Prediction of curve flattening time for COVID-19 infected countries using trends from recovered countries

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Research Article

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1. Introduction

At the beginning of the year 2020, the world was unaware that a serious threat to the mankind would appear in near future due to a virus that originated in Wuhan, the capital city of Hubei province of the People's Republic of China in December 2019 [1]. Initially, this deadly virus was named "2019-nCoV" (2019 novel coronavirus). Later, it was renamed to "SARS-CoV-2" (severe acute respiratory syndrome coronavirus 2) on account of its similarity to the earlier SARS-CoV [2]. Since its outbreak, the virus has been spreading all across the world rapidly and thus, COVID-19 has been among the worst pandemic in the history of mankind. As of 9 May 2020, more than 3.8 million positive cases and 265,000 deceased cases have been reported [3]. In view of this, the World Health Organisation (WHO) has already declared the COVID-19 as a worldwide pandemic on 11 March 2020.

Since the outbreak of COVID-19, the researchers have engaged themselves in developing drugs for SARS-CoV-2 treatment. Primarily, chloroquine and hydroxychloroquine, drugs used for the treatment of malaria are under investigation as a treatment for COVID-19 virus [4]. It has also been reported that the vaccine for this virus may only be available at the end of the year 2020 [5] or in mid-2021 [6]. Additionally, this virus transmits efficiently even with indirect contacts among the infected persons. In a situation like this, staying at home and lockdown seems to be the only solution at the moment which every economy across the world can afford. However, the lockdown has adversely hit the world economy [7], [8] and the psychological health of the people [9]. Looking at the ever-increasing number of infections, the countries across the world have been extending the lockdown period. The common mass is waiting for the end of COVID-19 pandemic so that the countries move out of the lockdown and the people may resume activities for their livelihood. To address the need of the current situation, this paper is an attempt to estimate the date on which the countries across the world would probably recover from COVID-19.

With the outbreak of COVID-19, the researchers have shown interest in developing the prediction model of the pandemic curve. Every pandemic (or epidemic) is characterised by a typical sigmoid curve [10] which flattens at the end indicating the pandemic-free situation. The models generally used to predict the pandemic situation mainly attempt to fit these curves. A recent work presented in [11] shows 30 days ahead prediction of positive cases in India using a deep learning method, long short-term memory (LSTM). However, in the field of mathematical epidemiology, the susceptible-infectious-recovered (SIR) model is a reliable and paradigmatic model [12] which was developed by Kermack and McKendrik [13]. In the SIR model, the entire population is divided into susceptible (S), infected (I) and recovered (R) count of individuals [14]. A case study using the SIR model to predict the number of cases in India has been done in [15]. It is predicted that the number of cases in India on 20 April 2020 under severe lockdown condition (70%) will be around 30000. However, the actual number was around 17000 on 20 April 2020. This clearly shows that the SIR model has limitations on account of factors like additional outbreak and degree of lockdown.

The well-known SIR model prediction results on COVID-19 have been updated daily by the Data-Driven Innovation (DDI) Laboratory of Singapore University of Technology and Design (STDU) under an independent project "Predictive Monitoring of COVID-19" [16]. The DDI Lab. updated the probable end date of COVID-19 daily based on the latest available data sets on "Our World in Data" [17]. However, the project has been internalized as of 11 May 2020. The DDI Lab. used the SIR algorithm proposed recently by Milan Batista [18] for COVID-19. Another forecast and analysis related to the spreading of COVID-19 in China, Italy, and France have been done recently using the SIR model [19]. The SIR model required three sets of data (susceptible, infected and recovered data). Additionally, these methods (both SIR and LSTM), however, are meant to be understood by the experts of the area while the effect of the COVID-19 has been seen all across communities around the world. In view of these, this paper presents an approach to estimate the curve flattening time for COVID-19 which is easy to be understood by a larger section of the community and uses the least amount data.

The proposed work fits the pandemic curve by a suitable order polynomial model. The gradients of these curves are captured from the countries which are almost out of the COVID-19 situation (recovered). With a simple "learn-from-other" approach, the most suitable simulated trend from the list of recovered countries is identified and then patched-up with the trend of the infected country to obtain the decline time of the curve. This approach utilizes only the per day count of infected individuals. Further in Section 2, the details of the data used in this work have been described. The adopted methodology has been detailed in Section 3. In Section 4, the prediction results have been presented and discussed which is followed by the conclusion in Section 5.

