Modeling and Comparing the COVID-19 Infection Rate for Taiwan and the United States of America Using Phase-Specific Nonparametric Density Regression Technique

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Abstract

This project uses nonparametric density and regression to construct a technique that can accurately and consistently model different countries' cumulative growth curve through phase divisions. Previous outbreaks (SARS, MERS, and the 1918 flu pandemic) and existing models (SIR and logistic/exponential) were initially consulted to help model the growth, but the unique replication and circumstances of COVID-19 is unlike any other. Additionally, different countries have different approaches to the pandemic, and using one prediction line for the whole curve will not model the growth patterns accurately. This paper utilizes the first and second nonparametric densities to divide up the graph into separate phases and then model each phase using regression. Although each phase already provides a general picture of the different stages of the COVID-19 pandemic, Taiwan's and United States' graphs were further studied and compared to uncover other underlying patterns. The importance of factors such as strictness and timing of government regulations, testing availability, and a working contact tracing system are all reflected in the slopes and durations of each country's models. This tool can be further applied across other nations that have reached farther phases in the outbreak to predict the duration and slopes for countries that are still trying to control the outbreak.

Key Words: COVID-19, Phase Modeling, Nonparametric Density, Regression

1. Introduction

The coronavirus pandemic has changed the lives of pretty much everyone around the world, causing job losses, panic buying, a global recession, school closures, and other devastating effects. One persisting question that people continue to ask is "How bad will this pandemic be?" From a scientific perspective, this question is extremely hard to answer. When a vaccine will arrive and how long the world can continue to stay sheltered at home are just some of the factors that make this question so hard to answer accurately. Before building a different model, the authors first consulted previous outbreaks and existing models across the world.

1.1 Coronavirus Overview

Coronavirus replication was studied to better understand the virus behind the SARS, MERS, and COVID-19 pandemics. "Coronaviruses are the largest groups of viruses belonging to the Nidovirales order" [1] and contain four main structural proteins – spike, envelope, membrane, and nucleocapsid. The virion (a form of the virus before infection) attaches to the host cell initially between the spike protein and its receptor [2]. After the receptors have bound to the host cell, the virus must gain access to the cytosol, a fluid-like component in the cytoplasm of the cell. This releases the viral genome into the cytoplasm

[3]. The coronavirus genome acts like a messenger RNA, enabling it to be directly translated on the cell's ribosomes. The virus then makes the cell copy the virus's RNA in bulk in a double-membrane compartment which keeps the virus hidden. These copies teach the cell's ribosomes how to make viral proteins [4]. Then, a copy of the virus's RNA corrals the newly made viral proteins which forms a new virus. The new viruses travel in a compartment to leave the cell, infect other cells, and produce even more viruses [5]. The replication process is outlined in Figure 1.

