Public Health Implications of a delay differential equation model for COVID 19

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ABSTRACT

This paper describes the strategies derived from a novel delay differential equation model[1], signifying a practical extension of our recent work. COVID -19 is an extremely ferocious and an unpredictable pandemic which poses unique challenges for public health authorities, on account of which "case races" among various countries and states do not serve any purpose and present delusive appearances while ignoring significant determinants. We aim to propose comprehensive planning guidelines as a direct implication of our model. Our first consideration is reopening, followed by effective contact tracing and ensuring public compliance. We then discuss the implications of the mathematical results on people's behavior and eventually provide conclusive points aimed at strengthening the arsenal of resources that are helpful in framing public health policies. The knowledge about pandemic and its association with public health interventions is documented in the various literature-based sources. In this study, we explore those resources to explain the findings inferred from delay differential equation model of covid-19.

KEYWORDS

Delay differential equation, Contact tracing, Socio-behavioral theories, Lockdown, Reopening

1 INTRODUCTION

The national (USA) and global spread of Coronavirus Disease 2019 (COVID-19), following its origins in Wuhan, China in at least December 2019 and possibly earlier still [2] has been alarmingly rapid and deadly. From the 25 individual national forecasts received by CDC, predicts that there is possibility of the total reported COVID -19 deaths is between 160,000 and 175,000 by August 15th, 2020 [3]. Some features however, both nationally and globally, have proved counterintuitive. For example, a 76-day lockdown resulted in the outbreak's containment in Wuhan. A similar measure has produced similar results in New Zealand. However, lockdown appeared only marginally effective in New York State, USA where the case and death counts decreased only after reaching horrifying peak levels [4]. It was contended that the stay at home order in New York came too late. This apparent delay was not present in California, USA. The case counts there went up all the same, and the rate is high even today. We would like to mention that such spatiotemporal anomalies are present not just in the US but also in other countries such as Canada, Russia and India [5] which witnessed high case growth despite being in lockdown. In order to better understand the epidemiology of the transmission of COVID-19, we have constructed a delay differential equation model. Here we present its practical implications which tries to encapsulate a myriad of factors associated with the current scenario.

2 MATHEMATICAL MODELING TO UNDERSTAND THE EPIDEMIOLOGY

Since many decades, mathematical modelling has been used as an integral tool in recognizing the trend of disease progression during pandemics. For example, using a simple model explaining the transmission dynamics of the infectious disease between the susceptible, infected and recovered population (SIR Epidemic Models) Kermack and McKendrick proposed and later established a principle – the level of susceptibility in the population should be adequately high in order for that epidemic to unfold in that population. Such mathematical models can give impressionable insights in explaining the epidemiological status of the population, predict or calculate the transmissibility of the pathogen and the potential impact of public health preventive

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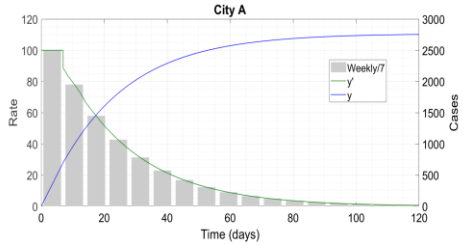
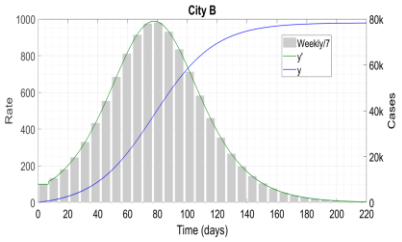
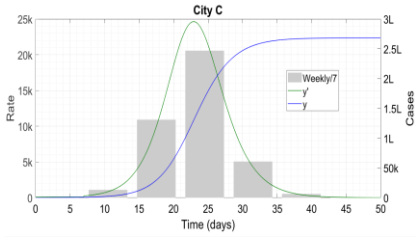
practices [6]. However, a significant body of evidence suggests that decisions should be made regarding the parameters to be included, being contingent on the impact of the precision of predictions. Several policy questions about the containment of this outbreak have been considered in our recently proposed simple non-linear model [1]This paper delves into the practical solutions that can be devised utilizing the directions of our models' outcome.

