Singapore's SARS-CoV-2 Infection Trend In 2020: A Lower Bound Estimate

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Abstract: Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) infection causes Coronavirus Disease 2019 (COVID-19). Knowledge on the SARS-CoV-2 infection trend is, however, lacking. This viral infection is invisible to the naked eye and is challenging to profile in real-time. Its closest indication is its documented COVID-19 epidemic trend. Fortunately, that is published daily and globally due to the pandemic situation of COVID-19. Leveraging the empirical nature and availability of these COVID-19 epidemic trends, this paper posits that these trends are, in fact, lower-bound estimates of the respective localities COVID-19 epidemic situation, and each is interrelated to the lower-bound SARS-CoV-2 infection trend in their locality. A model based on this posit is developed and applied to Singapore. The predicted Local SARS-CoV-2 infection trends provided a novel reference to understanding the Singapore COVID-19 epidemic that was previously not possible. They evidenced the window of opportunity where Singapore could have mitigated its COVID-19 epidemic via its Circuit Breaker (CB) that it had missed. They evidenced Singapore's additional tighter CB measures and extended CB dateline, both implemented during the CB on 21st April 2020, were timely and effective. They derived the population of imminent COVID-19 individuals that the empirical Local COVID-19 epidemic trend had undocumented daily. These undocumented populations are sizable and a possible factor for the COVID-19 epidemic and its protracted recovery. Finally, these SARS-CoV-2 trends provided circumstantial evidence that Singapore's COVID-19 epidemic originated from COVID-19 cases imported into Singapore.

Keywords: SARS-CoV-2 infection trend· COVID-19 epidemic trend· COVID-19 Confirmation Period · Normal Distribution · Cartesian Product · Backcasting · Forecasting · Lower-bound · Modelling · Python Programming ·

1 Introduction

Singapore reported its first two Coronavirus Disease 2019 (COVID-19) [1] cases on 23rd January 2020 [2]. This disease onset evolved from several independent sporadic outbreaks into an epidemic within that year. Publicly accessible daily COVID-19 Case Reports and Situation Reports issued by the Ministry of Health of Singapore [3] describe the extent of this epidemic. The *number of daily confirmed COVID-19 cases* is their unit of measurement of daily COVID-19 prevalence; they are the daily cumulative positive real-time reverse transcription-polymerase chain reaction (rt-PCR) tests and serologic assays [4]. Its daily compilation constructs the Singapore COVID-19 epidemic curves [5] for Imported and Local cases.
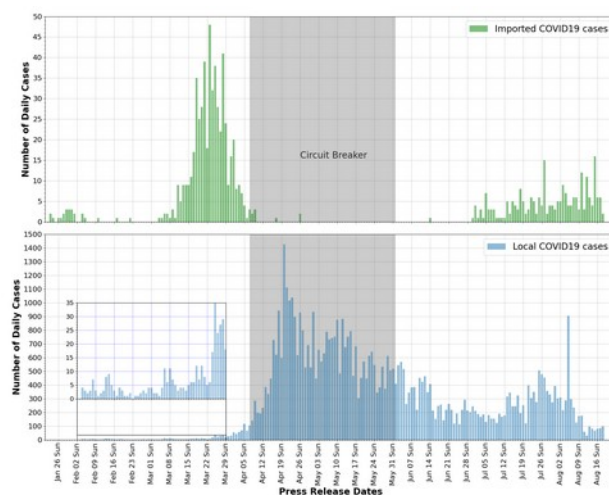
Figure 1: Singapore's COVID-19 Epidemic Curves from 23rd January to 18th August 2020.

Figure 1 illustrates these Imported and Local COVID-19 epidemic trends of Singapore (from 23rd January to 18th August 2020). It evidences the pervasiveness of the COVID-19 epidemic in Singapore that caused the implementation of a nationwide Circuit Breaker (CB), alternatively known as a Lockdown, that year. Although these trend curves are informative, they do not describe the events that caused COVID-19, i.e. they do not show when Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) infection had

occurred. The SARS-CoV-2 infection trend curve fulfils this function, yet it is unreported. A means to monitor SARS-CoV-2 transmission in real-time is unavailable. Also, COVID-19 patients could not see and did not know when they had contracted SARS-CoV-2.

There is unanimous consensus that the SARS-CoV-2 infection trend is not identical to the COVID-19 epidemic trend. One reason for this is that SARS-CoV-2 infection is a precursor of COVID-19. SARS-CoV-2 infection takes time to cause COVID-19 and takes time to be discovered and confirmed [6] by the patients, their doctors and contact tracers. Furthermore, COVID-19 confirmation can occur during the incubation, symptomatic and recovery periods of a SARS-CoV-2 infection as positive rt-PCR results are obtainable during these periods regardless of the virus transmissibility [7,8]. Presymptomatic SARS-CoV-2 transmissions, which occurs during the incubation period, have been evidenced in Singapore [9], China [10], and the USA [11]. In 2020, the incubation period of SARS-CoV-2 variants averaged at 5 to 6 days and ranged from 1 to 14 days [12,13]. Thereon, positive rt-PCR have evidenced too. A multi-centre USA study of 70,406 unique COVID-19 patients [14] found that a majority of COVID-19 patients yielded positive rt-PCR, i.e. shed SARS-CoV-2 ribonucleic acid (RNA), three weeks after their first positive SARS-CoV-2 rt-PCR test. Another study that reviewed 77 COVID-19 reports [15] found that the duration of SARS-CoV-2 RNA shedding can range from a minimum of 1 day to a maximum of 83 days. According to WHO [16], rt-PCR positivity generally appears up to 3 weeks or more for mild to moderate COVID-19 and a more extended period for severe COVID-19. These findings evidence the amount of lag that a COVID-19 epidemic trend could have against a SARS-CoV-2 infection trend.

The second manner where the SARS-CoV-2 infection trend is dissimilar to the COVID-19 epidemic curve is in their population. The SARS-CoV-2 infectee population, in reality, is more than the documented COVID-19 epidemic population. The under-reporting of asymptomatic and presymptomatic SARS-CoV-2 transmissions cause this phenomenon [17]. In Wanzhou, China, a 14-weeks COVID-19 mass testing program [18] found that asymptomatic and presymptomatic SARS-CoV-2 transmission accounted for 75.9% of all SARS-CoV-2; the abundance of close contacts before symptom onset or diagnosis facilitated them. Using a model that incorporates daily testing information fit to the COVID-19 case and serology data from New York City, researchers estimated that presymptomatic and asymptomatic SARS-CoV-2

transmissions together comprised at least 50% of the infections at the outbreak peak [19]. A decision analytical model study estimated that asymptomatic and presymptomatic SARS-CoV-2 accounted for >50% of all transmissions [20]. These studies exemplify the extent of under-reporting possibility occurring between the documented COVID-19 epidemic population against the actual SARS-CoV-2 infectee population.

