

Research Article

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A gravity model approach to understand the spread of pandemics: Evidence from the COVID-19 outbreak

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Abstract: Pandemics disrupt the global economy. Understanding the transmission pattern of pandemics informs policies to prevent or reduce the catastrophic consequences associated with pandemics. In this study, we applied the gravity model of trade to investigate the transmission pattern of the coronavirus disease 2019 (COVID-19) across countries. The results suggest an outbreak in a country is likely to spread faster (slower) from a shrinking (booming) economy to a booming (shrinking) economy.

Keywords: pandemic, outbreak, COVID-19, contagious disease, gravity model

1 Introduction

A disease outbreak in a country becomes a pandemic when the disease has spread to several countries. From the initial case of Ebola reported in Guinea in December 2013, the disease spread to Mali, Nigeria, Senegal, Spain,

Italy, the United Kingdom, and the United States [1]. Coronavirus disease 2019 (COVID-19) started in Wuhan, China, on December 31, 2019. On March 11, 2020, when the World Health Organisation (WHO) declared COVID-19 a pandemic, the disease had spread to 114 countries and territories [2]. Also, outbreaks spread to some countries faster than to other countries. For example, the Category 2 Flu pandemic, sometimes called “the Hong Kong Flu,” first reported on July 13, 1968, in Hong Kong, spread to Singapore and Vietnam within 17 days and to Philippines, India, Australia, Europe, and the United States within 3 months [3]. COVID-19 spread to Italy, Iran, and the United States before it spread to Croatia, Hungary, and Kenya, respectively. This observation begs the question of what factors are associated with the spread and early spread of outbreaks across countries.

Pandemics disrupt the global economy. COVID-19 might not be as deadly as earlier pandemics such as the Black Death (1346–1353), Spanish Flu (1918–1919), or Ebola (2013–2016), but its economic consequences might be worse than some earlier pandemics [4]. The United Nations Conference on Trade and Development (2020) reported that the global economy declined by 3% in the first quarter of 2020 due to the COVID-19 outbreak. Global output losses were estimated to be US\$ 8.5 trillion between 2020 and 2024 [5]. At both micro and macro levels, prevention and control measures help countries to reduce the catastrophic consequences (health, economic, etc.) associated with outbreaks. This requires knowledge of factors that influence the spread of outbreaks. In this study, we examined the determinants of the transmission of COVID-19 across countries to inform policies to reduce the transmission rates of pandemics.

2 Literature review

The theory of contagious disease causation is a series of theories, refined one after the other, to explain the cause of contagious disease to change people’s view about the

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cause of contagious diseases [6]. Contagious diseases were attributed to spiritual forces such as punishment from God for sinful behaviour and demonic attack on people with weak moral character. The belief of cause of contagious diseases was changed from being due to supernatural forces (punitive theory and demonic theory) to due to natural processes with introduction of medicine to give scientific basis to the cause of contagious disease. The germ theory of disease provided more weight to the scientific explanation. The germ theory posits that contagious diseases are caused by germs, microbes, or pathogens [6,7].

The epidemiologic triad theory builds on the germ theory to provide a better explanation of the spread of diseases [8]. The epidemiologic triad theory, consists of the infectious agent, the host (infected), and the environment. Susceptible-infected-recovered (SIR) models, underpinned by the epidemiologic triad theory, are developed to explain the pattern of spread of contagious diseases. SIR models focus on transmission of outbreaks by a host (infected) either directly, such as kissing, sneezing, and coughing on the face of the uninfected, or indirectly such as the uninfected putting into his mouth contaminated utensil, pen, bottle, etc. [9]. That is, SIR model studies largely focus on how a disease [10] or COVID-19 [11–14] spreads from one person to another. These studies focus on individuals. Pandemic is where an outbreak in a country has spread to a given number of countries or a proportion of the global population is infected [15]. Countries that have not yet recorded cases of an outbreak may be prone to acquiring the disease and may acquire the disease in due course. But SIR models are not suitable for explaining the spread of disease from one country to another because SIR models deal with person-to-person transmission of diseases.

In the epidemiologic triad theory, environmental factors such as trading activities allow the infected and uninfected to physically interact [16] to spread a contagious disease to the uninfected [9,16]. The gravity model of international trade, proposed by Tinbergen [17], is an economic model used to study trade flows between countries. According to this model, countries that are economically and/or geographically close will trade with each other. Lewer and Van den Berg [18], however, applied the model to study immigration flow. This is because the gravity model can be applied in situations where movements of people are involved [19]. This means the model can be used to study the spread of diseases across countries since it involves movement of the infected from one place to another. In the gravity model of trade flows, each variable is bilateral, that is, trade volumes from country i to country j and *vice versa*. Nonetheless, the model can be

applied to test the influence on a phenomenon of unilateral variables that reflect characteristics in only the source or destination country [18].

The widespread of the COVID-19 provides the opportunity to investigate the pattern of spread of the disease across countries to inform health policies to deal with pandemics. But COVID-19 related studies have largely focused on containment [20,21], impact [22,23], health system resilience [15,24,25] and efficiency [26], demand for vaccine [27], and post COVID-19 recovery measures [28,29]. In a pandemic study, such as this current study, an outbreak occurs in a country before it spreads to another country. We therefore examine the determinants associated with the spread of the outbreak from one country to another country, not from one person to another person. As far as we know, this is the first study to apply the gravity model to study the spread of diseases across countries.