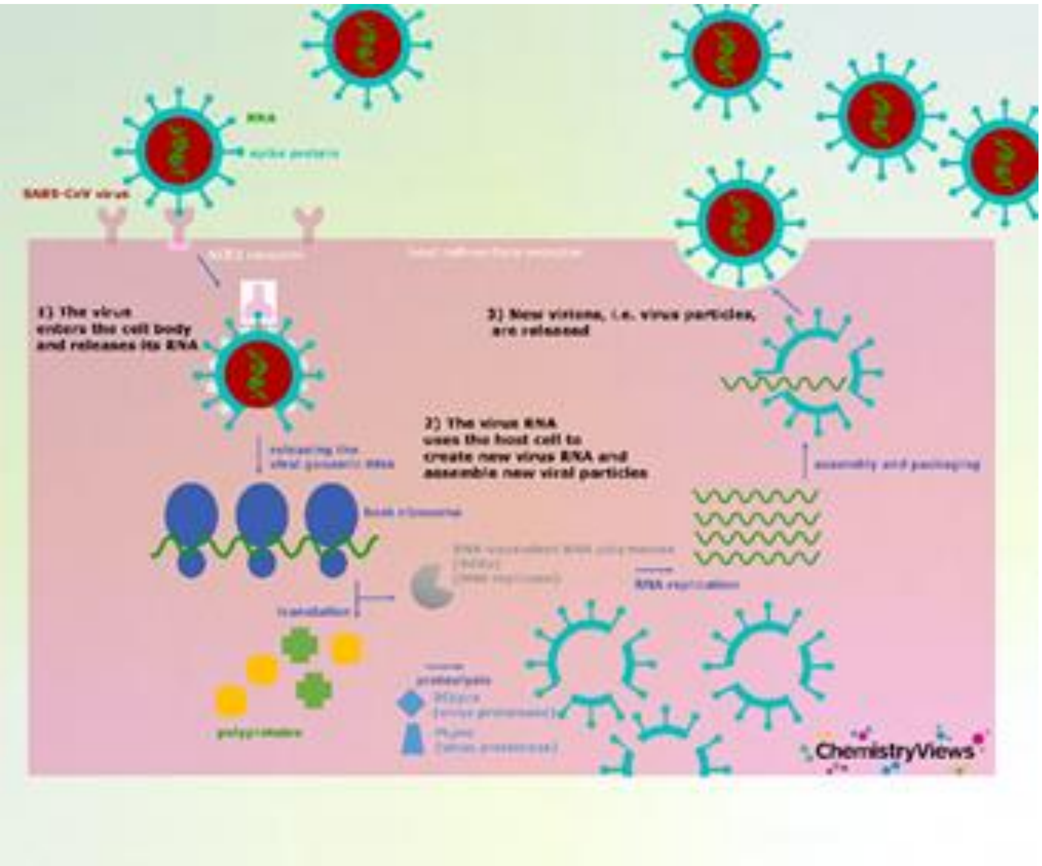


Figure 1: Diagram of Coronavirus (SARS-CoV) entry and replication [6]

1.2 SARS, MERS, and other pandemics

Coronaviruses can have varying degrees of mortality rate. An estimated 15% of common colds are caused by certain coronaviruses [7]. Some more deadly outbreaks like the SARS-CoV (severe acute respiratory syndrome – coronavirus) have affected over 8000 people in 29 countries and killed nearly 80 people [8]. The 2012 outbreak of MERS (Middle East respiratory syndrome) had a whopping 37% fatality rate, spreading in over 27 countries [9]. Although these outbreaks are caused by similar viruses to the COVID-19 pandemic, the MERS outbreak is not as infectious, only affecting 29 countries, but seemed to be much deadlier. SARS, on the other hand, was generally transmitted after people started showing symptoms, helping contain the outbreak (and as a result only spreading to 27 countries). COVID-19 has been reported in more than 188 countries [10], and large proportion of those who have the virus show no symptoms, so it is not accurate to consult these previous outbreaks only when modelling the COVID-19 pandemic.

What about other, older pandemics like the 1918 Spanish flu? Although some sources estimate that more than 50 million people died of the disease [11], the actual number is unclear as some countries covered up actual statistics due to World War I (to maintain morale). At the same time, the virus was caused by influenza, a different virus than the coronavirus (and consequently has a different behavior). The types of technology available now and improved global communication are just a few factors that make the COVID-19 pandemic different from the Spanish flu.

1.3 Investigating Existing Models

It is tough to compare previous pandemics with the COVID-19 as there are just too many differences. Many models have been consulted to help predict and estimate the COVID-19 infection rate – the most common one being the SIR model. The "SIR represents the three compartments segmented by the model: Susceptible, Infectious, Recovered" [12]. This model uses the R0 factor, or the basic reproduction number, that measures the average number of people (who initially do not have the disease) that one person who has the disease can transmit to (e.g. if the R0 factor is 2, then an infected person transmits the disease to an average of 2 people who were originally uninfected).

Another, simpler but effective method uses linear regression after a logarithmic transformation, (in the form of $\log(x(t)) = \log(x0) + \log(b)*t$) where t goes on the x-axis and $\log(x(t))$ on the y-axis. This method was used to predict the infection rate towards the beginning (from 1/24 to 3/16) of the pandemic before switching to a logistic growth model after hitting the peak infection of the virus.

