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Abstract

Background: Since the outbreak of coronavirus disease (COVID-19), a country's ability to control the epidemic depends on how well its health system accommodates COVID-19 patients.

Objective: The aim of this study was to assess the ability of different countries to contain the COVID-19 epidemic in real-time with the number of confirmed, death and recovered cases.

Methods: Using the dataset provided by the Humanitarian Data Exchange (HDX), we compared the data from 16 countries between 2020/01/22 to 2020/09/15. We analyze the spreading of the virus using Little's Law to predict a country's ability for epidemic control.

Results: According to the changes in the average recovery time curve, 16 countries are divided into different cases – Outbreak, Under Control, Second Wave of Outbreak, and Premature Lockdown Lift. Analyzing the dataset with Little's Law, the curves of some countries (i.e., U.S., Spain, Netherlands, Serbia, France, Sweden, and Belgium) showed an upward trend representing their medical systems in these countries have been overloaded and unable to provide effective medical services to patients, i.e., those countries have lost control (i.e., Outbreak case) of COVID-19. On the other hand, after the pandemic-prevention policy was applied in some countries (i.e., Iceland, New Zealand, Taiwan, Thailand, and Singapore), the average recovery time dropped with the number of new cases decreased (i.e., Under Control case). The prevention policy, e.g., lockdown and gathering restrictions, shows the effect after 14 days, which is the same as the incubation period of COVID-19. The result shows that the average recovery time (T) can be used as an indicator of the ability of a country on controlling the pandemic.

Conclusions: In this paper, we use Little's Law to estimate the capacity of each country's healthcare system for the COVID-19 pandemic and find out a new estimator to represent the severity of the pandemic. We study the impact of interventions on the average recovery time in some countries. The result shows that the average recovery time (T) can be used as an indicator of the ability on controlling the pandemic.

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Original Paper

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Background: Since the outbreak of the coronavirus disease (COVID-19), a country's ability to control the epidemic depends on how well its health system accommodates COVID-19 patients.

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Conclusions: In this paper, we use Little's Law to estimate the capacity of each country's healthcare system for the COVID-19 pandemic and find out a new estimator to represent the severity of the pandemic. We study the impact of interventions on the average recovery time in some countries. The result shows that the average recovery time (T) can be used as an indicator of the ability on controlling the pandemic.

Keywords: Infodemiological; Coronavirus; COVID-19; Outbreak Control; Queuing Theory; Little's Law

Introduction

In December 2019, the novel coronavirus disease (COVID-19) appeared in Wuhan City and quickly became the epicenter of the epidemic. Before the world realized the fatality of the COVID-19 and the way it was transmitted, the virus had already spread to several other nearby cities in the region. In less than two months, COVID-19 already surpassed the death toll of the severe acute respiratory syndrome (SARS) pandemic. Not only the virus quickly spread to many neighboring countries, but also several cases were reported throughout Europe.

To contain the virus and prevent the outbreaks, it is essential to have accurate information and correctly estimate the spreading rate in order for early detection and implement containment strategies. Taiwan is a leading example of using accurate information and estimation regarding the virus which results from early responses and implemented aggressive containment strategies, such as screening of passengers at airports, mandatory to wear a face mask, a strict 14-days quarantine law with smart phone location-aware monitoring program. With the windows of opportunity for early epidemic control, the country has not reported only 7 deaths and no community spread from COVID-19 since the beginning of the epidemic.

Without question, the Internet is the largest source for millions of people seeking information about the current status of COVID-19 around the world. “Infodemiological” method, defined by Gunther Eysenbach, is the concept of information epidemiology that uses the Internet for user-contributed health-related content. Using the data from the Humanitarian Data Exchange (HDX) [1], regional analysis is performed to determine a country’s ability to accommodate patients of COVID-19. In this context, we investigated and estimated how well a country’s health system accommodates COVID-19 patients reflects their ability in control over the epidemic using Little's Law.

Methods

Data Collection and Processing

We used the confirmed case data from the Humanitarian Data Exchange (HDX) for this study. HDX is managed by the Office for the Coordination of Humanitarian Affairs (OCHA) which is the part of the United Nations Secretariat responsible for bringing together humanitarian actors to ensure a coherent response to emergencies. Launched in July 2014, HDX is an open platform for sharing humanitarian data across crises and organizations which allow easy access and analysis. The collected datasets have been accessed by users in over 200 countries and territories. The dataset contains the daily cumulative number of confirmed, death and recovered cases from 2020/01/22 to 2020/09/15.

