. The probability of the secondary infections with a single index case in an enclosure of the city bus and the sub-urban train general coach and ladies coach was found to be 0.192, 0.074 and 0.114 respectively.

Conclusions: Nowcasting at the early stage of the epidemic predicts the probable time point of the exponential transmission and alerts the public health system. After the lockdown release, public transports will be the major sources of SARS-CoV-2 transmission in metro cities and appropriate strategies based on nowcasting are highly desirable.

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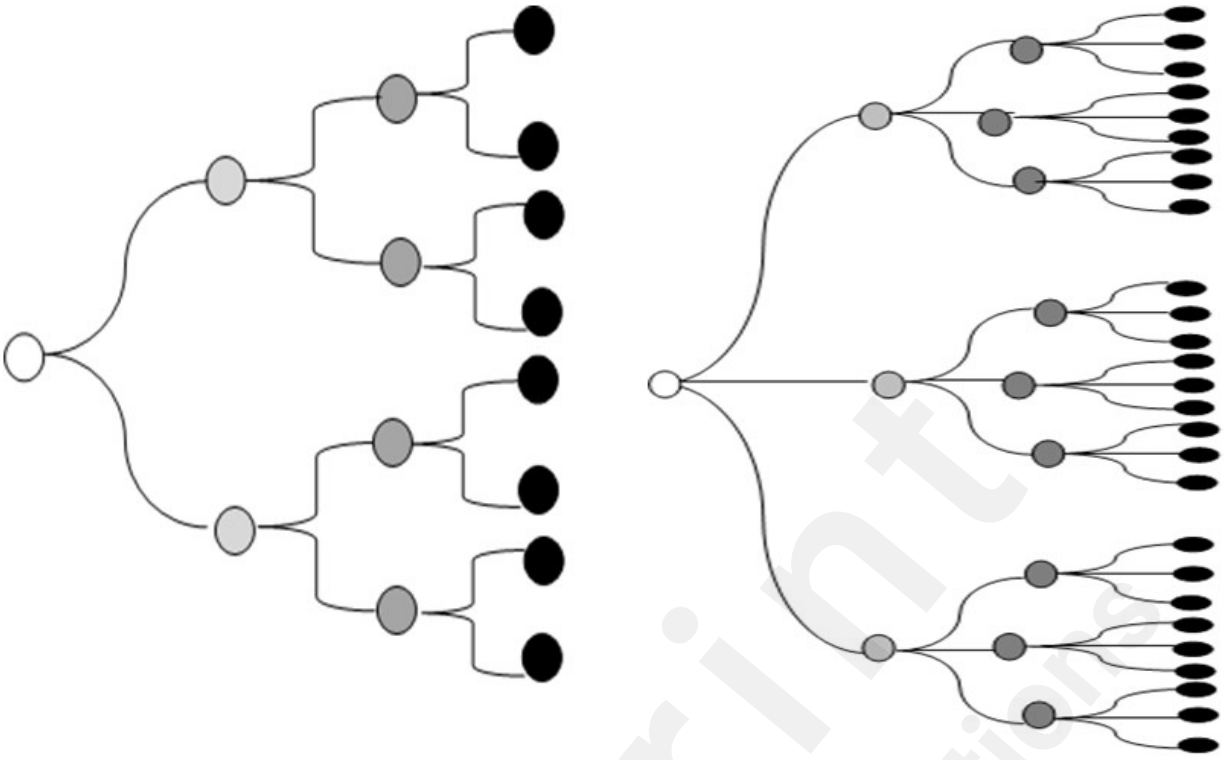
Introduction

Severe acute respiratory syndrome 2 or COVID-19 emerged in Wuhan city of China and has quickly spread to most of the countries around the world. As on 10th May 2020, 3,917,366 COVID-19 cases and 274,361 related deaths were reported worldwide. At the same point of time, the Ministry of Health and Family Welfare, India reported 62,939 confirmed cases and 2,109 deaths in India. India has 28 states and eight union territories, out of which 26 states and seven union territories have reported COVID-19 cases. However, a large proportion of the cases were reported from the four States, Maharashtra, Tamil Nadu, Gujarat and Delhi. The case-fatality rate in India remains low as compared to the global rate (7.0% vs 3.35) [1].

The estimated population of the Tamil Nadu State for the year 2020 is 82.2 million and is the seventh most populated State in India. It has 37 districts and Chennai is the largest and most populated city in Tamil Nadu and based on the nationwide census 2011, the projected total population of Chennai district is around 4,935,550 [2]. The whole geographical zone of Chennai district is well connected through two major public transport systems, Metropolitan Transport Corporation and Chennai Suburban Railways. These transports are also extended to the three bordering districts namely Kanchipuram, Chengalpattu and Thiruvallur. The Department of Health and Family Welfare of Tamil Nadu reported a total of 3,839 COVID-19 cases in Chennai, 267 cases in Chengalpattu, 122 cases in Kanchipuram and 337 cases in Thiruvallur, as on 10th May 2020. The maximum numbers of infected cases were registered in Chennai [3] and the first SARS-nCov-2 infection was reported in Kanchepurram district on 7th March 2020.

Public transportation such as trains and buses is an essential service with specific route systems. The Chennai suburban railway consists of two major networks, Chennai Suburban Railway Network and Mass Rapid Transport System and as on 2015-16 it carried about 1.17 million passengers every day [4]. The Metropolitan Transport Corporation (MTC) operates 3233 services carries about 3.3 million passengers per day [5]. In the current COVID-19 pandemic situation, commuting in public transport is associated with two major risks: asymptomatic passengers play a major role in SARS-CoV-2 transmission through aerosol particles or indirect transmission from symptomatic may occur through fomites. Further, public transport employees are at a higher risk of infection through long hours multiple sources of exposure [6]. Even an increase in R_0 from a value of 2 to 3 leads to a huge amplification in the number of infected cases over subsequent generations, as shown in Figure 1.



(a) (b)

Figure 1. Increase in the number of cases over subsequent generations of the infection for (a) R_0=2 and (b) R_0=3

Mathematical modelling plays an important role for predicting, assessing and controlling potential outbreaks for infectious diseases such as HINI [7], SARS [8], MERS [9], Ebola [10], etc. At present, several researchers have used mathematical modelling to predict the SARS-nCoV-2 pandemic using model structures such as the SIR model, exponential model, SEIR model etc. [11-13]. The early epidemic growth can be well-drawn using sub-exponential and exponential models. Such models are highly appropriate when there is a major uncertainty regarding the epidemiology of a novel infectious disease, for which the transmission pathways are not completely known. In such cases, sub-exponential and exponential models serve as reasonable tools for analyzing the progression of the early epidemic and for short-time prediction of the infected cases in the near future [14].

Recently, modelling approaches have been utilized for analysis of the transmission of COVID-19 infection with travel interventions [15]. Anzai et al. (2020) [16] have investigated the impact of travel interventions in China and outside during the COVID-19 pandemic. and concluded that travel intervention during COVID-19 pandemic resulted in less number of cases. However, a

significant number of infected individuals with mild or no symptoms, are likely to pass through border control, if travel interventions are not imposed properly.

When India had gone through the five weeks of continuous lockdown during the last week of April 2020, there were 33050 confirmed cases and 1074 deaths [17]. An overview of the case distribution indicated that there were more of urban clustering, in particular, the three major metro-cities Mumbai, Delhi and Chennai. Therefore, it was proposed for nowcasting the COVID-19 epidemic in Chennai metro-zone using different predictive mathematical models to generate an evidence for focussed public health interventions in metro-zones. In support of this, the probability of infection and the related secondary infections due to the COVID-19 infected population in public transport systems such as busses and train coaches is analyzed using probabilistic models.

Methodology

Study site

India reported more than 100 thousand cases of COVID-19 as on 18th May 2020 even after consecutive lockdown for a period of 55 days. Though the epidemic was slowed down as expected, three states contributed more than 58% of the total cases in the country and in each State more than 60% of the cases were reported from the respective capital cities Mumbai, Chennai and Ahmadabad. Therefore, containment the SARS-CoV-2 transmission in these three cities is critical in favourably modifying the transmission in India. These three cities share the same characteristics in terms of population structure, density and movement of the people towards these cities for the employment.

Chennai is a metropolitan city surrounded by three other districts Kancheepuram, Thiruvallur and Chengalpattu. Based on the connectivity through three transport systems, widespread locations of the educational institutes and the movement of the population from these three districts into every nook and corner of the Chennai, we felt it appropriate to predict the SARS-CoV-2 transmission considering all these four districts as a single unit. In this work, we constructed a single geographical zone "*Chennai-Metro-Merge'* by combining Chennai district with the bordering three districts for the development of a predictive model. (Figure-2).

Modelling of the COVID-19 epidemic in four districts of Tamil Nadu using sub-exponential and exponential models

In this work, the total reported COVID-19 cases in the constructed geographical zone *Chennai-Metro-Merge* (Figure 2) were considered for the development of a predictive model. The number of infected cases from 7th March 2020 to 30th April 2020 was adopted from the open-source

data provided by the Department of Health & Family Welfare, Government of Tamil Nadu [18] and was utilized for the modelling the short-term progression (nowcasting) of the epidemic in these four districts, considered in a single geographical boundary, since these four districts are well connected by roadways and suburban train services for the public movements and the movement of the materials. The nowcasting was further extended up to 30 the June 2020 by adopting the reported cases from 16th May to 10th June 2020.