2. Data sets

As mentioned in Section 1, this work uses only one data set for each country, i.e., the number of infected persons per day. The work presented by DDI Lab. of STDU [16] which has been discussed earlier uses the daily data (susceptible, infected and recovered data) from the "Our World in Data" [17]. This work also uses the same data (only infected data) so that comparisons may be done at a later stage. The counts of infected individuals sampled per day have been collected for 43 major countries. The starting date of the count is from 31 December 2019 when 27 infected individuals were recorded for the first time in China. The data set for 130 days till 8 May 2020 has been used for analysis in this paper. Looking at the current situation and as reported by WHO till date, five countries have been considered in this work as “COVID-19 recovered countries (CRC)” while rest of the countries have bee listed under “COVID-19 infected countries (CIC)”. The list of CRC includes China, Iceland, New Zealand, South Korea, and Australia.

3. Methodology

3.1 Development of the polynomial model

The polynomial models are very elementary mathematical models used for curve fitting application. The first-order polynomial model starts with a straight line representation. The second and third-order polynomials are used to fit the parabolic and the cubic plane curves, respectively. Therefore, the order of the polynomial may be further increased to model more complex curves. This work uses the polynomial function of higher-order to model the curve of the pandemic curve of COVID-19 for various countries. Let us assume that $F(t)$ is the required polynomial model with respect to time (t). The general equation of polynomial of n^{th} order is given by Eq. (1).

$$F(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + \cdots . + a_n t^n \quad (1)$$

where $[a_0,\ a_1,\ a_2,\ \ldots,\ a_n]$ is the vector of unknown coefficients. The estimation of coefficients of a polynomial function to fit a curve is among the simplest of the optimization problems. These parameters have been estimated using the curve fitting toolbox of MATLAB (2017a). The order of the polynomial function has been estimated iteratively. When the simulated curve follows the path close to that of the actual curve, the model is said to perform better. The measure of model performance is represented here by the root mean square error (RMSE) criterion calculated by Eq. (2).

$$\text{RMSE} = \frac{1}{N} \sum_{1}^{N} \sqrt{(I_A - I_M)^2} \quad (2)$$

where, I_A= actual number of infected individuals on a given day, I_M= modelled (simulated) number of infected individuals on a given day, N= number of days considered for calculation. The calculation of the RMSE values for simulate curves has been done for all 43 countries which are presented and compared with an existing method at a later stage in this paper.

3.2 Estimation of gradient and curve flattening date

As soon as the polynomial model given by $F(t)$ is obtained, the rate of change of the function (derivative) is plotted with time which gives the numerical values of the number of new cases per day. In Fig. 1, the new cases/per day has been shown for China as an example of a typical CRC. The blue bars show the actual rate of new cases on the given day while the orange line is the predicted rate using the polynomial model. The maximum cases/day (peak rate) shown by the model for a CRC is denoted by I_r. It may be noted that the maximum number of new cases (peak rate) was abruptly very high in China (on 13-02-2020) which came normal the next day. This explains the reason why the modelled I_r is used in this work to avoid any outliers which may severely affect the results. The symbols used in this work have been explained in Table 1 for clarification.

With reference to Fig. 1, D_{pr} is the day (date) on which the rate of new cases was maximum for a given CRC. Also, D_r represents the day of recovery for all the CRCs which is 130 days as of 8 May 2020 (calculated from 31 December 2019). The three points I_r, D_{pr},

Table 1 Symbols used in this work

Symbol	Details
I_r	Maximum cases/per (peak rate) in a COVID-19 recovered country (CRC)
D_{pr}	Day (date) on which the peak rate was observed in a CRC
D_r	Day (date) of recovery from pandemic for CRCs
D_i	Day (date) of recovery from pandemic for a COVID-19 infected country (CIC)
I_i	Maximum cases/per (peak rate) in a CIC
D_{pi}	Day (date) on which the peak rate was observed in a CIC

and D_r are joined to form a right-angled triangle as shown in Fig. 1. The gradient (slope) of the triangle is given by Eq. (3).

