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AN ACTUARIAL MODEL OF THE ECONOMIC COST OF THE FIRST YEAR OF A PANDEMIC AND THE COMMUNITY MOBILITY INDEX

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Abstract. *The COVID-19 pandemic significantly affected world economics. Thus, to anticipate the possibility of a future pandemic, it is crucial to find a proper way to simulate and estimate the cost of a pandemic, which is critical to the economy and welfare. This paper presents an actuarial Susceptible-Infected-Recovered and Death (SIR-D) multiple-state model that estimates the cost of a pandemic through the Cost-of-Illness (COI) analysis for both individual and regional levels. The model can be used to design financial products anticipating future pandemics. Formulas are constructed for two categories of COI, i.e., direct costs and productivity losses. The COIs are calculated annually and weekly throughout the year 2020. We also build and analyze multiple regression models that picture the relationships between community mobility and the amount of economic burden. We apply the model to studying the USA, India, Indonesia, Canada, Australia, and Taiwan. Indonesia, India, and the USA have the world-largest populations. In addition, Australia and Taiwan were known to apply strict border control, tracking, and quarantine in 2020. The models indicate moderate to high correlations between community mobility and economic burden during the first year of the COVID-19 pandemic.*
Keywords: Pandemic, Economic cost, COVID-19, Google community mobility reports

1. **Introduction.** When a new infectious disease emerges and swiftly spreads, a pandemic will happen, and unexpected treatment and testing costs will arise. To save life and ease the healthcare system, governments would order lockdowns that negatively impact economic growth. Furthermore, isolation and quarantine of infected individuals reduce people's productivity at work, adding an extra economic burden to the government. To survive, the government must have adequate funds to handle (at least) the first year of a pandemic [1]. In this article, we show a way to estimate the cost of a pandemic at the individual and the territorial level by combining the Cost-of Illness (COI) analysis [2] and actuarial models for insurance and annuities [3]. The model helps create financial products, such as pandemic insurance or bonds [1]. Using the COVID-19 pandemic as a case study, we show how to estimate the first-year cost of the USA, Australia, India, Indonesia, Canada, and Taiwan. Assuming that data is right-censored, the Nelson-Aalen estimator is applied to getting the hazard rates [4]. Daily transition probabilities are then obtained by solving Kolmogorov's forward equation [3]. Components of COI are interpreted as insurance benefits and discrete annuities. Through the equivalence principle, the cost per individual citizen is interpreted as the single net premium or the Expected Present Value (EPV) of the cost calculated at the beginning of the year. The territorial cost is obtained by multiplying the calculated cost per citizen by the total population.

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Any pandemic would be accelerated by mobility [5]. Therefore, this study investigates the relationship between mobility and economic burden using a multiple linear regression model. Mobility data for each region was obtained through the COVID-19 Community Mobility Report released by Google from February 22, 2020, to January 29, 2021. The economic burden, as the dependent variable, is obtained from the weekly EPV of the cost. Weekly average mobility data are applied as predictor variables.

2. **Data.** Datasets on global SARS-CoV-2 cases, deaths, and recoveries were explained in [6] and are stored on Github[1]. Demographic data for the total population, Crude Birth Rate (CBR), and Crude Death Rate (CDR) were obtained from United Nations estimates[2]. The year 2020 interest rate compounded daily is calculated from the government bond[3]. For the five regions in the study, we use the one-year government bonds, while for Taiwan, we use the only available data, which is the two-year government bonds.

We aim to calculate the economic burden of the COVID-19 pandemic for one year (January 22, 2020, to January 21, 2021). The study approach is prevalence-based, and the study perspective is societal (covering all costs of all community members infected with the disease). The study takes COI types of direct costs and productivity losses [2]. Direct cost consists of the treatment cost for medicines and medical equipment and the cost of Polymerase Chain Reaction (PCR) tests, of which the daily amounts per person are denoted by B_1 and B_2, respectively. In this study, the cost of PCR tests consists of two components: PCR tests for screening the community and PCR tests for releasing those who recover/survivors. The method for calculating direct losses is the sum-of-all-diagnosis-specific. The method for calculating productivity losses is the human capital method, which measures losses from the perspective of the infected community or individual [7]. Productivity losses are taken as the income compensation for COVID-19 patients, given daily for a maximum of twenty days. Income compensation ceases for those who die before day 20. Patients who recover in less than twenty days will still get the income compensation up to day 20 – this is called “income compensation after the illness”. Thus, productivity loss consists of two components: income compensation during illness and income compensation after illness, of which the daily amount per person is denoted by B_3.