3 Methods

3.1 Conceptual framework

3.1.1 Country-to-country disease transmission pattern

Figure 1 illustrates the transmission pattern of an outbreak across countries. The nodes represent countries, and the arrows indicate the direction of the spread of the disease from one country to another. A1 is the originating country of the disease before it spread to other countries. For example, COVID-19 started in China and thus A1 represents China. We refer to A1, B2, and C3 as “disease-exporting countries” because the disease spread from these countries to other countries. The disease spread from A1 to B1, B2, B3, B4, and B5. Therefore, we refer to B1–B5 as “disease-importing countries” because they acquired the disease from another country, A1. B3 spread the disease to C1 while B4 spread it to C2 and C3. Therefore, B3 and B4 are exporting countries while C1, C2, and C3 are the importing countries. C1 then spread the disease to D1 while C3 spread it to D5 and D6. This means C1 and C3 are exporting countries while D5 and D6 are importing countries. The total number of exporting countries is 9 (i.e. A1, B2, B3, B4, B5, C1, C3, D1, D3) and the total number of importing countries is 20 (i.e. all countries except A1; $21 - 1 = 20$). Therefore, an exporting country on average spread the disease to 2 countries (i.e. $20 \div 9 = 2.2$). We observe that the disease did not directly spread from A1 to C1. Rather, it spread from A1 to B3 and then to C1. Also,

though $D1$ is closer to $A1$ than to $B3$ or $C1$, the disease did not directly spread from $A1$ to $D1$. Rather, it spread from $A1$ to $B3$ and then to $C1$ before it spread to $D1$. Also, $E1$ acquired the disease from $D1$ but not from $D2$, $B1$, or $A1$. This phenomenon begs the question of why a country acquired the disease from a particular country.

Again, from Figure 1, the length of the arrows indicates the proximity of countries but not transmission duration. That is, a shorter (longer) arrow does not indicate a shorter (longer) duration of the spread of the disease to another country but that a country is closer to (farther from) another country. Country $B3$ is farther from $A1$ than $B2$ is, but $B3$ may acquire the disease before $B2$ does. A country that acquired the disease in a shorter (longer) period means it had a higher (lower) probability to acquire the disease. Suppose the disease spread from $D1$ to $E2$ in a shorter period (e.g. 5 days) but it took a longer period (e.g. 15 days) to spread from $C1$ to $D1$, this means upon $D1$ acquiring the disease, $E2$ acquired the disease earlier than $D1$ did upon $C1$ acquiring the disease. From this observation, one wonders the factors associated with the spread and early spread of diseases across countries.

3.1.2 Conceptual specification

The law of universal gravitation in physics, developed by Isaac Newton in 1687, posits that every object attracts

other object with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centres [30]. This is expressed in equation (1), where F is the force, G is the gravitational constant, m_i is the mass of object i , m_j is the mass of object j , and d is the distance between the centres of the masses.

$$F_{ij} = G \frac{m_i m_j}{d_{ij}^2}. \quad (1)$$

Equation (1) has been adapted to study bilateral trade flows in economics, where trade between countries depends on economic sizes measured by gross domestic products (GDPs) of trading countries and proximity measured by geographical distance between the two countries' capital cities [19,31]. This is expressed in equation (2), where T is the export volume from country j to i , G is a constant, m_i is the GDP of country i , m_j is the GDP of country j , and d is the distance between the countries.

$$T_{ij} = G \frac{m_i m_j}{d_{ij}}. \quad (2)$$

Equation (2), simply referred to as gravity model in economics, can be applied to study the spread of diseases from one country to another since it involves movements of people. An outbreak in a country becomes a pandemic largely due to movements of the infected population across countries to infect others. Economic performance attracts people to move between countries. For example,

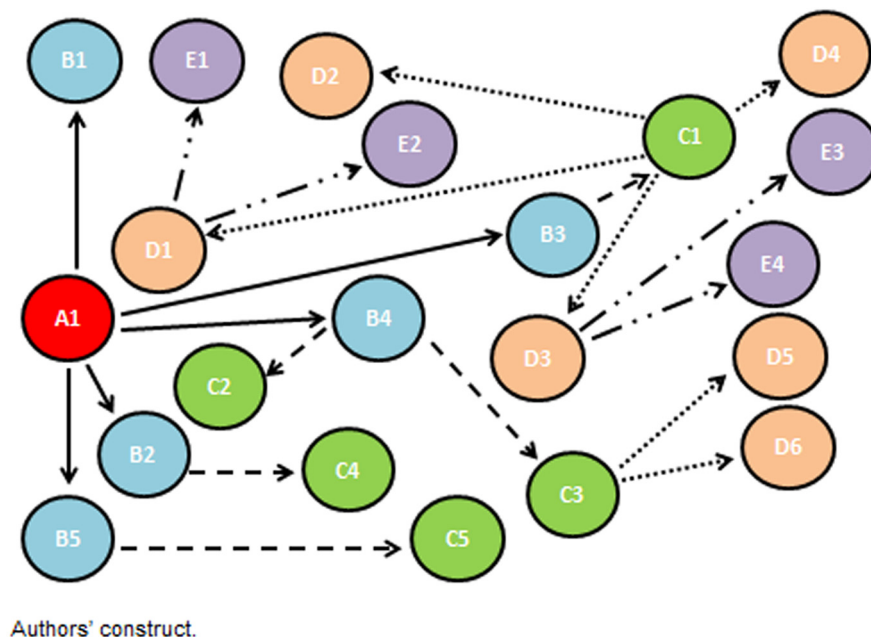


Figure 1: Conceptual framework of the spread of diseases across countries.

people travel across countries to trade or for trade related activities such as education and vacation. Also, geographical distance between countries influences the decision to travel to a particular country; the shorter (longer) the distance, the higher (lower) the number of people that will travel to a particular country, with other factors being constant.

