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The Prediction for COVID-19 Outbreak in China by using the Concept of Term Structure for the Turning Period

George X. Yuan[a,b,c,d,*], Lan Di[e], Zheng Yang[f], Guoqi Qian[g], Xiaosong Qian[d], Tu Zeng[c]

[a] *Business School, Guangxi University, Nanning 530004, China*
[b] *Business School, Sun Yat-sen University, Guangzhou 510275, China*
[c] *BBD Technology Co., Ltd.(BBD), No.966-#9 Builiding, Tianfu Avenue, Chengdu 610093, China*
[d] *Center for Financial Engineering, Soochow University, Suzhou 215008, China*
[e] *School of Artificial Intelligence and Computer Science, Jiangnan University, Wuxi 214122, China*
[f] *School of Traditional Chinese Medicine, Beijing University of Chinese Medicine, Beijing 100029, China*
[g] *School of Mathematics & Statistics, University of Melbourne, Melbourne VIC 3010, Australia*

Abstract

This study aims to develop a general framework for predicting the duration of the *Turning Period* (or *Turning Phase*) for the COVID-19 outbreak in China that started in late December 2019 from Wuhan. A new concept called the *Term Structure* for *Turning Period* (instead of *Turning Point*) is used for this study, and the framework, implemented into an individual SEIR (iSEIR) model, has enabled a timely prediction of the turning period when applied to Wuhan's COVID-19 epidemic, and provided the opportunity for relevant authorities to take appropriate and timely actions to successfully control the epidemic. By using the observed daily COVID-19 cases in Wuhan from January 23, 2020 to February 6 (and February 10), 2020 as inputs to the framework it allowed us to generate the trajectory of COVID-19 dynamics and to predict that the *Turning Period* of COVID-19 outbreak in Wuhan would arrive within one week after February 14. This prediction turned out to be timely and accurate, which has provided adequate time for the government, hospitals and related sectors and services to meet peak demand and to prepare aftermath planning. We want to emphasize that emergency risk management entails the implementation of an emergency plan, where timing the *Turning Period* is key to express a clear timeline for effective actions. Our study confirms the observed effectiveness of Wuhan's *Lockdown and Isolation* control program imposed since January 23, 2020 to the middle of March, 2020 and resulted in swiftly flattened epidemic curve, and Wuhan's success offers an exemplary lesson for the world to learn in combating COVID-19 pandemic.

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Keywords:
Coronavirus (COVID-19); iSEIR Model; Term Structure for Turning Phase; Emergency Plan; Outbreak of Epidemic Infectious Disease; Supersaturation Phenomenon; Lockdown and Isolation control program; Multiplex network.

* Corresponding author. Tel.: +0-086-150-1098-3759; fax: +0-086-150-1098-3759.
E-mail address: george_yuan99@yahoo.com

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1. Introduction

Infectious disease epidemics always present challenges to human society, threatening the safety of human life and causing social upheaval and economic losses. In recent years, novel virus infection outbreaks have been increasing globally, from the 2003 SARS-CoV, the H1N1 influenza A in 2009, the MERS-CoV in 2012, the Ebola in 2015, the Chai in 2016, the H5N7 avian influenza in 2017, to the current corona-virus infection (COVID-19) that emerged at the end of 2019 (in Wuhan, China). These outbreaks have brought great loss to human life, disrupted population movement, and adversely impacted global development.

The COVID-19 outbreak began in Wuhan City (in Hubei province of China) in late December 2019 and quickly spread to other parts in China in a matter of days. It was announced as a public health emergency of international concern by the World Health Organization (WHO) on January 30, 2020. Predicting the trajectory of the outbreak timely and reliably is crucial for deploying emergency response actions to prevent further spread of infections. Such kind of predictions are urgently needed at the present time as the COVID-19 outbreak has become a worldwide epidemic, yet there is still no unanimous metric to predict when this pandemic will be under control.

In this study, we first extend our iSEIR model of Yuan et al. [28] to describe the progression of COVID-19 daily cases in Wuhan. We then propose a new concept called the *Turning Phase* (or *Turning Period*), which is motivated by the *Delta* and *Gamma* concepts practiced in financial risk management (see Hull[37]), to divide the duration of outbreak into different phases each with markedly different characteristics. These turning periods can be accurately predicted based on the iSEIR model. By applying the iSEIR model together with the Turning Period concept to analyze the COVID-19 cases in Wuhan until February 10, we are able to predict that the number of daily new cases would start to drop no later than one week after February 14.