Medical costs for each severity level and the cost of PCR tests were calculated according to the third version of the World Health Organization COVID-19 Essential Supplies Forecasting Tool (WHO COVID-ESFT)[4]. In the WHO COVID-ESFT, there are only estimated costs from WHO, not costs for individual countries. Therefore, the study assumes that the six regions have the same values of B_1 and B_2. We only take prices for medicine and medical equipment for the medical cost. In 2020, these prices were similar in many places. Hospital room fees and healthcare worker salaries vary, even within a sub-region; thus, we do not consider these in our calculation for B_1 and B_2.

Based on WHO COVID-ESFT, the treatment cost per patient per day is USD 2.47 (B_{mild} and $B_{moderate}$), USD 278.57 (B_{severe}), and USD 438.41 ($B_{critical}$). The percentages of disease severity mild, moderate, severe, and critical are 40%, 40%, 15%, and 5%, respectively [8]. Then B_1 is calculated by weighted average of B_{mild}, $B_{moderate}$, B_{severe}, and $B_{critical}$. The cost of the diagnostic test per person (B_2) was taken according to WHO COVID-ESFT, which is USD 51.21 per person per test in 2020. We need the number of PCR test specimens from each region to calculate the cost of PCR tests for screening

[1]Retrieved from https://github.com/CSSEGISandData/COVID-19

[2]Retrieved from https://population.un.org/wpp/Download/Standard/Population/

[3]Retrieved from https://www.investing.com/rates-bonds/world-government-bonds?maturity_from=10 &maturity_to=310

[4]Downloaded from https://www.who.int/publications/i/item/WHO-2019-nCoV-Tools-Essential_forecasting-2022.1

the community. Data on the number of test specimens were obtained through the official government websites of each region. The number is counted until January 21, 2021, except for Taiwan, which is counted until January 18, 2021. Therefore, in the study, the number of COVID-19 test specimens is 289,418,762 (USA)[5], 12,594,719 (Australia)[6], 190,148,024 (India)[7], 8,560,220 (Indonesia)[8], 16,895,320 (Canada)[9], and 326,755 (Taiwan)[10].

Daily income compensation (B_3) is taken as the average income per person per day in 2019. Data is obtained through Census and Economic Information Center Data[11]. We assume that a month consists of thirty days; thus, B_3 is USD 129.75 (USA), USD 114.90 (Australia), USD 9.83 (India), USD 6.12 (Indonesia), USD 105.72 (Canada), and USD 59.86 (Taiwan).

3. **Model.** The model is presented in Figure 1. In the first year of the pandemic, reinfection was rarely reported, and vaccines were not yet available; thus, this model is sufficient. In the model, susceptible persons stay in state 0, move to state 1 when tested positive, and further to state 2 when tested negative or to state 3 if they die.

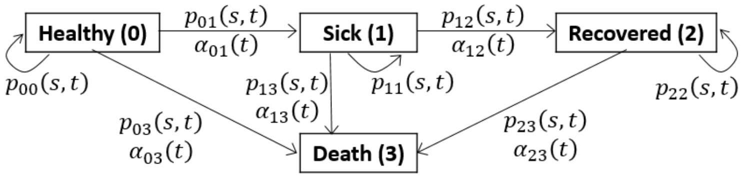

FIGURE 1. The model

The unit time is daily. Using the Nelson-Aalen estimator [4], we use the COVID-19 daily data of new cases, recovered, and death to calculate $\alpha_{ij}(t)$, i.e., the day-t hazard rate from state-i to state-j. Here $p_{ij}(s,t)$ is the probability of a person being at state-i on day-s and at state-j on day-t, obtained by solving the Kolmogorov forward equations [3]. Transition time can be anytime between day-s and day-t, and the person remains in state-j until day-t. Following the explanation on pages 181-182 of [4], the formulae for $p_{ij}(s,t)$ are given by $p_{00}(s,t) = e^{-\int_s^t \alpha_{01}(\tau)+\alpha_{03}(\tau)d\tau}$, $p_{11}(s,t) = e^{-\int_s^t \alpha_{12}(\tau)+\alpha_{13}(\tau)d\tau}$, $p_{22}(s,t) = e^{-\int_s^t \alpha_{23}(\tau)d\tau}$, and $p_{33}(s,t) = 1$, which are probabilities of staying in a state; and the probabilities of changing states are given by

