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Predicting turning point, duration and attack rate of COVID-19 outbreaks in major Western countries

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ABSTRACT

In this paper, we employed a segmented Poisson model to analyze the available daily new cases data of the COVID-19 outbreaks in the six Western countries of the Group of Seven, namely, Canada, France, Germany, Italy, UK and USA. We incorporated the governments' interventions (stay-at-home advises/orders, lockdowns, quarantines and social distancing) against COVID-19 into consideration. Our analysis allowed us to make a statistical prediction on the turning point (the time that the daily new cases peak), the duration (the period that the outbreak lasts) and the attack rate (the percentage of the total population that will be infected over the course of the outbreak) for these countries.

1. Introduction

The spread of coronavirus disease 2019 (COVID-19) has become a global threat and the World Health Organization (WHO) declared COVID-19 a global pandemic on March 11, 2020 [1]. As of April 9, 2020, there were 1,604,252 confirmed cases and 95,714 deaths from COVID-19 worldwide [2]. The COVID-19 pandemic has been greatly affecting people's lives and the world's economy. Among many infection related questions, governments and people are most concerned with (i) when the COVID-19 outbreak will peak; (ii) how long the outbreak will last and (iii) how many people will eventually be infected.

Since the early spread of COVID-19 in December of 2019 in Wuhan, China, there have been tremendous efforts to understand the spread dynamics and to propose effective prevention and control strategies [3–7,9,10]. To stop the spread of COVID-19 from the early epicenter-Wuhan, China unprecedentedly locked down the entire city of Wuhan on January 23. It was shown that the Wuhan lockdown delayed the occurrence of COVID-19 in other cities by 2.91 days and may have prevented more than 700,000 COVID-19 cases outside of Wuhan [8]. This massive lockdown was then later served as a model for several other countries battling COVID-19 around the world. Currently the development of vaccines is still in progress and there are no effective antiviral drugs for treating COVID-19 infections. The only practical therapeutic option is hospitalization and intensive care unit management. Thus predicting the peak time (or turning point), the duration and the final size of the outbreak for each country becomes crucial for policy makers and public health authorities to have informed decisions on appropriate interventions and resource allocations. However, since the COVID-19 virus is a novel coronavirus, key infection parameters such as the mean incubation period and the mean infection period are not known. This, together with the complex contact patterns, makes predictions based on previously established compartmental models for other viruses very challenging.

In this study, we simply regarded the daily new cases as a function of time t and coupled a power law with an exponential law. We also incorporated government's major interventions against the spread of COVID-19 such as stay-at-home advises/orders, lockdowns, quarantines and social distancing into our modeling. By fitting the available daily new cases data to our model, we were able to identify the peak time of daily increased new cases, predict the duration, the final size and the attack rate of the outbreak for each country. More specifically, we analyzed the data (up to April 9) of Canada, France, Germany, Italy, UK and USA (the six members of the Group of Seven (G7) countries). The data on daily new confirmed cases of COVID-19 in these countries we used were taken from the Wind Database [11] and from the webpage on US and Canada COVID-19 live updates [12].

2. Segmented Poisson model for daily new cases

To identify the turning point and predict the further spread of COVID-19 outbreaks while accounting for governments' enforce-

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Table 1
Estimated parameters and the associated 95% confidence intervals (CI) for Canada, USA and Italy.

	Canada	USA	Italy
$\log\alpha_1$	0.789	0.763	−24.620
CI	(−0.461, 1.683)	(−0.470, 1.653)	(−30.720, −18.520)
β_1	−2.882	−2.877	9.720
CI	(−3.424, −2.275)	(−3.231, −2.419)	(7.120,12.310)
γ_1	−0.299	−0.319	0.093
CI	(−0.335, −0.266)	(−0.332, −0.305)	(0.002,0.184)
$\log\alpha_2$	−186.229	−182.809	−55.399
CI	(−167.932, −148.791)	(−185.273, −180.349)	(−56.515, −54.282)
β_2	59.710	57.549	21.156
CI	(47.696,53.764)	(56.791,58.308)	(20.780,21.533)
γ_2	0.862	0.738	0.377
CI	(0.666,0.761)	(0.727,0.748)	(0.370,0.384)

Table 2
Estimated parameters and the associated 95% confidence intervals (CI) for Germany, France and UK.