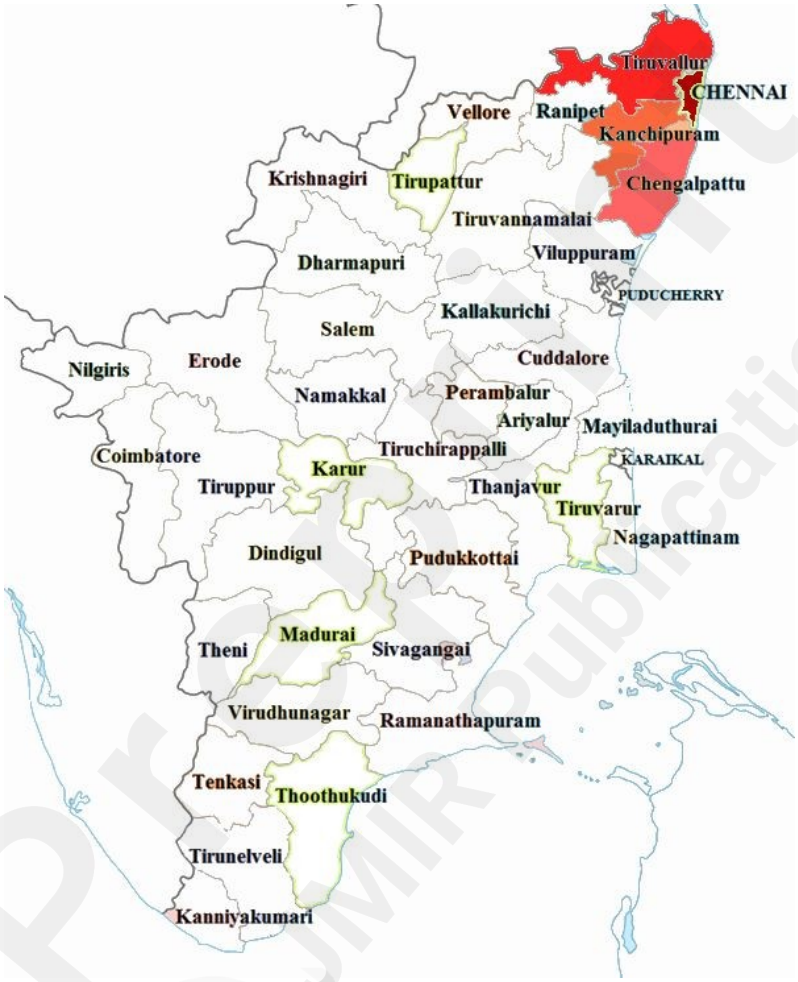


Figure 2. Constructed study site "*Chennai-Metro-Merge"* by combining Chennai district with three bordering districts Chengalpattu, Kanchepuram and Thiruvallur**.** The estimated total population of the constructed single geographical zone by 2020 is 15,208,505

Two different models were considered for the study. First, an exponential model of the form:

$$\frac{dx}{dt} = rx \tag{1}$$

The solution of equation (1) is given as:

$$x(t) = x(0)e^{rt} \tag{2}$$

Second, a sub-exponential model of the form:

$$\frac{dx}{dt} = kx^{p} \tag{3}$$

with solution:

$$x(t) = \left(\frac{k}{m}t + A \right)^{m} \tag{4}$$

where, $x(t)$ is the number of infected cases at time t, $p = 1 - \frac{1}{m}$ and $A = \sqrt[m]{x(0)}$ [17].

This study utilizes the sub-exponential and the exponential models to estimate the date of transition of the epidemic and in the field of epidemiology, these models are well suited for the study of the early epidemic growth [19]. Using the reported cases, the parameters of both the considered models were estimated using the minimization of the objective function given by:

$$\min_{k,p} J = \sum_{1}^{t} \left(x(t) - h(t) \right)^{2} \tag{5}$$

where, $x(t)$ is the model output and $h(t)$ is the reported infections at t^{th} day. The optimization problem was solved using the MATLAB programming software. The sub-exponential and exponential models were analyzed and a technique for the prediction of the onset date of exponential transmission was identified. Further, the developed model was simulated to approximately predict and analyze the future COVID-19 infections in these four districts.

Analysis of transmission of COVID-19 due to public transport in the considered districts of Tamil Nadu

In an enclosed environment, the number of secondary infections (R_A) arising due to the introduction of infectious cases into the susceptible population in an enclosed environment is given by:

$$R_A = (N - I)P \tag{6}$$

where, N is the total population inside the enclosed environment such as busses or train compartments, I is the number of infected individuals inside the same enclosed environment and P is the probability of infection. The equation (6) was utilized to analyze the transmission of COVID-19

in busses and train compartments, when the lockdown is released and the public transportation is resumed in Tamil Nadu. The busses in Tamil Nadu are to be operated with 50% capacity on the immediate release of the lockdown.

The Probability of infection P is given by:

$$P = 1 - \exp\left\{ - \frac{Iqft}{N}\left[1 - \frac{Vf}{Npt}\left(1 - \exp\left(- \frac{Npt}{Vf} \right) \right) \right] \right\} \quad (7)$$

where, N is the number of individuals in the bus or train compartment, V is the volume of shared air space in m^3, t is the total exposure time in hours, p is the breathing rate in m^3/hour, f is the fraction of indoor air exhaled by the infected people, q is the quantum generation rate, and I is the number of the initial number of infected people. The values of q, f and p was adopted from [20]. The volume of the single train coach was considered from literature [21]. Further, the maximum initial infected in the bus, train coach and the ladies' compartment in the train was assumed as 3, 4 and 3 respectively. This assumption is based on the volume of the bus and the train, the number of passengers and the commuter density in the bus-stops and railway stations.

Results

Figure 3 shows the exponential and the sub-exponential models fitted to the reported number of infections in the four considered districts, as a function of time in days. The data available from 7th March 2020 to 29th April 2020 was used to generate the models, and the predictions are further presented up to 15th May 2020. It is observed that during the early stage of the epidemic, the sub-exponential model best describes the progression of the infected cases. However, after a particular point of time, infected cases are closely tracking the curve described by the exponential model. The week in which the transition from the sub-exponential to the exponential progression begins is an important marker of the change in the course of the epidemic, as described in Figure 3. Both the developed models were simulated to predict the future number of COVID-19 cases and the resulting curves were compared with the actual reported cases. It is seen that there was no uniform pattern in the day to day reporting of the cases. Therefore, initially the trend of the progression of the reported number of infections is close to the predictions made by the exponential phase and in short period to the sub-exponential phase. However, the merging and the transition from the sub-exponential to exponential phase was clearly visible at particular point of time.

The exponential model was further updated using the data available from 16th May to 10th

June 2020 and the model is utilized to further predict the future number of cases up to 30th June 2020, in the considered geographical boundary. The updated exponential model output and the reported cases are shown in Figure 4.

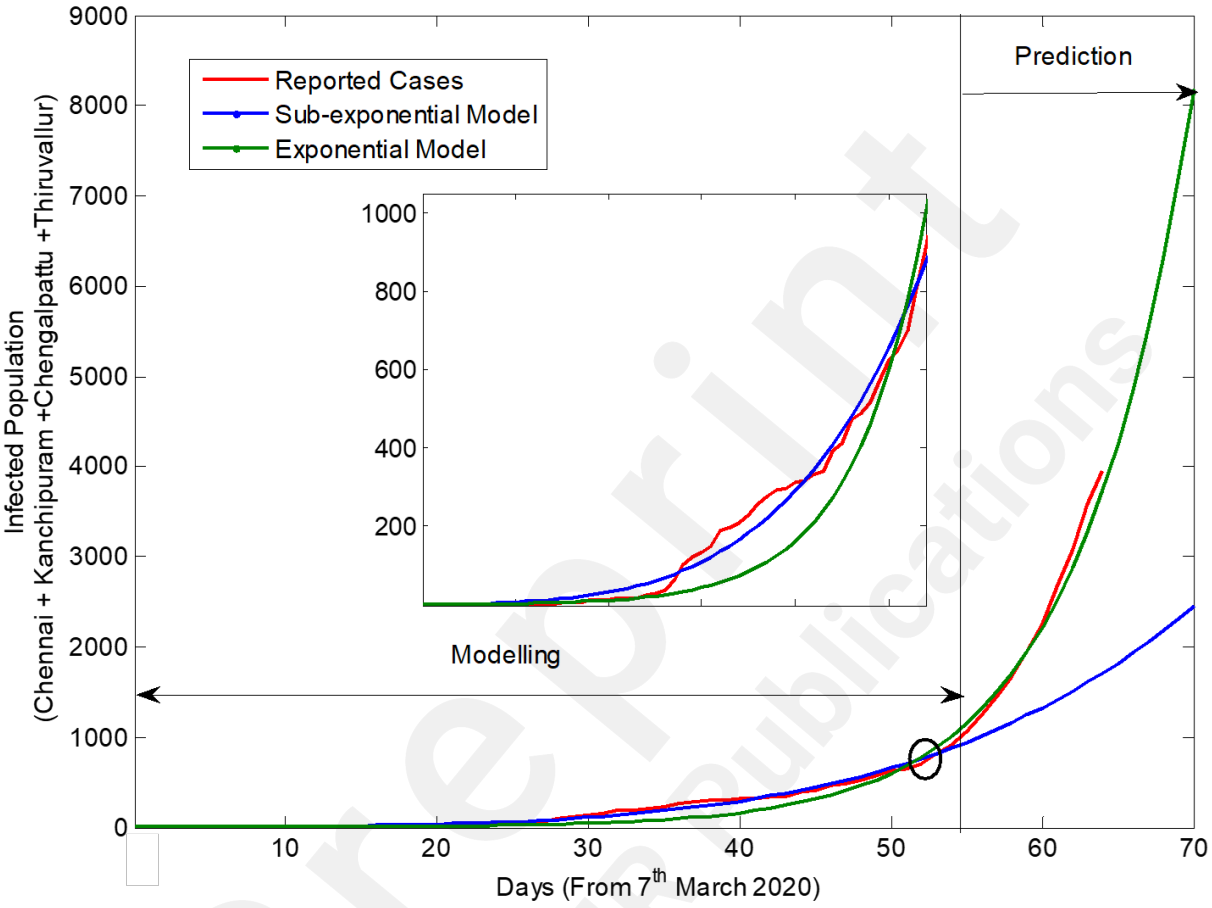


Figure 3. The reported number of COVID-19 cases (includes effect of intervention) and the output of the sub-exponential and the exponential models, shown as a function of time