$$\tan \theta_r = \frac{I_r}{D_r - D_{pr}} \quad (3)$$

$$\tan \theta_r = \frac{I_r}{130 - D_{pr}} \quad (4)$$

Now the gradient ($\tan \theta_r$) of a suitable CRC (explained further in section 3.3) is used to track the trajectory of the rate of new cases for a CIC. And ultimately, this would help to evaluate the number of days (D_i) that a CIC would take for recover from COVID-19. The rate of new cases per day for a typical CIC has been exemplified using the plot of new cases/day for India in Fig. 2. Here, the gradient $\tan \theta_r$ from China (a CRC) has been used as the slope for the triangle shown in Fig. 2 under the assumption that both these countries follow the same trends after they reach the peak rate. With I_i and D_{pi} being the peak rate of new cases and its day of occurrence, respectively, the relation between $\tan \theta_r$ with these parameters of the triangle shown in Fig. 2 is given by Eq. (5).

$$\frac{I_i}{D_i - D_{pi}} = \tan \theta_r \quad (5)$$

$$D_i = D_{pi} + \frac{I_i}{\tan \theta_r} \quad (6)$$

The value of D_i from Eq. (6) will give the number of days that an infected country (CIC) would take to recover from COVID-19. The curve flattening date (CFD) may, therefore, be calculated by adding D_i to the date 31-12-2019 when the pandemic started. Therefore, the CFD is represented by Eq. (7).

CFD= D_{pi} + [31-12-2020] (7)

3.3 Selection of reference COVID-19 recovered country (CRC)

It is assumed that the infected countries follow the trend of at least one of the recovered country from the list of CRC. The trend of the two counties may be compared based on the overall number of infected population, peak rate of cases/day, and particularly the trends before reaching the peak rate. Therefore, the peak rate day D_{pr} and D_{pi}, are identified for all CRC and CICs, respectively and the correlation coefficients are calculated for the previous 30 days from there. These correlations give an idea of how similar the raise characteristics of cases/day of the two countries were before reaching the peak. On this basis, the reference CRC which has a maximum correlation with an infected country (CRC) is selected. However, the correlation criteria may fail on account of multiple outbreaks in a country. The large difference in the population may also give insignificant results. Alternate selection criteria may be required in the countries where the infected population count is relatively less. Nevertheless, the priority in the selection of reference CRC is given to the correlation; else, the overall count of the infected population (as of 8 May 2020) is considered. In this alternative situation, that reference CRC is selected whose overall count of the infected population is close to that of the given CIC.

4. Results and discussion

4.1 Performance analysis of the proposed method

The results of the polynomial model to fit the COVID-19 pandemic curve for 43 countries have been presented here. The orders of the polynomial (Eq. (1)) were identified as iteratively to achieve a maximum fit between the actual and simulated curve. A higher-order polynomial was expected as the curves being modelled have typical epidemic dynamics. These dynamics include sudden or multiple outbreaks, initial no-epidemic zone, sudden flattening dynamics towards the end, and other local and global variables. In Fig. 3, the

Table 2 The RMSE values obtained from the proposed method and the SIR model for various countries to fit the COVID-19 pandemic curve

Countries	Polynomial order	RMSE (proposed model)	RMSE (existing SIR model)
Argentina	24	22	234
Australia	26	39	116
Austria	26	53	344
Belgium	26	166	719
Brazil	25	286	1384
Canada	22	108	1131
China	26	1032	1540
Croatia	27	7	37
Czech Rep.	26	33	257
Denmark	25	37	280
Estonia	25	15	42
Finland	26	25	160
France	26	542	1485
Germany	24	548	2361
Greece	23	17	48
Hungary	26	17	51
Iceland	28	8	17
India	22	77	865
Indonesia	24	26	371
Iran	26	290	2483
Italy	26	330	10455
Japan	24	101	575
Latvia	25	5	54
Lithuania	27	13	63
Netherlands	29	98	1246
New Zealand	27	6	15
Norway	26	37	191
Poland	28	33	699
Portugal	22	113	509
Romania	25	37	723
Russia	22	193	2138
Serbia	27	31	129
Singapore	24	85	289
Slovakia	26	13	44
Slovenia	29	9	28
South Korea	27	63	420
Spain	30	647	3354
Sweden	26	71	744
Switzerland	26	94	364
Turkey	28	235	4076
Ukraine	22	86	231
UK	21	435	3205
USA	22	2213	22488

comparison of actual and simulated epidemic curves has been shown for two CRCs (Fig. 3 (a) and Fig. 3 (b)) and three CICs (Fig. 3 (c) to Fig. 3 (e)). The model shows a very promising fit which is represented in terms of the RMSE calculated using Eq. (2). In the case of China (Fig. 3 (a)), there is a slight misfit between simulated and actual curve around 13-02-2020. This is due to an abrupt increase in new positive cases on that day which was never observed after that. The RMSE is expressed in terms of the number of infected cases. The RMSE shown by the model for China, Iceland, Germany, India, and Switzerland is 1.23%, 0.44%, 0.33%, 0.14%, and 0.31% of the overall number of infected people, respectively. The comparisons between actual and simulated curves in Fig 3 show that the modelling approach is valid for all countries irrespective of the count of infected people. The model also holds good for the infected countries (CICs) as well as for the recovered countries (CRCs).

