CROSS-BORDER TRANSPORTATION AS A DISEASE VECTOR IN COVID-19

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EXECUTIVE SUMMARY

The novel coronavirus disease 2019 (COVID-19) is a rapidly spreading infectious disease that was declared a pandemic by the World Health Organization (WHO) on March 11, 2020 (*1*). As of August 20, 2020, there were more than 20 million cases, with more than 800,000 deaths around the world. From a transportation perspective, understanding the key parameters that cause the faster spread of a disease is vital for decision-makers. Countries can then better prepare for a possible second wave of COVID-19 or potential new pandemics. The objective of this study was to conduct an extensive literature review on the COVID-19 pandemic from a transportation perspective, with a particular emphasis on binational metropolitan areas, and to develop an understanding of the relationship between cross-border transportation and the speed of the spread. A more thorough understanding of the links between transportation and the pandemic will allow researchers to recognize which transportation measures have the most potential to help mitigate the pandemic's impact and preserve cross-border mobility during a potential second wave or a future pandemic.

Currently, the United States and Mexico rank first and third, respectively, in the number of deaths due to COVID-19. Both countries took various precautions to slow down the spread. One precaution was to partially close border crossings. Nonessential travelers were restricted from crossing the border, which resulted in a more than 50 percent decrease in the number of people crossing the border daily. However, border cities still faced a high number of cases and fast community spread. Other countries around the world also implemented various pandemic-related international traveler precautions at border crossings and international airports. Some countries closed their borders and did not allow anyone to cross the border, while other countries allowed only their citizens and essential workers to enter. Most countries are providing travel warnings and advisories to their citizens. In a few countries, travelers are being asked to provide a medical certificate with a negative COVID-19 test or take compulsory testing upon entry. Some countries are requiring everyone who enters the country to quarantine in a government-funded facility for 14 days. A growing number of countries are using technology and implementing measures to regulate the movement of citizens to slow down the spread of COVID-19. Contact tracing, massive thermal screening, and artificial intelligence at the borders are some other examples of preventive measures worldwide. Each measure has its advantages and limitations, and each country has its own policy regarding the use of such technologies.

To understand the effect of cross-border transportation and other socioeconomic parameters on the speed of spread in the U.S.-Mexico border region, researchers developed two macro models, one for each side of the border. Information on more than 20 variables was gathered from publicly available sources. The U.S. macro model was developed at the county level using information from 687 counties. On the other hand, the Mexico macro model was developed at the state level using information from 32 states. The results for each model showed that population, number of households, mobility index, and border crossings have a significant effect on the speed of spread. The uninsured population rate, rate of transit users, and length of the stay-at-home order are other variables that were found to be significant for the United States. In addition, the Mexico model findings revealed that poverty rate is also significant. Because data were limited for Mexico and only 32 data points were found at the state-level model development, researchers conducted a follow-up study to illustrate the effect of border crossings in Mexican states that border the United States. The findings revealed that Mexican cities with border crossings have on average 3.6 cases per 1,000 population, while cities without border crossings only have 1.6 cases on average.

For the micro-model development, researchers focused on the El Paso–Ciudad Juarez region—which contains the busiest border crossing in Texas—due to its unique location and large metropolitan areas on both sides of the border. Daily border crossings and their effects on the daily increases of COVID-19 cases were explored. Since testing is not conducted every day and the results fluctuate day to day, researchers used 7-day averages for all parameters. Two models were developed using the El Paso and Juarez datasets separately. Due to collinearity issues, independent variables were tested individually, and the results from the El Paso dataset showed that the most significant variable is the mobility of the people, followed by the number of people working at their workplaces, and then the number of border crossings. Due to testing and reporting limitations in the Juarez dataset, no parameters were found to be significant, which also indicates the importance of having the necessary data when developing models.

This study clearly shows that border crossings have a significant effect on the spread of infectious diseases like COVID-19 in their surrounding communities. The main contributions of this research are the results of the macro- and micro-level models, which led to an understanding of the key influencers in the spread of infectious disease from a transportation and border-crossing perspective.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

COVID-19 is a rapidly spreading infectious disease that was declared a pandemic by WHO on March 11, 2020 (*1*). As of August 20, 2020, more than 20 million cases with more than 800,000 deaths around the world had occurred. The United States is the most affected country based on the total number of cases and fatalities. Since no treatment is currently available and a vaccine is not yet ready, most countries applied shutdowns for nonessential businesses and asked people to stay at home to slow down the rapid spread of the virus. Millions of people lost their jobs, and a worldwide economic recession is expected.