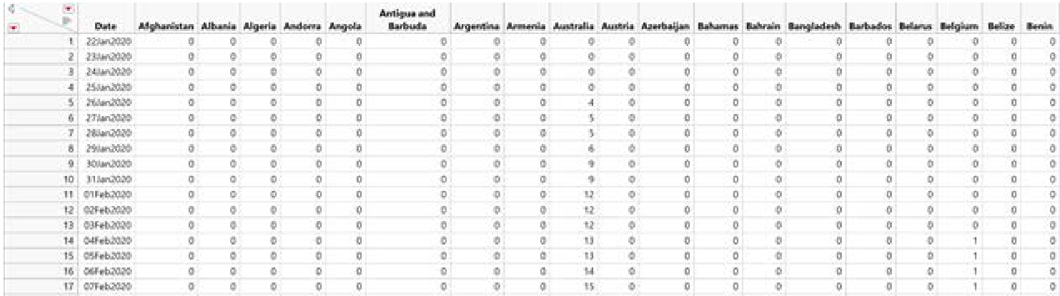
One major disadvantage of the logistic/exponential and SIR model is that ideal scenarios are assumed – that each country follows a similar, smooth infection curve. This is not the case, as each country has its own unique curve which may or may not be as smooth as expected (for example, a sudden outbreak in a certain city can change the trajectory of the curve drastically). Thus, using the same model across all different countries and time frames may not be the best way to model the COVID-19 outbreak, especially considering the different events that occurred specific to each country. Other factors including the extent and strictness of regulation, health resources, and prior experiences with pandemics can change each country's behavior. This paper will construct an overall model that uses different models for different time intervals (or phases). This phase-specific model can help compare different country's infection behavior and control over the virus.

2. Data Collection and Methods

This paper proposes a novel method of nonparametric density and density quantile estimation in JMP to delineate a phase-specific regression to model the COVID-19 infection rate. Taiwan's infection curve was chosen to be the benchmark for phase divisions as it has contained the virus to a certain extent and reached all the phases identified in this paper. This method can help uncover patterns such as the effect of timing and strictness of regulations across different countries by looking at the duration and slope of each phase, which will be explained further in this section.

2.1 Data Collection

The data used in this study are from John Hopkins University. As seen in Figure 2, the data starts from January 22, 2020 and is updated daily at 11:59 PM UTC. Each country's number of total cases (cumulative) are recorded until June 19, 2020, the last data point used in this paper.



	Date	Afghanistan	Albania	Algeria	Andorra	Angola	Antigua and Barbuda	Argentina	Armenia	Australia	Austria	Azerbaijan	Bahamas	Bahrain	Bangladesh	Barbados	Belarus	Belgium	Belize	Benin
1	22Jan2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	23Jan2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	24Jan2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	25Jan2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	26Jan2020	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
6	27Jan2020	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
7	28Jan2020	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
8	29Jan2020	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0
9	30Jan2020	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0
10	31Jan2020	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0
11	01Feb2020	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0
12	02Feb2020	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0
13	03Feb2020	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0
14	04Feb2020	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	1	0	0
15	05Feb2020	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	1	0	0
16	06Feb2020	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	1	0	0
17	07Feb2020	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	1	0	0

Figure 2: Screenshot of raw data in JMP software (ver.15 © SAS Inc, Cary NC, 2020)

2.2 Taiwan Curve

Taiwan's infection curve (cumulative number of cases versus days, as shown in Figure 3) was examined before applying any methods of analysis. It can be seen that it would be hard to fit a simple method that can precisely model the whole curve from start to end. Phase modeling can be used to divide up the curve, and then model each of the partitions or "phases" separately using regression – but how should the phases be divided? Partitioning the curve just from looking at the graph would be neither systematic nor consistent, so another method – the nonparametric density – can be used to help decide the phases more accurately.