In Table 2, the RMSE values for all the countries have been shown and compared with that of the conventional SIR model [16], [18]. The proposed model in this work shows reduced RMSE values for all the countries without exception. The polynomial model was able to perform well using only one set of data (infected data) while the SIR model required three data sets (susceptible, infected, and recovered date) for each country. Therefore, the proposed model not only gave a better fit but also proved to be data efficient compared with the existing technique of modelling.

4.2 Prediction of curve flattening date (CFD)

As mentioned earlier, the proposed model for each country is simulated and the corresponding rate cases/day is evaluated. The observed peak infected count rate (I_r and I_i) and the peak day (D_{pr} and D_{pi}) for all the countries are also calculated using the approach mentioned in Section 3.2. The values of gradient parameters (I_r and D_{pr}) for all the

Table 3 Calculated gradient parameters for reference CRCs

Candidate for reference CRCs	I_r	D_{pr}	Gradient ($\tan\theta_r$) = $\frac{I_r}{130-D_{pr}}$
Australia	390	87	9.29
China	4502	42	51.75
Iceland	71	89	1.78
New Zealand	70	89	1.75
South Korea	608	62	9.07

candidates for reference CRCs are listed in Table 3. The gradient ($\tan\theta_r$) shown in Table 3 is calculated using Eq. (4).

The selection of appropriate CRC is the next step which is based upon the dual criteria of correlation and the overall count of infected people in the country. The correlation of cases/day between a CIC and the CRCs are calculated for the duration mentioned earlier. Once the reference CRC is decided based on correlation and the gradient is made available, the value of D_i may be calculated using Eq. (6). Further, the CFD may be estimated using Eq. (7) which gives the date on which the curve of COVID-19 is supposed to get flatten. If the date calculated by the first criteria looks absurd due to the constraints mentioned previously, the overall count of infected people may be considered to the finalise the reference CRC. The date may be calculated again by using Eq. (7). Nevertheless, the correlation coefficients of the finalised reference CRC with all individual countries (CICs) are reported in Table 4 along with the overall count of the infected population.

In Table 4, the criteria used for the selection of reference CRC has been written in parentheses. For instance, Australia is found as the reference CRC for Argentina. This was decided on the basis of the overall count of the infected people. Therefore, the count (5358) has been put inside parentheses for clarification. For all the countries (CIC), the number of days (D_i) that it would take to recover from the pandemic has also been shown in Table 4. The estimated dates (CFD) on which the COVID-19 curve is supposed to get flattened have been mentioned for all these countries. For comparison, the dates estimated using the SIR model as of 8 May 2020 has also been shown.

Table 4: Estimated date of COVID-19 curve flattening for various countries reported based on data obtained till 8 May 2020