The effects of the pandemic are also being felt in the El Paso–Juarez region, resulting in the closure of the border to nonessential travel and a drop in personal vehicle crossings of more than 60 percent. Currently, El Paso has nearly 20,000 confirmed cases of COVID-19 (*2*) and nearly 400 deaths, while Juarez has reported nearly 5,000 confirmed cases and 700 deaths. Furthermore, Juarez accounts for the majority of the confirmed cases (9,000) and deaths in the state of Chihuahua (1,000) (*3*).

The main goals of all governments' efforts are to flatten the curve of infection and establish testing and contact tracing mechanisms before they consider relaxing social distancing directives. Countries apply various methods to reach those goals. From an epidemiological perspective, available and fast transportation is considered the major reason for the rapid spread. Mobility of people leads to mobility of the communicable disease. Therefore, transportation of people is a key component of disease spread and needs to be understood correctly to ensure that subsequent efforts to contain disease spread are productive.

1.2 OBJECTIVE

The objective of this study was to conduct an extensive literature review on the COVID-19 pandemic from a transportation perspective, with a particular emphasis on binational metropolitan areas, such as El Paso–Juarez, and to develop an understanding of the relationship between cross-border transportation and the speed of spread. Topics in the review included government control measures and public reaction behavior, innovative technology applications to screen people, and contact tracing. Transportation- and border-crossing-related statistics were gathered to develop macro- and micro-level econometric models that helped researchers explore the relationship between transportation and the speed of spread.

A more thorough understanding of the links between transportation and the pandemic will allow researchers to recognize which transportation measures have the most potential to help mitigate the impact and preserve cross-border mobility during a potential second wave or a future pandemic. This study helps expand the understanding of cross-border transportation as a disease vector and enable researchers to develop technology applications with potential to mitigate the impact of a second COVID-19 wave on cross-border transportation.

1.3 OUTLINE OF REPORT

The remaining chapters of this report include the following:

- **Chapter 2: Literature Review**—This chapter reviews existing literature and reputable U.S. and Mexican news sources to provide background information about the COVID-19 pandemic and its effect on U.S.-Mexico border communities. Previous similar outbreaks (severe acute respiratory syndrome [SARS], Middle East respiratory syndrome [MERS], Ebola) are also examined. Literature documenting the use of technology applications, ranging from applications to identify potentially infected people to applications to trace exposure, are explored.
- **Chapter 3: Model Development**—Researchers collected data from various U.S. and Mexican sources. This chapter explains the data collection methodology and provides descriptive statistics about the collected data and insights about the econometric model development.
- **Chapter 4: Model Results**—This chapter shares the findings from the model deployment at the macro and micro levels.
- **Chapter 5: Findings and Conclusions**—This chapter presents the main findings and conclusions drawn from the study and discusses the potential for further studies.

CHAPTER 2. LITERATURE REVIEW

2.1 PANDEMICS AND COVID-19

According to WHO, a pandemic is the worldwide spread of a new disease (*4*). The most common occurring pandemic is influenza since the virus constantly changes, thereby creating a new disease each time it does so. Throughout history, as humans move, infectious diseases have spread across the world, and millions of people have died because of pandemics (black death, smallpox, Spanish flu, HIV, etc.). WHO officially declared COVID-19 a pandemic on March 11, 2020 (*1*), and as of August 20, 2020, the number of cases was above 24 million globally, with more than 800,000 deaths (*5*).