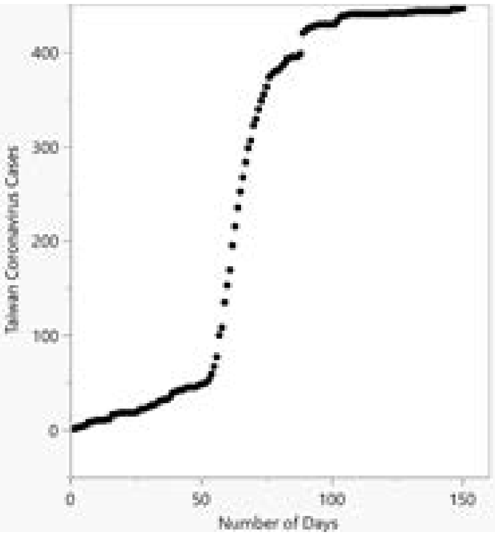


Figure 3: Taiwan infection curve

2.3 Non-Parametric Density

Nonparametric densities can be generated in JMP software in order to provide "a smooth nonparametric bivariate surface that describes the density of the points [13]." This tool can help visualize density patterns for large datasets. The plot has a set of contour lines, and different colors represent different % of points that are "outside" the contour lines. In Figure 4, the contour lines and contour fills are applied to the graph from Figure 3. The outer purple contour has an estimated 0-10% of the points outside the lines (so 90-100% of the points are inside the region), while the darkest red contour has an estimated 90-100%

of points outside the lines. The quantile intervals used in this paper are 10% as seen in the legend labeled “Quantile Density Contours” at the bottom of Figure 4.

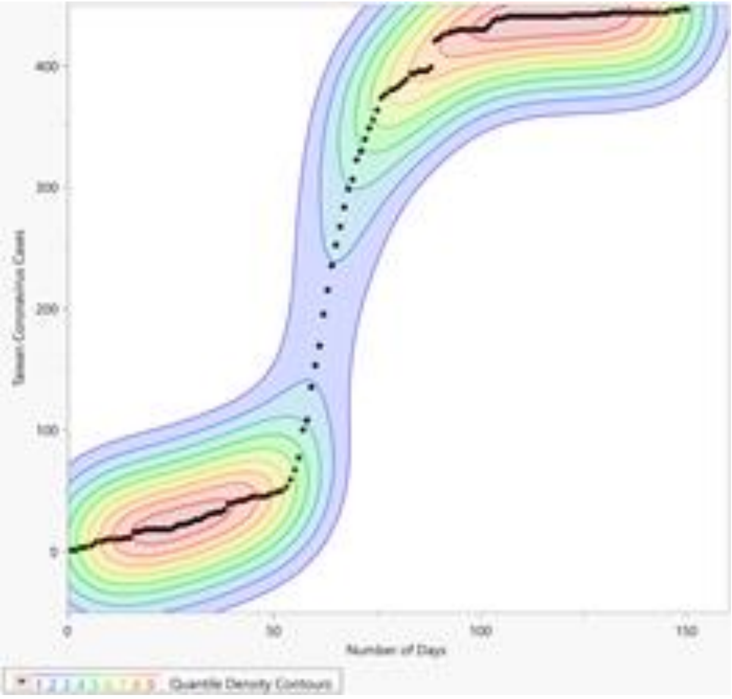
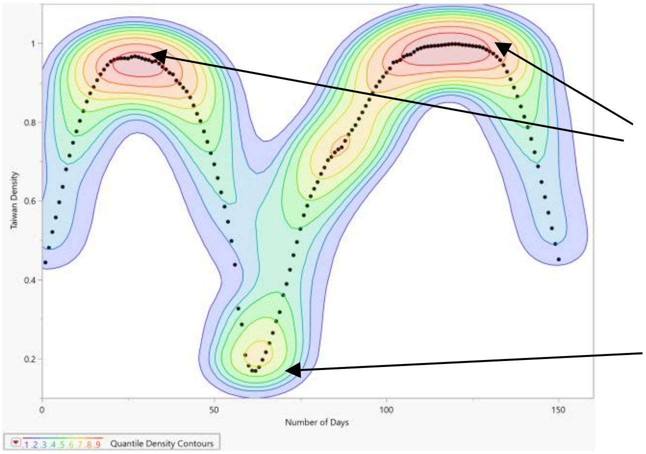