	Germany	France	UK
$\log\alpha_1$	−11.963	0.309	0.239
CI	(−15.663, −8.492)	(−1.214, 1.354)	(−1.339, 1.310)
β_1	3.006	−2.435	−2.302
CI	(1.766,4.323)	(−2.863, −1.848)	(−2.782, −1.654)
γ_1	−0.155	−0.320	−0.318
CI	(−0.335, −0.266)	(−0.337, −0.302)	(−0.341, −0.293)
$\log\alpha_2$	−85.712	−117.464	−117.602
CI	(−91.980, −79.454)	(−120.773, −114.165)	(−122.203, −113.021)
β_2	29.892	38.078	38.885
CI	(27.907,31.881)	(37.040,39.119)	(37.403,40.374)
γ_2	0.468	0.508	0.559
CI	(0.437,0.4996)	(0.492,0.523)	(0.535,0.584)

ment of stay-at-home advises/orders, social distancing, lockdowns, and quarantines against COVID-19, we combine the power law with the exponential law for daily new cases based on a segmented Poisson model. Let Y_t be the daily new cases at day t since the first case was reported on day 1. Our model takes the following form

$$Y_t \sim \text{Poisson}\ (\mu_t), \tag{2.1}$$

where μ_t is the expectation of Y_t with segmented expressions given below.

$$\mu_t = \begin{cases} \alpha_1 t^{\beta_1} e^{-\gamma_1 t} & \text{for } t = 1, \ldots, s, \\ \alpha_2 t^{\beta_2} e^{-\gamma_2 t} & \text{for } t = s+1, \ldots, T, \end{cases}$$

where α_k, β_k and γ_k are regression parameters and $k = 1, 2$ correspond to periods before and after the day of major government actions (stay-at-home advises/orders, lockdowns, quarantines and social distancing) against COVID-19 at day s. The advantage of our segmented Poisson model is that the observed daily new cases before and after the day of major government actions are characterized integrally under a single model, but with separate mean curves. Unlike the widely used log-transformed linear model, our Poisson modeling approach enables us to deal with daily new cases as a count response with many zeros. In addition, our segmented Poisson model allows us to account for governments' interventions at different stages dynamically by incorporating stage specific segments.

As major government actions are taken when COVID-19 outbreaks deteriorate seriously, the maximum number of daily new cases occurs during the period after the day of major government actions. It follows from (2.1) that the maximum value of Y_t is

$$\max Y = \alpha_2 \left(\frac{\beta_2}{\gamma_2}\right)^{\beta_2} e^{-\beta_2},$$

which occurs at

$$t = \frac{\beta_2}{\gamma_2} =: t_{peak} \tag{2.2}$$

Once the parameters α's, β's, and γ's have been estimated, we can then find the peak time t_{peak} and make a prediction for the further spread of the outbreak. Let N be the smallest integer of t such that $Y_t \le 1$ for $t > t_{peak}$. Then the outbreak would last for N days, that is, the duration of the outbreak is N days. In addition, the total

Table 3
Predictions on turning point, final size, duration and attack rate.

Country	Turing point (Range)	Final size	Duration	Attack rate
France	Apr. 07 (Apr. 03 ~ Apr. 12)	219,583	Feb. 01 ~ Jun. 10	0.3364%
Italy	Mar. 26 (Mar. 24 ~ Mar. 28)	172,451	Jan. 31 ~ Jun. 01	0.2852%
USA	Apr. 07 (Apr. 03 ~ Apr. 09)	835,158	Jan. 21 ~ Jun. 03	0.2523%
UK	Apr. 09 (Apr. 03 ~ Apr. 15)	133,206	Jan. 31 ~ Jun. 05	0.1962%
Germany	Mar. 31 (Mar. 23 ~ Apr. 09)	159,437	Jan. 28 ~ Jun. 01	0.1903%
Canada	Apr. 06 (Mar .29 ~ Apr. 16)	33,948	Jan. 27 ~ May 21	0.0899%