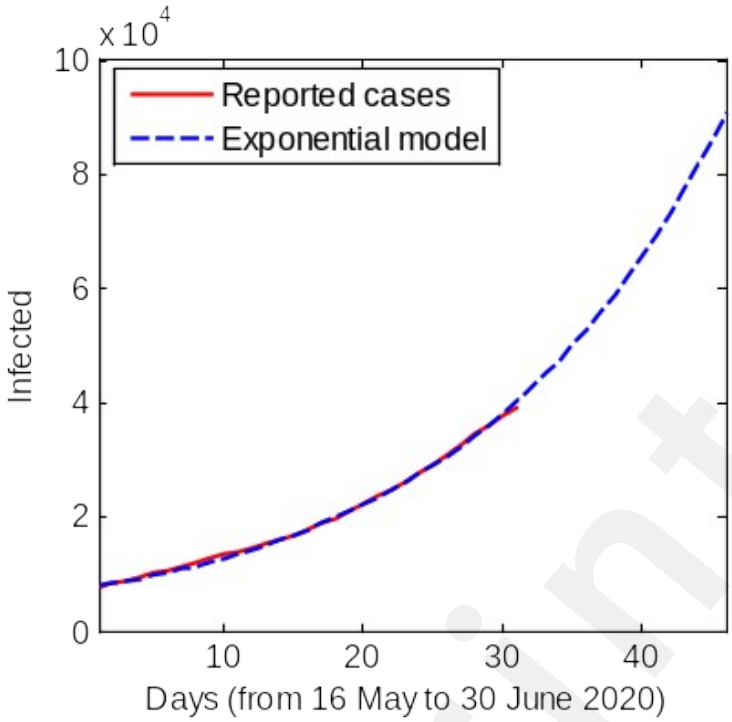


Figure 4. The total COVID-19 cases in the four considered districts of Tamil Nadu predicted using the updated exponential model and the actual reported cases.

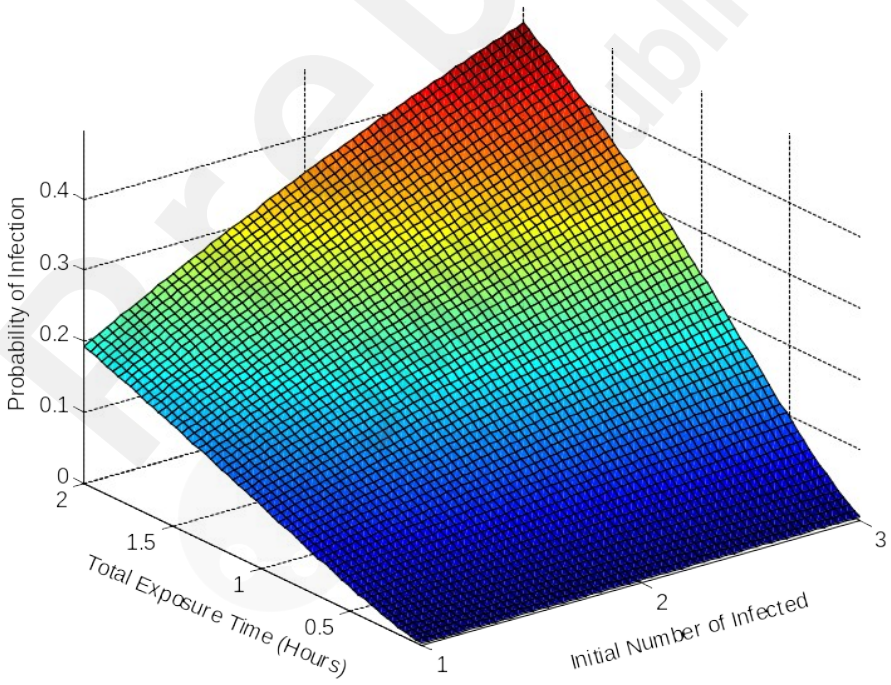


Figure 5. The probability of infection in a public bus with 20 passengers shown as a function of the total exposure time and the initial number of infected

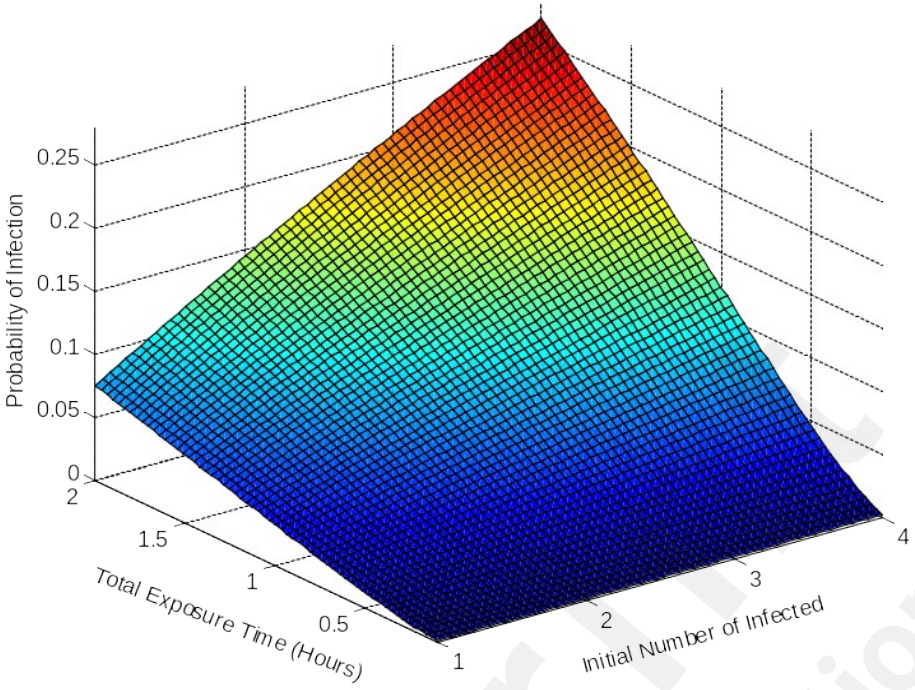


Figure 6. The probability of infection in a single train coach with 54 passengers shown as a function of the total exposure time and the initial number of infected

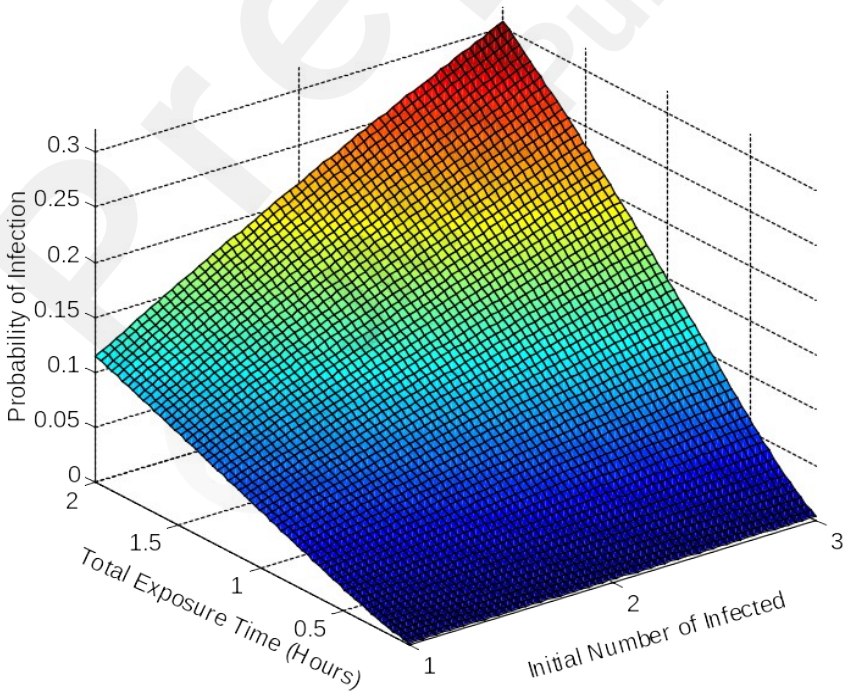


Figure 7. The probability of infection in a single train coach (ladies compartment) with 36 passengers shown as a function of the total exposure time and the initial number of infected

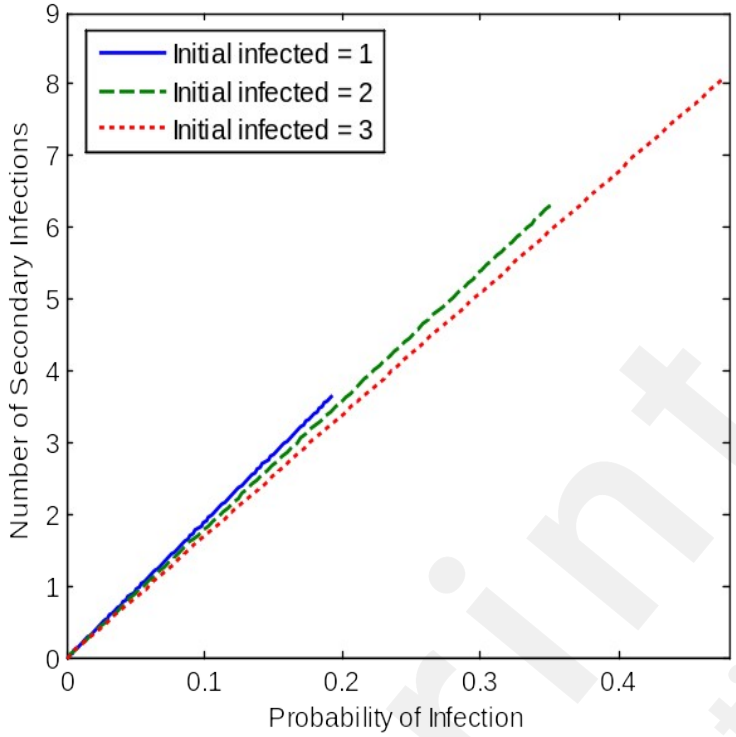


Figure 8. The number of secondary infections in the bus due to the introduction of infected individuals into the susceptible population (total population of N=S+I=20), shown as a function of the estimated probability of infection