Since almost 100 years ago, in order to study and model the dynamics of infectious diseases, a model named SEIR and many of its variants have been developed, and have been widely used for analyzing and predicting the temporal dynamics of an epidemic. Naturally, the SEIR models are used for analyzing COVID-19 outbreaks as well; see Liu et al. [1], Murray [2], Wu et al. [3-4], Prem et al. [5], Li et al.[6], Lin et al.[7], Kuniya [8], Roosa et al. [9] and references therein. By an SEIR model individuals in a population are classified into four groups according to the following four states of their response to the presence of an infection: susceptible S, exposed E, infected I, and resistant R. Note that S, E, I and R are also used to represent the number of people in the respective groups. The quantity *basic reproduction number* is one of the most important parameters in an SEIR model, which is defined as the average number of susceptible people that are exposed to an infected case. Many characteristics on dynamics of an epidemic, such as stability, equilibrium and various thresholds etc., are intrinsically related to the basic reproduction number, and have been studied for COVID-19 outbreaks; see Cao et al. [10-11], Cowling and Leung [12], Hermanowicz [13], Li et al. [14], Guan et al. [15] and reference wherein.

So far most research on dynamics of COVID-19 outbreaks focus on modelling or forecasting the spread of infections, but not on predicting the duration of outbreak turning period. The object of this paper is to fill this gap by answering when the outbreak of COVID-19 in each country or region will be under control or rounded. It is not difficult to realize that, regarding spread of any infectious disease, it is practically impossible and also unnecessary to predict the exact (turning) time point from which on the spread will become downward, since this time point is determined by too many factors of which we do not have full information. On the other hand, it is possible to use an SEIR type of models, e.g. the iSEIR model [28] to predict the turning time period – based on the observed data – during which both numbers of exposures (S) and infections (I) stop accelerating and become extinct at the end. This problem of predicting the turning time period is to be fully investigated for the COVID-19 outbreak in Wuhan, China, where the observed data from January 23, 2020 to February 6 (and February 10), 2020 are sufficient for obtaining an accurate prediction of the turning period. Based on these data we successfully predicted that the turning period of COVID-19 outbreak in Wuhan would arrive within one week after February 14.

2. Emergency Mechanism of Epidemic Prevention

The idea of the classic *SEIR Epidemic Model* can be traced back to Dr. Ronald Ross who received the Nobel Prize for Physiology or Medicine in 1902 for his work on malaria which laid the foundation for combating the epidemic disease (see [25]). In 1927, Kermack and McKendrick formulated a simple deterministic model called *SIR* to describe

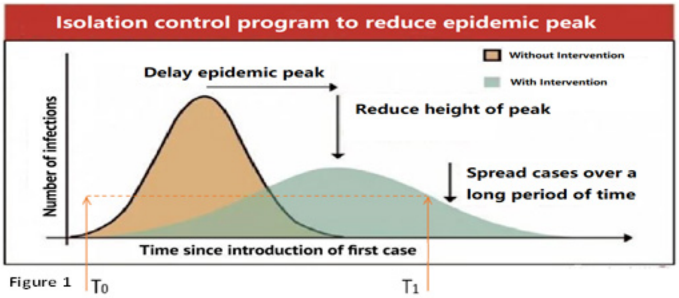


Fig. 1. The Isolation Control Program to Reduce Epidemic Peak

the dynamic mechanism for direct viral or bacterial transmissions/infections in a closed population (see [26]). Since then, a great deal of research have been made to advance this field. A milestone in this advancement is the publication of “The Mathematical Theory of Infectious Diseases” in 1957 by Bailey [27], following which the famous SEIR model (see Murray [38] and related literature there) has been developed as a core model for describing the mechanism of the spread of infectious diseases. Recall that in the SEIR model, S refers to the susceptible group (or ignorants) who are susceptible to disease but have not been infected yet; E refers to the exposed group who are infected but are not infectious yet (or lurkers); I refers to those infected who also become infectious; and R refers to those who have recovered from the infection (through treatment or natural recovery) who may or may no longer be infectious, or those who have passed away. Depending on the context, S, E, I and R may also be used to denote the numbers or proportions of the respective groups in the population.