Suppose there are N countries in the world and there is a disease outbreak in one of the countries that can spread to any of the $N - 1$ countries. This means any country without the disease has a given probability to acquire the disease from a country that has recorded cases of the outbreak. Therefore, the probability of country i or j to acquire the disease from either country is specified in equation (3) where P is the probability, G is the constant, m_i is the GDP of country i , m_j is the GDP of country j , and d is the distance between the countries.

$$P_{ij} = G \frac{m_i m_j}{d_{ij}}. \quad (3)$$

The econometric application of equation (3) is equation (4) where PROB , $0 < \text{PROB} < 1$, is the transmission probability, GDPM is the GDP of country i , GDPX is the GDP of country j , DIST is the distance between countries i and j , β_0 is a constant, β_1 , β_2 , and β_3 are estimable parameters of GDPM , GDPX , and DIST , respectively, and e is the error term. Taking the natural log of equation (4) yields equation (5) where $\ln$ is natural logarithm and ε is the error term assumed to be log-normally distributed.

$$\text{PROB}_{ij} = \beta_0 \frac{\text{GDPM}^{\beta_1} \text{GDPX}^{\beta_2}}{\text{DIST}^{\beta_3}} e, \quad (4)$$

$$\ln \text{PROB}_{ij} = \beta_0 + \beta_1 \ln \text{GDPM} + \beta_2 \ln \text{GDPX} - \beta_3 \ln \text{DIST} + \varepsilon. \quad (5)$$

The attractiveness of a country, in terms of economic performance measured by GDP, encourages people to reside in or travel to a particular country. For example, the higher (lower) the economic activities of country i , the more (less) attractive the economy to people and the higher (lower) the number of people that will travel from country j to i . Equally, the lower (higher) the economic activities of country j , the less attractive the economy to people and the higher (lower) the number of people that will travel from j to i . This suggests that the probability of country i to acquire the disease from country j is positively related to economic activities of country i and inversely related to economic activities of country j and distance between the countries. This is expressed in equations (6) and (7). The linear form of equation (7) is expressed in equation (8).

$$P_i = G \left(\frac{m_i}{m_j} \right) \frac{1}{d_{ij}}, \quad (6)$$

$$\text{PROB}_i = \beta_0 \left(\frac{\text{GDPM}^{\beta_1}}{\text{GDPX}^{\beta_2}} \right) \frac{1}{\text{DIST}^{\beta_3}} e, \quad (7)$$

$$\ln \text{PROB}_i = \beta_0 + \beta_1 \ln \text{GDPM} - \beta_2 \ln \text{GDPX} - \beta_3 \ln \text{DIST} + \varepsilon. \quad (8)$$

Equation (6) can be re-specified as in equation (9) where $m_{ij} = \frac{m_i}{m_j}$. m_{ij} falls when m_i falls or m_j rises, with other factors being constant. In contrast, m_{ij} rises when m_i rises or m_j falls, with other factors being constant. The econometric specification of equation (9) is equation (11) where $\text{GDPMX} = \frac{m_i}{m_j}$ (i.e. the ratio of GDP of country i to GDP of country j). The linear form of equation (11) is equation (12).

$$P_i = G \frac{m_{ij}}{d_{ij}}, \quad (9)$$

$$m_{ij} = \frac{m_i}{m_j}, \quad (10)$$

$$\text{PROB}_i = \beta_0 \frac{\text{GDPMX}^{\beta_1}}{\text{DIST}^{\beta_2}} e, \quad (11)$$

$$\ln \text{PROB}_i = \beta_0 + \beta_1 \ln \text{GDPMX} - \beta_2 \ln \text{DIST} + \varepsilon. \quad (12)$$

3.2 Empirical specification

We use the term “COVID-19 exporting country” or “exporting country” to refer to the country a person infected with COVID-19 travelled from and “COVID-19 importing country” or “importing country” for the country the infected person travelled to which made the importing country record its first COVID-19 case. Suppose country i acquired the disease from country j , it is possible that an infected resident of i will travel to j to infect an uninfected person in j . Since cases of the disease are already in j , and spreading to other parts of the country, the spread of the disease from i to j (i.e. the reverse spread) attracts little attention. Rather, much attention is given to first or initial cases of the spread of the disease from j to i . Therefore, our empirical analysis focuses on the transmission of first cases to countries.

We introduce control variables in equations (8) and (12) to obtain equations (13) and (14), where TESTX and PREVX are, respectively, COVID-19 testing intensity and prevalence rate of the COVID-19 exporting country.

$$\begin{aligned} \ln \text{PROB}_i = & \beta_0 + \beta_1 \ln \text{GDPM} - \beta_2 \ln \text{GDPX} \\ & - \beta_3 \ln \text{DIST} + \beta_5 \ln \text{PREVX} \\ & - \beta_4 \ln \text{TESTX} + \varepsilon, \end{aligned} \quad (13)$$

$$\ln \text{PROB}_i = \beta_0 + \beta_1 \ln \text{GDPMX} - \beta_2 \ln \text{DIST} + \beta_4 \ln \text{PREVX} - \beta_3 \ln \text{TESTX} + \varepsilon. \quad (14)$$

GDPM is real GDP of the COVID-19 importing country. This is a measure of the economic activities of the country. GDPM is measured in United States dollars. The spread of disease to the importing country might be influenced by the attractiveness of the importing country's economy to residents in another country. Given that diseases spread from countries with cases of the disease to countries with no cases of the disease, it is expected that increase in the importing country's economic activities will attract travellers into the country. This increases the likelihood of COVID-19 infected person(s) among the travellers to spread the disease, to the importing country. Therefore, the a priori sign of GDPM is positive.

GDPX is the real GDP of the COVID-19 exporting country. This is a measure of economic activities of the country. GDPX is measured in United States dollars. People are likely to reside in places with increased economic activities. Increased economic activities of the exporting country might induce a number of the residents to stay in the country and thus not travel to another country while a decrease in the economic activities of the country might influence some residents to leave the country for another country. Upon an outbreak in a country, the economic activities of the country are likely to fall. This might induce some residents to relocate to another country; especially, non-citizens of the country are likely to relocate to their countries to stay there for a while. Some of these travellers might be infected and thus spread the disease to the destination country. Hence, we expect GDPX to have a negative relationship with PROB.