We selected the countries based on the well-known data, events, and cases. Also, we excluded the countries with outdated or unfitted data. For example, U.K. did not update their number of recovery for a period of time. China’s outbreak started at Day One which will not apply to our analysis.

Data Analysis

We analyze whether a country is under a good control of the pandemic based on its daily cumulative number of confirmed, death and recovered cases. First, we start with an explanation of Queuing Theory. Queuing Theory is a simple mathematical study to predict lengths and waiting time of queues or waiting lines. It is often used in different areas from engineering to business management to determine the resources needed to provide a service.

One of the simplest queuing models is Little’s Law. The Little's Law was proposed by John Little in 1961, and it states that the average number N of customers in a stationary system is equal to the average arrival rate λ multiplied by the average time T that a customer spends in the system. Algebraic expression of the theorem is

$$N = \lambda \times T \quad \text{(Eq. 1)}$$

For example, in a small bank with a single teller where only one customer can be at the teller at a time. If average 20 customers arrive every hour (i.e., λ = 20 per hour) and stay in the bank for 30 minutes (i.e., T = 0.5 hours) , then the average number of customers in the bank will be 10 customers (i.e., N = 10 customers) at any given time.

The system is in a stable state if the rate of arrival λ (e.g., customers come) to the system is less or equal to the rate of exiting the system. On the other hand, if the arrival rate is greater than the exit rate, the system is in an unstable state.

Applying Little’s Law to COVID -19, N represents the prevalence of COVID-19, which is the proportion of infected people in a given time period, i.e., the total number of the confirmed cases minus the death cases and the recovered cases. The given time period is the window size W. In our study, the window size is twice of the maximum length of the COVID-19 cases which is about 2 months (60 days), i.e., 120 days. The average arrival rate λ is the incidence rate per day and T represents the average recovery time (i.e., the time from onset to clinical recovery or death) of confirmed cases.

The Little's Law holds when the pandemic is under good control, i.e., in a stable state. In such cases, T is expected to be stable in a reasonable range, and the value of N may vary with λ up to a certain value that represents the capacity of a health system.

When an outbreak occurs, the Little's Law no longer holds, and λ may increase sharply resulting in an extensive number of active confirmed cases (N) out of its health system capacity. During that period, the value of T also increases due to limited healthcare resources, and it may become even far greater than the reasonable range.

In order to recover from the outbreak, it is essential to lower N under its health system capacity. There are two ways to put a country back to under good control of the pandemic. First, it needs to reduce λ by promoting mask-wearing, strengthening quarantine measures, tightening border control, etc. Second, a country needs to reduce T by improving treatments (i.e., increasing recovery rate), patient prioritization, etc.

Results

Evaluation Outcomes

We marked the time points of the policies and the disease outbreak of multiple countries to observe whether these countries are under well control of the epidemic. According to the changes in the average recovery time curve, we divide countries into different cases as follow: (a) Outbreak - U.S., Spain, Netherlands, Serbia, France, Sweden, and Belgium; (b) Under Control - Iceland, New Zealand, Taiwan, Thailand, and Singapore; (c) Second Wave of Outbreak - Australia and Hong

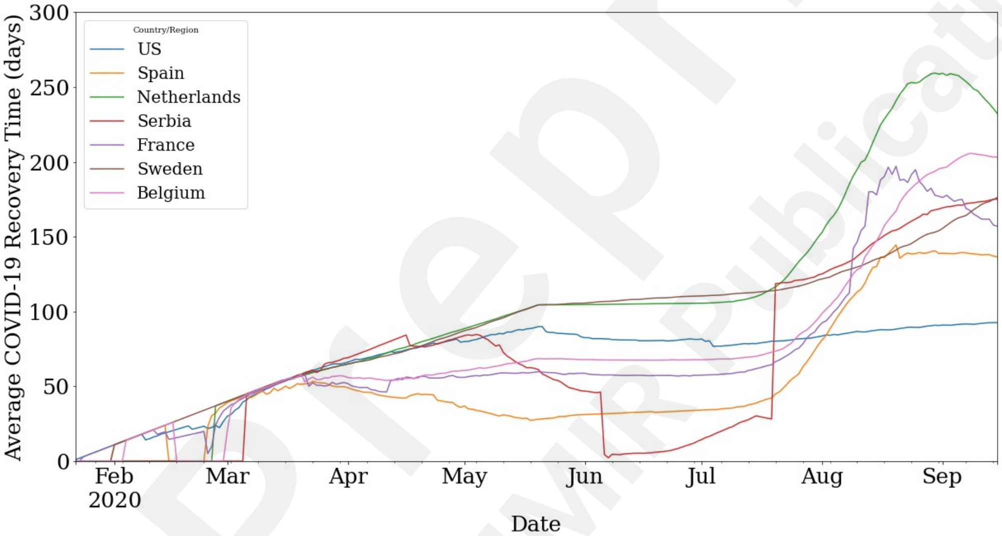
Kong; and (d) Premature Lockdown Lift - Malta and Spain.