Figure 4: Taiwan infection curve with quantile density contours in 10% intervals

In addition to viewing the infection curve with density contours (“first density”), the density quantiles (“second density”) can be generated and saved for each point (creates a new column in JMP of the exact density each point is in). Then, the same procedure can be conducted (fit “Number of Days” with the density quantiles), and then add the contour lines again (the rest of the paper will use “second density” to describe this method) as seen in Figure 5. Both the first and second density graphs will be used to divide up the phases. Comparing these two graphs (Figure 5 and 6) shows that the lower the second density is on the y-axis, the more the infection rate is increasing (as the density points are farther apart and thus the infection rate is climbing faster – and fastest at around day 40, the lowest point on the second density graph). However, if the second density is relatively high (0.8-1 range on the y-axis), the number of cases is increasing gradually, as seen before the virus went out of control and once again after the virus was under control.



Infection rate increasing gradually near quantile density = 1.

Infection rate increasing the fastest near quantile density

Figure 5: Taiwan infection curve with quantile density contours in 10% intervals

2.4 Phase Divisions

Nonparametric density helps visualize where to separate the phases much more easily. Using both the first density and second density, Taiwan's curve can be divided into 4 main phases. Figure 6a shows the Taiwan coronavirus curve with contour lines (from Figure 4) and the phase divisions. Phase 1 follows an incremental, linear curve lasting 51 days with the density cutoff at 0.7 (as seen on the y-axis for the Phase 1 cutoff in Figure 6b). Phase 2 lasts for 10 days, until the second density graph reaches a minimum at 0.168 on Day 62 (once again, the cases climb the fastest on Day 62 as it has the lowest density). Phase 2 seems to follow an exponential or quadratic pattern. Phase 3 is the mirror image of Phase 2, following a logarithmic/square root pattern. Nevertheless, due to the two sudden jumps (the first one labeled "Phase 2.5" and the second shortly before the end of Phase 3), Phase 2 was modeled only until the "Phase 2.5" label as it is not plausible to model all the way up to the "Phase 3" mark due to the "disruptions" (as it would fit poorly). If the "disruptions" had not occurred, Phase 4 would most likely have started at the "Phase 2.5" mark. These "disruptions" in the graph will be further discussed in Section 3, but for now, they are just identified. Phase 3 lasts for 43 days (only 27 of the days are modeled), ending where the second density is inside the 0.9 (darkest red) contour. In Phase 4, the total case increase seems to return to a linear pattern similar to Phase 1 but with a smaller slope. Taiwan has been in Phase 4 for 47 days as of June 19, 2020.

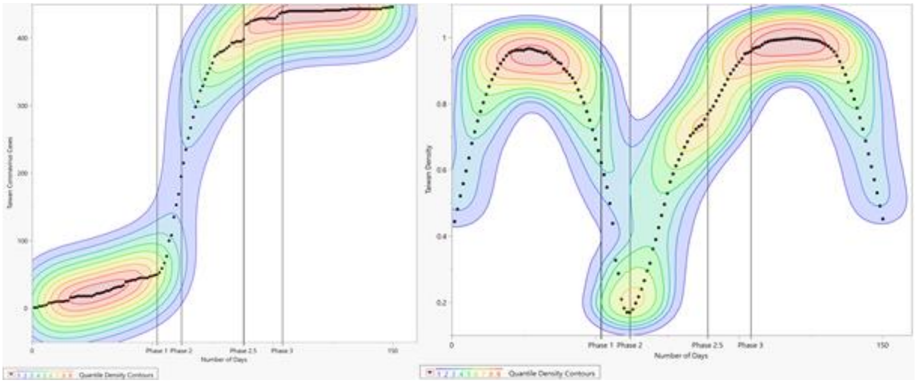


Figure 6: a) Taiwan's cumulative infection curve with quantile densities and phase divisions and b) Taiwan "second density" curve