Succinctly put, the actual SARS-CoV-2 infection trend will always appear ahead and exhibit a larger integral than its empirical COVID-19 epidemic trend. Its modelling is non-trivial to perform; the number of transmission factors for SARS-CoV-2 is many, their quantification remains challenging to implement, and SARS-CoV-2 transmission is opportunistic. To simplify its modelling while retaining an empirical basis, I posit that the officially published Local COVID-19 epidemic trend is, in fact, a lower-bound estimate of the Local COVID-19 epidemic and that it is a result of the lower-bound Local SARS-CoV-2 infection trend. Such a postulation is the basis of this paper.

The following sections present a model that utilises the abovementioned postulation, statistics, Cartesian-product, computation algorithm and empirical Local COVID-19 epidemic data to estimate the lower-bound Local SARS-CoV-2 infection trend of Singapore from January to August 2020. Its results contain the findings on the estimation of Singapore's daily mean Local COVID-19 confirmation period trend, lower-bound daily Local COVID-19 epidemic trend, and lower-bound daily Local SARS-CoV-2 infection trend. Their discussions give new insights into Singapore's COVID-19 epidemic situation in 2020.

2 The Model

2.1   *Assumptions*

The primary assumptions of the model are:

i.   Local SARS-CoV-2 infections that are presymptomatic, asymptomatic or symptomatic but are undocumented are negligible. Therefore, an empirical Local COVID-19 epidemic trend is a reasonable lower-bound estimate of the Local COVID-19 epidemic trend and is relatable to the lower-bound Local SARS-CoV-2 infection trend that precedes it.

ii. The Local COVID-19 confirmation event always lags behind its Local SARS-Cov-2 infection event. The duration between these two events is called

the *COVID-19 confirmation period (CCP)*. It follows the Normal/Gaussian distribution theory. Daily, the *CCP* probability density function is:

$$P(X) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp^{-\frac{(X-\mu)^2}{2\sigma^2}} \qquad (1)$$

Here, $X \in (-\infty, \infty)$ is the random variate of Eqn(1) and denotes the daily *CCP*, μ denotes its daily mean, σ denotes its daily standard deviation, and π denotes the *pi* constant. μ is not constant over the Local COVID-19 population history, i.e. μ is a function of days.

2.2   Hypothesis

The *backcasting* of a documented Local COVID-19 epidemic curve using μ and σ yields a lower-bound estimate of the SARS-CoV-2 infection trend. Vice versa, the *forecasting* of the lower-bound Local SARS-CoV-2 infection trend with μ and σ yields an estimate of the lower-bound Local COVID-19 epidemic trend, which is the empirical Local COVID-19 epidemic trend.

2.3   Methodology

Backcasting is a statistical computation algorithm performed from the Local COVID-19 confirmation event day. It involves:
1. Estimating the *CCP* of each Local COVID-19 patient with Normal distribution theory.
2. Determining the SARS-CoV-2 infection event day of each Local COVID-19 patient by subtracting the estimated *CCP* from the COVID-19 confirmation event.
3. Getting a histogram of all the estimated SARS-CoV-2 infection events. This histogram estimates the lower-bound Local SARS-CoV-2 infection trend of the Local COVID-19 population.

Forecasting similarly is a statistical computation algorithm. But unlike *backcasting*, its execution is from the SARS-CoV-2 infection event day. It involves:
1. Estimating the *CCP* of each Local SARS-CoV-2 infection event (this step is identical to *backcasting*).
2. Determining the Local COVID-19 confirmation event day of each Local SARS-CoV-2 infectee by adding the estimated *CCP* to the Local SARS-CoV-2 event.
3. Getting a histogram of all the estimated Local COVID-19 confirmation events. This histogram yields the lower-bound Local COVID-19 epidemic trend that should

resemble the empirical Local COVID-19 epidemic trend.

In *backcasting* and *forecasting*, the profile of the estimated lower-bound Local SARS-CoV-2 infection and COVID-19 epidemic trends rely on the values of the *CCP*, which in turn are a function of μ and σ. Empirical data on the μ and σ of Singapore's Local COVID-19 epidemic trend are unpublished. As such, they have to be estimated.
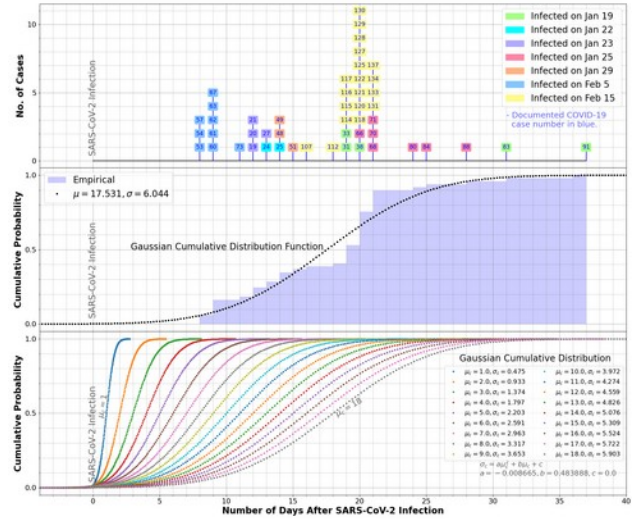
Figure 2: Illustration of the *CCP* of a sample of Singapore's Local COVID-19 cases, their cumulative probability distribution, and the Gaussian cumulative probability distribution parameters used to estimate the μ of Singapore's Local COVID-19 epidemic trend.

The procedure developed to estimate μ involves:
1. Iteratively perform the *backcasting* and *forecasting* algorithms for a range of constant μ scenarios (termed as μ_c).
2. Select μ_c as a probable value of μ for a given day when the number of estimated Local COVID-19 confirmation events that day is identical to its empirical data.
3. Complete this selection procedure upon reaching 300 samples of the μ estimates per day for the Local COVID-19 epidemic population.