2.1. Epidemic Prevention and Control via Emergency Management

Outbreak of an infectious disease may lead to serious consequences to various aspects of human society, threatening the safety of human lives and causing social upheaval and economic losses, etc. Preventing the spread of infection from evolving into an epidemic and restraining an epidemic from deterioration entail a comprehensive and responsive emergency management system of public health. Developing such a system faces a set of challenges: the unknown nature of the new pathogen/strain responsible for the infection, lack of immediate effective treatment and vaccine, and insufficiently prepared public health infrastructure to accommodate the surge of patients and testing needs. Massive governmental and societal engagement is required for supporting the public health sector to develop emergency planning and intervention strategies to combat the outbreak. Here we address three key issues pertaining to this practice:

1. How to use an individual SEIR model to describe the spatiotemporal mechanism of the spread of an infectious disease.
2. How to conduct numerical simulations based on the observed data so that the results can be used to accurately predict the turning phase (instead of turning point) of the infectious disease’s dynamics.
3. How to carry out the predictive analysis on the infectious disease’s dynamics on an ongoing basis, and then to implement the results into public health emergency plans/services and support the community’s combating the epidemic.

Figure 1 illustrates the effect of implementing an emergency intervention plan on delaying the peak arrivals of infections in combating the COVID-19 outbreaks. Thereby one can see a successful emergency plan lengthens the turning Phase (or turning time period $[T_0, T_1]$ so that the epidemic peak is much delayed (see [29], [30] and also [34]). Effective ways of flattening the curve include intervention actions such as social distancing, isolation and quarantine etc., see [33-35] and [36].

Therefore, a prerequisite for effective epidemic prevention and infectious disease control is to find a way to predict the *Turning Period* (or *Turning Phase*) effectively. Getting this done timely is crucial in combating the COVID-19 outbreaks.

2.2. The Framework of our iSEIR Dynamic Model with Multiplex Networks

For ease of discussion, we give an overview on the general framework of our iSEIR model introduced in [28]. Briefly, our iSEIR model operates under a probability perspective for each individual in the population and stands for the individual Susceptible-Exposed-Infective-Removed model, which is an extension of the classic SEIR one. The iSEIR model allows us to conduct simulations at the individual levels located on the nodes of different community networks so that the simulations are random, incorporating the uncertainty in the corresponding multiplex network.

For the iSEIR model, we use $S(t)$, $E(t)$, $I(t)$ and $R(t)$ to represent the proportions of individuals in the population C being in state S, E, I and R at time t, respectively, which satisfies $S(t) + E(t) + I(t) + R(t) = 1$ at each $t \geq 0$. We assume all individuals live in a multiplex network which consists of N communities, i.e., $C := \bigcup_{j=1}^{N} C_j$; and the N communities are partitioned into M domains, i.e. $C := \bigcup_{i=1}^{M} \mathbb{U}_i$. This implies $C = \bigcup_i \bigcup_j C_{ij}$ where C_{ij} refers to community j in domain i. As an example, C_{ij} may represent a household living in a residential district, and individuals in C_{ij} can be in any of the states S, E, I and R at time t. With these notations and considerations, the iSEIR model can be formulated of the following form:

$$\begin{cases} \dfrac{dS}{dt} = A - S(t)E(t)\sum_i \mu_i \sum_j p_{ij} - S(t)\sum_i \varepsilon_i \\ \dfrac{dE}{dt} = S(t)E(t)\sum_i \mu_i \sum_j p_{ij} - E(t)I(t)\sum_j \beta_j \sum_k q_{jk} - E(t)\sum_j \alpha_j \\ \dfrac{dI}{dt} = E(t)I(t)\sum_j \beta_j \sum_k q_{jk} - I(t)\sum_k \lambda_k \\ \dfrac{dR}{dt} = S(t)\sum_i \varepsilon_i + E(t)\sum_j \alpha_j + I(t)\sum_k \lambda_k. \end{cases} \tag{1}$$

The related parameters in the system (1) are interpreted as following:

A is the growth rate of new arrivals; μ_i is the transfer probability of an individual in domain i moving from state S to state E; p_{ij} is the contact probability between two individuals in community j of domain i who are in state S and E respectively; p_{ij} equals 1 if the two individuals have contact, and 0 if not; ε_i is the transition (removal) probability of an individual in domain i moving from S to R; β_j is the transfer probability of an individual in domain j moving from E to I; q_{jk} is the contact probability between two individuals in community k of domain j who are in state E and I respectively; q_{ij} equals 1 if the two individuals have contact, and 0 if not; α_j denotes the transfer probability of an individual in domain j moving from E to R; and λ_k denotes the transfer probability of an individual in domain k moving from I to R.