The curve of countries that have lost control of COVID-19 will show an upward trend, see Figure 1.. And the medical systems in these countries have been overloaded and unable to provide effective medical services to patients. Therefore, as the number of confirmed cases increases, patients will stay in the disease state for a longer time. In other words, the overall the average recovery time will be longer.

Outbreak Cases

First, we study some of known countries that are out of control such as U.S., Spain, Netherlands, Serbia, France, Sweden, and Belgium. In Figure 1., all seven countries are experiencing rapid increase of newly confirmed cases (i.e., average arrival rate λ). As the λ increased, the number of active confirmed cases (N) also increased sharply which most likely it exceed each countries' health system capacity. The steeper slope means faster of newly confirmed cases arrived in a country. As results, the average recovery time (T) increases to an unreasonable range when an outbreak occurs.

Figure 1. Average Recovery Time for U.S., Spain, Netherlands, Serbia, France, Sweden and Belgium.



Under Control Cases

In this section, we study countries with better control of the COVID-19 pandemic. We defined a country is under well control if its number of new confirm cases (N) is less than 7 cases per day for 30 consecutive days and the average recovery time (T) is less than 20 days. The five that are under well control are Iceland, New Zealand, Taiwan, Thailand, and Singapore.

In Figure 2., the four countries all adopted policies such as lockdown or border control during the first wave of the epidemic, and only lifted restrictions after the epidemic was well controlled. Iceland banned gathering and implemented travel restrictions on mid-March. Afterwards, Iceland enforced stricter gathering restrictions on 03/24/2020 (I_1) [2] and partially ease the lockdown after 05/04/2020 (i.e.,I_2) [3]. When number of new domestic cases started to increase around 07/23/2020 (I_3) [4], Iceland tighten the restrictions on 07/30/2020 (I_4) [5]. New Zealand started their lockdown on 03/25/2020 (N_1) [6] and partially eased the lockdown after 05/14/2020 (N_2) [7]. When familial cluster infection cases appeared in Auckland on 08/11/2020 (N_3) [8], New Zealand reinforce the lockdown rules in Auckland on 08/14/2020 (N_4) [9] after the cluster outbreak.

Taiwan took actions after the number of new imported cases start increasing from 03/15/2020 (TW_1) [10], such as prohibiting foreign nationals from entering their country on 03/19/2020 (TW_2) [11] and wearing mask mandatory on public transportation on 04/01/2020 (TW_3) [12]. They started to lift the restrictions, such as the limitation of sport game spectators, from 05/06/2020 (TW_4) [13]. Taiwan started facing second wave of the epidemic on 07/27/2020 (TW_5) [14]. Since Taiwan still requires a 14-day quarantine after entry, the epidemic is still under control and the average recovery time fluctuates rather than rises steadily.