Corona infected countries (CIC)	Criteria used for selection of reference CRC		Reference CRC	D_i	Proposed CFD	CFD as per existing SIR model	Average cases/day reported in last 1 week
	Correlation	Infected people					
Argentina	0.5698	(5358)	Australia	148	27-05-2020	15-09-2020	140
Austria	(0.9941)	15673	Australia	170	18-06-2020	10-05-2020	36
Belgium	0.5373	(51420)	South Korea	260	16-09-2020	15-06-2020	398
Brazil	(0.9311)	135106	China	326	21-11-2020	01-09-2020	7253
Canada	(0.7942)	64922	China	162	10-06-2020	15-07-2020	1644
Croatia	0.9441	(2125)	Iceland	132	11-05-2020	01-06-2020	7
Czech Rep.	0.9061	(8031)	Australia	123	02-05-2020	01-06-2020	49
Denmark	(0.9839)	10083	New Zealand	281	07-10-2020	10-07-2020	129
Estonia	0.8947	(1720)	Iceland	128	07-05-2020	01-06-2020	4
Finland	-0.4129	(5673)	Iceland	233	20-08-2020	01-08-2020	104
France	(0.9853)	137779	China	177	25-06-2020	01-06-2020	1266
Germany	0.9787	(167300)	China	198	16-07-2020	01-06-2020	933
Greece	(0.8280)	2678	New Zealand	141	20-05-2020	01-06-2020	15
Hungary	0.8967	(3178)	Iceland	158	06-06-2020	01-07-2020	39
India	(0.9557)	56342	China	194	12-07-2020	01-08-2020	3168
Indonesia	0.5866	(12776)	South Korea	174	21-06-2020	01-08-2020	371
Iran	0.9297	(103135)	China	151	30-05-2020	01-07-2020	1248
Italy	(0.9910)	215858	China	197	15-07-2020	01-07-2020	1405
Japan	0.9634	(15547)	South Korea	175	23-06-2020	07-06-2020	167
Latvia	0.9429	(909)	New Zealand	107	16-04-2020	10-06-2020	7
Lithuania	0.9971	1433)	Iceland	124	03-05-2020	01-06-2020	6
Netherlands	0.5464	(41774)	South Korea	229	16-08-2020	20-06-2020	331
Norway	0.8749	(7995)	Australia	120	29-04-2020	01-06-2020	39
Poland	-0.6631	(15047)	South Korea	169	17-06-2020	01-08-2020	324
Portugal	0.8775	(26715)	South Korea	182	30-06-2020	15-06-2020	227
Romania	-0.2949	(14499)	South Korea	170	18-06-2020	01-08-2020	322
Russia	(0.9508)	177160	China	342	07-12-2020	10-07-2020	10455
Serbia	0.8662	(9848)	South Korea	152	31-05-2020	15-06-2020	107
Singapore	(0.9981)	20939	Australia	223	10-08-2020	15-06-2020	640
Slovakia	0.8969	(1445)	New Zealand	144	23-05-2020	01-07-2020	7
Slovenia	0.7113	(1449)	New Zealand	119	28-04-2020	01-06-2020	3
Spain	(0.9860)	221447	China	250	06-09-2020	01-06-2020	811
Sweden	-0.0638	(24623)	South Korea	216	03-08-2020	15-08-2020	517
Switzerland	0.9254	(30043)	South Korea	209	27-07-2020	20-05-2020	70
Turkey	(0.9808)	133721	China	193	11-07-2020	15-06-2020	1888
Ukraine	0.4206	(13691)	South Korea	195	13-07-2020	01-07-2020	380
UK	-0.2070	(206715)	China	254	10-09-2020	01-07-2020	4877
USA*	(0.9874)	1256972	China	712	11-12-2021	01-07-2020	25532

As per the results shown in Table 4, Argentina, Iran, Serbia, and Slovakia could be virus-free by the end of May 2020. However, according to the SIR model, the CFD for Slovakia is at the beginning of July 2020 even though the average number of cases being reported per day in last 1 week is only 7. The proposed result for Serbia and Argentina seems reasonable as per the current situation. However, the CFD for Iran looks better with the SIR model which is around 1 month ahead of the predicted CFD. As per SIR model, Austria has arrived at the CFD but still, 36 new cases per day are being reported on an average. The proposed model has predicted the CFD as 18-06-2020 for Austria. The predicted dates for Croatia and Hungry by the SIR model also seem to be ahead as per the current situation and number of new cases per day. In countries like Estonia, Greece, Lithuania, and Slovenia, the situation is very much under control as of 8 May 2020 which is shown by the proposed model as well. But the SIR model says that these countries have one more month to get recovered from the COVID-19 situation.

Highly infected countries such as France, India, Italy, Spain, and Turkey show a strong correlation in trends with China till date. By observing the average new cases per day, all these countries may take more time than predicted time by the SIR model. In India, on account of the relatively low number of total infections and severe lockdown condition, the situation should be under control by the middle of July 2020. Canada, on the other hand, shows relatively less correlation in trends with that of China which probably has impacted the proposed results compared to that of SIR model. The SIR model has predicted 01-09-2020 as the CFD for Brazil. However, with more than 7000 new cases on an average over the last 1 week, the proposed CFD (21-11-2020) for Brazil should not be overlooked. The case of the UK should be treated similarly.