The parameters $\varepsilon, \mu, \beta, \alpha$ and λ introduced in (1) above give the various population-level effects manifested in the network of individuals subject to a disease infection. These effects can be regarded as aggregations of the corresponding domain-community level effects and cross-states effects in the dynamics of an infectious disease outbreak.

3. The Framework for the Prediction of the Critical Turning Phase

As previously discussed, for epidemic prevention from and control over infectious disease outbreak, it is crucial to apply effective intervention measures in early stage of the outbreak. This is facilitated by identifying the beginning and ending points of the time interval which forms the *Turning Time Period* (*Time Period*), This then informs us how long the emergency protocol is expected to be taken to flatten the infection curve. Predicting the turning time period can be achieved by using the iSEIR model, the effectiveness and reliability of which are ensured by the model's *Supersaturation Phenomenon* (see [28] for detail).

3.1. Term Structure for the "Turning Time Period (Turning Period)"

While the exact turning time point (or critical turning time point) for any infectious disease spread cannot be precisely determined due to various dynamics and associated uncertainty, by borrowing the variables of "Delta" and "Gamma" practiced in financial risk management (see Hull [37]) it is possible to identify the upper and lower limits of the turning period using, for example, the instantaneous changes in daily infection cases predicted from the iSEIR model. These indicators then allow us to identify the different phases and stages of an infectious disease outbreak, which are elaborated in Part A and Part B below.

Part A: Identifying Different Time Phases of an Infectious Disease Epidemic

We propose to identify three phases (time periods) in regard to applying emergency measures to tackle the outbreak of an infectious disease in communities.

1. *Phase 1*. This is the starting stage spanning from the emergence of sporadic infections until a precursory outbreak. An emergency management system for tackling the outbreak should be established and ready for implementation by the end of this stage.
2. *Phase 2*. In our viewpoint, this is the most important phase which is the so-called *First Half-Time Phase* otherwise known as the *Turning Phase* (or *Turning Period*). It starts from the precursory outbreak (T_0 in Figure 1 or 2) until the epidemic peak. The epidemic peak would arrive very quickly in an explosive rate, if no intervention measures are taken; but can be substantially delayed with significantly suppressed magnitude if interventions are applied timely. The First Half Time phase involves the "Delta'" and "Gamma" indicators (elaborated in Part B below) to measure the daily change in number of new infections (i.e., "Delta"), and the rate of the daily change in number of new infections (i.e., "Gamma").
3. *Phase 3*. During this stage, the epidemic enters the so-called *Second Half -Time Phase* (starting from the epidemic peak until T_1 in Figure 1 or 2), which means the epidemic peak is gone and the rate of spread is under greater control. This is measured by a continuously decreasing rate of new infections per day, which ultimately leads to any but not exclusively of the following scenarios: a): the disease completely disappears; b): an effective vaccine/treatment is introduced; and c): the strain could also disappear and reappear cyclically in seasons, or other reasons.

Of the three phases, the most important time period to identify is the beginning and the peak time points of the First-Half Phase (known as the *Turning Period*). This phase is crucial to controlling the outbreak and managing the spread of an infectious disease epidemic. Thus, being able to identify the *First Half-Phase* is crucial for the reliable prediction of the *Turning Period* (or *Turning Phase*) as the ending time point of the Turing Period will allow us to predict when the outbreak of the infectious disease is under the control by the level we may settle (incorporating with ability and capability in the practice).

Next we address how to identify or predict this Turning Period in practice. In order to determine the Turning Period, we make use of the timing of the so-called *Supersaturation Phenomenon* (see [28-31, 34]) which can be obtained based on the trajectory of $S(t), E(t), I(t)$ and $R(t)$ that are simulated by our iSEIR model and the observed data in Phase 1. The time T_1 is defined as the starting moment of *Supersaturation Phenomenon*. In practice, T_1 is estimated as the time moment from which on $E(t)$ and $I(t)$ both start to decrease, see Figure 3 for illustration.