The approximation of the range of μ_c in step 1 of this procedure is determined using empirical *CCP* data. Figure 2 illustrates the *CCP* from a sample of Local COVID-19 cases obtained from [3] and various national news sources. Its cumulative probability-density distribution is Gaussian-like with a mean and standard deviation of 17.531 days and 6.044 days, respectively. Assuming this empirical mean value indicates the maximum range of μ_c while letting a day be its minimum, then $\mu_c=[1,18]$ since the ceiling value of 17.531 days is 18 days. Furthermore, σ is assumed to be a quadratic function of μ:

$$\sigma = f(\mu) = a\mu^2 + b\mu + c \tag{2}$$

where a = -0.008665, b = 0.483888, c = 0.0 and $\mu=\mu_c$. Figure 2 illustrates the Normal Cumulative Probability Distributions of μ_c=[1,18].

The estimation of μ via the abovementioned procedure will, unfortunately, continue indefinitely when one or more elements of μ are unpredictable, i.e. when the element(s) of μ have zero value. In such an eventuality, a *Resemblance Algorithm* is to complete the estimation of μ. Firstly, the Cartesian Product of μ_c=[1,18] replaces the element(s) of μ that has zero value. Doing so allows the exploration of every possible sequencing of μ_c in these missing μ elements. Next, the *backcasting* and *forecasting* of each possible sequencing of these μ estimates the Local COVID-19 epidemic trend. Finally, the sequence of μ that yields the Local COVID-19 epidemic trend that best resembles its empirical counterpart is its μ. The measurement of resemblance is via a *cumulative-absolute-difference* (*CAD*) criterion:

$$CAD = \sum_{d=0}^{d_{max}} |T_e - T_m| \tag{3}$$

and its *weighted* counterpart (*WCAD*) criterion:

$$WCAD = \sum_{d=0}^{d_{max}} \left(\frac{T_e}{p} * |T_e - T_m|\right) \tag{4}$$

Here, T_e and T_m, respectively, denote the estimated and documented daily number of Local COVID-19 cases, d denotes the day, d_{max} denotes its maximum, and p denotes the population of the empirical Local COVID-19 epidemic. A complete resemblance occurs when the criterion $\to$ 0. The opposite is true when their value $\to$ ∞.

2.4 Computation

The implementation of the methodology is by the Python3 scripting language [21] and optimized libraries such as NumPy [22] and SciPy [23]. The visualization of their results is through Matplotlib [24]. Their source codes are in [25]. All computations are by a workstation installed with an overclocked Intel® Core™ i9-7960X CPU comprising 32 logical cores and 94.0GB of DDR4 RAM.

A strategy to achieve high computation efficacy is executing an instance of the *concurrent.futures.ProcessPoolExecutor* class of Python3 within a nested logical *while*-loop structure. This arrangement provides a continuous-concurrent stream of computation using every available logical core of the CPU. Also, large three-dimensional instances of the NumPy *ndarray* class facilitated data parallelism within each CPU logical core. The 1st, 2nd and 3rd dimensions of these *ndarrays*, respectively,

represent the number of iterations performed in each CPU logical-core, the range of μ_c, and the Local COVID-19 epidemic population. On this workstation, the optimum *ndarray* size to operate 28 logical cores is 150x18x55136= 148,867,200 elements.

The generation of pseudo-randomness in the results are by the NumPy Permuted Congruential Generator 64-bit with DXSM (*PCG64DXSM*) class and the NumPy *random.SeedSequence* class. Also, three unique random seeds had primed the *random.SeedSequence* class, and thus the *PCG64DXSM* bit generator, to understand possible variance in their computed results.

3 Results

3.1 The Statistical μ Estimates
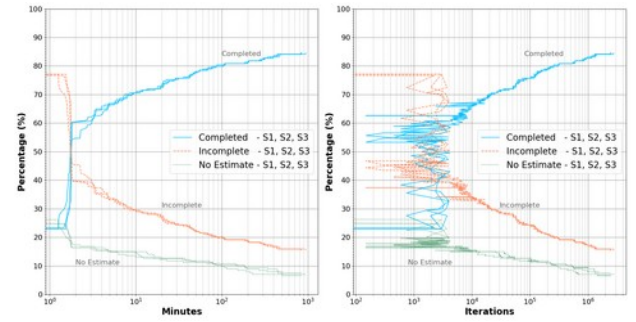
Figure 3: Illustration of the duration and iterations to estimate μ. "Completed" denotes achieving a sample quota of 300 estimates per day. "Incomplete" denotes not achieving the sample quota. "No Estimate" is a subset of "Incomplete" without an estimation of μ.
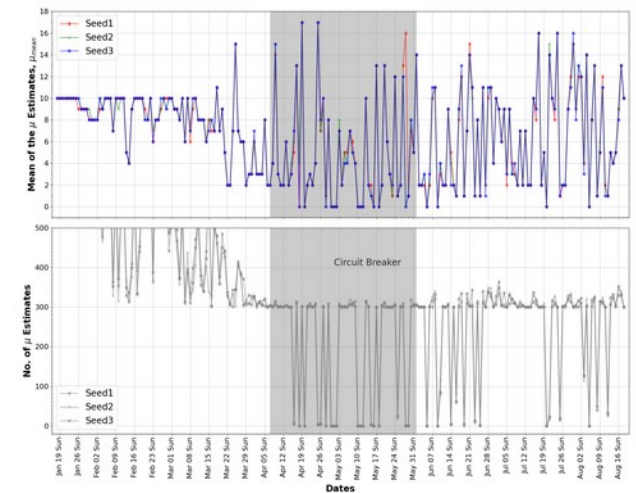
Figure 4: The mean of the respective estimates of μ for Random Seeds 1, 2 and 3. μ_{mean}=0 denotes no estimate of μ.

Figure 3 shows that the statistical estimation of μ for each random seed took 14 to 15hrs or ~2.48x10^6 iterations to complete ~84.58% of the Local COVID-19 population history of 214 days. This result

meant that 181 days of the 214 days achieved the sampling quota of 300 estimates per day. Of the remaining 15.42% (or 33 days of the 214 days) that are incomplete, 6.54-7.48% (or 14-16 days of the 214 days) achieved no estimate of μ. Beyond these thresholds, the statistical estimation of μ became unproductive and discontinued. Figure 4 shows the mean of the estimated μ, *i.e.* μ_{mean}, of each unique random seed. The low variance in these μ_{mean} trends indicates that the sampling quota of the μ estimates is sufficiently large.
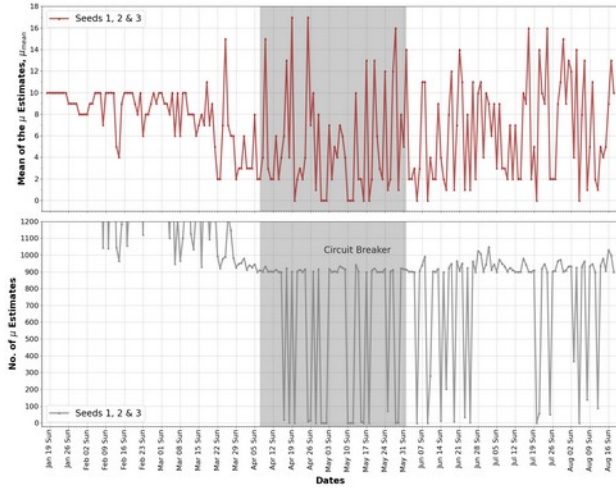
Figure 5: The mean of the combined estimates of μ for Random Seeds 1, 2 and 3. $\mu_{mean}=0$ denotes no estimate of μ.