The pandemic rate curve for some countries does not exhibit trends similar to any of the CRCs. This is reflected by their negative correlation. In such cases, the correlation was not considered as a criterion for the selection of suitable CRC. For Finland and Sweden, as per to the proposed method and the SIR model, the pandemic should end in August 2020. In Russia, more than 10000 new cases are being reported on an average. In this situation, the CFD of 10-07-2020 predicted by the SIR model seems to be very much earlier. The USA* follows the trend of China with a correlation of 0.9874. On account of a huge infected population and more than 25000 average new cases being reported daily, the CFD (01-07-2020) predicted by SIR model should not be taken for granted. However, the proposed model also failed to estimate a reasonable CFD in case of USA for similar reasons.

The prediction results of the proposed method show some good logical CFDs for various countries compared to that of SIR model predictions. It should be emphasised that the idea of identifying a suitable reference CRC is justified in most of the cases. The method, however, does not predict the number or rate of infections in future, but a good estimate of the CFD has been seen in the results. At the same time, the model produced some over-estimated and under-estimated results especially in case of USA. This drawback may be understood with the fact that the method doe not used the number of recovered cases and the number of susceptible people around. Still, the proposed method gives a simple way to find the probable date of curve flattening which is supposed to be understood by the audiences from all academic backgrounds.

5. Conclusion

The proposed method clearly outperforms the curve fitting produced by the SIR model with a substantial margin of in RMSE. Unlike the SIR model, this work is data-efficient as it uses only the count of infected individuals. The gradient-based approach in this work successfully captured the trends of the countries which are almost out of the pandemic to estimate of curve flattening time for the infected countries. The predicted CFD using this approach is noteworthy when compared with that of the existing SIR model. It is important to note that the presented results hold good only for the data used in this work and are supposed to be affected by the real-time changes. This paper should be used only to understand and estimate the characteristic of the COVID-19 outbreak. Therefore, no government/institution should change policies accordingly.

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Competing interests

The author declares no competing interests.