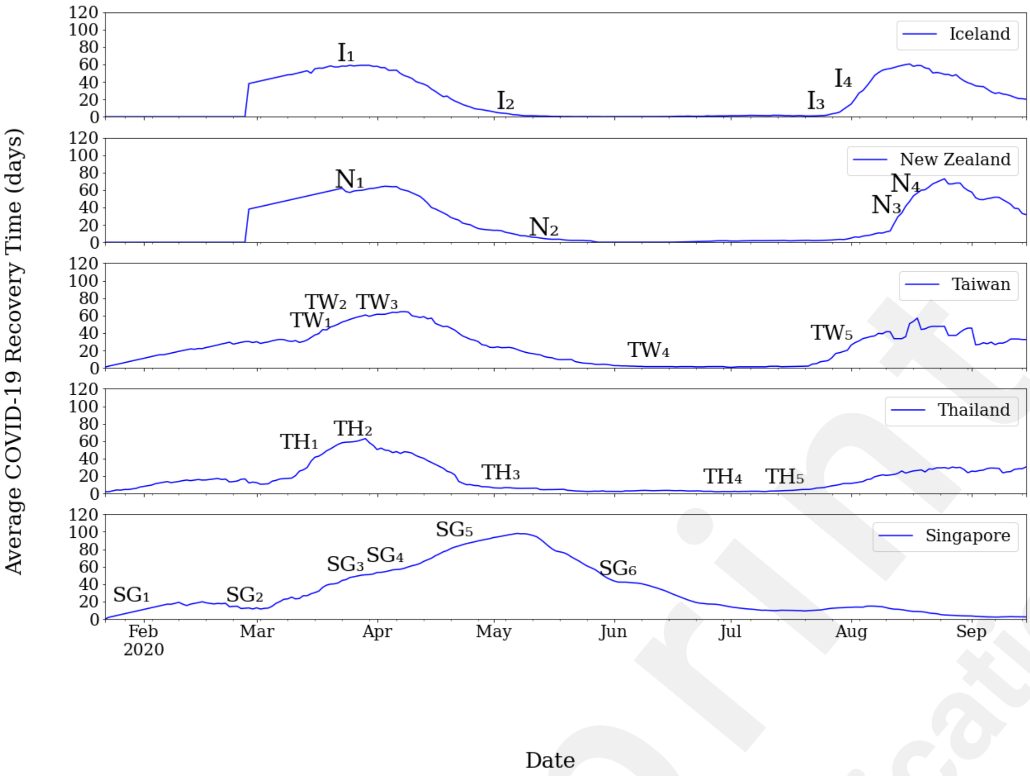
Thailand announced a cluster outbreak on 03/12/2020 (TH_1) [15] and the outbreak of cluster infection cases in the boxing stadium from 03/15/2020 [16]. Subsequently, Thailand government declared the state of emergency from 03/26/2020 (TH_2) [17]. Related measures include lockdown and the closure of borders. Thailand started a four stages of relaxation of restrictions from 05/03/2020 (TH_3) [18] and eased the entry restrictions on 07/01/2020 (TH_4) [19]. Afterwards, Thailand closed the border again to prevent an increase in imported cases on 07/14/2020 (TH_5) [20].

Singapore experienced the outbreak in February of 2020 after The Life Church and Missions Singapore outbreak (i.e., SG_1, 01/29/2020) and in March after SAFRA Jurong cluster (i.e., SG_2, 02/27/2020) [21]. After the outbreak, Singapore started enforcing the lockdown rules step-by-step with different rules, such as closing border on 03/24/2020 (i.e., SG_3) [22], partially lockdown on 04/03/2020 (i.e., SG_4, circuit breaker - advising to stay home as much as possible) [23], enforce wearing mask on 04/14/2020 [24], tightened measures of circuit breaker on 04/21/2020 (i.e., SG_5) [25] and scaled-up testing on 04/27/2020 [26].

In Singapore, the government started to slowly reopen activities from May. The lockdown lifted on 05/02/2020 [27] and the entry restrictions eased on 06/17/2020 (i.e., SG_6) [28]. Meanwhile, the government still expended the cover of testing to reduce the risk of cluster infections [29]. Due to the early detection, the number of new confirmed case, i.e., the arrival rate λ, has decreased, which leads to a decrease in the average recovery time.

All five countries (Iceland, New Zealand, Taiwan, Thailand, and Singapore) waited until the COVID-19 pandemic is under well control before they eased their lockdown restrictions. As the result, those countries is able to keep the number of confirmed cases (N) below their health system capacity which also lower the average arrival rate (λ) to keep the countries in a stable state which the Little's Law holds when the pandemic is under good control.

Figure 2. Under Control of the Outbreak in Iceland, New Zealand, Taiwan, Thailand, and Singapore.