Part B: Predicting the Turning Period by using the iSEIR Model and the Delta and Gamma Risk Indicators

We suggest that, before COVID-19 outbreak leaves its Phase 1, we use the Delta and Gamma indicators to measure daily changes of new patients and the change rate of the daily changes. These measurements will allow us to identify the beginning point T_0 of the turning time interval period. For example, to identify T_0 in China's COVID-19 outbreak, we set the threshold level for Delta to be no greater than 20% daily; and for Gamma to be no larger than 1% daily.

Next, to predict the future ending time point T_1 of the Turning Period, which measures when the epidemic disease spread is under control, we run numerical simulations of our iSEIR model as shown in Figure 3. Note that T_1 is determined to be the time point from which on both variables $E(t)$ and $I(t)$ start to drop.

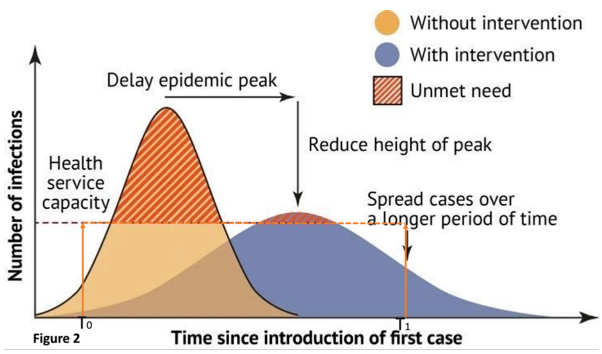
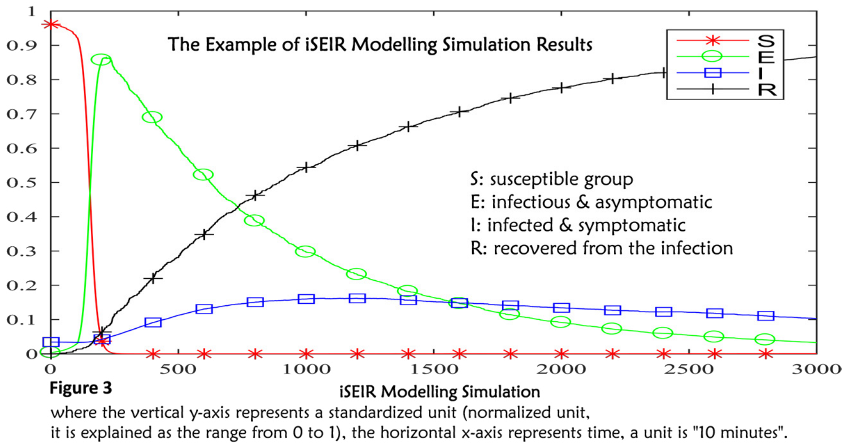


Fig. 2. The Concept of the Term Structure for Turning Period instead of Turning Point

Parts A and B together have allowed us to reliably predict the Turning Period of COVID-19 since its first case in Wuhan of China in late December 2019. Using the data released by the National Health Commission of China over the period of time until February 10, 2020, we correctly assessed that "COVID-19 would peak in around mid- to late February, and enters in the Second Half Period on around February 20, 2020" (see our report [31] which is validated by reports [34] and [35]).

To further understand our predictive simulation, we briefly describe our iSEIR model and the related *Supersaturation Phenomenon* in the next section.



3.2. *The iSEIR Model as a New Tool to Accommodate the* "*Supersaturation Phenomenon*"

Most SEIR type of models for depicting the epidemic mechanism of an infectious disease are established under deterministic frameworks which assume that all individual behaviors and patterns are not randomly varying. But this is not realistic as each individual's behavior of infecting or being infected is related to too many factors that cannot be accurately specified by a deterministic framework. In order to feasibly describing the dynamics of epidemic in a multiplex network of individuals in a population, we resort to use the iSEIR model (1) (see Yuan et al. [28] for more in details) where the parameters account for the randomness involved in individuals' behaviors in the multiplex network. The trajectory of $S(t)$, $E(t)$, $I(t)$ and $R(t)$ can be simulated from the iSEIR model with properly specified values of the parameters and the observed data of daily infections. Figure 3 illustrates the result of a typical simulation from the iSEIR model.

The simulation results based on the iSEIR model suggest that the intensity and extensiveness of the spread of the disease can be lowered by external intervention under a so-called *Supersaturation Phenomenon*. This phenomenon starts to occur at some time point in the future (i.e. T_1) when both $E(t)$ and $I(t)$ start to drop in value and do not increase anymore. From Figure 3, $T_1 \approx 1500$ time units, suggesting the *Second Half-Time Phase* is to conclude at about 1500 time units.