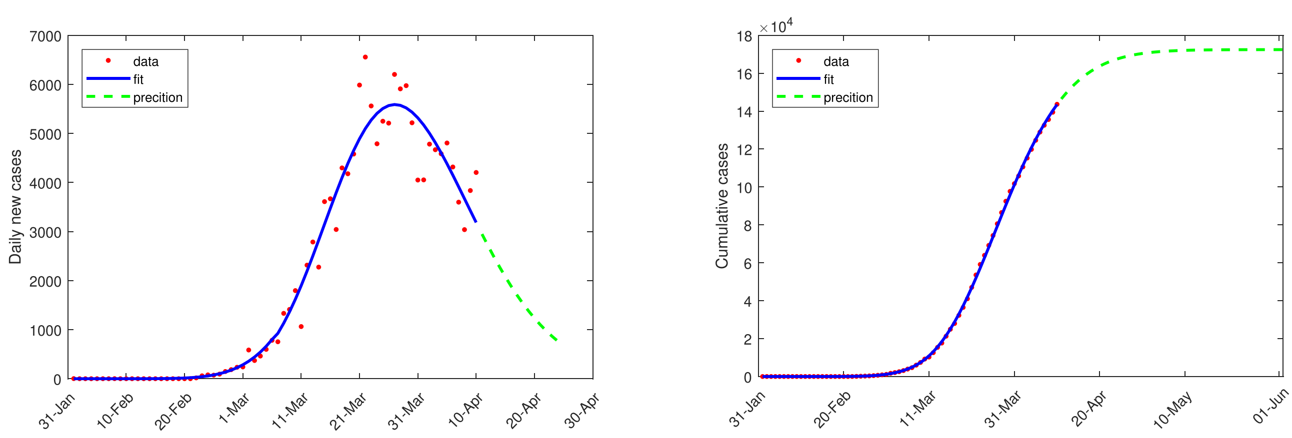

Fig. 1. Left: Italy's daily new cases; Right: Italy's cumulative cases.

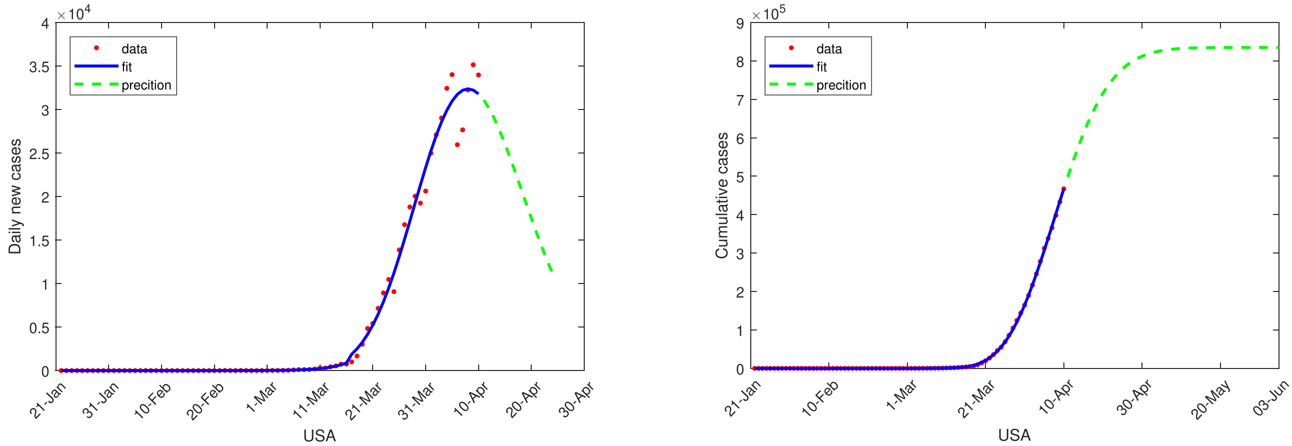

Fig. 2. Left: USA's daily new cases; Right: USA's cumulative cases.

cumulative number of infected individuals, i.e., the final size of the outbreak, can be estimated by

$$C_{total} \approx \sum_{t=1}^{s} \alpha_1 t^{\beta_1} e^{-\gamma_1 t} + \sum_{t=s+1}^{N} \alpha_2 t^{\beta_2} e^{-\gamma_2 t}. \tag{2.3}$$

Then for a given country, the ratio of the total cumulative number of infected individuals and the total population (The 2020 population data was taken from Worldometers [2]) would give the so-called attack rate of the COVID-19 outbreak in that country.