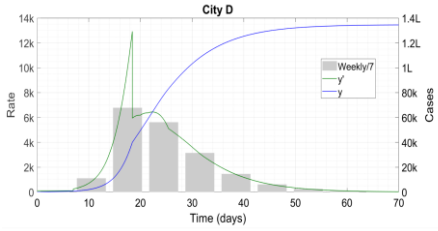
In generating interpretable results gathered from epidemiological models, we have used the examples of six types of cities [1]:

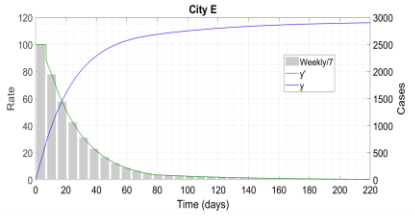
1) City A – Moderately effective contact tracing in a hard lockdown. This city has R (reproductive number) <1 and drives epidemic to extinction in time.
2) City B – Less effective contact tracing in a hard lockdown. It starts off R >1, but reached R =1 at 15% infection level. The epidemic ends at 30% infection rate and takes a very long time to get there.
3) City C – Less effective contact tracing (Like City B) with milder restriction on mobility. It proceeds rapidly to herd immunity.
4) City D – Combination of City B and City C. Starts with mild restriction on mobility and progresses towards restriction. The duration of the epidemic as well as of the final case count is between CITIES B and C.
5) City E - Starts off like City A, it reopens with very effective contact tracing and drive the epidemic to extinction in time.
6) City F – Starts off like CITY A, it reopens with less effective contact tracing and suffers a second wave.

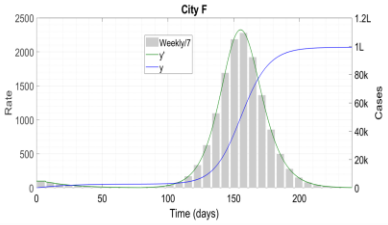












Pragmatic implications of our work are as follows:

3 REOPENING CONSIDERATIONS, ROLE OF TESTING

The unemployment situation generated as a result of lockdowns is currently forcing countries and states to partially reopen their economies even though many of them have not yet got the virus under control. The reopening is easiest in City A regions where cases have slowed down to a trickle. With every new case being detected, swift isolation of all potential secondary, tertiary and maybe even quaternary cases, both forward and backward, should prove possible while the rest of the economy functions in a relatively uninhibited way. Even one mass transmission event can restart an exponential growth regime and force a rollback to a fully locked down state. Reopening beyond a skeletal level is impossible in City B regions which are still in the ascending phase. The ascent implies that contact tracing is already inadequate, and on top of that if mobility increases then the region might turn into City C, overstress healthcare systems, and become a massacre. An ascending B-City has little option other than to contact trace as hard as possible and wait for partial herd immunity to kick in. Only when that happens and the cases slow down on their own can it consider a more extensive reopening like a City A region.

Testing is an important part of the epidemic management process no doubt since it enables the authorities to get an accurate description of the spread of the disease. As we have already discussed, limited testing capacity is giving us a partial or distorted picture in many regions. There is a widespread media perception that extensive testing is one of the prerequisites for any kind of reopening process [7], [8]. Much criticism has also been levelled at certain countries for having inadequate testing programs (we shall further elaborate the blame aspects later). However, we would like to emphasize that testing is as of yet a diagnostic tool and not a preventive one. Currently, it can show us how the disease is behaving but cannot slow its spread in any way. Test-induced slowing can come only when the capacity expands to such a level as to be able to preventively test potential super-spreaders such as grocers and food workers every single day. We hope that such a development may prove possible in the near future – many Universities for example are making reopening arrangements with provision for very frequent testing of the entire community.