GDPMX is the ratio of GDP of the importing country to the GDP of the exporting country (i.e. $\text{GDPMX} = \frac{\text{GDPM}}{\text{GDPX}}$). Since GDPX is likely to fall during an outbreak, GDPMX is expected to increase. Generally, since people prefer to reside in a booming economy for jobs and better standard of living, we expect an increase in GDPMX to have a positive relationship with PROB and thus an increase in the spread of the disease to the importing country. Therefore, the a priori sign of GDPMX is positive. Holding other factors constant, an increase in GDPMX means either GDPM rises to attract a person to travel from country j to i , or a fall in GDPX to induce a person to relocate from j to i . This means a positive relationship between GDPMX and PROB is consistent with the positive effect of GDPM and negative effect of GDPX.

DIST is the geographical distance between the importing and exporting countries. Generally, transportation cost increases with distance and this might induce a person

to travel to a shorter-distance country, other factors being constant. Hence, a country closer to a COVID-19 exporting country is more likely to acquire the disease earlier than a country farther from the exporting country. This means the longer the distance between countries, the lower the transmission of COVID-19, while other factors remain the same. DIST is expected to negatively influence the transmission of COVID-19 to other countries.

PREVX is the prevalence rate of COVID-19 in the COVID-19 exporting country. It is the proportion of the exporting country's population that is infected. The prevalence rate measures the extent of the outbreak in a country. The higher the prevalence rate, the higher the spread of the disease in the exporting country and the higher the likelihood that a traveller from the exporting country has contracted the disease to spread it to the importing country. Therefore, we expect a positive relationship between PREVX and the transmission of COVID-19 to other countries.

TESTX is testing intensity of the COVID-19 exporting country. Testing intensity is the number of COVID-19 tests per million people. Testing intensity measures the exporting country's efforts to contain the disease to reduce the likelihood of the spread of the disease to another country. Providing treatment to suspected COVID-19 infected persons required laboratory tests to enable the health professionals to identify those infected and, perhaps, to quarantine them or treat the disease. This reduces the likelihood of a person traveling to the COVID-19 importing country to be infected to spread the disease to the importing country. Therefore, the higher the testing intensity of the exporting country, the lower the probability of the spread of COVID-19 to the importing country.

While equations (13) and (14) investigate the contributions of the explanatory variables to the probability of country i to acquire COVID-19 from country j , equations (15) and (16) investigate the contributions of these determinants to the early spread of COVID-19, where ESP is a binary variable for whether or not the importing country acquired COVID-19 quicker than the exporting country. ESP equals 1 if the importing country acquired the disease quicker than the exporting country and 0 if otherwise. For example, France acquired COVID-19 from China. Cameroon acquired it from France. France acquired the disease 24 days after the outbreak in China. Cameroon acquired the disease 42 days after France acquired the disease. Since it took Cameroon a longer period (42 days) to acquire the disease from France than France acquired it from China (24 days), ESP was 0 for Cameroon.

$$\begin{aligned} \text{ESP} = & \beta_0 + \beta_1 \ln \text{GDPM} - \beta_2 \ln \text{GDPX} - \beta_3 \ln \text{DIST} \\ & + \beta_5 \ln \text{PREVX} - \beta_4 \ln \text{TESTX} + \varepsilon, \end{aligned} \quad (15)$$

$$\begin{aligned} \text{ESP} = & \beta_0 + \beta_1 \ln \text{GDPMX} - \beta_2 \ln \text{DIST} + \beta_4 \ln \text{PREVX} \\ & - \beta_3 \ln \text{TESTX} + \varepsilon. \end{aligned} \quad (16)$$

3.3 Data and estimation technique

Given the data availability, we use cross-sectional data from 128 countries (Table A1 displays the countries sampled for the study). We sourced the December 31, 2020 coronavirus data from the World Health Organisations' coronavirus dataset (WHO, 2020). The GDP data in 2020 were sourced from the World Bank's World Development Indicators (World Bank, 2022a). We use the dates on which the countries recorded their first cases of COVID-19 to compute the number of days the disease took to spread to countries. We obtained the information on COVID-19 first case dates from Wikipedia (www.wikipedia.com). Finally, we use the online distance calculator (<https://www.distancecalculator.net/>) to compute the distance, in kilometres, between countries (capital cities). The departure and arrival cities of COVID-19 infected travellers are used to compute the distance. Where either the departure or arrival city is not reported, the capital cities are used to compute the distance between countries. We use Wuhan instead of Beijing, the capital city, as a reference location for China since Wuhan is the source of the COVID-19 virus.

Data on PROB, the dependent variable, are not directly available in the data sources. We compute PROB as follows: suppose there are N countries in the world and there is a disease outbreak in one of the countries. Suppose the disease can spread to any of the $N-1$ countries with a probability PROB. When a country records its first case of the disease before another country it means the former has a higher probability than the latter to acquire the disease. Put differently, if the disease spreads to country x before country y , it means the disease spread to country x at a higher probability than to country y . The spread of the disease to countries x and y on the same day means an equal probability of the spread of the disease to the countries. We assign a probability of 1 to the COVID-19 exporting country to indicate the certainty of the disease in the country. Therefore, the probability of COVID-19 to spread from the exporting country to the importing country i is expressed in equation (17), where D is the number of days taken for the disease to spread to the importing country.

$$\text{PROB}_i = \frac{1}{D_i}, \quad (17)$$

From equation (17), countries that record their first cases early (i.e. shorter days) have higher probabilities than countries that record the disease late (i.e. longer days). This means the shorter (longer) the duration of the transmission to the importing country, the higher (lower) the probability of the transmission. For example, Japan, France, and Italy imported the disease from China. These countries respectively acquired the disease in 16 days, 24 days, and 31 days after the outbreak in China. Therefore, the probabilities to acquire the disease, using equation (17), were 0.062, 0.041, and 0.032 for Japan, France, and Italy, respectively. Also, Greece, Ireland, and Portugal acquired the disease from Italy in 26 days, 29 days, and 31 days after Italy acquired the disease from China. This means Greece, Ireland, and Portugal, respectively, had 0.038, 0.034 and 0.032 probabilities to acquire the disease from Italy. We compute the probabilities for the sampled countries in this fashion. We employ the ordinary least squares (OLS) estimator to analyse equations (13) and (14) where the dependent variable is quantitative and the logit regression to estimate equations (15) and (16), the binary dependent variable equations. We report the marginal effects estimated at the sample means. Also, we employ the Pearson correlation coefficient to investigate the correlation between variables.