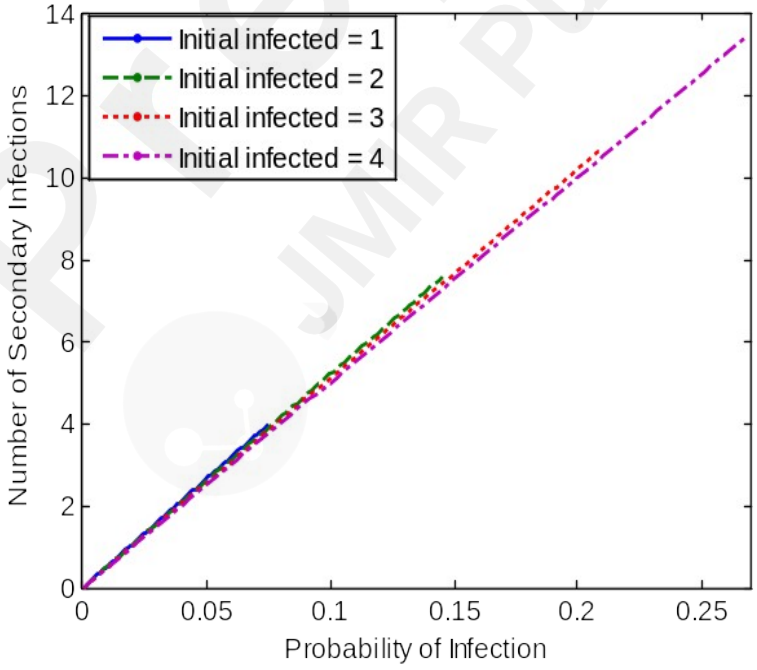


Figure 9. The number of secondary infections in the train compartment due to the introduction of infected individuals into the susceptible population (total population of N=S+I=54), shown as a function of the estimated probability of infection

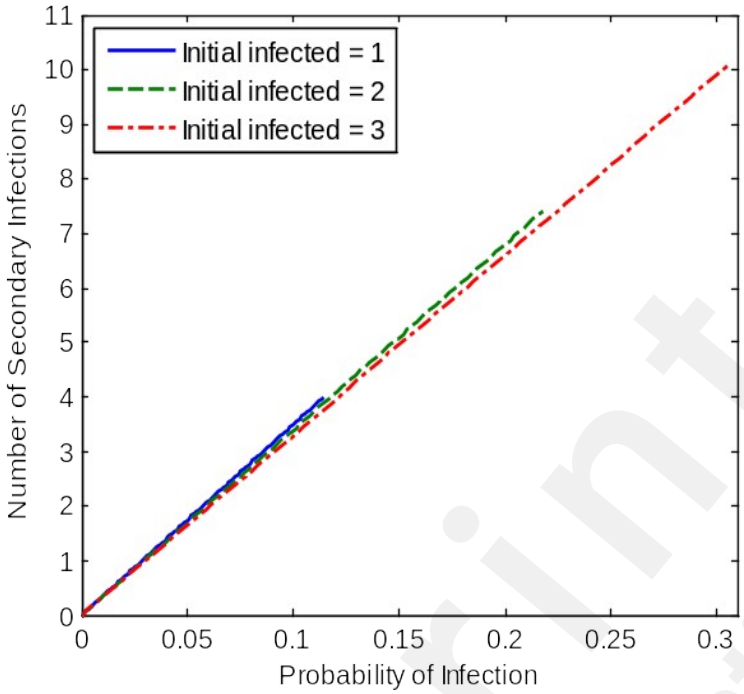


Figure 10. The number of secondary infections in the train coach (ladies compartment) due to the introduction of infected individuals into the susceptible population (total population of N=S+I=36), shown as a function of the estimated probability of infection

Figures 5, 6 and 7 show the probability of infection as a function of both the travelling time (exposure time) and the number of infected individuals travelling in the bus, a single train coach and a single train coach (ladies compartment) with a total of 20 passengers and 54 passengers, and 36 passengers respectively. It is seen that the increase in the initial number of infected individuals and the increase in the exposure time leads to an increased probability of infection of the susceptible. In the bus, for an exposure time of two hours and with three initial infected individuals, the probability of infection is around 0.4741 (47.41%). Further, the number of secondary infections arising due to the infected individuals travelling in the bus, single train compartment and a single train coach (ladies compartment), is shown in Figures 8, 9 and 10 respectively, as a function of the probability of infection and for various numbers of initially infected individuals. Results demonstrate that the operation of the train coaches at a reduced capacity of 50%, provide a maximum probability of infection of 0.2674. Further, the maximum probability of infection in a single train coach (ladies compartment) was found to be 0.3061.

Discussion

In the present study, we constructed a mathematical model based on the reported cases from 07th March 2020 to 29th April 2020 to analyse the transition of the COVID-19 epidemic from the sub-exponential to the exponential stage, in the combined Chennai metro-merge. Further, the reported cases from 16th May to 10th June 2020 were used to update the exponential model to nowcast the progression of the epidemic up to 30th June 2020. Currently, five metro cities in India and several cities in South East Asian Region (SEAR) are facing the similar SARS-CoV-2 epidemic. The results of the modelling indicate that the transmission in all the four districts exhibited exponential transmission from the third or fourth week of the first reported case in each district. However, the number of predicted cases for this period was considerably less and there was an opportunity until eighth week i.e first week of May 2020 to favourably contain the epidemic and reverse to the sub-exponential transmission. On the other hand, the Government of Tamil Nadu proposed resuming both the bus and train services initially for the officials followed by the public in a phased manner. In public health as well as the individual perspective, it is desirable to assess the risk of acquiring the SARS-CoV-2 infection while travelling for a considerable period of time in an enclosed environment. We utilized a probabilistic model and observed that the probability of acquiring the infection in the event of a single index in the closed environment is lower in suburban train travel with a restricted occupancy of 50% as compared to the bus travel with the same proportion of occupancy (0.19 vs 0.07). The results also indicate that during the sub-urban train travel the probability of infection is higher in ladies' compartment as compared to the open compartment, for an exposure time of 2 hours and when a single infected case is introduced (0.11 vs 0.07).

For the predictions to be reliable, the model parameters were estimated with the reported values using the optimization technique of the minimization of the sum square error between the model outputs and the reported values. Also, standard probabilistic models were utilized to analyze the probability of infection in busses and trains which are to be operated at reduced passenger loads, after the release of the lockdown. Using the probability of infection due to the total exposure or travel time of the passengers and the initial number of infected individuals travelling in the bus or train coach, the numbers of possible secondary infections were estimated. The modes of SARS-CoV-2 transmission in an enclosed environment are droplet nuclei from the asymptomatic persons as well as the aerosol droplet especially when the infected person sneezes or coughs during the travel. It has been reported earlier in SARS-CoV-1 transmission that all the passengers infected during the flight travel were seated in close proximity to index cases [22]. Another investigator showed that the persistence of SARS viruses is longer compared to the influenza virus [23]. Therefore, there are

likely to be a higher number of SARS-CoV-2 secondary infections during the bus and train travel as reported for CoV-1 transmission [24]. Data-driven estimate in China during the early phase of the SARS-CoV-2 epidemic showed a highly significant association with train travel [25]. A comprehensive review by Perri et.al revealed that the massive rail connectivity to Wuhan in China favoured the widespread transmission [26].

SARS-CoV-2 pandemic has gone through several continents in a short span of 12 weeks and the length of the epidemics in various countries indicate that there is likely to be a prolonged pandemic for a period of 18-24 months as observed in Spanish flu pandemic in the early twentieth century. Based on the R_0 during the initial phase of the epidemic in China, it is estimated that about 60% of the population will be infected if the epidemic is not mitigated [27]. Modelling studies suggest that to contain the epidemic before the exponential phase, about 70% of the contacts must be traced and quarantined [28]. Data from the earlier phase of the epidemics outside China indicate that nearly 80% of the infected remain asymptomatic or mild-symptomatic and resolve by self-healing [29].

Disease transmission models and the epidemic forecasts at national level provide valuable information for the policymakers to implement appropriate intervention strategies in an appropriate time. However, it is critical to design a data-driven reliable models for nowcasting also for the small population where clustering of transmission occurs. It is a routine practice among the public health specialists to rely on mechanistic epidemic models and the major disadvantage with these models is that there is an underlying assumption of exponential transmission during the early phase of the epidemic itself [30, 31] and therefore, the predicted number of cases after 12 weeks or the final size of the epidemic are unusually high. Forecasts on the final size of the HIV and Ebola epidemics proved this phenomenon [32, 33]. In our model, we considered both the sub-exponential and exponential transmission and attempted to identify the time point at which there is a transition from sub-exponential to the exponential phase. The model predicted that the transition for the constructed geographical zone on Chennai-Metro-Merge falls at the eighth week of the epidemic. In order to avoid the unrealistic size of the epidemic for a small geographical area, we restricted to nowcasting approach to predict the numbers of cases for the next 6 weeks. In a nation-wide epidemic of SARS in large countries like India, there must be two levels of transmission control, one at the national level and the other at the State level. At both the levels, it is all the more necessary to plan for the early forecast instead of identifying the magnitude of the epidemic as short-term timely projections provides an opportunity for the type and intensity of interventions for the particular population [34] so that the epidemic is contained without causing any strain on public health infrastructure. It is

important to know the size of the epidemic for the budget allocation and the mobilization of the public health infrastructure.