During reopening it is vital to get a true picture of the disease evolution so that we can gauge the effect of any relaxation of restrictions – whether it keeps the outbreak under control as in City E or brings about the beginnings of a second wave as in City F. Such beginnings are heralded by a rise in the case rate. As we saw, there was no such rise in City E even though R increased after the reopening. If the rise takes place, the relaxation must immediately be rolled back to avert the disaster. Hence, during reopening, the testing capacity must be high enough to detect such incipient rises. As per China's state media reports, with an aim to reopen the economy, the city of Wuhan conducted 6 million tests in one week; we present this fact without discussion or comment. A second reason why testing is still not all that it could have been is the high false-negative rate during the initial stages of infection [9]. Suppose a contact tracing drive identifies Mr X as a potential case, having been exposed to a known case yesterday. Then, it can be that Mr X contracts the virus ten days from now, in which situation he will report negative if tested today or tomorrow, but will still amount to a spreading risk ten days later if he is at large then. This also means that secondary contact tracing, i.e. finding Mr. X's contacts, must go ahead irrespective of his test results. Indeed, the medical authorities are well aware of this loophole.

The US Chamber of Commerce has given out state by state reopening guides for small businesses which are mandated to be followed across the US. Continued following of federal, state, tribal, territorial and local recommendations is of paramount importance.

Prior to resuming work, all workplaces should have a carefully chartered exposure control, mitigation and recovery plan. Although essential guidance is specific for each business, there are certain measures that can be generally adopted across all workplaces.

1) Reopening in phases – The US government has laid down guidelines to open the country in 3 phases. First phase involves continuation of vulnerable individuals to remain at home. When in public, people are expected to wear masks, have maximum physical separation, avoid places with more than 10 people and limit non-essential travel. Second phase allows gatherings of 50 people, some nonessential travel and reopening of schools. Third phase involves relaxation of restrictions, permitting vulnerable populations to operate.

2) Defining new metrics – Post-corona world will witness some significant changes in regulatory controls, and behavioral drift in personal and professional spheres. Cleanliness standards, safety standards, infection prevention practices with regular monitoring and inspection for its assurance are some of the new terms that will have to be a part of a daily life of the people for at least the next few months.

3) Organizational changes – To help essential operations to function, companies and organizations will have to be prepared with advanced IT systems (in case of continuation of remote working), supply of PPE, setting up travel facilities to avoid public transport, providing behavioral health services, and leave no stone unturned in overcoming biological, physical, and emotional challenges. We can see that the above guidelines are broadly conformal to our model predictions.

4 METHODS OF CONTACT TRACING

As we have already mentioned, contact tracing is probably the single most important factor in determining the progression of COVID-19 in a region. We can see from the model that the faster the contact tracing takes place, the better; the more delay we have, the higher R becomes. Moreover, our model does not account for backward contact tracing. In practice however, a sufficiently high level of detection might not be possible to achieve with forward contact tracing alone. As much as it is important, contact tracing is also one of the trickiest aspects to handle since it can interfere with people's privacy. In classical

contact tracing, human tracers talk to the confirmed cases and track down their movements as well as the persons they interacted with over the past couple of days. This method has worked well in Ithaca, USA and in Kerala, India. While it is the least invasive of privacy, it is also the most unreliable since people might not remember their movements or their interactions correctly. The time taken in this method is also the maximum. A more sophisticated variant of this supplements human testimony with CCTV footage and credit/debit card transaction histories – this approach is possible only in countries such as USA where card usage predominates over cash. The most sophisticated contact tracing algorithms use artificial intelligence together with location-tracking mobile devices and apps – while they are quick and fool-proof, they automatically raise issues of privacy and security. For example, the TraceTogether app in Singapore, which worked very well during the initial phases of the outbreak, has not found popularity with many users [10]. Similarly, India's Aarogya Setu has also raised privacy concerns [11]. Americans too have expressed their aversion to using contact tracing apps in a recent poll, with only 43 percent of people saying that they trusted companies like Google or Apple with their data.