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Figures

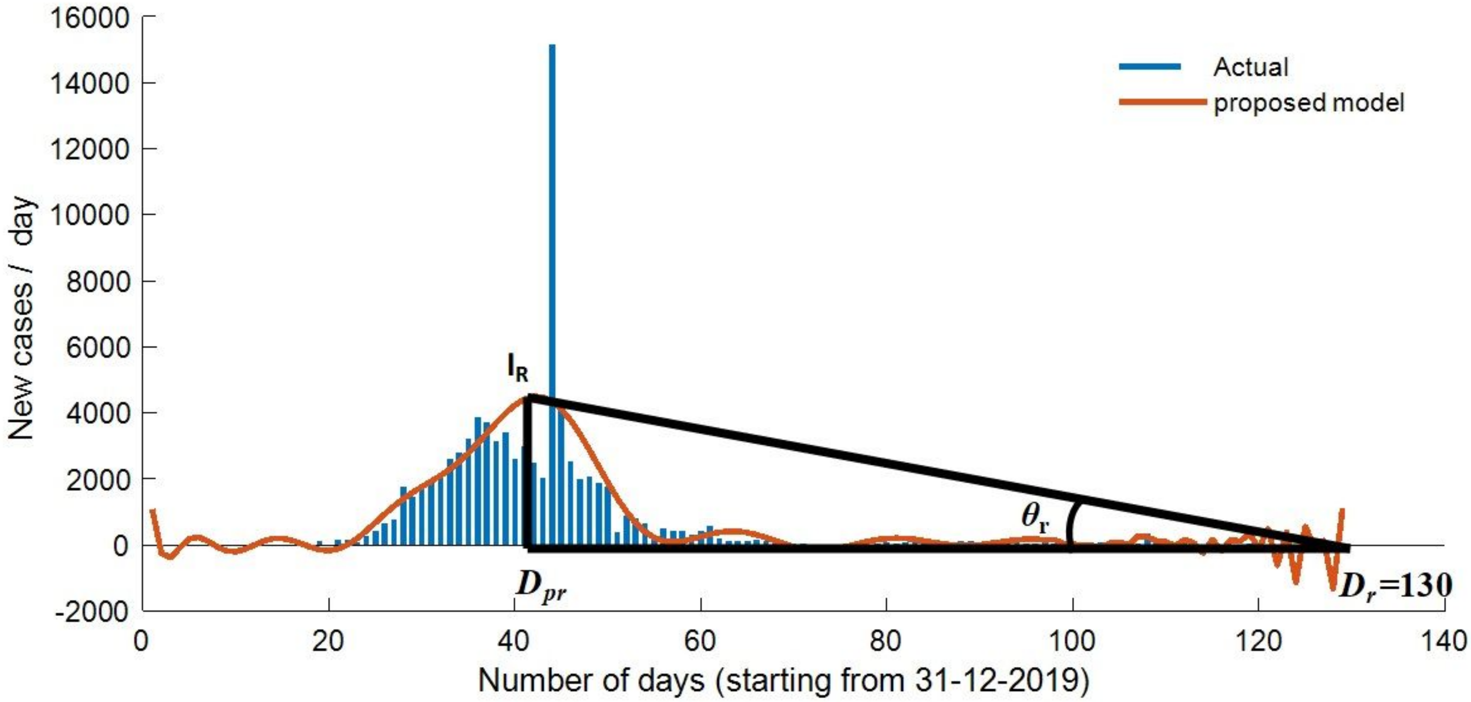

Figure 1

Comparison of the actual and the simulated rate of new cases per day and the triangle showing gradient (tan θr) in the case of China as a CRC

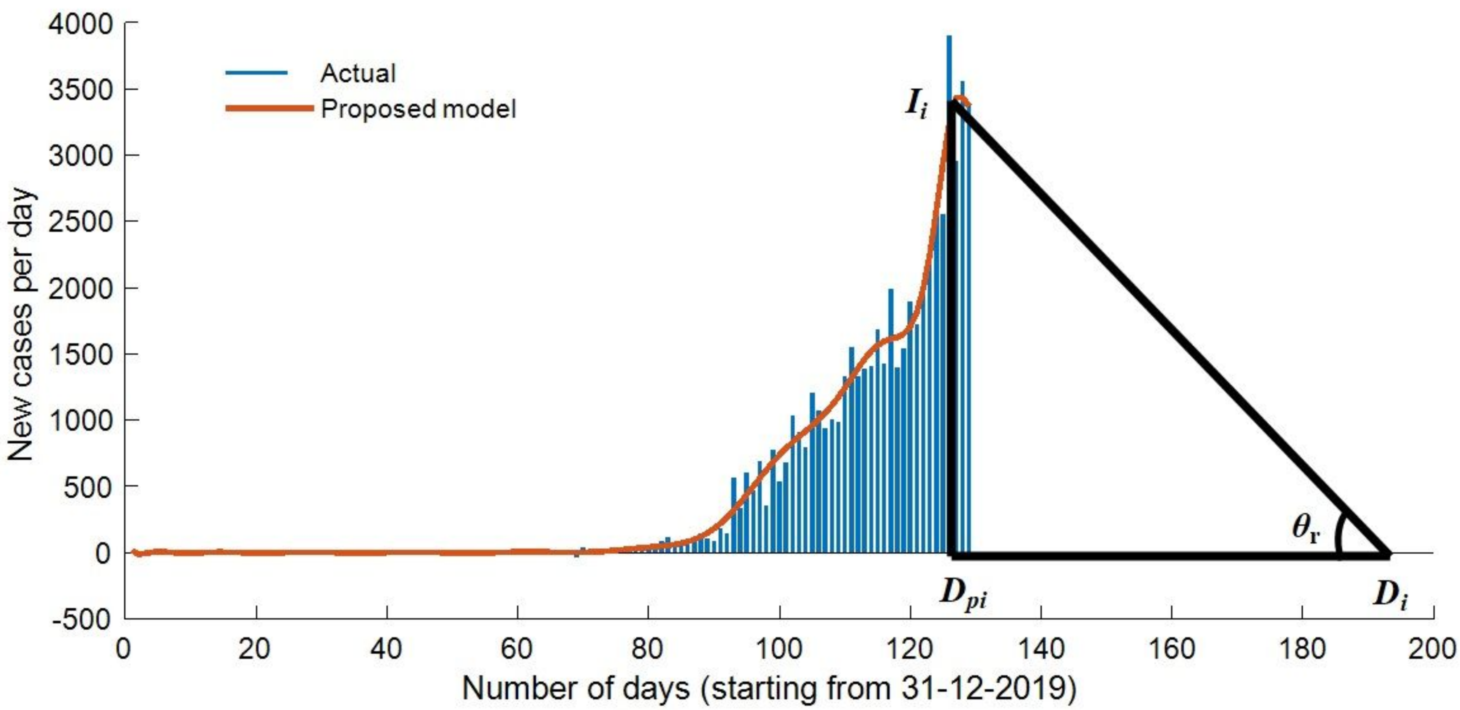

Figure 2

Comparison of the actual and the simulated rate of new cases per day and the triangle showing the captured gradient (tan θr), Ii, and Di in the case of India as a typical CIC