Figure 5 shows the μ_{mean} trend of all the μ estimates combined. ~85.05% of the 214 days (or 182 days) achieved the sample quota of μ while ~14.95% of 214 days (or 32 days) did not. Of which, ~6.07% of the 214 days (or 13 days) had no estimates of μ. The completion of the μ_{mean} trend via the *Resemblance Algorithm* is needed and presented in the next section.

3.2   The Estimated μ_{mean} Trend

The Cartesian product of $\mu=[1,18]$ for thirteen missing elements of the μ_{mean} trend in Figure 5 is needed. Accordingly, $18^{13}=2.082296487\times10^{16}$ possible sequencing of these missing μ_{mean} elements, as well as the *backcasting-forecasting* and the *CAD-WCAD* treatments of their constituted μ_{mean} trends, needs computing. The completion of this Big-O time complexity is too computationally intensive to achieve on a workstation. Addressing this issue requires a reduction of the problem size. To this end, the following *Modified Resemblance Algorithm* is implemented:

1. The Cartesian product of $\mu=[1,18]$ shall not exceed five missing μ_{mean} elements for each computation. This decision discretizes the computation problem into three reasonably sized prediction steps (since 13days//5days=3

and $18^5=1,889,568$ iterations of the *backcasting-forecasting* and the *CAD-WCAD* treatments of their constituted μ_{mean} trends takes an hour or two to complete). The selection of these five missing μ_{mean} elements is according to whether they have the five highest empirical Local COVID-19 case counts and thus reordered. This reordering is performed on the three missing μ_{mean} elements of the last prediction step too.

2. In the 1st prediction step, the values of the eight missing μ_{mean} elements that are not selected are made constant for every possible scenario of $\mu_c=[1,18]$. In subsequent prediction steps, the μ_{mean} values from the iteration with the least *CAD* and *WCAD* scores in its previous prediction step replaces the unselected missing μ elements.

3. In each prediction step, the μ_{mean} trend of the iteration with the least *CAD* and *WCAD* score, respectively, are carried over to the next prediction step. In the final prediction step, the μ_{mean} trend with the least *CAD* and *WCAD* score, respectively, are selected.

Consequently, Step0 (the 1st prediction step) performs $18^5\times18=1,889,568\times18=34,012,224$ iterations, Step1 performs $18^5\times2=1,889,568\times2=3,779,136$ iterations and Step2 performs $18^3\times2=5,832\times2=11,664$ iterations, of *backcasting-forecasting* and *CAD-WCAD* treatments of their constituted μ_{mean} trends. These computations are performed for three unique random seeds to quantify the effects of statistical variances. Therefore in total, $37,803,024\times3=113,409,072$ iterations of *backcasting-forecasting* and the *CAD-WCAD* treatments of their constituted μ_{mean} trends are solved. Figure 6 shows the value assigned to the unselected missing μ_{mean} elements via the *CAD* and *WCAD* criteria for different Random Seeds from Step0 can be similar and dissimilar. Table 1 evidence small improvement gains in *CAD* and *WCAD* step after step of the *Modified Resemblance Algorithm*, the values of *WCAD* are one order smaller than *CAD*, and Seed2 yielded the least *CAD* while Seed3 yielded the least *WCAD*.
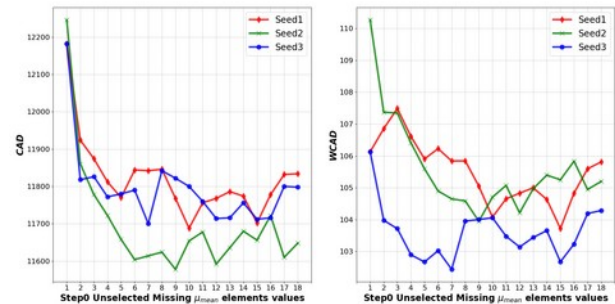
Figure 6: The least-*CAD* and least-*WCAD* scores obtained in Step 0 of the *Modified Resemblance Algorithm* for three unique random seeds.

	CAD			WCAD		
	Seed 1	Seed 2	Seed 3	Seed 1	Seed 2	Seed 3
Step0 :	11688	11578	11700	103.72	103.95	102.44
Step1 :	11598	11436	11546	102.52	102.66	100.29
Step2 :	11466	11304	11452	101.57	101.54	99.41

Table 1: The least-*CAD* and least-*WCAD* scores of Steps 0, 1 and 2 for three unique random seeds.

Figure 7 illustrates the μ_{mean} trends of Figure 5 after the *Modified Resemblance Algorithm* treatment for three Random Seeds. Their 14 days windowed Simple Moving Averages (SMA) show:

1. Singapore started with the SMA daily *CCP* of 9 days until ~1st March 2020.
2. In the next five weeks, i.e. leading into the CB, this duration decreased to 4 days.
3. Throughout the CB until 12th June 2020, this duration ranged from 4 to 8 days. This variation appears cyclical over a 4 to 5 weeks period.
4. Over the last 4 to 5 weeks, the SMA daily *CCP* ranged between 5 to 9 days.