5 ENSURING SOCIAL COMPLIANCE – A BEHAVIORAL PERSPECTIVE

As the epidemic drags on and on, the continued restrictions on social activity are becoming more and more unbearable. There is an increasing tendency, especially among younger people who are much less at risk of serious symptoms, to violate the restrictions and spread the disease through irresponsible actions. However, City F, a rise in violator behavior can completely nullify the effects of lockdown over the past few weeks or months. Here we discuss how public health professionals and policy makers can resort to behavior/psychological theories to ensure compliance among the common people. The most widely used model is Health Belief Model which has been used successfully in addressing public health challenges. We briefly discuss the utility of this model in the current situation.

Health belief model is a theoretical model which hypothesizes that interventions will be most effective if they target key factors that influence health behaviors such as perceived susceptibility, perceived severity, perceived benefits, perceived barriers to action and exposure to factors that prompt action and self-efficacy. In general, this model can be used to design short and long term interventions. The prime components of this model which are relevant in the current scenario can be outlined as follows.

1) Conducting a health need assessment to determine the target population – The best example is the demarcation of zones in India depending on the level of risk. Red zone is highest risk, orange zone is average risk and green zone translates into no cases since last 21 days. Classification is multifactorial, taking into account the incidence of cases, the doubling rate and the limit of testing and surveillance feedback to classify the districts.

2) Communicating the consequences involved with risky behaviors in a transparent manner – Central and state ministers as well as public health authorities are in constant communication with the masses.

3) Conveying information about the steps involved in performing the recommended action and focusing on the benefits to action – Famous celebrities, in addition to state and central governments, spread the messages explaining the required steps cogently and ensuring that it has the maximum reach, especially among social media-addicted millennials and similar populations.

4) Being open about the issues/barriers, identifying them at early stage and working toward resolution – Activating all sorts of helpline numbers, email addresses, personal offices etc to address any grievances around the topic.

5) Developing skills and providing assistance that encourages self-efficacy and possibility of positive behavior change – Adequate arrangements for people from lower socio-economic strata, stable and trustworthy financial schemes for middle class, plan to support small business and a means to become a bridge between the affluent class and the needy class are some of the ways to foster positive behavior change and develop natural trust. Other than health belief model, some theories that can be useful are:

Theory of Reasoned Action – This theory implies that an individual's behavior is based on the outcomes which the individual expects as a result of such behavior. In a practical scenario, if the health officials want the people to follow a particular trend, let us say based on our model, they need to reinforce the advantages of targeted behavior and strategically address the barriers. For instance, to enforce separation minima even when it is apparently proving ineffective and the cases are increasing, they can use the examples of Cities B and C to convince the citizens that violations – and hence violators – can be responsible for thousands of excess deaths. Trans-theoretical Model – This model posits that any health behavior change entails progress through six stages of change: precontemplation, contemplation, preparation, action, maintenance and termination. For instance, it was observed that in March, despite a rise in cases in New York City (NYC), people were not observing social restrictions the way they should have. Now, we can see that with passing time, the behavior of the masses transforms according to the stages of this model

Precontemplation – This is a stage where people are typically not cognizant of the fact that their behavior is troublesome and may cause undesirable consequences. There is a long way to go before an actual behavior change. This phase coincides with the commencement of cases in NYC.

Contemplation – Recognition of the behavior as problematic begins to surface and a shift begins towards behavior change. When the cases started being reported all over media and the major cause of spread began to surface, citizens started paying attention to their activities.

Preparation – People start taking small steps toward behavior change like in our case, exhibiting hygienic practices and ensuring six feet separation minima.