$$p_{01}(s,t) = \int_s^t p_{00}(s,\tau)\alpha_{01}(\tau)p_{11}(\tau,t)d\tau, \quad p_{12}(s,t) = \int_s^t p_{11}(s,\tau)\alpha_{12}(\tau)p_{22}(\tau,t)d\tau, \tag{1}$$

$$p_{03}(s,t) = \int_s^t p_{00}(s,\tau)\alpha_{03}(\tau)p_{33}(\tau,t)d\tau + \int_s^t p_{00}(s,\tau)\alpha_{01}(\tau)p_{13}(\tau,t)d\tau, \tag{2}$$

$$p_{13}(s,t) = \int_s^t p_{11}(s,\tau)\alpha_{13}(\tau)p_{33}(\tau,t)d\tau + \int_s^t p_{11}(s,\tau)\alpha_{12}(\tau)p_{23}(\tau,t)d\tau, \text{ and} \tag{3}$$

$$p_{23}(s,t) = \int_s^t p_{22}(s,\tau)\alpha_{23}(\tau)p_{33}(\tau,t)d\tau. \tag{4}$$

We know that $\alpha_{ij}(\tau)d\tau$ is the probability of being in state j at time $\tau + d\tau$ conditioned on being in state i at time τ [4]. Therefore, we interpret the probabilities in Equations

[5]USA: https://covidtracking.com/data/national

[6]Australia: https://www.health.gov.au/resources/publications/coronavirus-covid-19-at-a-glance-21-january-2021

[7]India: https://www.icmr.gov.in/pdf/covid/update/archive/ICMR testing_update_22Jan2021.pdf

[8]Indonesia: https://kawalcovid19.id/

[9]Canada: https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection.html

[10]Taiwan: https://sites.google.com/cdc.gov.tw/2019-ncov/total-tests-conducted-en

[11]Retrieved from https://www.ceicdata.com/en/indicator/monthly-earnings

(1)-(4) as the sums over all probabilities of all possible movements from state i to state j at time τ, for which $s < \tau < t$.

There are five components in the actuarial model of the economic cost of COVID-19. Each component uses either one of the costs per person, i.e., B_1, B_2, and B_3 described in Section 2. We denote v as the discount factor for the time-value-of-money, calculated from the government bonds data. We define the following two actuarial symbols for an individual at state l at day s. The first symbol is the n-days term discrete insurance benefit, payable when moving to state j via state k, given by

$$A^{lkj}_{\overset{1}{s:n|}} = \sum_{t=0}^{n-1} v^{t+1} p_{lk}(s, s+t) \cdot p_{kj}(s+t, s+t+1). \tag{5}$$

The second one is the n-days discrete annuity payable daily while in state j, given by

$$a^{lj}_{s:n|} = \sum_{t=1}^{n} v^t p_{lj}(s, s+t). \tag{6}$$

The five components of the economic cost are given as follows.

1) Medical cost $= B_1 a^{01}_{0:366|}$.
2) PCR test cost for survivor $= 2B_2 A^{012}_{\overset{1}{0:366|}}$.
3) PCR test cost of screening healthy population $= B_2 v^{366} \frac{\text{TS(366)}-2\text{R(366)}}{\text{Total population}}$, where TS(366) is the cumulative number of PCR test specimens on the 366th day, and R(366) is the cumulative number of people recovering from COVID-19 as of the 366th day.
4) Income compensation during illness $= B_3 a^{01}_{0:366|}$.
5) Income compensation after illness $= B_3 \left(\sum_{n=1}^{346} v^n p_{01}(0, n-1) \cdot p_{12}(n-1, n) \cdot a^{22}_{0:366|} + \sum_{n=347}^{365} v^n p_{01}(0, n-1) \cdot p_{12}(n-1, n) \cdot a^{22}_{k:366-n|} \right)$.