The 14 days window of the SMA reflects the self-isolation/quarantine period mandated by Singapore's Stay-Home-Notice (SHN) Order [26]. These SMA trends of μ_{mean} evidenced the collective effort by Singapore to quickly confirm COVID-19 (given its SHN) started a month after the confirmation of its 1st Local COVID-19 case. This success then became periodic, fluctuating per month, during and post CB.
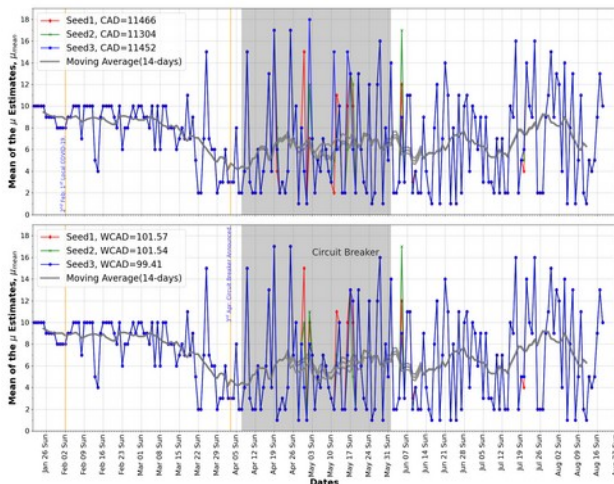

Figure 7: The mean of the estimates of μ, i.e. μ_{mean}, for Random Seeds 1, 2 and 3 combined (see Figure 5) completed with the μ_{mean} predicted by the *Modified Resemblance Algorithm*. Included is also their 14 days windowed Simple Moving Averages.

3.3 The Estimated Lower-bound Local COVID-19 Epidemic Trends.
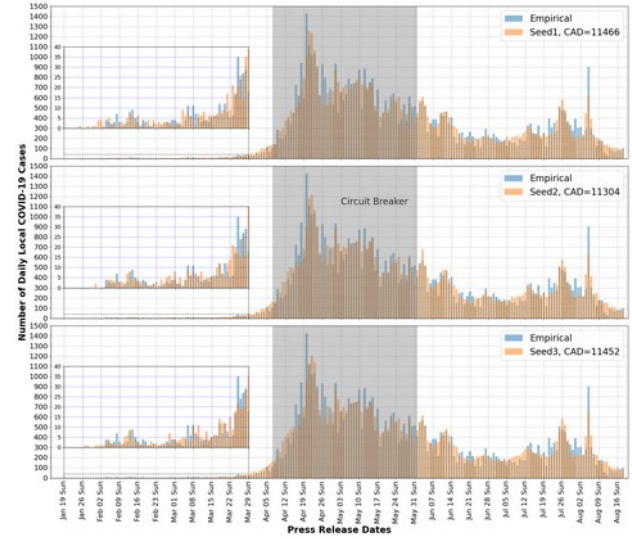
Figure 8: Comparison of the lower-bound Local COVID-19 epidemic trends estimated by the least-*CAD* criterion against its empirical counterpart.
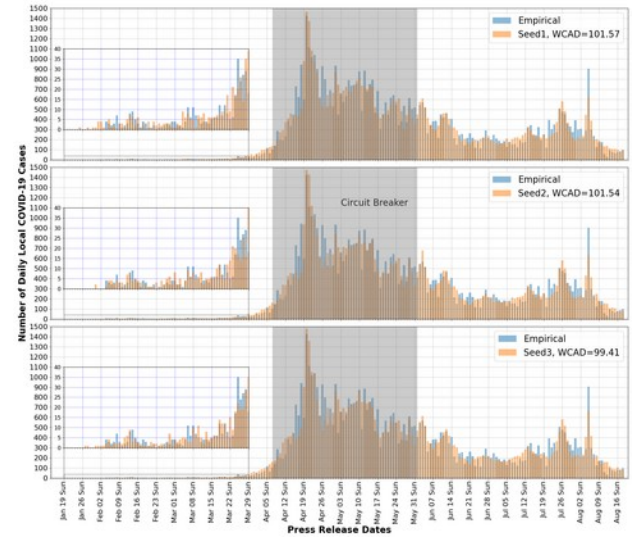
Figure 9: Comparison of the lower-bound Local COVID-19 epidemic trends estimated by the least-*WCAD* criterion against its empirical counterpart.

Population: 55136

	CAD			WCAD			CAD / Population		
Criterion:	Least-CAD	Least-WCAD	Diff.	Least-CAD	Least-WCAD	Diff.	Least-CAD	Least-WCAD	Diff.
Seed1:	11466	11660	-194	103.55	101.57	1.98	20.80%	21.15%	-0.35%
Seed2:	11304	11536	-232	101.96	101.54	0.42	20.50%	20.92%	-0.42%
Seed3:	11452	11552	-100	101.97	99.41	2.56	20.77%	20.95%	-0.18%
Mean:	11407	11583	-175	102.49	100.84	1.65	20.69%	21.01%	-0.32%
STDEV:	90	67	68	0.92	1.24	1.11	0.16%	0.12%	0.12%

Table 2: The *CAD* and *WCAD* scores of the lower-bound Local COVID-19 epidemic trends estimated by the least-*CAD* and least-*WCAD* criteria.

The estimated lower-bound Local COVID-19 epidemic trends resembled their empirical counterpart (see Figures 8 and 9). According to Table 2, the *CAD* scores from these estimated trends are ~21% of the Local COVID-19 population. This result means that

these estimated trends predicted or resembled ~79% of the empirical data.

An advantage of the least-*WCAD* criterion appears to be its ability to capture the peak of the Local COVID-19 epidemic trend (see Table 3). It predicted 1474 peak cases. This amount is closer to the actual 1426 cases than the 1226 cases estimated by the least-*CAD* criterion. Moreover, it correctly predicted the day of the peak event. The least-*CAD* criterion predictions were a day or two later.

Empirical: 1426 COVID-19 cases on 20th Apr 2020
Estimated: Local COVID-19 Daily Epidemic Peak

|	Max. Daily Case			Max. − Empirical		Date	
Criterion:	Least-*CAD*	Least-*WCAD*	Diff.	Least-*CAD*	Least-*WCAD*	Least-*CAD*	Least-*WCAD*
Seed1:	1255	1465	-210	-171	39	21st Apr	20th Apr
Seed2:	1217	1476	-259	-209	50	22nd Apr	20th Apr
Seed3:	1206	1479	-273	-220	53	22nd Apr	20th Apr
Mean:	1226	1473	-247	-200	47		
STDEV:	26	7	33	26	7		

Table 3: Data on the estimated and empirical peak daily number of confirmed COVID-19 cases.