3. Statistical analysis

We applied our model to study the turning point and further spread of COVID-19 outbreaks in the six Western countries of G7, namely, Canada, France, Germany, Italy, UK and USA. The parameter estimates together with their 95% confidence intervals for each of these six countries are displayed in Tables 1 and 2. Using the 95% confidence intervals of β_2 and γ_2, we can also find the range of the turning point computed by $(\min \beta_2/\max \gamma_2, \max \beta_2/\min \gamma_2)$. The estimated turning point, duration time, final size and the attack rate for each of the six major Western countries are presented in Table 3.

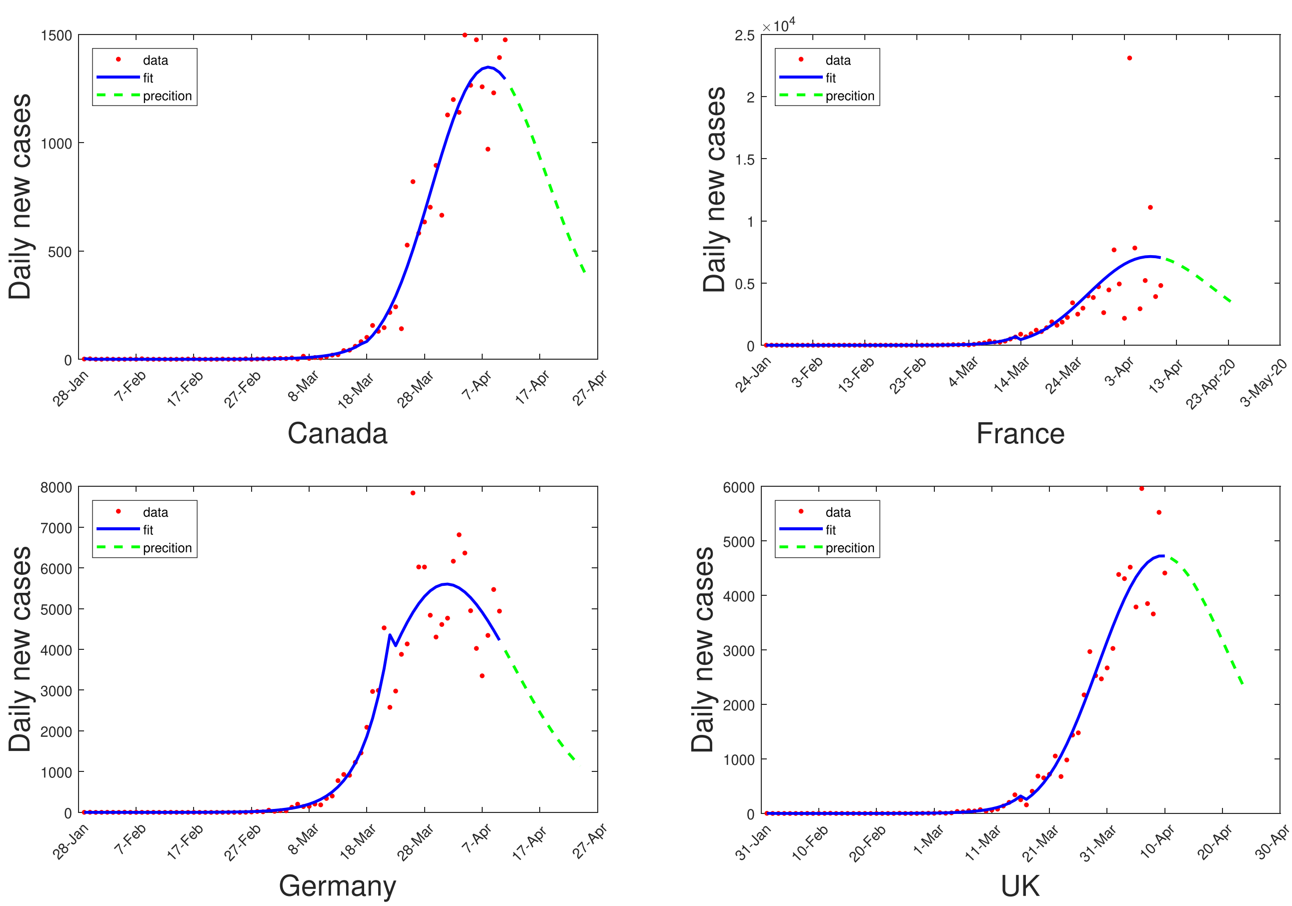

Fig. 3. Fitting and prediction of daily new cases for Canada, France, Germany and UK.

Italy is the first country in this group (also in the world) whose cumulative confirmed cases overpass 100,000 (It occurred on March 30,2020). Based on our estimate, Italy's turning point is March 26 (in the range of (March 24 ~ March 28)), the outbreak is estimated to end around June 1, and the final size is 172,451, which gives an infection attack rate of 0.285%. The observed data, our fitting and a 14-day prediction on the daily new cases and the cumulative cases are plotted in Fig. 1.

The USA now becomes the country with the most confirmed cases in this group (also in the world). Our analysis found that USA's turning point is April 07 (in the range of April 03 ~ April 09)), the outbreak is expected to end in the early June (June 03), and the cumulative cases would be about 835,158, i.e., the attack rate is 0.2523%. The fitting and prediction result is presented in Fig. 2.

The fitting and prediction for the other four countries are given in Fig. 3.

Using the 95% confidence intervals of γ_2, we could also give an upper bound for the final size. The upper bounds for the final size of USA, Germany, UK, France, Italy and Canada were estimated to be 1.98 million, 1.27 million, 800 thousand, 750 thousand, 261 thousand, and 118 thousand, respectively.

4. Conclusion

We have combined a power law with an exponential law with our segmented Poisson model to analyze the COVID-19 daily new cases data for six major Western countries in the G-7 group. It is seen from Figs. 1 to 3 that the observed and estimated daily new cases are in good agreement. This together with the forecasted trend indicated that our model has well characterized the COVID-19 outbreaks in these six major Western countries.