4. Predicting the "Peak Period" of COVID-19 in China as Being Early February 2020

The methodology outlined above is what we have used when modeling a disease epidemic, including COVID-19 outbreak which has become a global pandemic since the case firstly detected in Wuhan in late December 2019. Taking into consideration that the emergency lockdown measure was enforced in Wuhan (i.e., Wuhan quarantine program in Hubei province; see [35]) since January 23, 2020 and in other regions of China with different levels of variation, we predicted the *Peak Period* of COVID-19 in China using our iSEIR model and *Turning Time Period* framework in two separate reports on February 7 and 11, 2020, respectively (see [29-35]). The results are summarized in the following.

4.1. The "Turning Period" of COVID-19 in China Started on February 1, 2020

We use the two concepts "Delta" and "Gamma" called Greek Letters that are used in financial risk management: "Delta" measures the daily change of both "E" and "I"; and "Gamma" accounts for the speed of the daily change for the number of new confirmed cases of both "E" and "I". In order to predict the Turning Phase for COVID-19 in China, we need to first identify the starting point, i.e. T_0, of the outbreak's *Turning Period*.

By using the daily observations from January 23, 2020, to February 6, 2020, we first observed that "Delta" and "Gamma" were below 20% and 2% daily, respectively, for 5 consecutive days since February 1,2020, leading us to conclude that February 1, 2020 heralds the start of a precursory outbreak, with the following conclusion (see [29] for more details).

Conclusion A. February 1, 2020 started the precursory outbreak of COVID-19 in China (including Wuhan, Hubei); namely, started the *Turning Period* of China's COVID-19 outbreak (see report [29] released on February 7, 2020). This is verified by the official daily data released by NHC of China on February 28, 2020 (see also reports [31-34]). Indeed, from Table 1 below, we see that Delta and Gamma are below 20% and 2% respectively for 5 consecutive days since February 1, 2020. This concludes that February 1 is the starting point of the precursory outbreak.

Table 1: The Daily Change of Infected COVID-19 Patients by The National Health Protection Committee of China from Feb. 1 to Feb. 6 2020

Times	Feb.01/2020 Turning point	Feb.02/ 2020	Feb.03/ 2020	Feb.04/ 2020	Feb.05/ 2020	Feb.06/ 2020
COVID-19 Infected Patients in Hubei	9,074	11,177	13,522	16,678	19,665	22,112
COVID-19 Infected Patients in rest of China	5,306	6,028	6,916	7,646	8,353	9,049
China COVID-19 Infected Patients in China	14,380	17,205	20,438	24,324	28,018	31,161
Delta: Daily Change of COVID-19 Infected Patients in Hubei	27%	23%	21%	23%	18%	12%
Delta: Daily Change of COVID-19 Infected Patients in rest of China	14%	14%	15%	11%	9%	8%
Delta: Daily Change of COVID-19 Infected Patients in China	22%	20%	19%	19%	15%	11%
Gamma: Speed of Daily Change of COVID-19 Infected Patients in Hubei	16%	-14%	-9%	11%	-23%	-31%
Gamma: Speed of Daily Change of COVID-19 Infected Patients in rest of China	-25.6%	-2.8%	8.3%	-28.3%	-12.4%	-9.9%
Gamma: Speed of Daily Change of COVID-19 Infected Patients in China	1%	-11%	-4%	1%	-20%	-26%

4.2. *COVID-19 outbreak in China Predicted to Peak around Mid- to late-February 2020*

Using the concept of Turning Phase and the application of the iSEIR model on February 10, 2020, based on 3 weeks of available daily data (from January 23 to February 10,2020) released by NHC of China, our simulation successfully predicted the trajectory of the outbreak in the following 3 weeks, see reports [29-30]. It amounts to the following conclusion.

Conclusion B. Given that the lockdown program was enforced since January 23, the COVID-19 outbreak in China would peak on around mid-February and no later than the end of February. This conclusion was obtained by applying the iSEIR model and the conceptual *Supersaturation Phenomenon*, with the details illustrated in Figure 4 and Table 2 where we see:

1. The number of infected and asymptomatic cases $E(t)$ reached the peak in about 2 days after February 10, 2020; and then after about 7 days (i.e. February 17, 2020), the rate of increase in $E(t)$ decreased to less than 10%;
2. The daily increase in the number of infected and symptomatic cases $I(t)$ was of a steady downward trend, and the rate of increase in $I(t)$ decreased to within 10% after about 14 days (Feb. 24, 2020);
3. The proportion of people recovering from infection ($R(t)$) returned to more than 80% after about 17 days (i.e. February 27, 2020).