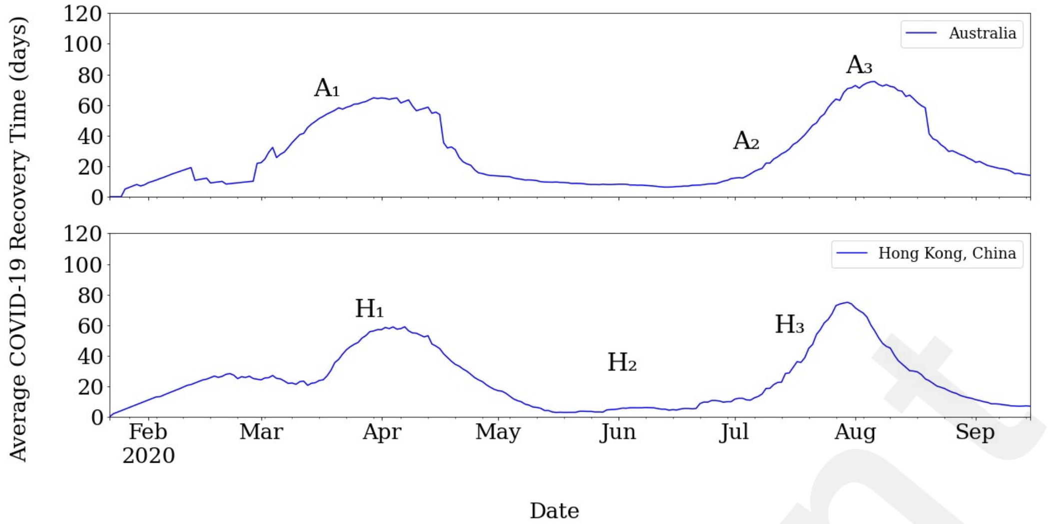


Second Wave of Outbreak Cases

In this study, we study Australia and Hong Kong that have experienced the 2nd wave of outbreak. In both countries, the lockdown rules started after the first wave of outbreak which the number of COVID -19 cases start to increased. In Figure 3., Australia and Hong Kong began their measures for social distancing on 03/18/2020 (A_1) [30] and 03/29/2020 (H_1) [31], respectively.

After the lockdown rules, the number of newly confirmed cases (i.e., average arrival rate λ) started to decrease in both countries. However, the second wave of outbreak start to appeared as nations loosen their lockdown rules. In Australia, significant of community transmission cases started appear from 06/23/2020 [32]. Then the local outbreak from 07/06/2020 (A_2) [33] caused mass number of increased and results of the second wave of outbreak. Australia is able to regain control by reinforce the lockdown rules across the state of Victoria, including metropolitan Melbourne (A_3) [34]. Similarly, the second wave situation began in Hong Kong, initial community transmission started from 06/02/2020 [35]. Then multiple districts of local infection started on 07/06/2020 (H_2 and H_3) [36].

Figure 3. Second Wave of the Outbreak in Austrlia and Hong Kong (China).

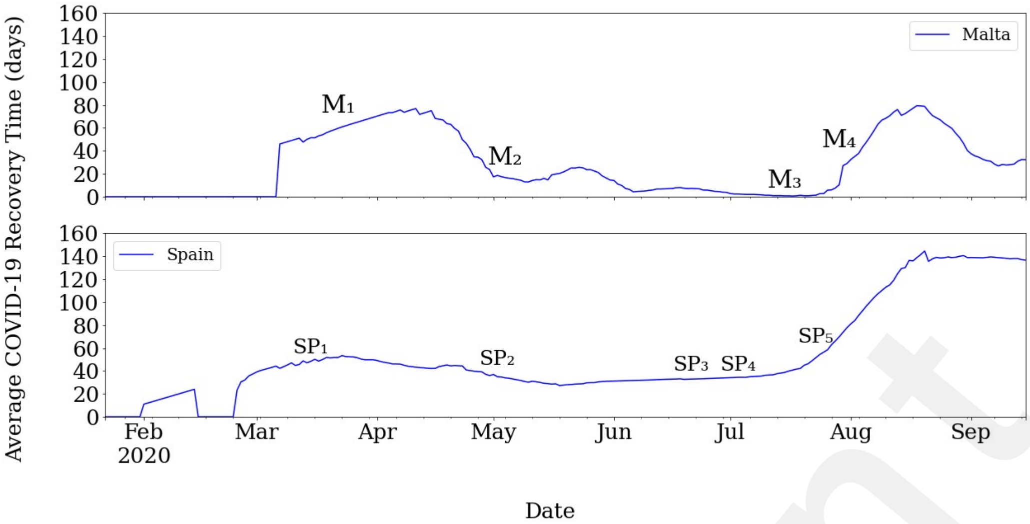


Premature Lockdown Lift Cases

In this section, we study two countries, Malta and Spain, lifted the lockdown too early. Malta started the lockdown restriction on 03/22/2020 (M_1) [37]. However, it eased the lockdown on 05/04/2020 (M_2) [38] when the average recovery time (*T*) is still about 20 days. Then the country lifted restrictions for all arrival planes on 07/15/2020 (M_3) [39] when *T* is about 1. However, the mass of events, e.g., Catholic Saint feast celebrations and Feast of St. Venera, at the end of July (M_4) [40] cause the second wave in Malta.