Our analysis allowed us to identify/predict the turning point, to predict the further spread, the duration and the final size (the attack rate) of the outbreak of COVID-19 in those six countries we studied. We found that among those six countries, France would have the highest attack rate (0.3364%), while Canada would have the lowest attack rate (0.0899%). The USA would have the most cumulative cases (835,158), Canada's cumulative cases (33,948) would be the least. On average, the turning point occurs at day 69 (in the range of 56 ~ 78). If the current government actions remain unchanged, the outbreaks would likely to end at the beginning of June (ranging from May 21 to June 10) and the average duration of the outbreaks is 127 days (ranging from 115 to 138 days).

It is seen from Tables 1 and 2 that the estimated parameter γ_1's are all negative (except for Italy's, which is close to zero), and all γ_2's are positive. This implies that if there were no major enforcement actions on control strategies such as lockdowns, social distancing, stay-home-advises/orders, then the COVID-19 would have spread exponentially. For example, the total confirmed cases in the USA would have passed 1,000,000 on April 05, 2020. This indicates that the interentions/actions greatly reduced the outbreak sizes and flatted the epidemic curves.

Our prediction is based on the assumption that the current government interventions/actions would be imposed until the estimated end dates of the outbreaks. If those interventions were lifted or removed earlier cautiously based on scientific evidences, we would not expect any dramatic differences. On the other hand, if those interventions were lifted or removed earlier hastily without scientific support, our prediction would provide a reference to assess consequences of such irresponsible decisions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Xiaolei Zhang: Software, Data curation, Formal analysis. **Renjun Ma:** Conceptualization, Formal analysis, Methodology, Writing - review & editing. **Lin Wang:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing.

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