4. **Model's Results.** The six figures on the left of Figure 2 show the graph of $p_{01}(t, t+1)$, i.e., the probability of a susceptible individual being tested positive the next day. The USA and Canada are higher than the others. In Indonesia, the curve is still rising through the end of 2020. The six figures on the right of Figure 2 show the graph of $p_{11}(t, t+1)$, i.e., the probability that an individual with COVID-19 is released from quarantine. This probability is influenced by the probability of recovering ($p_{12}(t, t+1)$) and the death probability from COVID-19 ($p_{13}(t, t+1)$). Low values of $p_{11}(t, t+1)$ could indicate either a good situation or a bad one. A good situation happened when many recovered and few died. On the other hand, a bad situation happens if vice versa.

The estimated five components of economic cost per individual/the cost per citizen, as explained in Section 3, are shown in Table 1. Component (1) shows medical costs per citizen, indicating the prevalence level of COVID-19 and the length of illness in a region. For example, the cost in the USA could be due to the high prevalence of the disease coupled with the length of hospital stay (indicated by high values of $p_{01}(t, t+1)$ and $p_{11}(t, t+1)$ – see Figure 2). Component (2) shows the cost per citizen for testing COVID-19 survivors. In 2020, it was advised that two PCR tests with negative results were necessary before releasing patients from quarantine. The cost does not indicate the cure rate. For example, the low cost of \$0.003 in Taiwan does not mean that the cure rate in Taiwan is very low, but it is due to the low prevalence rate of the disease in Taiwan. Component (3) shows the cost per citizen for screening the population through PCR tests. Components (4) and (5) show the burden of productivity losses per citizen, which are defined and explained in Sections 2 and 3. The wage of each region influences the magnitude of this number.

By multiplying the values in Table 1 by the total population, we get the regional economic cost for 2020 due to COVID-19. The values are given in Table 2. Notice the

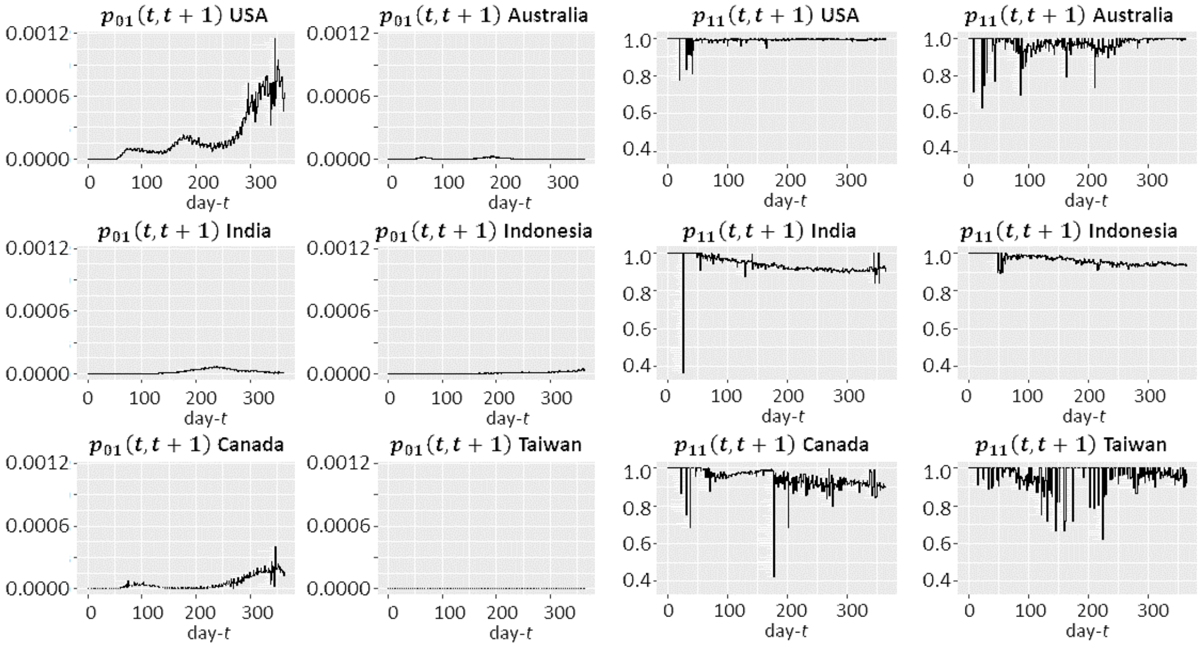

FIGURE 2. Results of $p_{01}(t, t+1)$ and $p_{11}(t, t+1)$

TABLE 1. Estimated five components of the economic cost of COVID-19 (in US Dollars) **per individual citizen** (period January 22, 2020 – January 21, 2021)