The major limitations of the study with reference to the predictions are the data inputs for the study were based on the limited numbers of testing in the study districts and the limited period of predictions for only 6 weeks. In addition, while calculating the probability, we assumed the maximum possible number of initial infections in a single enclosure in the bus or train from the initial part of the journey as 3 and 4 respectively. Chennai metro-services are always five times over-crowded during peak hours and most of the enclosures are expected to be full if the restrictions on the occupancy are imposed during the initial phase of the release. With the current exponential trends, even with random contact, the passengers are likely to be exposed repeatedly during the point to point travel for a period of two hours.

At present, several countries are going through the early phase or the sub-exponential phase of the epidemic and have not yet reached the exponential phase, the methods, results and experiences reported in this work are of high value in undertaking midcourse corrections in the implementation of the intervening strategies to contain the SARS-CoV-2 epidemic. The developed model in this study is a simple and can be constructed easily in any software package using the reported infections over a period of time. Hence, this methodology can be adopted by public health specialists and epidemiologists to trace the current trend of the epidemic and to nowcast the progression of the epidemic at small population level like in metro cities and districts.

Conclusions

Though all the countries are well aware of the rapid response to the epidemics, each epidemic exhibits certain challenges. There are several challenges during the current COVID-19 epidemic globally and locally. India imposed lockdown as an intervention reasonably in advance as compared to the other countries. However, this epidemic has shown categorically that lockdown alone is insufficient to contain the epidemic. Lockdown provides an opportunity for the symptomatic to surface out so that the contacts are traced, quarantined and the severe forms of the diseases/complications are identified and treated. As shown by Keeling et.al., it is essential to trace about 70% of the contacts to contain the epidemic spread. China succeeded in the COVID-19 epidemic control by strictly imposing lockdown and similar strategy may not be feasible in democratic countries. However, experiences during MERS-CoV epidemic in Taiwan proved that it is also possible to contain the epidemic by early intervention and community participation. The results

of our study proved that there was 3-5 weeks time for the SARS-CoV-2 epidemic to transit through the sub-exponential phase. If there had been an effective public health response in time, the exponential transmission could have been averted. We showed earlier that unplanned lockdown would enhance the exposure to the infection due to panic shopping and overcrowding in bus and train stations [35].

In India, the opportunity to favourably contain the exponential transmission was missed due to inadequate testing and contact tracing, especially in the over-crowded metro-cities and urban settings. Exposures in religious meetings and market places resulted in several epidemic clusters in Chennai-metro-city. Now, the three major cities Mumbai, Chennai and Ahmadabad contribute about 58% of the total cases in India and there are claims that there are only clusters of transmission in India. The results of our study show that the country needs an exclusive containment strategy in urban areas in particular in metropolitan cities.

The modelling outcome also forecasts the probability of the infection in the metro-zone when public transports are opened up after the lockdown. The long hours of travelling in congested metro-zone enhance the exposure even if there is a single infected person in the closed environment. Train travel appears to be safer although the travelling time is the same for the longest travel in the constructed study area due to the architecture of the train compartment that provides more air volume for the travellers. Our model did not include random contact with the infected person to estimate the probability of the infections and the resultant secondary infection. It is desirable to apply network modelling for precise estimation of the secondary infections.

Conflicts of Interest
None

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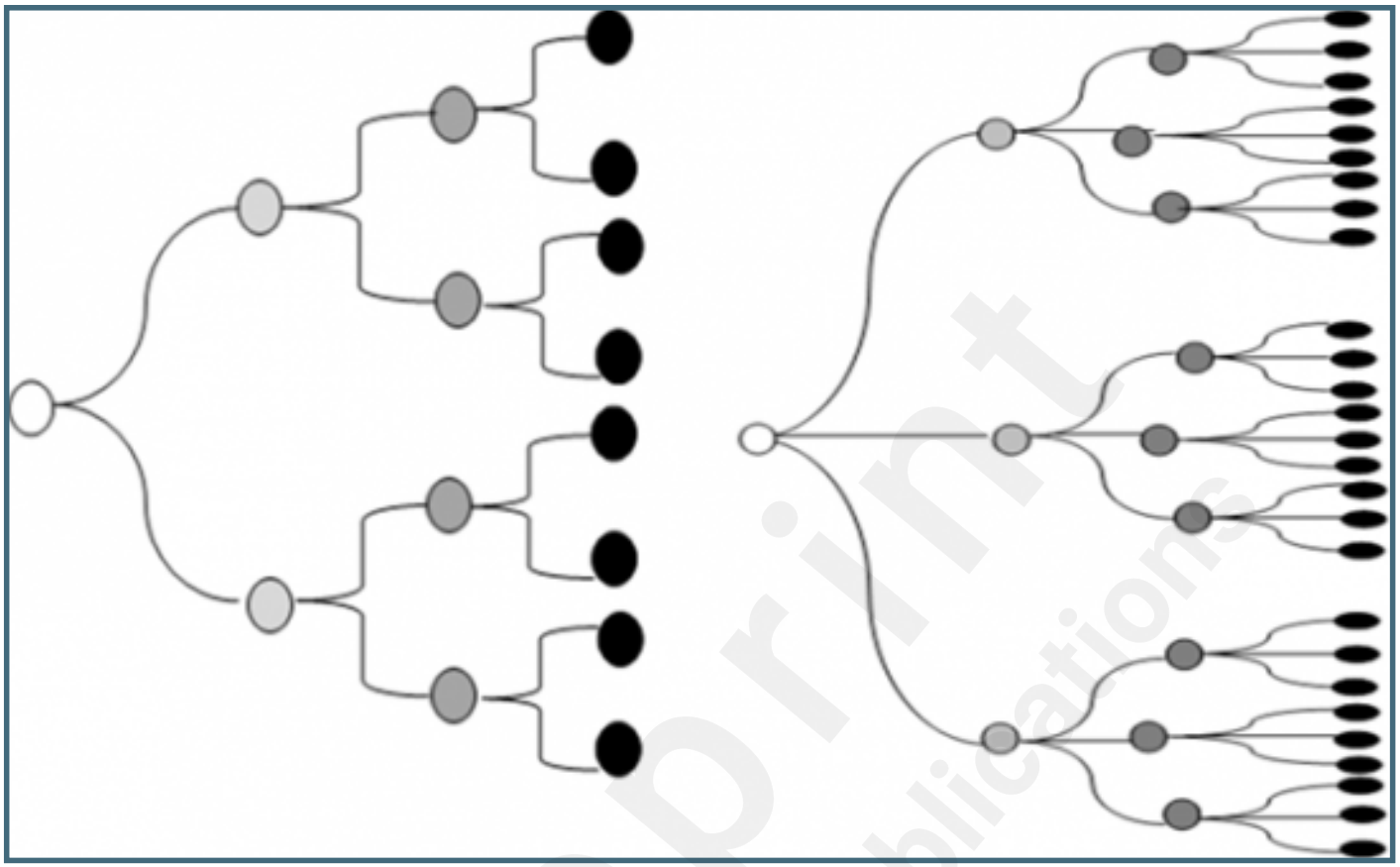
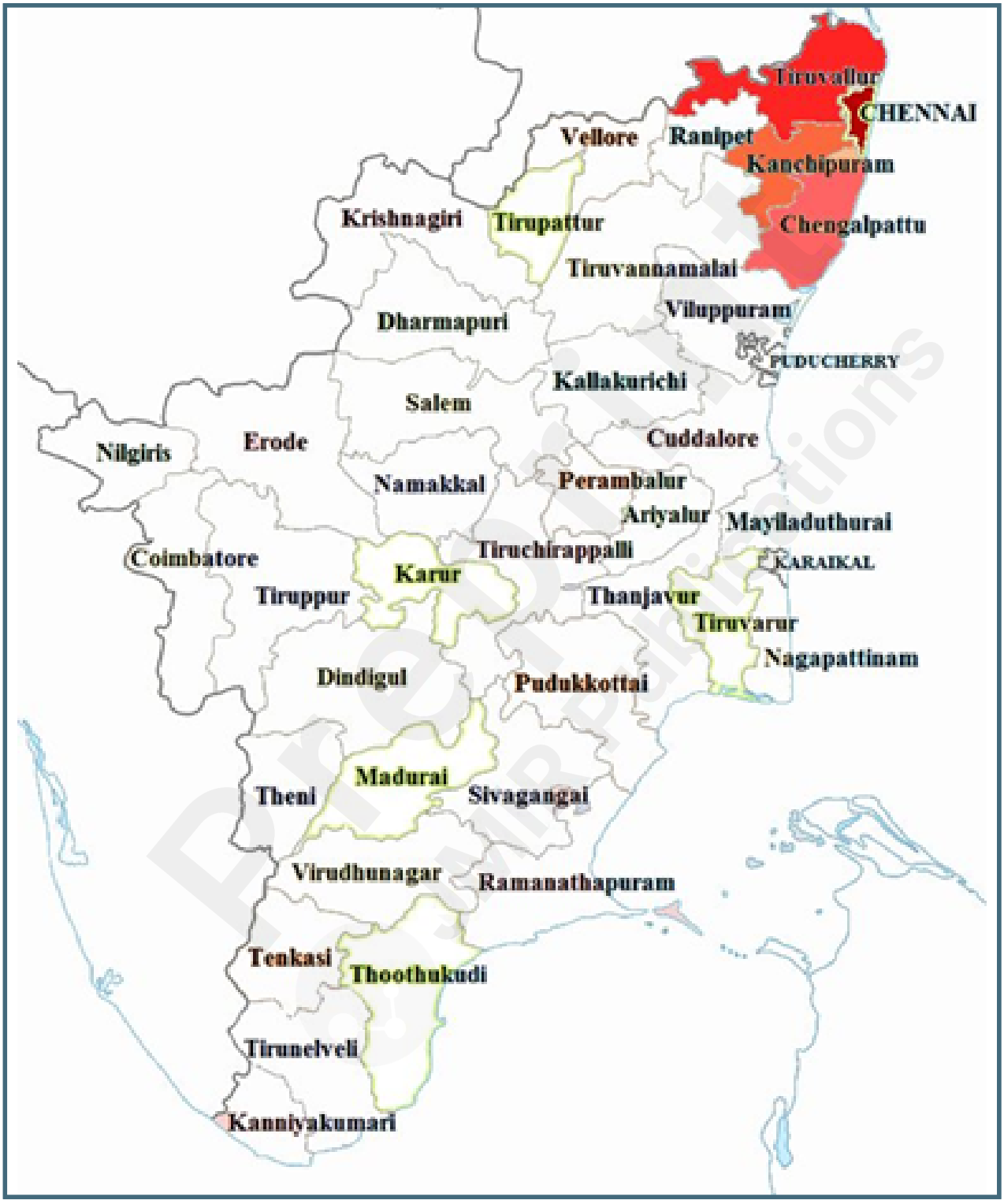
Supplementary Files