4 Results and discussion

4.1 Results

From Table 1, the average GDPMX (i.e. GDPM-to-GDPX ratio) is 0.126. Of the 128 countries sampled for the study, only 3 countries – Brazil, Saudi Arabia, and the United States – have their GDPs higher than that of their COVID-19 exporting countries – Italy, Iran, China, respectively. The average probability of a country to acquire COVID-19 from another country is 0.054. The WHO considers an outbreak a pandemic when the positivity rate of the disease is above or equals 0.05. The positivity rate is the share of total laboratory tests for the disease returning a positive result. Upon the COVID-19 outbreak in China on December 31, 2019, WHO declared the disease a pandemic on March 11, 2020, when the disease had spread to 114 countries and territories. The 0.054 transmission probability, equivalent to the positivity rate threshold, confirmed the high transmission rate of COVID-19.

Table 1: Descriptive statistics

Variable	Observations	Mean value	Stand. Dev.	Min.	Max.
PROB	128	0.054	0.081	0.015	0.5
GDPX (US\$)	118	4.49 tn	4.9 tn	405 bn	18.3 tn
GDPMX	128	0.126	0.234	0.0003	1.586
DIST (km)	119	5297.50	3802.75	96.30	16456.13
TEXTX	119	0.433	0.365	0.040	2.184
PREVX	118	0.026	0.017	0.00006	0.061

Prob. is probability of COVID-19 cases, bn is billion, and tn is trillion. Stand. Dev. is standard deviation.

From the appendix table, Table A1, 42 (58) countries acquired COVID-19 quicker (slower) than their exporting countries. For example, Hungary acquired the disease from Iran and Iran acquired it from China. Hungary (Iran) is the importing (exporting) country. Iran acquired the disease 50 days after the outbreak in China and Hungary acquired the disease 14 days after the outbreak in Iran. Therefore, Hungary acquired the disease quicker than Iran. Poland, however, acquired the disease slower than Germany (37 days and 27 days, respectively). Of the 128 countries, 80 countries (62.5%) acquired their first cases from their residents who returned from the exporting countries while 45 countries (35.16 percent), acquired the disease from visitors travelling from the exporting countries. Three countries, representing 2.34%, did not have information on the transmitters' nationality status. A similar pattern was observed in 58 countries that acquired COVID-19 late; 38 countries representing 65.52 percent acquired the COVID-

19 cases through returnee residents while 20 countries (34.48%) acquired the disease through visitors to the importing countries. Also, among the 42 countries that acquired COVID-19 cases quicker, 29 countries (69.05%) acquired the disease from their returnee residents while 13 countries (30.95%) acquired the disease from visitors to the importing countries.

Table 2 shows the OLS regression results. Results of five models (Models 1–5) are reported to check the robustness of the results. The overall performance of each model suggests that the models are well behaved as indicated by the models' probability values. All the explanatory variables had their expected signs. DIST and TEXTX had negative signs. The results show that a 1% increase in DIST (TEXTX) reduces the probability of the spread of COVID-19 by 0.168% (0.447%). The negative sign of GDPX means increase (decrease) in the exporting country's GDP decreases (increases) the importing country's

Table 2: OLS regression results of determinants of COVID-19 spread across countries

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
GDPM		0.154*** (0.024)	0.141*** (0.023)	0.076*** (0.031)	
GDPX		−0.381*** (0.073)	−0.315*** (0.065)	−0.278*** (0.064)	
GDPXM					0.150*** (0.0307)
DIST	−0.282*** (0.064)		−0.185*** (0.051)	−0.155*** (0.039)	−0.158*** (0.053)
TEXTX				−0.439*** (0.104)	−0.418*** (0.075)
PREVX				0.044** (0.035)	0.119*** (0.029)
Constant	−1.064* (0.559)	3.668* (1.988)	3.623* (1.855)	3.627* (2.028)	−1.441*** (0.427)
Model's <i>p</i> -value	0.000	0.000	0.000	0.000	0.000
<i>R</i> -square	0.178	0.334	0.403	0.597	0.4668
Root mean square	0.623	0.563	0.535	0.444	0.448
Observations	118	117	117	117	125

Robust standard errors in parenthesis. ***, **, and * indicate statistical significance at 1, 5, and 10% level, respectively.

probability to acquire COVID-19 from the exporting country. The positive sign of GDPM means increase (decrease) in the importing country's GDP increases (decreases) the country's probability to acquire COVID-19 from the exporting country. This means increase (decrease) in the economic activities of the exporting countries decreases (increases) the spread of COVID-19 to the importing countries, while increase (decrease) in economic activities of the importing countries increases (decreases) the spread of the disease to the importing countries.

In Model 4, the estimated coefficient of GDPX of -0.278 means that a 1% increase (decrease) in the economic activities of the exporting country decreases (increases) the probability of the spread of COVID-19 to the importing country by 0.278%. The negative effect of GDPX (-0.278) is greater than the positive effect of GDPM (0.076). The results show that the economic size of the exporting country contributes greatly (-0.278) to the spread of COVID-19 followed by distance (-0.155) and the economic size of the importing country (0.076). In Model 5, GDPMX shows a positive sign. The estimated coefficient of 0.150 means that a 1% increase (decrease) in the GDPM-to-GDPX ratio increases (decreases) the probability of the spread of COVID-19 to the importing country by 0.150%. This means, for example, a 10% increase (decrease) in GDPMX increases (decreases) PROB by 1.5%.