Region	Medical cost (1)	PCR test for survivors (2)	PCR test for screening the community (3)	Income loss during illness (4)	Income loss after illness (5)	**Total average cost per citizen**
USA	261.05	2.98	41.80	515.68	68.68	**890.19**
Canada	16.67	1.68	21.22	26.84	30.36	**96.77**
Australia	1.92	0.10	25.33	3.36	2.28	**33.00**
India	5.53	0.70	6.07	0.83	1.33	**14.47**
Indonesia	3.33	0.27	1.26	0.31	0.28	**5.45**
Taiwan	0.06	0.003	0.70	0.06	0.04	**0.86**

TABLE 2. Estimated **regional** cost of COVID-19 in 2020 (in **million USD**)

Region	Medical cost (1)	PCR test for survivors (2)	PCR test for screening the community (3)	Income loss during illness (4)	Income loss after illness (5)	Total loss
USA	86,060.31	982.25	13,780.54	170,005.86	22,642.31	293,471.27
India	7,607.56	967.99	8,349.56	1,138.55	1,821.79	19,885.45
Canada	624.73	62.92	795.06	1,005.55	1,137.43	3,625.69
Indonesia	907.42	72.88	343.47	84.55	77.48	1,485.80
Australia	48.59	2.59	640.69	85.00	57.75	834.62
Taiwan	1.5	0.08	16.62	1.38	0.85	20.43

change in the order of the region. The actuarial model estimates the proportion of three components of the regional cost, i.e., income loss (components (4) + (5)) : medical cost (component (1)) : PCR test (components (2) + (3)), as follows. For USA 66% : 29% : 5%, for India 15% : 38% : 47%, for Canada 59% : 17% : 24%, for Indonesia 11% : 61% : 28%, for Australia 17% : 6% : 77%, and for Taiwan 11% : 7% : 82%.

The USA has a very high number of infected cases and the highest average income, resulting in a significantly higher total loss than the others. Interestingly, the high number of infected cases in India results in income compensation being the second highest, even though the average income in India is the second lowest (see Section 2).

In Table 2, we notice that for regions with high average income, productivity loss (i.e., components (4) + (5)) is more significant than medical cost (component (1)), and vice versa for regions with low average income. We also notice that regions that apply strict border and quarantine rules in 2020, such as Australia and Taiwan, show a more dominant proportion of diagnostic test costs than medical costs.

We compare the economic cost per individual (citizen) with each region's nominal GDP per capita to see the actual percentage of the cost of the COVID-19 disease on the economy. The result is displayed in Figure 3, showing that the total economic burden per individual (citizen) due to COVID-19 compared to nominal GDP is reasonably low, below 1.5%. Thus, it is promising to design and sell financial products to anticipate the future pandemic, such as pandemic insurance or bonds [1].

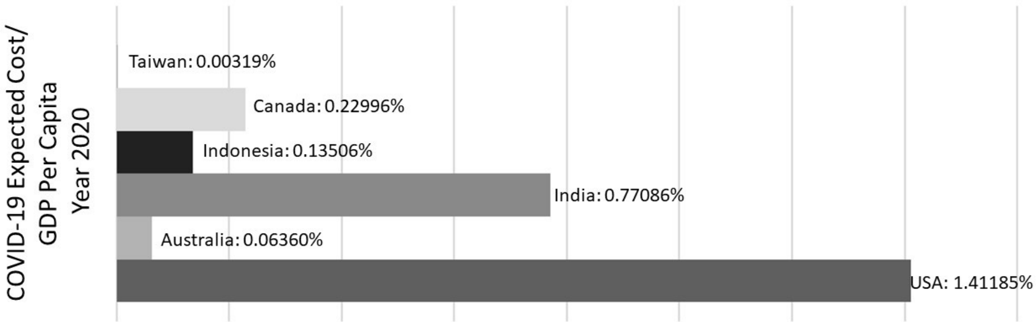

FIGURE 3. The percentage of the COVID-19 cost in the GDP per capita 2020

Table 3 shows the economic cost per sick/positively tested individual, which can be interpreted as the annual insurance benefit. The values are obtained by dividing each cost component by either the cumulative number of infected cases or the cumulative number of cured cases in that region. The cost component of screening the population (i.e., component (3) in Table 2) is not considered here. Table 3 shows components (1) plus (2) are the total cost during the illness period. Components (3) plus (4) give an additional cost for each COVID-19 survivor. The compensation income per sick individual is provided for 20 days unless the patient dies. Income compensation in each region varies according to the average income, interest rates, and distribution of recovery rates. For example, suppose all regions have the same average income. The higher the interest rate in a region, the lower the income compensation. In addition, if the probability of recovering is high and the distribution of recovery rates is mainly located at the end of the year, then the income compensation in that region will be low.