With the strong resemblances to the empirical Local COVID-19 epidemic trend achieved by the estimated lower-bound Local COVID-19 epidemic trends, credence in the estimated lower-bound Local SARS-CoV-2 trends by the least-*CAD* and least-*WCAD* criteria is reasonable and presented next.
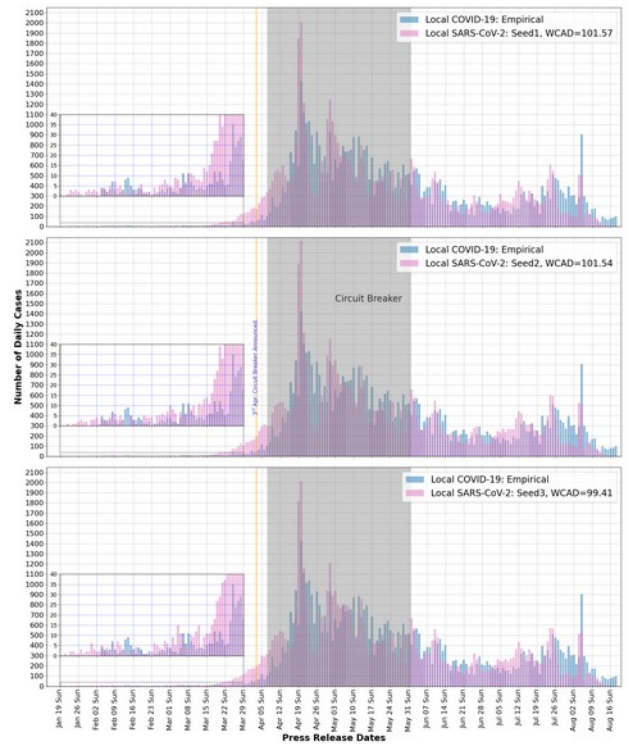
3.4   The Estimated Lower-bound Local SARS-CoV-2 Infection Trends.

Figures 10 and 11 plot the estimated lower-bound daily Local SARS-CoV-2 infections alongside the empirical Local COVID-19 epidemic trend. Table 4 presents data on their peak SARS-CoV-2 event. Together, they show that :

1. Local SARS-CoV-2 infection trends precede the Local COVID-19 epidemic trend.
2. The profile of the daily Local SARS-CoV-2 infection trends foreshadowed the growth and reduction of the daily Local COVID-19 cases.
3. Local SARS-CoV-2 infections had peaked on the same day as when the Local COVID-19 epidemic peaked, i.e. 20th April 2020. The least-*WCAD* criterion conservatively predicted that 2044 (±124 to ±183) daily SARS-CoV-2 infections had occurred that day. This amount is 618 (±124 to ±183) cases greater than the 1426 COVID-19 cases documented that day.
4. During the CB, a secondary peak SARS-CoV-2 infection event had occurred on 1st May 2020. A minimum of 1205 (±86 to ±129) to 1225 (±88 to ±132) Local SARS-CoV-2 infections occurred that day.
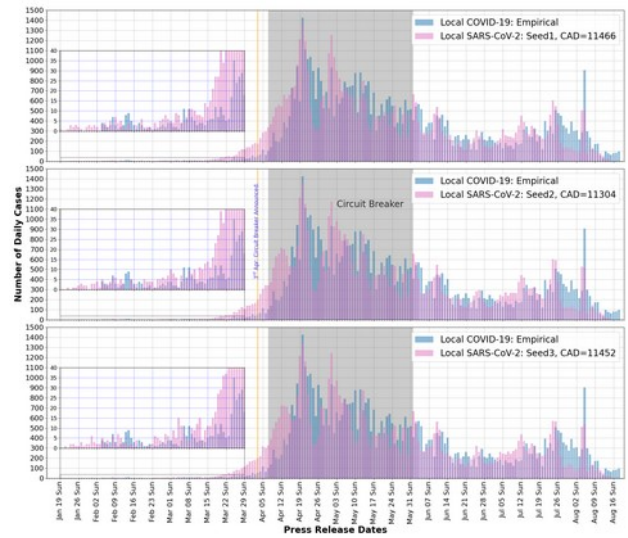
Figure 10: The lower-bound Local SARS-CoV-2 infection trends estimated by the least-*CAD* criterion contrasted against the empirical Local COVID-19 epidemic trend.

Figure 11: The lower-bound Local SARS-CoV-2 infection trends estimated by the least-*WCAD* criterion contrasted against the empirical Local COVID-19 epidemic trend.

Empirical: 1426 COVID-19 cases on 20th Apr 2020
Estimated: Local SARS-CoV-2 Daily Infection Peak

	Max. Daily Case			Max. − Empirical		Date	
Criterion:	Least-*CAD*	Least-*WCAD*	Diff.	Least-*CAD*	Least-*WCAD*	Least-*CAD*	Least-*WCAD*
Seed1:	1367	2007	-640	-59	581	20th Apr	20th Apr
Seed2:	1364	2116	-752	-62	690	20th Apr	20th Apr
Seed3:	1344	2009	-665	-82	583	20th Apr	20th Apr
Mean:	1358	2044	-686	-68	618		
STDEV:	13	62	59	13	62		

**Table 4:** Data on the predicted peak Local SARS-CoV-2 Infection event.

4 Discussions

The lower-bound Local SARS-CoV-2 infection trends in Section 3.4 provide a novel reference to understand the Local COVID-19 epidemic of Singapore. For example, Singapore could have mitigated the COVID-19 epidemic in 2020 if it had implemented its CB a week or two sooner. Figures 10 and 11 supports such a view as it shows that the origin of the exponential transmission of SARS-CoV-2 in Singapore predated the CB announcement and implementation by approximately two and three weeks, respectively. Also, given that Singapore had announced on 21st April 2020 further tighter CB measures until 4th May 2020 and extended the CB dateline to 1st June 2020 [27], in hindsight, these mitigation measures do seem appropriate in scale and timing. This conclusion is arrived at because this announcement predates 1st May 2020, the day sustain reduction in the transmission rate of SARS-CoV-2 in Singapore began to show signs.