Figures

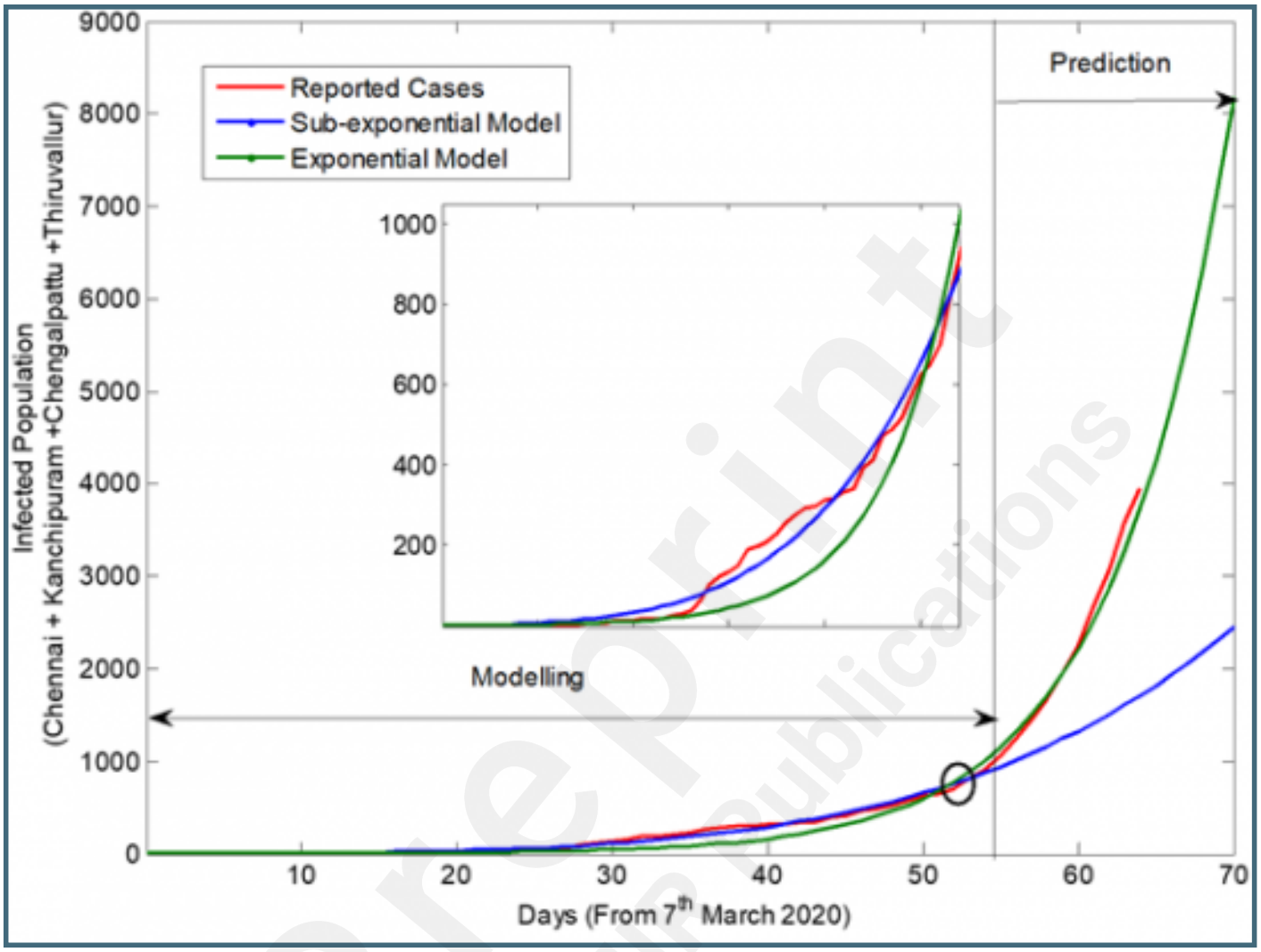
Increase in the number of cases over subsequent generations of the infection for (a) R0=2 and (b) R0=3.



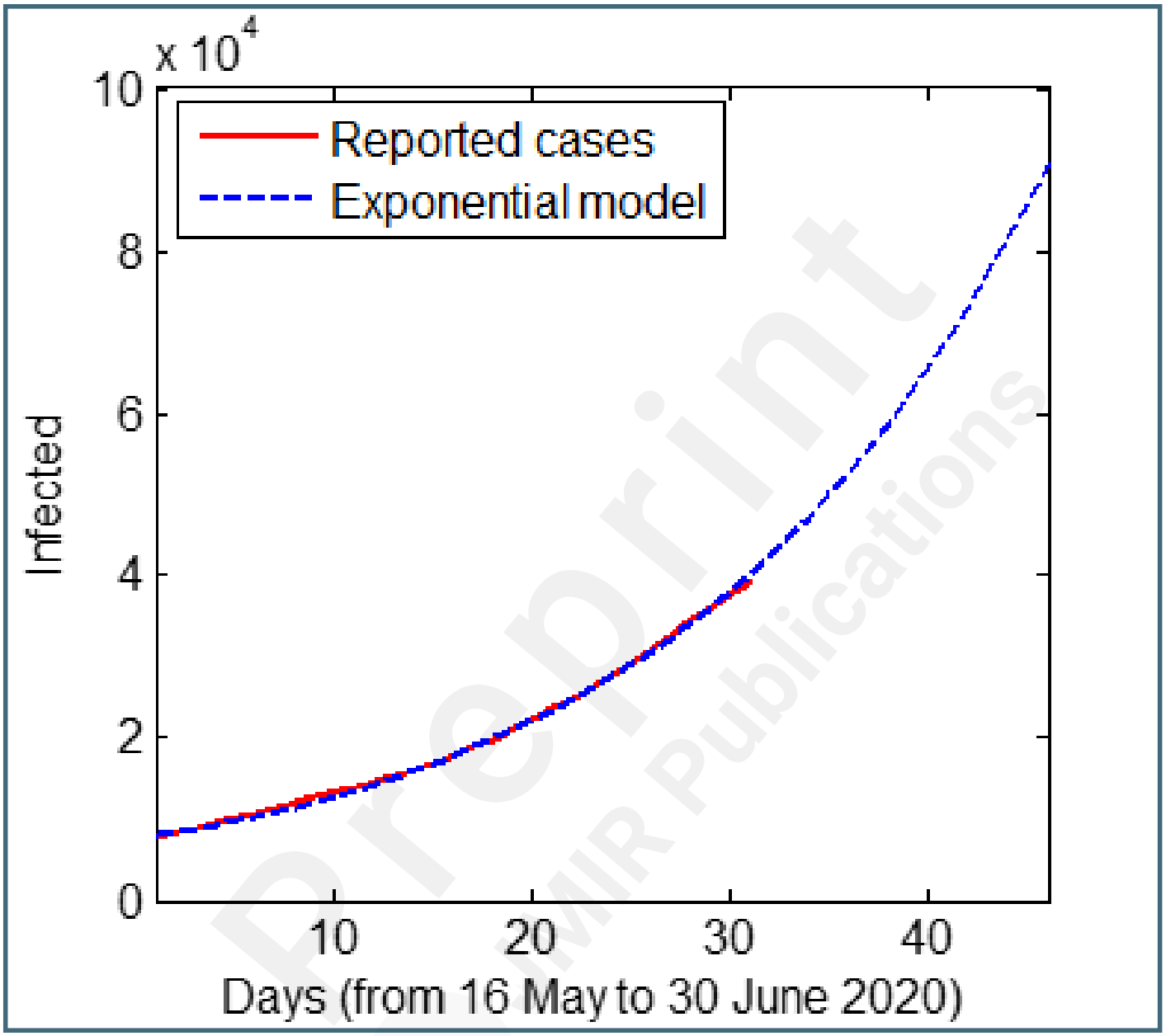
Constructed study site “Chennai-Metro-Merge” by combining Chennai district with three bordering districts Chengalpattu, Kanchepuram and Thiruvallur. The estimated total population of the constructed single geographical zone by 2020 is 15,208,505.