TABLE 3. The estimated economic cost of COVID-19 (in US Dollars) **per positively tested individual** (period January 22, 2020 – January 21, 2021)

Region	Medical cost (1)	Income loss during illness (2)	**Total cost per sick person (survive or die)**	PCR test cost for the survivor (3)	Income loss after illness (4)	**Total additional cost per survivor**
USA	3,493.86	6,901.86	**10,395.72**	100.62	2,319.35	**2,419.97**
Canada	848.31	1,365.42	**2,213.73**	96.47	1,743.86	**1,840.33**
Australia	1,689.86	2,956.13	**4,645.99**	99.60	2,224.53	**2,324.13**
India	953.52	88.85	**1,042.37**	94.31	100.26	**1,236.93**
Indonesia	715.98	107.15	**823.13**	94.13	177.15	**271.28**
Taiwan	1,718.38	1,566.07	**3,284.45**	100.29	1,092.37	**1,192.67**

The economic cost per individual (citizen) given in Table 1 can also be considered an insurance premium for COVID-19. In contrast, the economic burden per sick individual given in Table 3 can be seen as an insurance benefit. We notice that the insurance premiums are low, while the insurance benefits are high. Therefore, pandemic insurance is attractive. Furthermore, by comparing Tables 1 and 3, we notice that the chances of claiming benefits in the USA are much higher than that in Taiwan.

5. **Mobility and Economic Cost.** The study also looked at relationships between mobility and the COVID-19 economic cost through a multiple regression model. Mobility data for each region is obtained through the COVID-19 Community Mobility Report released by Google. The data shows changes in the number of visitors (or time spent) in places categorized against a baseline. The baseline is obtained from the median value for January 3, 2020, to February 6, 2020, before the pandemic. The value of the change to baseline is expressed as a percentage, negative or positive. There are six categories of mobility places: retail and recreation (x_1), grocery and pharmacy (x_2), parks (x_3), transit stations (x_4), workplaces (x_5), and residential areas (x_6).

Each model is built using a dataset with 49 to 52 observation values (i.e., 49 to 52 weeks, depending on the lag between dependent and independent variables). The dependent variable is $\ln(y+1)$, where y is the weekly Expected Present Value (EPV) of the economic cost, rigorously explained and derived in [9]. The values for y are presented in Figure 4(a). We experiment with different lags between dependent and independent variables. The best models are reported in Table 4. We conclude that in 2020, mobility will influence the economic cost of COVID-19. The adjusted R^2 is very high for the USA and Canada, high for India, Indonesia, and Australia, and moderate for Taiwan. For Taiwan, the value of the economic cost can be influenced by factors other than mobility, such as strict border control, quarantine, tracking, and people's obedience to mask mandates. Finally, we check the model's accuracy by plotting the logarithmic transform of the weekly EPV and predicted values. The results are presented in Figure 4(b), showing that the models are accurate and do not overfit.