Similarly, Spain started the national lockdown on 03/15/2020 (SP_1) [41]. But, it prematurely lifted the lockdown on 5/2/2020 (SP_2) [42] with first stage and second stage of ease the lockdown restriction on 5/11/2020 and 5/18/2020, respectively. Then Spain's national state of alarm expired on 06/21/2020 (SP_3) [43]. However, the cluster infection appeared in Segria (SP_4) [44] and outbreak at local bars in Totana (SP_5) [45]. Compared to Taiwan and New Zealand, the ease is too early to ensure the outbreak has been completely controlled. As the result of prematurely lift their lockdowns, the second wave outbreak appeared in both countries at the end of July.

Figure 4. Premature Lift the Lockdown in Malta and Spain.



Discussion

The result shows that the average recovery time can reflect the severity of the pandemic. When a cluster infection occurred, the average recovery time increase with the number of new cases rapidly. After the pandemic-prevention policy was applied, the average recovery time dropped with the number of new cases decreased. We also observed that the prevention policy, e.g., lockdown and gathering restrictions, shows the effect after 14 days, which is the same as the incubation period of COVID-19.

There are some advantages of the average recovery time as a pandemic severity index. First, the average recovery time requires fewer parameters to be estimated. Compared with R_0, which usually needed to build an epidemic model with many hyper-parameters to estimate, the average recovery time only needs to consider the window size. Second, the average recovery time considers the influence of medical capacity. The higher the medical capacity in a country, the higher the ability to control the epidemic.

The window size (*W*) will affect the sensitivity of the index, i.e., the average recovery time. A large window size flattens the curve of the average recovery time and ignores the occurrence of small cluster infections. In contrast, a small window size overestimates the average recovery time and fails to highlight the outbreak. According to the Sampling Theorem, the sampling frequency should be twice the sampling rate. The COVID-19 report from WHO shows that the recovery time of COVID-19 patients is about 2-6 weeks on clinical, and the time for the onset of the disease to death is about 2-8 weeks [46]. Therefore, we use twice the maximum length of the average COVID-19 cases which is about 2 months.

Conclusions

In this paper, we use Little's Law to estimate the hospital capacity for the COVID-19 pandemic of each country and find out a new estimator to represent the severity of the pandemic. We study the impact of interventions on the average recovery time in some countries. The result shows that the average recovery time (*T*) can be used as an indicator of the ability on controlling the pandemic. In the near future, we plan to study the scaling of window size and forecasting the average recovery time for pandemic prevention.

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Conflicts of Interest

None declared

Disclose any personal financial interests related to the subject matters discussed in the manuscript here. For example, authors who are owners or employees of Internet companies that market the services described in the manuscript will be disclosed here. If none, indicate with "none declared".

Abbreviations

COVID-19: Coronavirus Disease 2019
HDX: Humanitarian Data Exchange
JMIR: Journal of Medical Internet Research
OCHA: Office for the Coordination of Humanitarian Affairs
SARS: Severe Acute Respiratory Syndrome