The results in Table 3 show that geographical distance relates negatively with the probability of the spread of COVID-19 to the importing country (-0.295) with -0.285 for delayed cases and -0.264 for early cases. We find similar correlation results between PROB and GDPX, which show that increases in GDP of the exporting country (GDPX) negatively correlates with the probability of spread of the disease to the importing countries (-0.228). Also, the results show that the higher the GDPM-to-GDPX ratio (i.e. increase in GDPM or decrease

in GDPX), the higher the probability of COVID-19 spread to the importing countries (0.1679).

Table 4 reports the results of the logit model on determinants of the early spread of COVID-19. Similar to the OLS results in Table 2, we estimated five models, Models 1–5, to check the robustness of the results. The marginal effects are estimated at the sample means. All the explanatory variables are statistically significant at a 5% significance level and have the expected signs. The results show a negative (positive) effect of the exporting (importing) country's GDP on the probability of the early spread of COVID-19. In model 4, the estimated marginal effects show that a unit decrease (increase) in the exporting (importing) country's GDP increases the probability of early spread by 0.237% (0.115%). A unit decrease (increase) in distance between the exporting and importing countries increases (decreases) the probability of early spread of the disease by 0.119%. Increase (decrease) in COVID-19 testing intensity (prevalence rate) of the exporting country is associated with decrease in the probability of early spread by 0.593% (0.710%). In Model 5, we find that a 1% increase (decrease) in GDPMX increases (decreases) the probability of early spread by 0.128%.

4.2 Discussion

In this study, we adapted the gravity model of trade to provide evidence of the contributions of economic sizes and distance between countries for the transmission of COVID-19. Studies that have used the gravity model for analyses find economic sizes of countries to positively influence trade [32,33] and immigration [18]. In this study, however, we find economic size of the disease-importing (-exporting) country to positively (negatively) influence the spread of the COVID-19. Also, we find the

Table 3: Correlation between variables

	Prob. and Dist.	Prob. and GDPM	Prob. and GDPX	Prob. and GDPMX
All countries	-0.295 (128)	-0.017 (128)	-0.228 (128)	0.1679 (125)
Delayed countries	-0.285 (58)	0.428 (58)	-0.24 (57)	0.8983 (57)
Early countries	-0.264 (42)	-0.108 (42)	-0.382 (42)	0.0286 (42)

Prob. is the probability of importing country recording its first case of COVID-19, and Dist. is flight distance (in kilometres) between the COVID-19 importing and exporting countries. Delayed countries are importing countries that recorded COVID-19 slower than their exporting countries and early countries are the importing countries that recorded COVID-19 quicker than their exporting countries. Numbers in parentheses are the number of observations.

Table 4: Logit regression results of determinants of early spread of COVID-19 across countries

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
GDPM		0.126*** (0.038)	0.118*** (0.337)	0.115** (0.048)	
GDPX		−0.370*** (0.101)	−0.337*** (0.111)	−0.237*** (0.095)	
GDPMX					0.128*** (0.041)
DIST	−0.985*** (0.056)		−0.129*** (0.049)	−0.119** (0.051)	−0.108* (0.059)
TESTX				−0.593** (0.277)	−0.551** (0.201)
PREVX				0.710*** (0.265)	0.478** (0.196)
Model's <i>p</i> -value	0.000	0.000	0.000	0.029	0.000
<i>R</i> -squared	0.141	0.293	0.352	0.476	0.350
Observations	93	92	92	92	99

Robust standard errors in parenthesis. ***, **, and * indicate statistical significance at 1, 5, and 10% level, respectively.

economic size of COVID-19 exporting (importing) country to have a larger (smaller) effect on the transmission of the disease. These results are confirmed by increases in the GDPM-to-GDPX ratio, where either an increase in GDPM or a decrease in GDPX increased the probability of the spread of the disease to the importing country.

An increase in the economic performance of the importing country attracts travellers into the country and a fall in economic activities of the exporting country due to the outbreak induces residents to relocate to the importing country. Increase in travellers from the exporting country to the importing country increases the probability of the spread of the disease to the importing country. A larger number of the sampled countries acquired COVID-19 through the return of residents from the exporting countries (appendix table, Table A1). Reports showed that GDP growth in countries fell due to the COVID-19 outbreak [34,35]. Largely, because people relocated to avoid being infected [12] and governments restricted human movement in an attempt to reduce the in-country transmission of the disease [12,36,37]. This suggests that upon an outbreak in a country, economic activities of the country would decrease to induce some people, some of whom may be infected, to relocate to other countries.

Many Sub-Saharan African (SSA) countries imported COVID-19 from European countries (Table A1). The health consequences of the outbreak in the sub region were not as catastrophic as they were in Europe. This outcome was not necessarily because SSA countries rolled out robust measures to contain the disease but due to the younger age distribution and warmer temperature that reduced the

transmission rate and severity of the disease in the region [39]. The SSA sub-region has weak health systems, observed in a high prevalence of undiagnosed diseases, unmanaged pre-existing diseases, and a severe shortage of intensive care beds [40]. Governments in many SSA countries marginally increased the budgetary allocation to the health sector. Only a few SSA countries are able to meet the 2001 Abuja Declaration target of not less than 15% of government spending to the health sector. The low investment in SSA health systems renders the countries in the sub-region vulnerable to catastrophic consequences of outbreaks.

We find distance between countries to decrease the spread of COVID-19. This means the longer the distance the lower the probability of the spread of the disease to another country. This is, perhaps, due to higher transportation costs and different environmental conditions as countries far apart are likely to have non-similar climates and cultures to discourage people from going to long-distance countries. This means an outbreak is likely to spread faster from one country to another when there is a short distance between the countries compared to when there is a long distance between them. The findings suggest that an outbreak is likely to spread faster to trading countries that share land borders than countries that do not share land borders.