Action – This stage covers the phase where people have just changed their behavior and have positive intention to maintain that approach. In this instance, people continue to practice social restrictions and hygiene positively.

Maintenance – This stage focuses on maintenance and continuity toward the adopted approach. Majority of people in NYC are exhibiting positive behavior and maintaining it throughout the stages of reopening phases. This is vitally important to ensure that NYC stops at partial herd immunity like City D instead of blowing up again like City C.

Termination – There is lack of motivation to come back to the unhealthy behaviors and some sections of people across the country/world will continue practicing good hygiene (though not social restrictions!) in our day-to-day lives.

Social Ecological theory – This theory highlights multiple levels of influences that molds the decision. In our case, let us say for example that the decision is to maintain sufficient physical separation once offices are opened up. To successfully follow this, there is a complex interplay between individual, relationship, community and societal factors that comes into action. Law enforcement authorities need to take this into consideration. A group of individuals when motivated by one another to follow the guidelines, builds a good connection within the society, and in turn there is a high probability to build a healthy network within a defined area. A negative interplay at different levels of motivation may in turn, prove disastrous and cause all efforts go down the drain. A perfect illustration of this in the present condition is how various NGO's are working in conjunction with public health authorities to bring about a change at an individual level by door-to-door campaigning. This propels the behavior of even the most potentially recalcitrant population in the most desirable way i.e. wearing masks and gloves, adopting hand hygiene, being cognizant of symptoms arising in any member of the family and following quarantine rules in case of travel from other states.

6 SOCIAL ATTITUDES AND BEHAVIOUR

In this Section we address another important issue related to the Coronavirus. This is that the widely heterogeneous case profiles in different regions have often led to "corona contests" among these regions. Far too often, the residents of better-off regions are seen heaping scorn on worse-hit regions. We have selected a tiny handful of representative media articles, castigating the approaches of India, USA and Sweden, to show the breadth and vitriol of such commentary [12][13][14] [15][16].A feature common to almost all opinion pieces like this is that their authors do not have the slightest knowledge of the issues involved, either epidemiological or economic.

Before embarking on criticisms, we should note that policy decisions need to be taken in real time, as the situation evolves. The authorities do NOT have the benefit of hindsight to decide on their course of action. Since the virus is a new one, there is no precedent which can act as a model. Even among emerging infectious diseases, this latest one is particularly unpredictable, since minuscule changes in parameters can cause dramatic changes in the system's behavior. This phenomenon is best illustrated by the notional cities, discussed previously. For example, to get from City A to B, all we did was increase by 50 percent the fraction of people who escaped the contact-tracers' net. The result was a 30 times (not 30 percent!) increase in the total number of cases. Similarly, the difference between Cities B and D is an 11-day delay (recall that the first seven days in the plots are the seeding period, so they don't count) in imposing the lockdown in D. 11 days out of a 200-plus-day run might not sound like a lot. But, that was enough to create tens of thousands of additional cases, risk overstressing healthcare systems and at the same time shorten the epidemic duration by a factor of three.

Further uncertainty comes from the fact that the parameter values are changing constantly. It is a well- known fact the reported fraction of asymptomatic carriers has increased continuously over the last three months or so. Considering the sensitivity of this or any other model to parameter values, such changes can completely invalidate the results of a model as well as any decision which was made on their basis. Identifying potential exposures is much easier in a smaller city than a large or densely populated one. It is also more effective if the cases are mostly from the sophisticated social class who can use mobile phone contact tracing apps or otherwise keep (at least mental) records of their movements and of the people they interacted with. However, if there is an outbreak among the unsophisticated class, then even the most skillful contact tracer might run up against a wall of zero or false information. In such cases there are limited options that are left to the authorities to proceed in a conducive manner.