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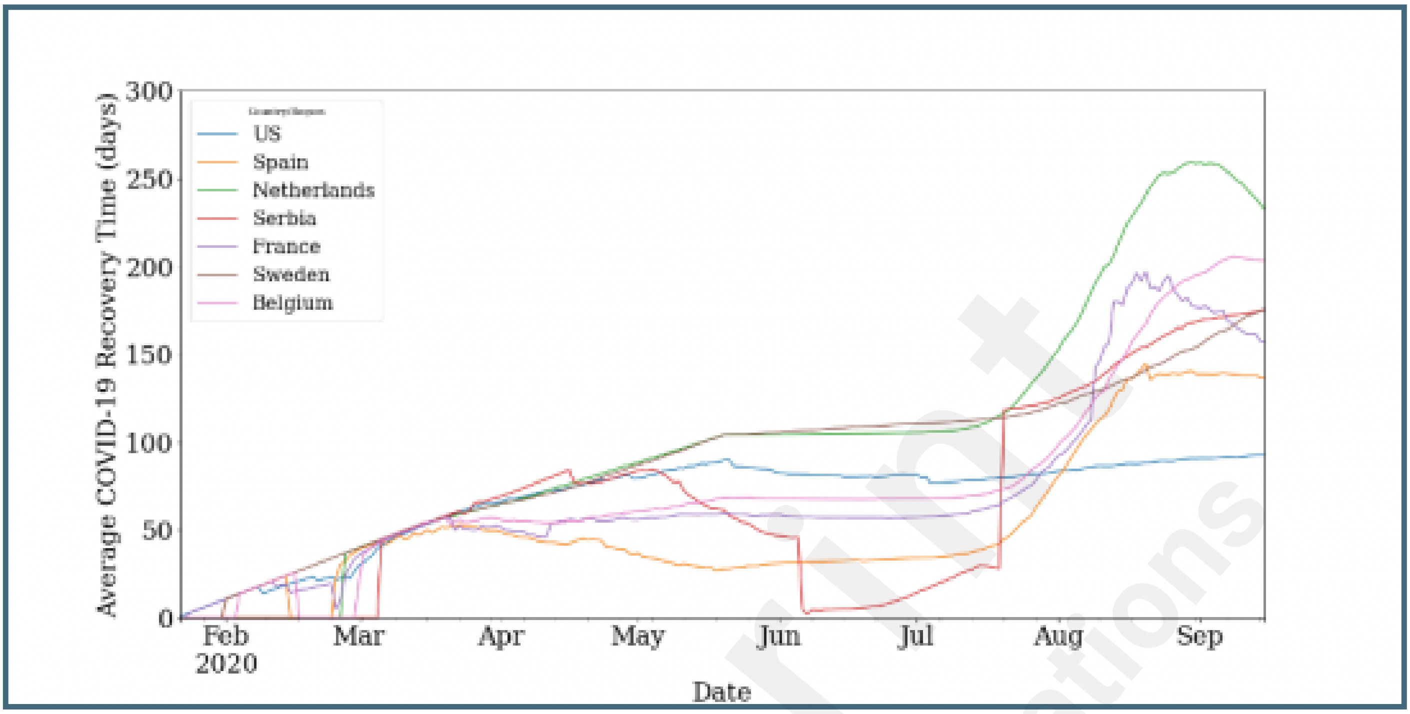
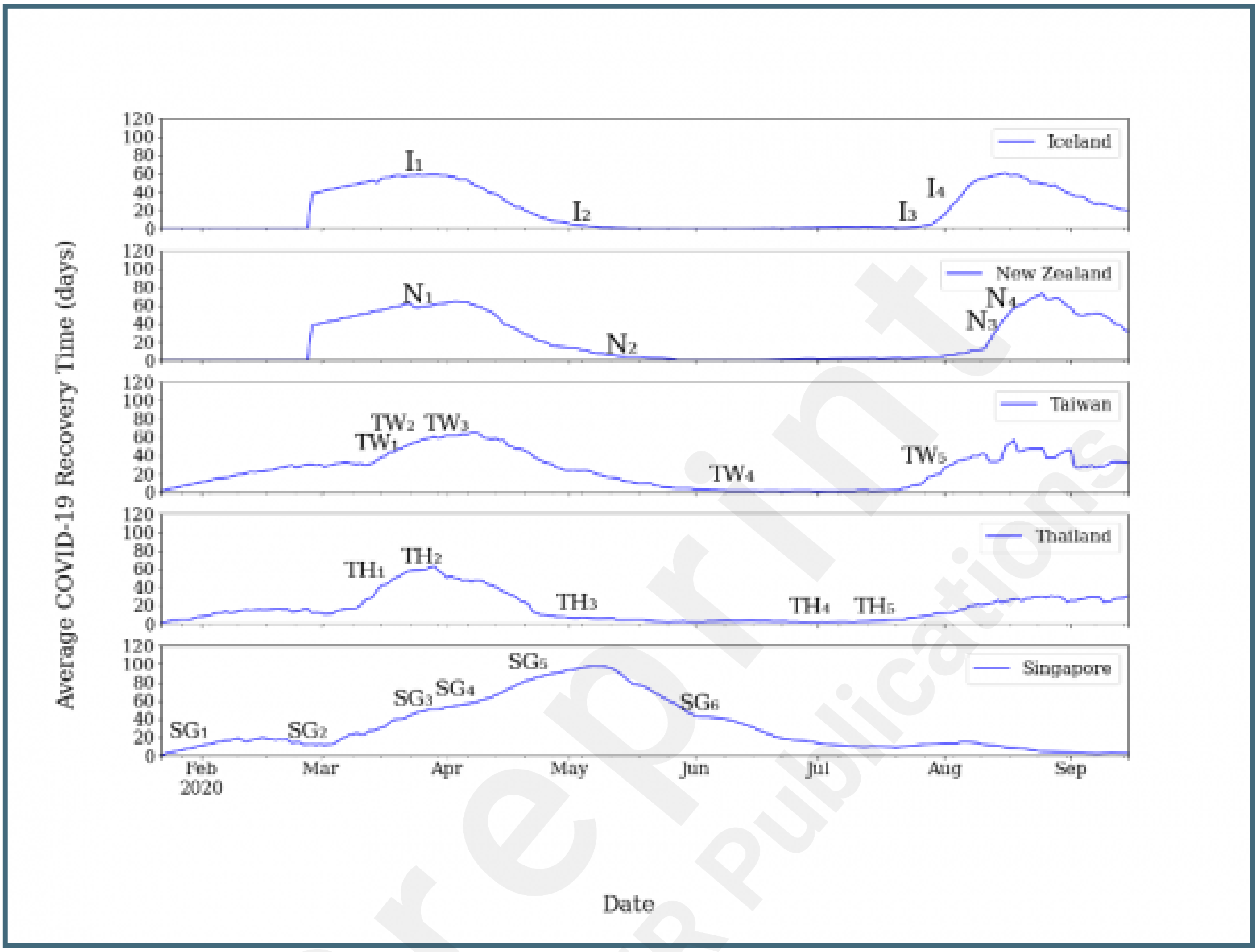
Supplementary Files