Finally, we find higher testing intensity of the exporting country to reduce the spread of COVID-19 to the importing country. Testing for the disease enables provision of effective treatment to the infected or isolate the infected from the population to reduce the spread of the disease. A large

number of undetected COVID-19 cases in Mainland China were dispersed to international and local locations [38]. Those who contract the disease and are not quarantined or do not receive effective treatment are likely to carry the disease to other countries to infect others. Many a time, those who do not receive treatment are those who exhibit mild symptoms or do not exhibit symptoms of the disease, because they do not know they are infected and as such increase the transmission rate of the disease.

A limitation of this study is that we used geographical distance as a proxy for travel enhancing and hindering variables, including transportation costs, visa requirements, travel regulations, and means of transportation. We were unable to estimate the separate effects of these variables because we could not obtain data on the variables. Notwithstanding this limitation, an increase in distance suggests impediment, discomfort, inconvenience, or higher monetary cost to travel from one country to another and thus might discourage embarking on a journey to another country. Another limitation is that the gravity model is traditionally applied to study a phenomenon overtime, we used a cross-sectional data instead of panel data for the analysis. This is because time series data for the spread of COVID-19 were not available. But since first or initial cases of imported diseases attract more attention than subsequent imported cases, the cross-sectional analysis of the initial imported cases provides insight into the pattern of spread of diseases across countries. To our knowledge, this is the first study to use the gravity model to study the spread of diseases across countries. We hope future studies will build on this study.

5 Conclusion

Identifying the pathways through which diseases spread across countries informs the design and implementation of policies to reduce the pace of the spread of an outbreak from one country to another. We have provided evidence of the effects of economic sizes and geographic distance on the spread of the COVID-19 across countries. Since an outbreak in a country is more likely to decrease than to increase the economic activities of the country, an outbreak is likely to spread faster (slower) from a shrinking (booming) economy to a booming (shrinking) economy and faster (slower) when there is a shorter (longer) distance between the countries. In this regard, while ensuring the health and safety of people and reducing the transmission rate during an outbreak in a country, facilities should be provided to enable the residents to engage in their

economic activities to help reduce the economic consequences of the outbreak. This will help to stabilise the economic welfare of the residents and reduce the tendency to relocate to another geographical area which contributes to the spread of the disease. Also, since every country is a potential disease-exporting country, because people travel between countries, increased investment in infrastructure and capacity to handle contagious disease before the onset of outbreaks would reduce the transmission probabilities of any outbreak.

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Ethical approval: The conducted research is not related to either human or animal use. Therefore, ethical approval was not required.

Data availability statement: The data used for the analysis are publicly available from the WHO (<https://covid19.who.int/>) and World Bank (<https://databank.worldbank.org/source/worlddevelopment-indicators>).