2.5 Phase Modeling

The first and second quantile graphs can help visualize the phase divisions much more clearly. Now, each of these phases can be modeled using simple linear regression with or without a transformation of x (with x being the number of days since the last day of no recorded cases – January 21, 2020) and y being the number of Taiwan coronavirus cases. The r2 statistic was used to assess the model "fitness" as it measures the amount of variation in y explained by x (and has a very practical meaning in bivariate regression unlike its square root counterpart, r). Phase 1 and 4 are modeled using linear regression (without a transformation). Phase 2 uses a quadratic transformation (number of days was squared) instead of the exponential model as it has a higher r-squared value (0.99 versus 0.63). Phase 3 uses a logarithmic transformation (log number of days) instead of a square root model since it is a slightly better fit (0.97 versus 0.95), and only the first 27 of the maximum 43 days are modeled due to the disruptions. All 4 phases are modeled well, with more than 90% of the variation explained by their lines of best fit. The 4 phases' durations, lines of best fit, and r2 are summarized in Table 1 and will be revisited in Section 3.

Table 1: Summary statistics for all 4 phases of Taiwan

Phase	Duration (days)	Line of Best Fit	Fit Description	r^2
1	51	$0.1356x – 1.688$	Linear	0.90
2	10	$1.259x^2 – 48.63$	Quadratic	0.99
3	27-43	$72.06*\log x + 438.4$	Logarithmic	0.97
4	47	$0.1351x + 7957$	Linear	0.90

2.6 Phase Characteristics

Using nonparametric density and regression, each phase can be modeled pretty accurately, but what are the characteristics of these phases? What do the slope and duration indicate? Each phase represents different stages of the COVID-19 spread, and this subsection will try to explain the connection between and the importance of the 4 phases.

2.6.1. Phase 1

Phase 1 follows a linear pattern and has a relatively small slope. People go about their regular, daily lives in this phase. Cases in Phase 1 are usually from large, international cities such as Seattle and New York City for the United States. Since the virus originated from Wuhan, China, large cities are most likely to be where the first cases originate as some travelers returning home from Wuhan carry the virus. Phase 1 is a critical period for nations to prepare for Phase 2 before the outbreak starts to spiral out of control, and the longer the duration of Phase 1, the more time for preparation. Countries that prepare well in Phase 1 may not even enter Phase 2 and transition directly into Phase 3.

2.6.2. Phase 2

The virus starts to spread uncontrollably in this phase. Sometimes, the start is rather sudden, fueled by a local outbreak that causes the country's infection curve to change immediately from Phase 1 to 2. Preparation from Phase 1 such as vigorous testing, contact tracing systems, and strict/early government regulations can help lower the slope and shorten the duration of Phase 2. Simultaneously, places where the outbreak occurs widely must prepare for Phase 3 when health resources (beds, ventilators, workers) are desperately needed to help treat those who have the virus.

2.6.3. Phase 3

Phase 3 starts when the virus has just spread at its fastest and is starting to decrease. An excellent healthcare system and strict shelter-in-place rules are crucial to containing the outbreak by lowering local transmission or preventing hospital infections. Countries which do not have enough resources or have already started to relax regulations may continue to stay in Phase 3 for a long time. An aggressive approach and citizen awareness are needed to decrease this phase's slope and duration.

2.6.4. Phase 4

Phase 4 is the best-case scenario. Countries in this phase have reached a steady state and have the virus under control for now. Most people are very alert of the virus now but continued control and monitoring is still important, so that the nation's curve will stay in this phase and not return to Phase 3 or 2. Countries usually start relaxing regulations when this phase has been reached which may cause the curve to "backtrack" to a previous phase pattern, although gradual relaxing and continued tracking can help nations keep the virus under control.

3. Statistical Analyses

Section 2 demonstrated how this nonparametric density regression modeling technique can be used to divide up a country's curve of total Coronavirus cases into different phases. Each phase has its own characteristics, and the slope and duration for each phase represent how well the country has the outbreak under control at different stages. Although this gives a general picture of the COVID-19 outbreak, do different approaches to containing the outbreak actually affect the slope and duration of each phase? This section will look into the infection curves for Taiwan and United States, two countries which have different responses to containing the virus. The uniqueness of each country will be discussed, and the slope, duration, and timing for each phase will be studied and connected to events and decisions that may have influenced it.