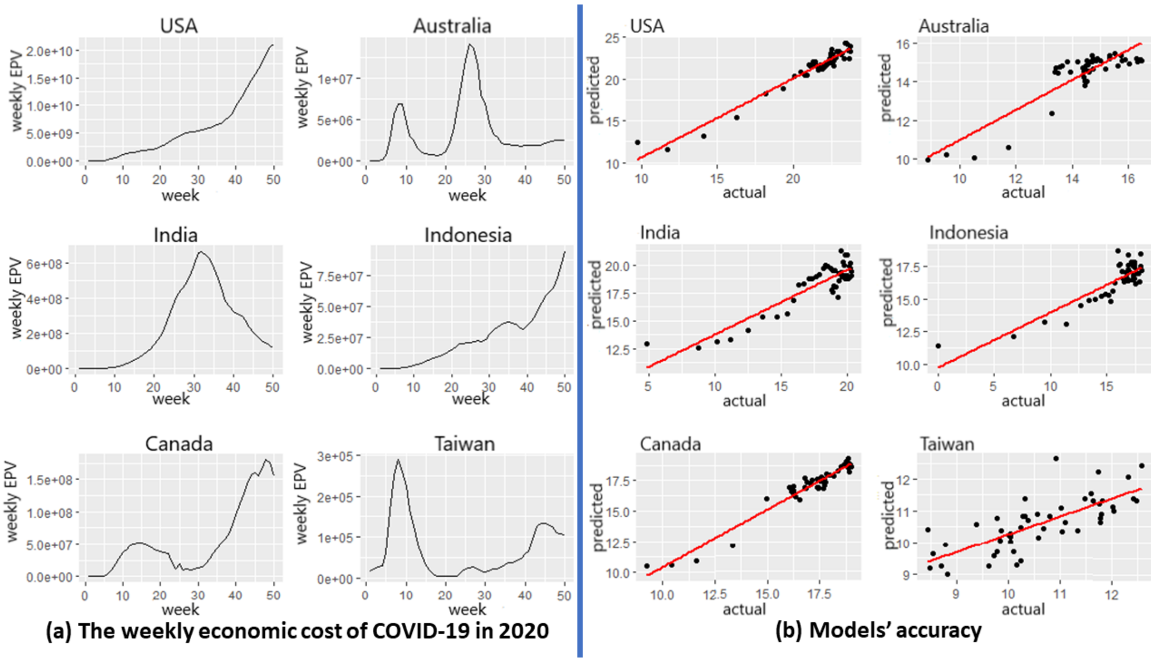

FIGURE 4. (a) The values are calculated by using an actuarial approach explained in [9]; (b) regression models in Table 4 give the vertical axes, and the horizontal axes are given by the log-transform of weekly EPV depicted in Figure 4(a).

TABLE 4. Regression models between mobility variables and the log-transform of COVID-19 weekly economic cost for 2020. "–" in cells indicate insignificant variables.

Region	Lag (week)	Intercept	Coeff. of x_1	Coeff. of x_2	Coeff. of x_3	Coeff. of x_4	Coeff. of x_5	Coeff. of x_6	R^2	Adj. R^2	F-statistics (p-value)	Residual standard error
USA	1	11.7434	0.2594	0.0999	–	−0.6327	−0.0920	−0.7966	0.95	0.94	<2.2e-16	0.71 on 43 DF
Canada	1	9.9010	0.1352	–	0.0080	−0.2214	0.1540	0.4070	0.94	0.93	<2.2e-16	0.53 on 43 DF
India	3	12.9582	0.0648	0.1241	−0.1286	–	–	−0.2983	0.82	0.81	2.801e-15	1.06 on 43 DF
Indonesia	3	12.3828	–	0.2087	0.0735	−0.1751	–	–	0.78	0.77	2.626e-14	0.86 on 43 DF
Australia	0	10.5795	–	–	0.0283	−0.1340	−0.0586	–	0.78	0.76	1.142e-14	0.75 on 45 DF
Taiwan	0	9.3020	−0.2374	–	–	0.0785	–	0.2407	0.57	0.54	2.988e-08	0.77 on 45 DF

6. **Conclusions.** We have shown a methodology to calculate the economic cost of a pandemic on an individual and regional level. Taking COVID-19 as a case study, we use the model to estimate the cost of the pandemic's first year (2020). Comparing the values given in Table 2 with the amount of USD 500 million of the Pandemic Emergency Facilities/PEF (a 5-year bond launched by the World Bank in 2017)[12], we see that the losses from the first year of COVID-19 are much higher than the fund prepared by the PEF. Therefore, to prepare for a future pandemic, the actuarial methodology presented here can be used to simulate the benefits and premiums of pandemic financing products.

In the first year of COVID-19, weekly economic losses are correlated with the Google community mobility variables. Therefore, it is promising to develop further statistical models that are more robust. The model can be combined with the actuarial model to simulate different scenarios regarding a future pandemic.

The interest of the present study is to investigate how well the mobility variables explain the economic cost. Thus, we neglect the multicollinearity in the significant variables for the USA, Canada, India, and Australia. Only Indonesia and Taiwan do not show multicollinearity. Nevertheless, the fact that the adjusted R^2 is surprisingly high should motivate further research on finding a better approach to model economic cost and mobility.

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