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Appendix

Table A1: Countries sampled for the study

CHINA [#]		ITALY		SPAIN	
1. Russia	31 (0.032), <i>V</i>	44. Ukraine	32 (0.031), <i>D,V</i>	89. Panama	38 (0.026), <i>D,R</i>
2. France	24 (0.041), <i>V</i>	45. Czech	30 (0.033), <i>E,V</i>	90. Honduras	39 (0.025), <i>D,R</i>
3. Italy	31 (0.032), <i>V</i>	46. Netherland	27 (0.037), <i>E,R</i>	91. Peru	35 (0.028), <i>D,R</i>
4. Belgium	35 (0.028), <i>R</i>	47. Portugal	31 (0.032), <i>Q,R</i>	92. Ecuador	29 (0.034), <i>D,R</i>
5. Sweden	26 (0.038), <i>R</i>	48. Switzerland	25 (0.04), <i>E,R</i>	93. Uruguay	42 (0.023), <i>D,R</i>
6. Norway	57 (0.017), <i>R</i>	49. Austria	25 (0.04), <i>E,V</i>	94. Namibia	43 (0.023), <i>D,V</i>
7. Finland	29 (0.034), <i>V</i>	50. Slovakia	35 (0.028), <i>D,R</i>	95. Angola	50 (0.02), <i>D,R</i>
8. USA	20 (0.50), <i>R</i>	51. Croatia	25 (0.04), <i>E,R</i>	96. Djibouti	47 (0.021), <i>D,V</i>
9. Canada	27 (0.037), <i>R</i>	52. Denmark	27 (0.037), <i>E,R</i>	97. Equa. Guinea	43 (0.023), <i>D,R</i>
10. India	30 (0.033), <i>R</i>	53. Ireland	29 (0.034), <i>E,R</i>	98. Papua N. Gui.	49 (0.020), <i>D,R</i>
11. Iran	50 (0.020), <i>V</i>	54. Lithuania	28 (0.035), <i>E,R</i>	USA	
12. Philippines	30 (0.033), <i>V</i>	55. Slovenia	33 (0.030), <i>D,V</i>	99. Costa Rica	46 (0.021), <i>D,V</i>
13. Nepal	23 (0.043), <i>R</i>	56. Moldova	36 (0.027), <i>D,R</i>	100. Belize	63 (0.015), <i>D,R</i>
14. Japan	16 (0.062), <i>R</i>	57. Greece	26 (0.038), <i>E,R</i>	101. Haiti	59 (0.016), <i>D,R</i>
15. UAE	29 (0.034), <i>V</i>	58. Bosn. & Herz.	34 (0.029), <i>D,R</i>	102. Venezuela	53 (0.018), <i>D,R</i>
16. Malaysia	25 (0.04), <i>V</i>	59. N. Macedonia	26 (0.038), <i>E,R</i>	103. Guyana	51 (0.019), <i>D,V</i>
17. South Korea	20 (0.05), <i>V</i>	60. Albania	37 (0.027), <i>D,R</i>	104. Kenya	53 (0.018), <i>D,R</i>
18. Singapore	23 (0.043), <i>V</i>	61. Latvia	31 (0.032), <i>Q,R</i>	105. Eswatini	54 (0.018), <i>D,R</i>
19. Egypt	45 (0.022), <i>V</i>	62. Luxembourg	29 (0.034), <i>E,R</i>	UK	
20. Australia	25 (0.04), <i>V</i>	63. Malta	36 (0.027), <i>D,V</i>	106. Jamaica	47 (0.021), <i>D,V</i>
21. Germany	27 (0.037), <i>U</i>	64. Andorra	31 (0.032), <i>Q,R</i>	107. Myanmar	60 (0.0167), <i>D,R</i>
22. UK	23 (0.043), <i>U</i>	65. Iceland	28 (0.035), <i>E,R</i>	108. Mozambique	59 (0.0169), <i>D,R</i>
IRAN		66. Mexico	28 (0.035), <i>E,R</i>	109. Zimbabwe	57 (0.017), <i>D,R</i>
23. Hungary	14 (0.07), <i>E,V</i>	67. Domini. Rep.	30 (0.033), <i>E,V</i>	110. Cape Verde	57 (0.017), <i>D,V</i>
24. Iraq	5 (0.20), <i>E,V</i>	68. Guatemala	42 (0.023), <i>D,R</i>	FRANCE	
25. Pakistan	7 (0.142), <i>E,R</i>	69. El Salvador	47 (0.021), <i>D,R</i>	111. Uzbekistan	51 (0.019), <i>D,R</i>
26. Saudi Arabia	12 (0.083), <i>E,R</i>	70. Cuba	40 (0.025), <i>D,V</i>	112. Cameroon	42 (0.023), <i>D,V</i>
27. Georgia	7 (0.142), <i>E,R</i>	71. Bangladesh	37 (0.027), <i>D,R</i>	113. Zambia	54 (0.018), <i>D,R</i>
28. Azerbaijan	9 (0.111), <i>E,V</i>	72. Jordan	31 (0.032), <i>Q,R</i>	114. Senegal	38 (0.026), <i>D,V</i>
29. Lebanon	2 (0.50), <i>E,R</i>	73. Cyprus	38 (0.026), <i>D,R</i>	115. DR. Congo	46 (0.021), <i>D,R</i>
30. Armenia	11 (0.090), <i>E,R</i>	74. Maldives	36 (0.027), <i>D,V</i>	116. Gabon	48 (0.020), <i>D,R</i>
31. Kuwait	5 (0.20), <i>E,V</i>	75. Brazil	25 (0.04), <i>E,R</i>	117. Congo Rep.	50 (0.020), <i>D,R</i>
32. Qatar	10 (0.10), <i>E,R</i>	76. Colombia	35 (0.028), <i>D,R</i>	118. Sierra Leone	67 (0.014), <i>D,V</i>
33. Oman	5 (0.20), <i>E,R</i>	77. Argentina	32 (0.031), <i>D,V</i>	JAPAN	
34. Bahrain	2 (0.50), <i>E,R</i>	78. Bolivia	39 (0.025), <i>D,R</i>	119. Indonesia	46 (0.021), <i>D,V</i>
35. Afghanistan	5 (0.20), <i>E,R</i>	79. South Africa	34 (0.029), <i>D,R</i>	120. Israel	36 (0.027), <i>D,R</i>
36. New Zealand	10 (0.10), <i>E,R</i>	80. Morocco	31 (0.032), <i>Q,R</i>	121. Ethiopia	57 (0.017), <i>D,V</i>
UAE		81. Tunisia	31 (0.032), <i>Q,R</i>	SINGLE*	
37. Uganda	53 (0.018), <i>D,R</i>	82. Nigeria	27 (0.037), <i>E,V</i>	122. Ghana	15 (0.066), <i>E,V</i>
38. Sudan	44 (0.022), <i>D,V</i>	83. Ivory Coast	40 (0.025), <i>D,R</i>	123. Libya	22 (0.045), <i>D,R</i>
39. Chad	57 (0.017), <i>D,R</i>	GERMANY		124. Nicaragua	9 (0.111), <i>E,R</i>
NETHERLAND		84. Spain	4 (0.035), <i>E,V</i>	125. Niger	21 (0.047), <i>E,V</i>
40. Suriname	15 (0.066), <i>E,V</i>	85. Poland	37 (0.027), <i>D,R</i>	126. Paraguay	7 (0.142), <i>E,V</i>
41. South Sudan	38 (0.026), <i>D,R</i>	86. Kazakhstan	46 (0.021), <i>D,R</i>	127. Serbia	2 (0.50), <i>E,R</i>

(Continued)

Table A1: Continued

CHINA [#]		ITALY		SPAIN	
INDIA		SWITZERLAND		128. Tanzania	40 (0.025), <i>D,V</i>
42. Malawi	63 (0.015), <i>D,R</i>	87. Trini. & Tob.	16 (0.062), <i>E,U</i>		
43. Guinea-Bissau	55 (0.018), <i>D,V</i>	88. Liberia	20 (0.05), <i>E,R</i>		

* Seven countries exported COVID-19 to one country only, at the time of the data collection. This means seven importing countries acquired their first cases from seven countries that did not export the disease to other countries. Norway (Nigeria) exported the disease to Ghana (Niger) only, Belgium (Hungary) exported it to Tanzania (Serbia) only, Saudi Arabia (Ecuador) exported it to Libya (Paraguay) only, and Nicaragua exported it to Panama only. The figures in parenthesis is the probability of COVID-19 importing country acquired the disease from the exporting country. The figures outside the parenthesis is the number of days elapsed for the importing country acquired the disease from the exporting country. For example, COVID-19 was reported in China on December 31, 2019. Russia recorded its first case of the disease on January 31, 2020. This means it took 31 days for the disease to reach Russia. *R* means a resident of the COVID-19 importing country brought the disease to the country, *V* means a visitor to the importing country brought the disease to the importing country, and *U* is unknown identity of the person(s) who brought the disease to the importing country (because the data source – www.wikipedia.com – did not indicate the identity of the person). [#] There is no indication of quicker or slower recording of COVID-19 for countries that acquired the disease from China because the disease started in China.