Figures

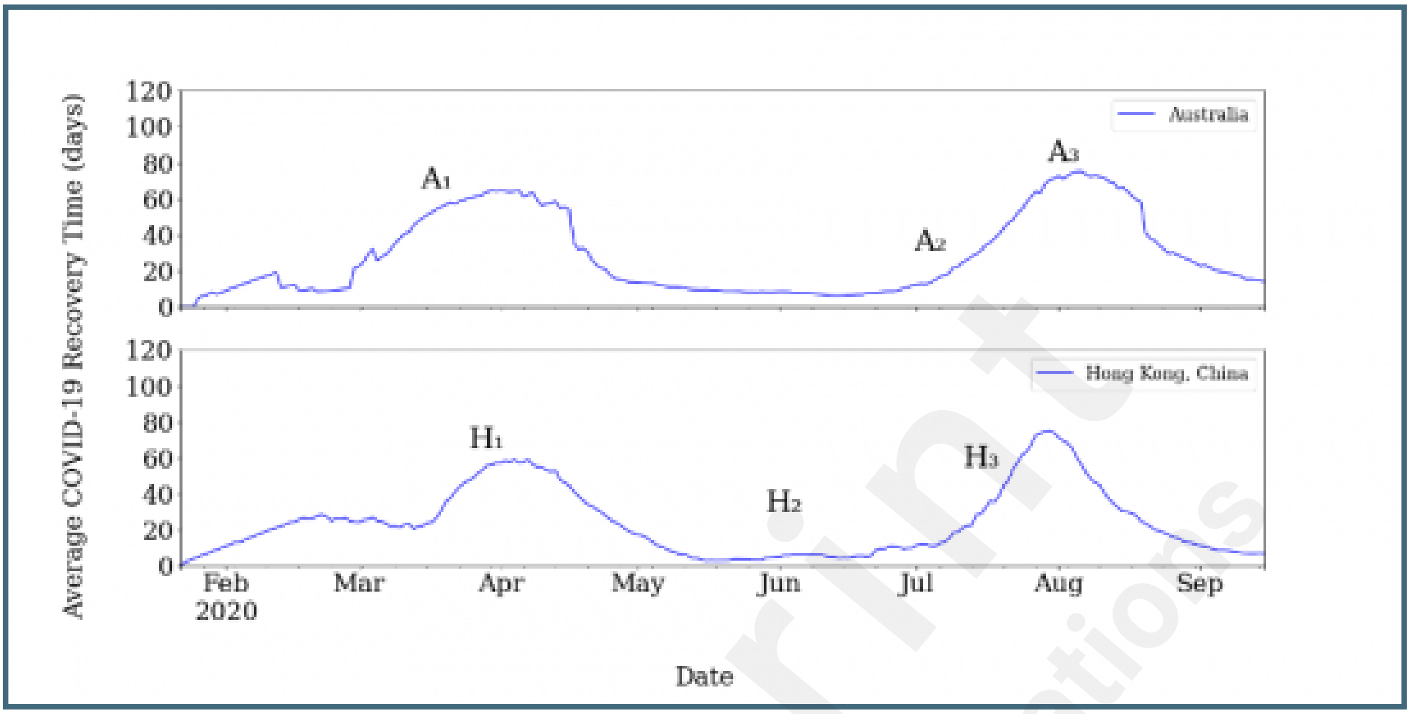
Average Recovery Time for U.S., Spain, Netherlands, Serbia, France, Sweden and Belgium.



Under Control of the Outbreak in Iceland, New Zealand, Taiwan, Thailand, and Singapore.



Second Wave of the Outbreak in Australia and Hong Kong (China).



Premature Lift the Lockdown in Malta and Spain.