Figure 12 plots the cumulative number of lower-bound Local SARS-CoV-2 infections leading to four events in Singapore's COVID-19 epidemic history. Namely, (a) the announcement of the CB, (b) the start of the CB, (c) when the daily Local COVID-19 epidemic peaked (this day also marks when daily Local SARS-CoV-2 infections peaked) and (d) when the 2nd highest peak in daily Local SARS-CoV-2 infection occurred. The figure also plots the cumulative number of empirical Local COVID-19 epidemic cases. Included are also the cumulative case counts on the day of these events. Together, these pieces of information illustrate the significant amount of imminent COVID-19 individuals undocumented by the Local COVID-19 epidemic trend. For example, at the CB announcement, the cumulative number of Local COVID-19 cases was only 570. However, the reality then was that 1800(±15) to 1807(±39) SARS-CoV-2 infectees, who shall develop COVID-19 within a week or later and who shall require medical resources, had already existed. Thus, a minimum of 1230(±15) to 1237(±39) COVID-19 individuals were still undocumented that day. These undocumented imminent COVID-19 individuals nearly doubled when the CB started. There were at least 2070(±15) to 2070(±39) such undocumented individuals that day. By the time the COVID-19 epidemic trend had peaked, the population of these undocumented individuals more than doubled to reach 4816(±15) to 4837(±39) such individuals. Despite decreasing to 3208(±15) to 3425(±39) ~1.5 weeks later, this amount of undocumented imminent COVID-19 individuals is still significant. Figure 13 also evidence that these undocumented individuals existed throughout the Local COVID-19 epidemic trend. The

inadequacy of the Local COVID-19 trend to document all carriers of SARS-CoV-2 that are guaranteed to develop COVID-19 in real-time is evident. It is a possible factor for the epidemic and its protracted recovery. The lower-bound Local SARS-CoV-2 trend avoids this inadequacy and is advantageous in this regard.
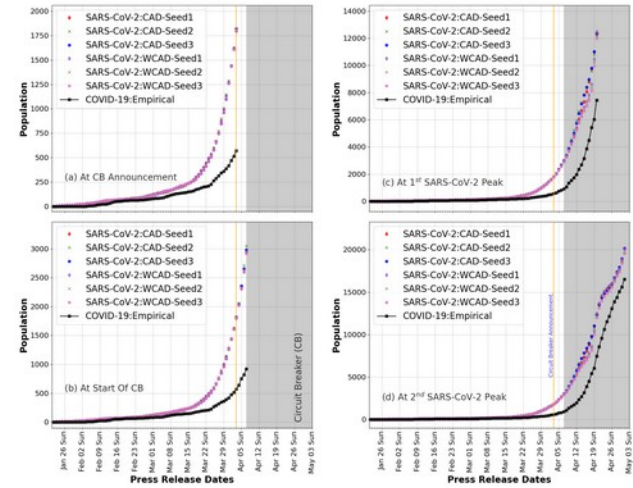
SARS-CoV-2:

Event:								
Criterion:	**(a)**		**(b)**		**(c)**		**(d)**	
	Least-CAD	Least-WCAD	Least-CAD	Least-WCAD	Least-CAD	Least-WCAD	Least-CAD	Least-WCAD
Seed1:	1795	1795	2942	2942	12349	12474	20057	20059
Seed2:	1805	1800	3052	2958	12156	12352	19652	19607
Seed3:	1820	1804	2982	2918	12353	11968	20168	19560
Mean:	1807	1800	2992	2939	12286	12265	19959	19742
STDEV:	13	5	56	20	113	264	272	276

COVID-19:	570		922		7449		16534	
Diff.:	1237	1230	2070	2017	4837	4816	3425	3208
Diff. / Mean	68%	68%	69%	69%	39%	39%	17%	16%

Figure 12: The evolving population of the estimated lower-bound Local SARS-CoV-2 infection trends and the empirical Local COVID-19 epidemic trend leading to (a) the announcement of the CB, (b) the start of the CB, (c) when the daily Local COVID-19 epidemic trend peaked (it is also when the daily Local SARS-CoV-2 infection trend peaked) and (d) the 2nd highest peak of the daily Local SARS-CoV-2 infection trend.
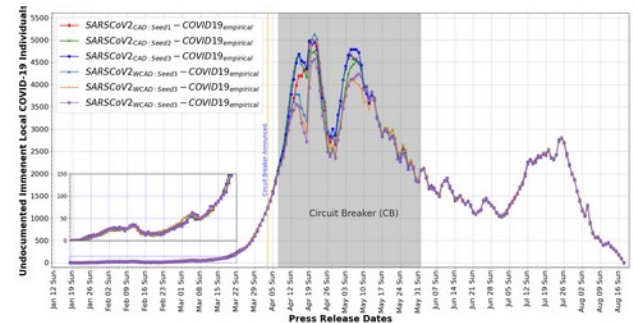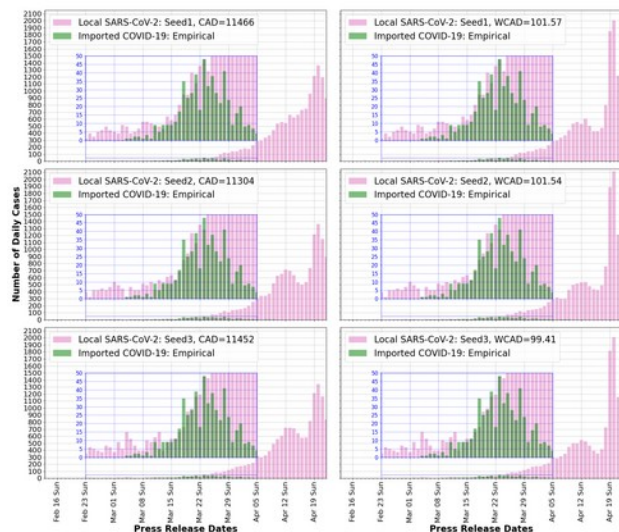

Figure 13: Differences in the population of the estimated lower-bound Local SARS-CoV-2 infection trends and the empirical Local COVID-19 epidemic trend, i.e. the undocumented imminent Local COVID-19 population. Note, its demise towards 18th August, though technically correct, is an artefact of the termination effect of the data used. If post 18th August 2020 COVID-19 epidemic data are included in the
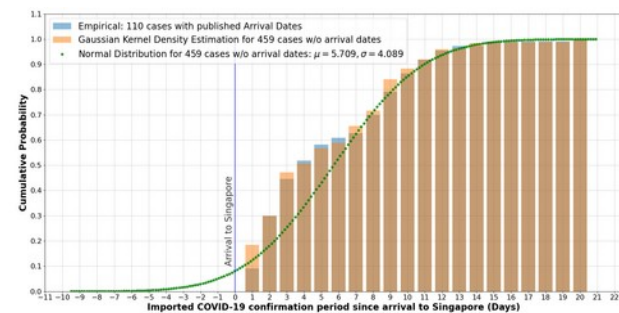
modelling, the sizable population of undocumented imminent Local COVID-19 individuals will have propagated.