3.1 Taiwan

Taiwan's models have already been developed in Section 2.5 and shown in Table 1. Although Taiwan may be "situated less than 100 miles from China, with more than 1 million Taiwanese working in China [14]" and "excluded from the World Health Organization [15]" (causing officials to miss out on early important information about the outbreak), it has only recorded 451 cases with only seven deaths even with a population of more than 23 million people [16]. Several factors have contributed to Taiwan's ability to control the virus in its early stages, causing Phase 1 to have an extremely small slope and last more than 50 days. After having the second-highest number of SARS cases and deaths after China [17] in 2003, Taiwan has been able to learn valuable lessons from it, and its government prepared a "strong plan … for managing a pandemic [15]" even before it struck.

First, Taiwan had easy access to free testing centers and ordered temperature checks at restaurants, gyms, offices, etc. since January [15], way before most nations. Taiwan has been able to get ahead of face mask shortages, cranking up face mask production since February [18]. People who do not wear masks in public areas would receive huge fines [15], and there was regular communication with the public, with Taiwanese health officials holding daily briefings for months [15]. Arguably most importantly, its advanced digital health system allowed doctors and nurses to access everyone's travel history, closely monitoring those who have been to places where COVID-19 is widespread [15]. In summary, easy and free testing, increased mask supplies, enforced mask laws, regular communication, and a well set up digital health system have all played a part, in not just lengthening Taiwan's Phase 1 duration, but also quickly transitioning it from Phase 2 to 3.

Although Taiwan seemed to have once again controlled the virus at around the Phase "2.5" mark, the cases suddenly jumped from 169 to 195 on March 23, 2020 – the biggest one-day increase for Taiwan. "All but one of the new cases was imported, in people with travel histories to the United States, Spain, the Netherlands, France, Switzerland, and Britain [19]." Taiwan would immediately shut its borders the next day, banning all airline transits from March 24, 2020, to April 7, 2020, causing the infection growth to immediately slow down and return to daily cases of less than 5 at the end of the ban. One last disruption would occur in Taiwan's curve on May 3, 2020, after 6 consecutive days of no new cases due to infections on three naval vessels [20]. Taiwan quickly controlled the cluster outbreak, and it would enter Phase 4 just the following day.

3.2. United States

The United States has struggled to contain the virus, and as seen in Figure 7a, it is still in Phase 3 as of June 19, 2020. The darkest red contour (90% density) has not appeared in Figure 7a after the end of Phase 2, indicating Phase 4 has not been reached. This dark red contour does appear in the Taiwan curve in Figure 6a, signaling that Taiwan has reached Phase 4, unlike the USA. The second density graph is shown in Figure 7b.

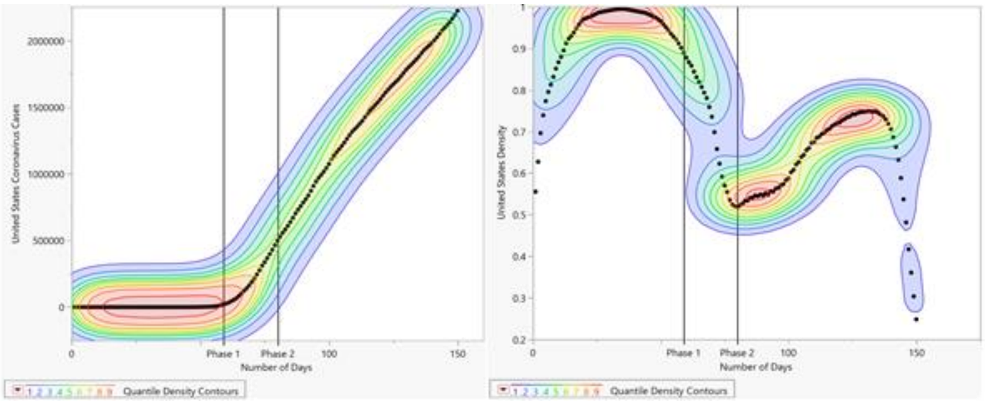


Fig. 7 a) United States' cumulative infection curve with quantile densities and phase divisions and b) United States "second density" curve