India went into lockdown on 25 March 2020. At that time, the official figures stated that there were only 571 cases, which made the decision appear premature to many people. Indeed, a seven-day delay of lockdown was suggested so that the migrant workers would have been able to return to their homes. However, when the lockdown was imposed, the testing had also been woefully inadequate, with a nationwide total of just 22,694 tests having been conducted up to that date. If we use the extrapolation technique of inferring case counts from death counts, then using the same 1 percent mortality rate and 20 day interval to death, we find almost 40,000 assumed cases on the day that the lockdown began. If we go by this figure, then the lockdown wasn't really early, and possibly should have been enforced earlier still in trouble zones such as Mumbai. Certainly, if the figure of 40,000 cases is true, then one further week of normal life (with huge crowds in trains and railway stations) might have been disastrous. From the vantage point of today, alternate arrangements should definitely have been made much earlier for rehabilitation of the migrant workers. However these arrangements would have involved considerable complexity in the prevailing situation, and were certainly not as easy as one

week's delay in announcing lockdown. Sweden, which has adopted a controlled herd immunity strategy, has been accused of playing with fire. It is also possible that the Swedish authorities are aware that they do not have the contact tracing capacity required for performing like City A and hence are attempting something like City D – a faster end of the epidemic than City B at the expense of a higher case count. To make a comprehensive analysis of their policy, it is crucial to know not only the last intricate detail of the epidemiological aspects but also the details of the economic considerations. That is almost impossible. On a different note however, we have seen reports [17], [18] stating that the virus has entered into old age homes and similar establishments, causing hundreds of deaths over there. Assuming that these reports are not overturned in the course of time, allowing the ingress of virus into high-risk areas is an indefensible action, whatever the overall epidemiological strategy.

Finally, extremely important public health factors such as the racial dependence of susceptibility and/or transmissibility have just started coming to the surface. Another complete grey area is the mutations which this new and vicious virus are undergoing and what effect they might have on the spreading dynamics. Some reports also reflect that the change in genetic composition due to mutation might be the reason behind huge differences in the crude infection rate between countries [19][20]. In the absence of a clear picture about this, any public health measure is all the more likely to be a random guess with non-zero probabilities of both success and failure. Not everything about corona is random or outside one's control though. Amongst the European countries, we can see that Germany, Austria, Switzerland, Denmark, Norway and Finland have definitely managed the epidemic while their neighbors have not, which rules out some hidden luck factor. The same has happened in Kerala and Karnataka (also in India). This has been feasible only due to governmental awareness and hard work, and people's cooperation. Similarly, there are some governments which have been clearly guilty of negligence or hubris in their management of the disease. It would also be noteworthy to observe and take lessons from the some of the new places like Alabama, Arkansas, Florida , Texas etc which have been recently identified as potential hotspots of this pandemic. Lastly, our conclusion best resonates with the message that coronavirus is not some kind of race but a public health disaster and we should adopt a unified approach to the fight against it.

CONCLUSION

Here, we summarize the take-home messages from this paper:

- A city can reopen only if it is past the peak of cases. Reopening must be accompanied by robust contact tracing. The US CDC has laid down a set of reopening guidelines which are compatible with our model and its solutions.

- Incorporation of socio-behavioral theories can come into play for effective execution of interventional strategies.

- Efficiency of contact tracing comes at the expense of people's privacy – balancing between the two is a delicate optimization problem.

- In some regions, restrictions such as masks and six-feet separation minima must be maintained for a very long time to come. The public health authorities can ensure compliance by resorting to socio –behavioral theories/approaches.

- In deploying advanced contact tracing techniques, significant consideration has to be given for ensuring high data security and lay down privacy regulations that are convincing to the users

- Control the spread by swift identification and isolation of cases accompanied by tracing and quarantine for at least 2 weeks

- Empowering of individuals and communities by the government to facilitate efficient capacity building.

- Multidisciplinary coordination, strong leadership to mobilize communities and take quick decisions coupled with thoughtful development of operation plans are likely to prove considerably efficient in handling this pandemic to the best of our capacity.

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