Another use of the lower-bound Local SARS-CoV-2 trends is in the forensic analysis of the Local COVID-19 epidemic origin. Figure 14 compares them against the empirical Imported COVID-19 epidemic trend. The steep rise in Local SARS-CoV-2 infections occurred when Imported COVID-19 cases rose in Singapore. These two events occurred concurrently; circumstantially, they appear related. The likelihood that the influx of Imported COVID-19 individuals into Singapore in March 2020 caused the exponential transmission of Local SARS-CoV-2 that led to the COVID-19 epidemic seems plausible. Comparisons of the arrival dates by the Imported COVID-19 individuals against the lower-bound Local SARS-CoV-2 infection trends can evaluate this plausibility. If the Imported COVID-19 individuals did not cause the Local COVID-19 epidemic, their arrival in Singapore would never precede the start of the exponential transmissions of Local SARS-CoV-2. The opposite rationale applies if the arrival of the Imported COVID-19 individuals to Singapore precedes the exponential Local SARS-CoV-2 infections.

According to published records [3], there were 569 Imported COVID-19 cases by 19th April 2020. Of which, 110 had their arrival date published while the remaining 459 did not and need to be estimated. Figure 15 shows that the cumulative probabilistic distribution of the confirmation period of the Imported cases can be modelled by Gaussian Kernel Density Estimation (KDE_{gauss}) theory better than Normal Distribution theory. Thus, subtracting the Press-Release Date of each of the 459 Imported COVID-19 cases by the COVID-19 confirmation period predicted by KDE_{gauss} could reasonably approximate their arrival dates.

The daily arrival of the Imported COVID-19 cases (both empirical and estimated) are in Figure 16. A sizable sample of these Imported COVID-19 cases precedes by a week or two the start of the exponential rise in daily Local SARS-CoV-2 infections in March 2020. This lead time certainly gave opportunities for SARS-CoV-2 transmission to Singapore residents. The ease to flout the SHN by overseas arrivals at that time [28] further increases the dangers posed by these lead times to transmit SARS-CoV-2.

Figure 14: Singapore's lower-bound daily Local SARS-CoV-2 infection trends vs its Imported COVID-19 epidemic trend.
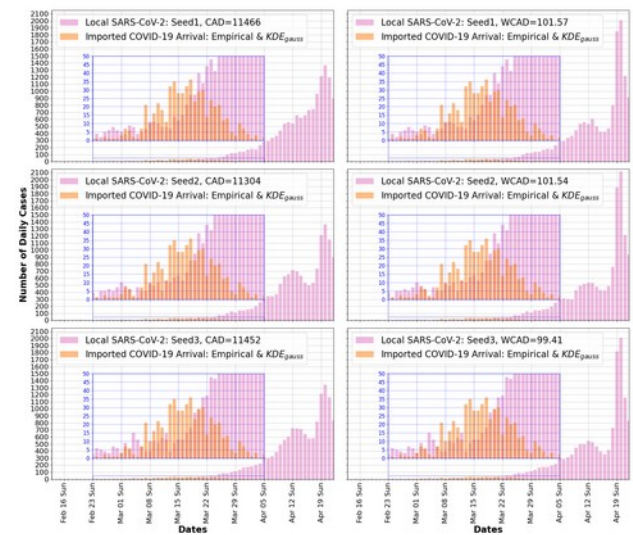
Figure 16: Singapore's lower-bound daily Local SARS-CoV-2 infection trends vs the arrival trend of its Imported COVID-19 cases.

Figure 15: The cumulative probabilistic distribution of the COVID-19 confirmation period of the Imported COVID-19 cases.

A prelude to the above events is that 11th March 2020 marked the pronouncement by the Director-General of The World Health Organisation that COVID-19 has evolved into a pandemic. Globally, the number of COVID-19 cases outside China had increased 13-fold, and the number of countries with COVID-19 cases had increased 3-fold [29]. In Singapore, this phenomenon resulted in an exodus of Singaporeans returning from many COVID-19 plagued countries that month. Minister Lawrence Wong [30], one of the co-chairs of Singapore's COVID-19 Multi-Ministry Task Force, made known in a Parliament

meeting on 25th March 2020 that the daily number of Imported COVID-19 cases would grow significantly. He described that there were about 200,000 Singaporeans abroad and that Singapore should be prepared to receive these returnees when they choose to weather out the COVID-19 pandemic in Singapore. Singapore had been witnessing ~1200 returnees from the UK and US daily. He feared the end of this high trend of returnees did not seem to be in sight. According to Figure 12, Singapore's Local SARS-CoV-2 population that day had reached at least a mean of 589 with a standard deviation of 9.849, while the officially reported Local COVID-19 population was only 264. That is, the dangers posed by at least 325 imminent COVID19 individuals were still unrecognised that day.

Viewing all this information together with the circumstantial evidence presented in Figures 14 and 16 and their reasoning, it is not plausible to not attribute the surge of SARS-CoV-2 infections in Singapore, hence Singapore's COVID-19 epidemic, to the influx of Imported COVID-19 individuals in March 2020.

5 Conclusions

A novel approach to estimate the lower-bound Local SARS-CoV-2 infection trend of Singapore between January to August 2020 is presented. It involved first modelling Singapore's daily mean COVID-19 confirmation periods, i.e. μ_{mean}, and the lower-bound Local COVID-19 epidemic trend. The former showed Singapore's ability to reduce its daily COVID-19 confirmation periods. Yet, this measure alone was not sufficient to avert a COVID-19 epidemic. The latter achieved resemblance to the empirical lower-bound Local COVID-19 epidemic trend. These resemblances gave credence to the estimated lower-bound Local SARS-CoV-2 infection trends. These trends showed Singapore missing an early window of opportunity to mitigate its COVID-19 epidemic with its Circuit Breaker. As such, an extended Circuit Breaker with tighter mitigation measures to quell Singapore's COVID-19 epidemic needed implementation. They also provided the ability to quantify the daily imminent Local COVID-19 population within a week or more before their confirmation by the Local COVID-19 epidemic trend. This undocumented population is sizable and evidenced the COVID-19 epidemic trend weakness to report the "real" COVID-19 population (i.e. those infected with SARS-CoV-2 that are, and also have yet to be, confirmed with COVID-19) promptly; a possible factor for the COVID-19 epidemic and its protracted recovery. These trends also elucidated Singapore's

COVID-19 epidemic origin. They provided circumstantial evidence that the exponential surge of SARS-CoV-2 in Singapore, hence Singapore's COVID-19 epidemic, was caused by the influx of Imported COVID-19 individuals in March 2020.

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