Several factors have caused the United States to fail to contain COVID-19 and account "for 28% of all deaths related to coronavirus disease, despite comprising only 4.25% of the world's population [21]." Previous outbreaks of dangerous viruses such as the Zika, Ebola, MERS, SARS have all had minimal impact on the United States, with zero mortalities for the latter two outbreaks [21]. This may have been due to USA's geographic location as it is an ocean away from all of the epicenters of recent major outbreaks. "The higher calculated case fatality by the World Health Organization early in the outbreak [21]" may have given a false impression that it would be similar to previous outbreaks which were all geographically contained. "Moreover, improper comparisons to seasonal influenza [21]" may have contributed to a false sense of safety (that if someone survived the flu, they too could survive COVID-19). Additionally, many believed that only the elderly was at risk as China initially reported a "fatality rate of 14.8% of 80 years or older [but only] 0.6% fatality in patients under 60 years old [21]." This may have led younger people to feel protected from the virus. All these factors have contributed to the United States' slow response to containing the virus, and consequently a 41-day long Phase 2 with a slope of 260 as seen in Table 2.

Even when the virus started spreading out of control in Phase 2, the United States did little to try to control it compared to other nations that have contained the outbreak. Countries such as Singapore and South Korea have been able to avoid the extreme lockdown (as seen in Italy) by implementing widespread testing, aggressive contact tracing, and a mandatory 14-day quarantine for those who have been identified as possible carriers of the virus [22]. The US has failed to deploy these methods effectively despite having the most expensive health care systems in the world [23]. Although a main reason that has prevented disease detectives from doing their job is because of early testing failures [22], there had not been an adequate testing supply for COVID-19 in the United States in Phase 2, when testing was most important [21]. The contact tracing system – an already costly and time-consuming procedure even when the outbreak is small in Phase 1 [21] – was not set up early enough, causing contact-tracing to become even harder in Phase 2.

Table 2: Summary statistics for all 3 phases of United States

Phase	Duration (days)	Line of Best Fit	Fit Description	r^2
1	38	$0.3810x – 2.886$	Linear	0.89
2	41	$260.0x^2 – 50229$	Quadratic	0.91
3	71+	$24033x + 544500$	Linear	0.99

Testing has since then started becoming more available across the US [21], entering Phase 3 almost two months since its first identified case. Nevertheless, its Phase 3 is a linear – not a logarithmic pattern – with a slope of 24,000, and the curve has yet to be flattened. The United States continues to struggle in keeping the nation locked down due to a growing fear of economic consequences [21], the major reason why it has not been able to enter Phase 4.

4. Results and Conclusions

Past experiences from the SARS pandemic has helped Taiwan implement an efficient virus control plan even before the Coronavirus pandemic. Vigorous testing, a digital tracking system, regular communication, and mask enforcements have helped Taiwan slow down and control the outbreak. Although two cluster infections occurred in Phase 3 (which hindered the start of Phase 4) – one from oversees travelers and another from naval ships, Taiwan has successfully controlled both events. Taiwan's Phase 4 slope is even a little less than its Phase 1 slope, a testament to their highly effective COVID-19 response. The United States' inability to contain the virus can be attributed to a slow initial response as well as false impressions of the virus. This shortened its Phase 1 length to merely 38 days, roughly two weeks less than the number of days of Taiwan's Phase 1 length. Even in Phase 2, the US lacked testing kits, strict government regulations, and an effective contact tracing system. Although increased availability of testing has helped the United States enter Phase 3, its slope follows a linear one contrary to Taiwan's Phase 3 curve. The United States has been desperate to reopen even with the virus still out of control due to fears of economic reasons, but reopening too soon may even cause the US to return to Phase 2's quadratic pattern.

Using a novel method of analysis combining first and second densities in phase-specific nonparametric regression, this paper has studied two different countries with different approaches to containing the virus. The effectiveness of each country's COVID-19 responses is reflected in their slopes and durations of the different phases. This method is a systematic way to model each country separately and accurately.

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