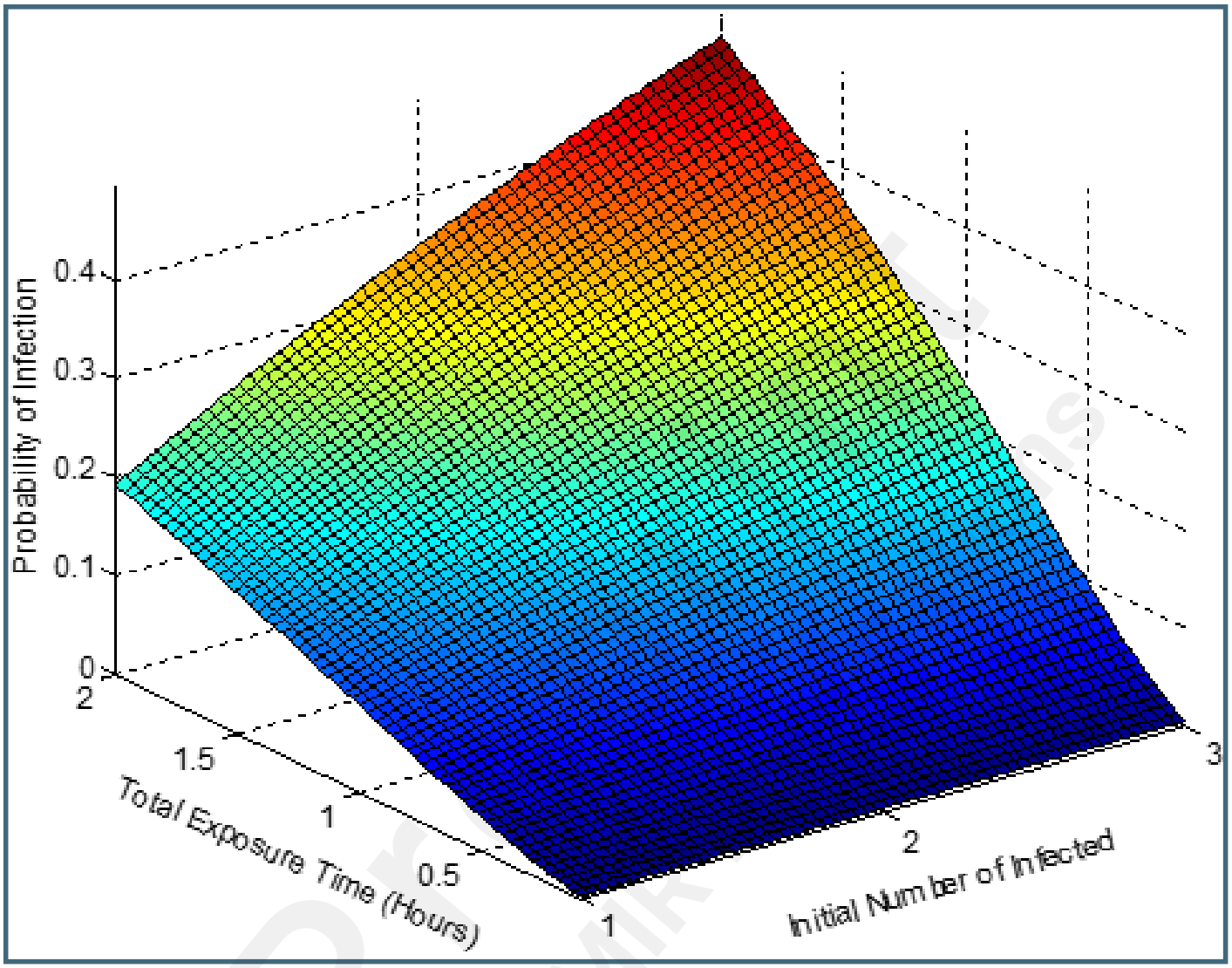
The reported number of COVID-19 cases (includes effect of intervention) and the output of the sub-exponential and the exponential models, shown as a function of time.



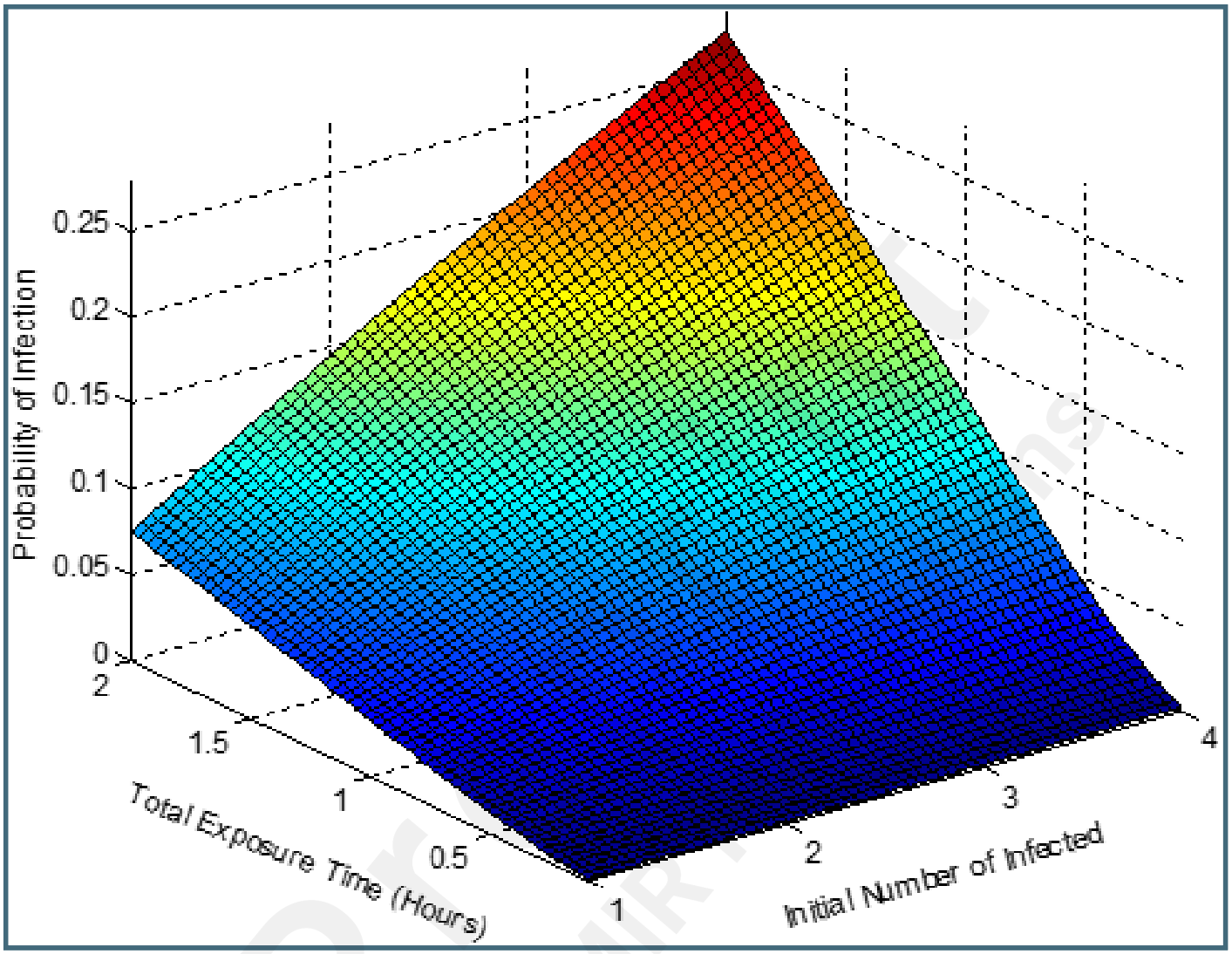
The total COVID-19 cases in the four considered districts of Tamil Nadu predicted using the updated exponential model and the actual reported cases.



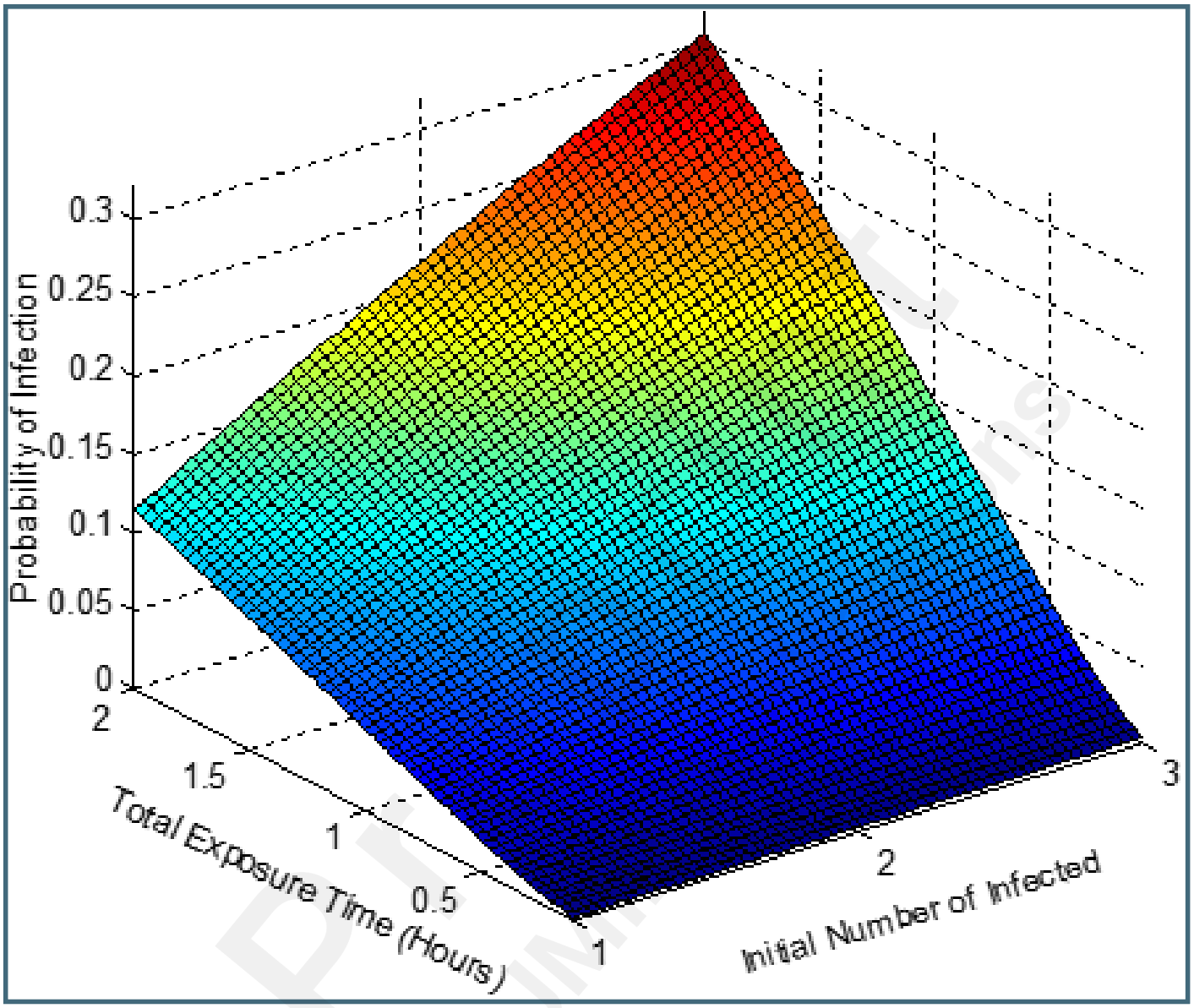
The probability of infection in a public bus with 20 passengers shown as a function of the total exposure time and the initial number of infected.