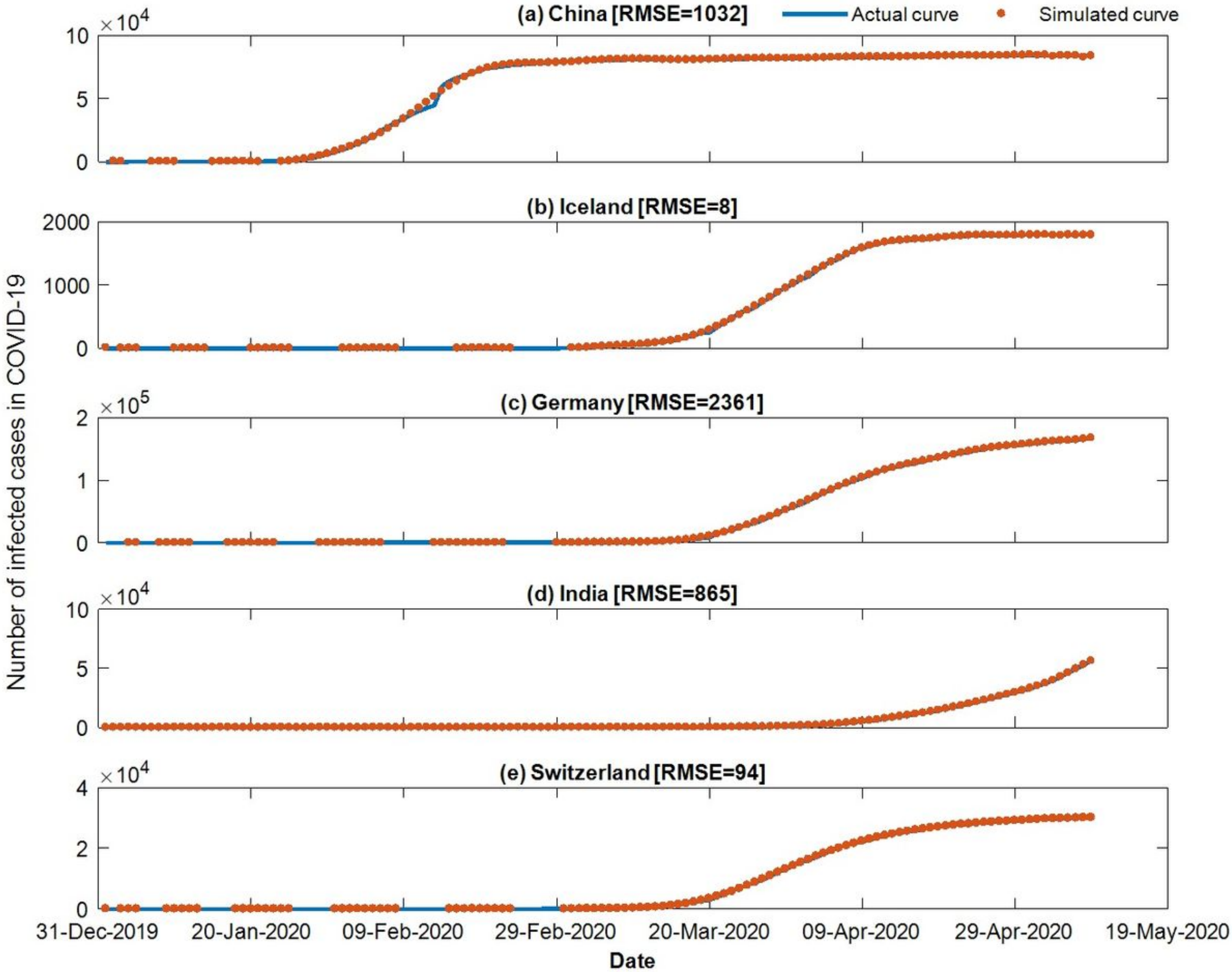

Figure 3

Comparison of actual and modelled COVID-19 pandemic curves for various countries