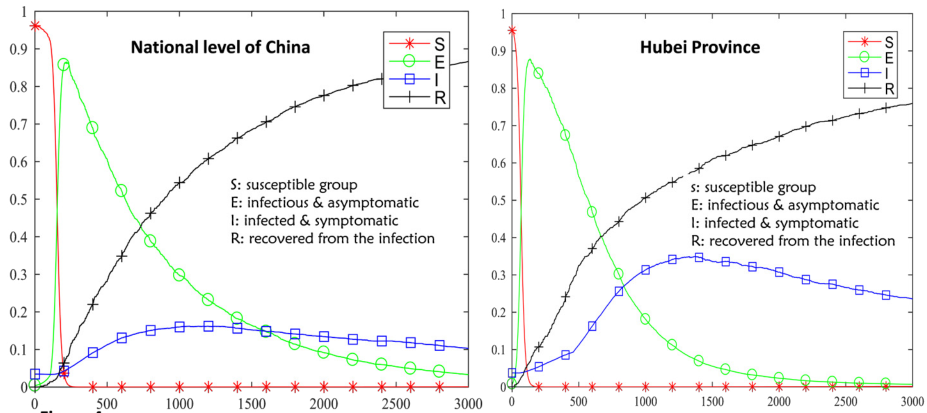


Figure 4 **The simulation results by iSEIR model on data of Feb/10/2020**
where the vertical y-axis represents a standardized unit (normalized unit, it can be explained as the range from 0 to 1), the horizontal x-axis represents time, one unit is "10 minutes".

The above results are found to conform very well to the actually observed data from the National Heath Commission (NHC) of China. Specifically, the daily official data show that February 11, 2020 is the peak time with its Delta value achieving 5.4% daily, the highest one from February 1 through to February 25. This corroborates our prediction that around February 12, 2020 achieves the outbreak peak based on our iSEIR model.

5. Concluding Remarks

We demonstrate that the "Term Structure" approach, consisting of the concepts of "Turning Phase" and "Supersaturation Phenomenon" and the iSEIR model, is an effective and reliable one for predicting the Turning Period of COVID-19 epidemic, where the effects of implementing emergency intervention measures can also be systematically accommodated. We want to reinforce that emergency risk management is always associated with timely implementation of an emergency plan. And identification of the Turning Time Period is key to effective emergency planning as it provides a timeline for timely risk-mitigating actions and solutions in combating the COVID-19 pandemic.

Table 2: The Daily Data of COVID-19 China

Item	2020/2/19	2020/2/18	2020/2/17	2020/2/16	2020/2/15	2020/2/14	2020/2/13	2020/2/12	2020/2/11	2020/2/10	2020/2/9	2020/2/8	2020/2/7
The number of Close contracts under the monitor in hospital(*more likely E in SEIR Model, Infectious*)	126,363	135,881	141,552	150,539	158,764	169,039	177,984	181,386	185,037	187,728	187,518	188,183	189,660
Its Delta	-7.0%	-4.0%	-6.0%	-5.2%	-6.1%	-5.0%	-1.9%	-2.0%	-1.4%	0.1%	-0.4%	-0.8%	1.9%
Its Gamma	74.8%	-32.9%	15.2%	-14.8%	20.9%	168.0%	-4.9%	37.6%	-1380.0%	-131.7%	-54.6%	-140.1%	-1271.8%
The number of Close contracts(*more likely S in SEIR Model, Susceptible*)	589,163	574,418	560,901	546,016	529,418	513,183	493,067	471,531	451,462	428,438	399,487	371,905	345,498
Its Delta	2.6%	2.4%	2.7%	3.1%	3.2%	4.1%	4.6%	4.4%	5.4%	7.2%	7.4%	7.6%	10.0%
Its Gamma	6.5%	-11.6%	-13.0%	-0.9%	-22.5%	-10.7%	2.7%	-17.3%	-25.8%	-2.3%	-3.0%	-23.7%	-9.2%

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