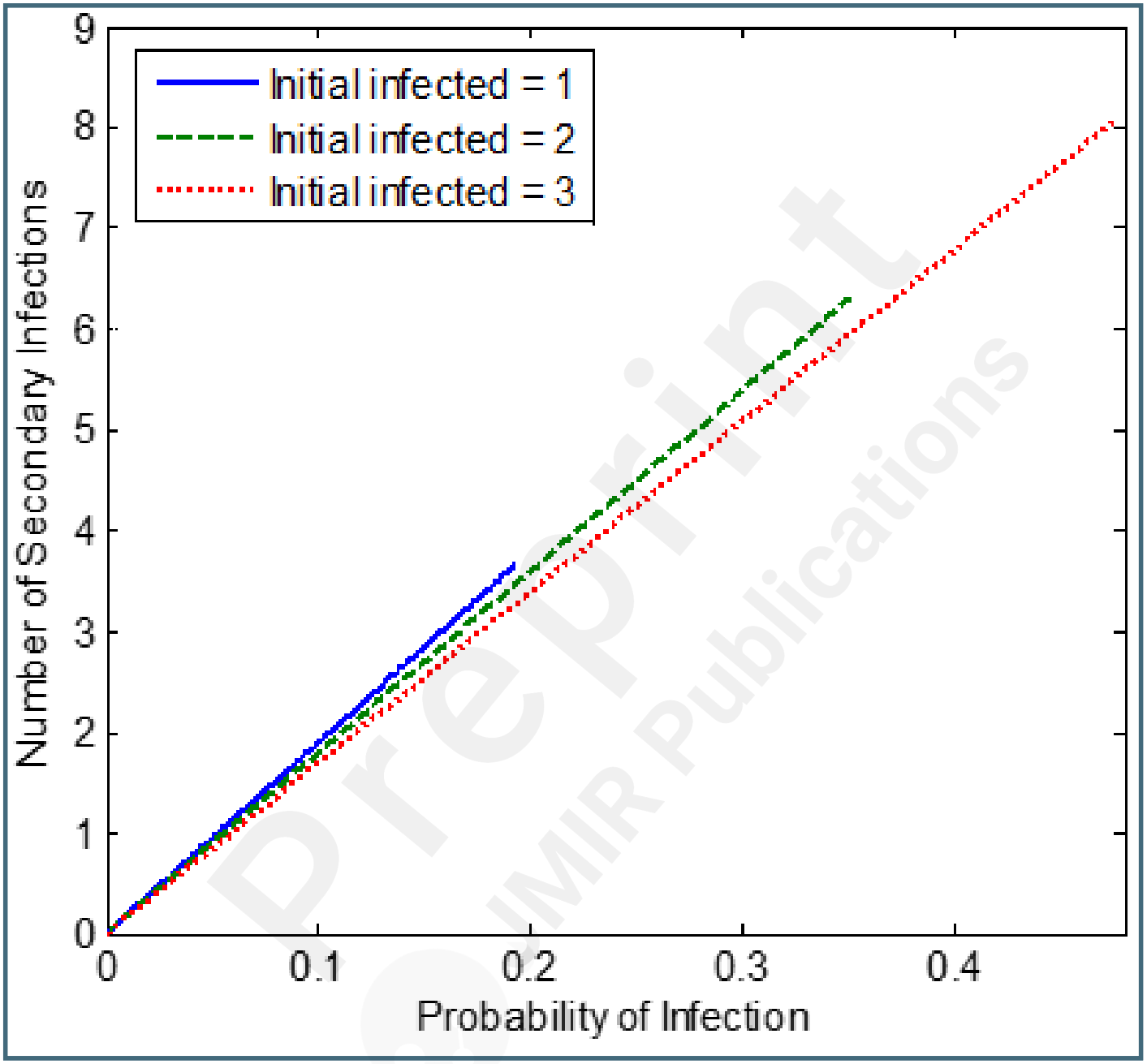
The probability of infection in a single train coach with 54 passengers shown as a function of the total exposure time and the initial number of infected.



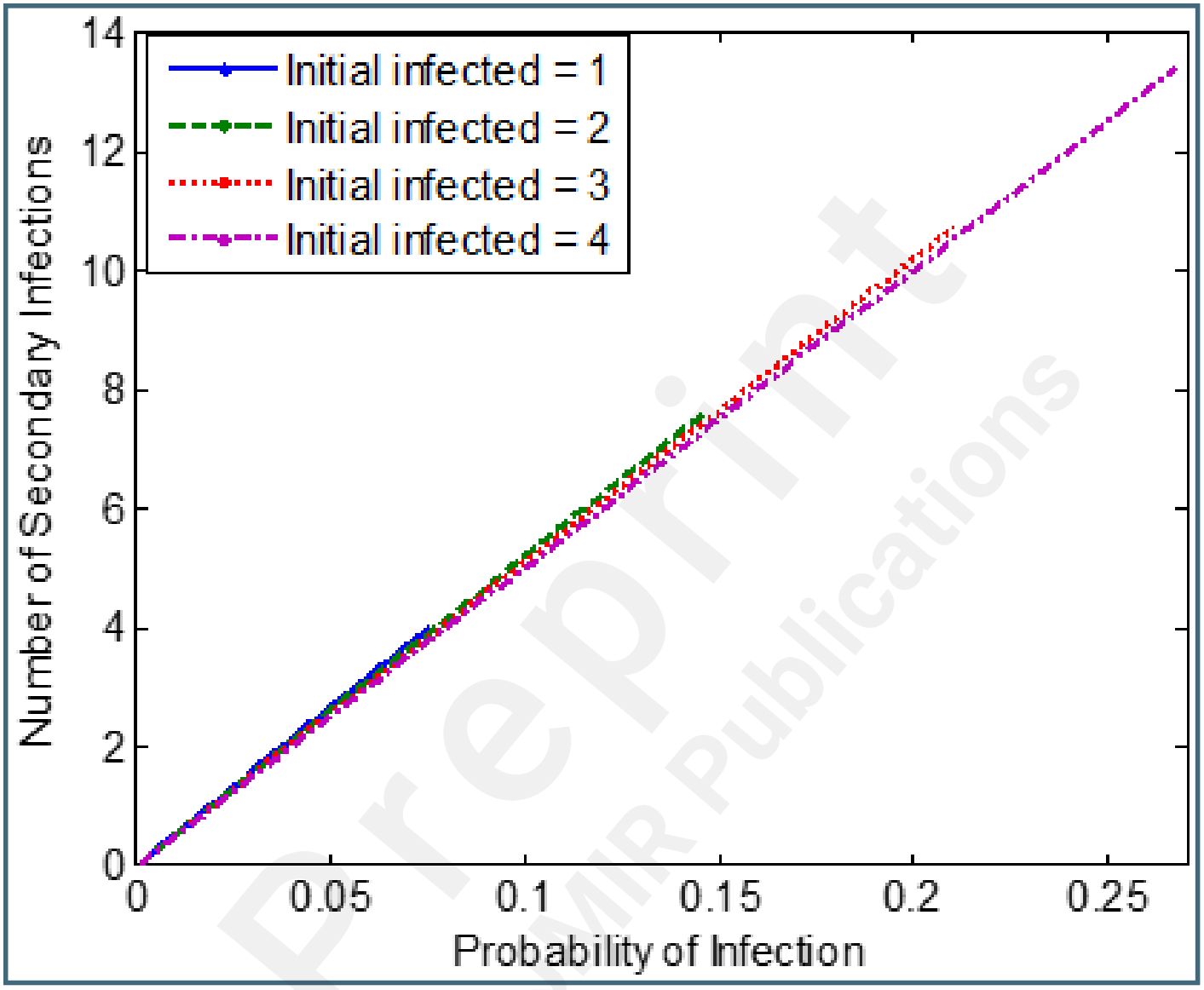
The probability of infection in a single train coach (ladies compartment) with 36 passengers shown as a function of the total exposure time and the initial number of infected.



The number of secondary infections in the bus due to the introduction of infected individuals into the susceptible population (total population of N=S+I=20), shown as a function of the estimated probability of infection.



The number of secondary infections in the train compartment due to the introduction of infected individuals into the susceptible population (total population of N=S+I=54), shown as a function of the estimated probability of infection.



The number of secondary infections in the train coach (ladies compartment) due to the introduction of infected individuals into the susceptible population (total population of N=S+I=36), shown as a function of the estimated probability of infection.