COVID-19 arrived in the United States early in 2020. Officially, the country had its first case on January 20; thereafter, the virus started to spread with increasing pace. Currently, the United States is the country with the most positive cases in the world. Over 75 million tests have been done, with an 8 percent positive rate. The country has had approximately 6 million COVID-19 cases and over 180,000 deaths, which constitutes a death rate of 3 percent among cases (*2,5*). Even though it is the country with the most deaths, it has one of the lowest death rates worldwide. In contrast to the uniform national-level approaches that other countries have taken in response to COVID-19, each state in the United States has developed its own approach and response using its own methods and criteria. Therefore, each state has tried different methods and, consequently, has experienced different results. For instance, there was a mandatory lockdown in almost all 50 states across the country and different reopening dates based on governors' discretion; only five states did not implement a mandatory lockdown (*6*). In addition, a mandate requiring masks in public has been applied in some states. Schools and high-risk institutions were closed, but these institutions reopened after establishing prevention methods and different rates of virtual classes. Travel restrictions into the country were applied by the federal government. Land border crossings have been limited to essential travel only since March 21, 2020 (*7*). Additionally, a stay-at-home quarantine was applied to travelers entering the country who may have been exposed to the virus and might pose the risk of transmitting it.

Mexico's first case was identified on January 13, but it was not until late February that the virus started to spread across the country. Currently, Mexico has tested over 1.2 million individuals, over 560,000 of whom tested positive. Mexico currently has the third most COVID deaths—over 60,000 deaths—which amounts to a 10.5 percent death rate (*3*). This situation has raised concerns among the Mexican public since the rate is high compared to countries that have had more positives cases and fewer deaths. In order to increase awareness among Mexican residents, the Mexican government and its designated COVID-19 leader started holding daily press conferences to update the data regarding COVID-19 as well as offer recommendations to help slow the spread of the virus. Although the Mexican federal government never issued a stay-at-home order or mandated the use of face masks, it encouraged residents to stay at home and to use a mask if going out. Schools and any other high-risk institutions were closed at an early stage of the pandemic and have yet to reopen (*8*). In addition, nonessential businesses closed on March 30 and remained closed more than 2 months. The national government did not allow each state to manage the situation individually. All 32 states were given the same preventions, instructions, and recommendations (*9*). Mexico implemented restrictions on visitors entering the country by land at the border with the United States on March 21, 2020 (*7*).

2.2 TRANSPORTATION AND PANDEMICS

Various factors promote the spread of infectious diseases, and one major factor is transportation. The transmission of infectious diseases has not changed over time. What has evolved, though, with technology and globalization, is the speed of the spread. Because of emerging technology and accessible air travel, recent outbreaks (SARS-2002, Avian Flu-2005, COVID-2019) spread quicker than the previous outbreaks (*10*). From an epidemiological perspective, transportation is considered a disease vector, particularly passenger transportation systems. Air transportation is linked to the early phases of a pandemic and can cause any outbreak to spread to the global level. Therefore, after WHO declared the COVID-19 outbreak a pandemic, under the provisions of the International Health Regulations, most countries adopted some form of cross-border measures, including travel and visa restrictions and border closures. In fact, a wider range of cross-border measures have been adopted by countries during the COVID-19 pandemic than in previous disease outbreaks. All those precautions resulted in a dramatic decline in air passenger activity after April 2020.

Community spread is the second step in pandemics; it starts when the disease is spread in a region not only because of the arrival of sick individuals but also because of existing community members. Health departments determine community spread based on local conditions by checking the infected people in the region who are not sure how or where they became infected. At this stage, the mobility and social distancing of the people in that region have vital importance.

2.3 BORDERS IN THE TIME OF PANDEMICS

The impacts of cross-border travel restrictions and screening measures during a pandemic are not well reviewed. Errett et al. (*11*) suggested that restrictions may help to delay the spread. In contrast, Chinazzi et al. (*12*) maintained that the effects are negligible. Some other studies even claimed that certain measures are counterproductive because they discourage potentially ill people from disclosing their symptoms and can create a false sense of security. A study conducted in Australia that examined the capacity of internal border control to limit influenza spread in an outbreak showed that population size, travel rates, and places had significant effects on the delay of the spread (*13*).

The United States established pandemic response plans to include border-crossing restrictions. Three countries (the United States, Mexico, and Canada) reached an agreement to limit all nonessential travel across their borders. These measures were initially implemented on March 21, 2020, and were in place for 30 days. After reevaluations, several further extensions were made, and the latest was put in place until August 20, 2020. Nonessential travel includes travel that is considered tourism or recreation oriented. U.S. citizens and lawful permanent residents are exempt from this action and are allowed to reenter the United States.

To regulate mobility and access during a pandemic, border restrictions shift. Governments set policies to limit access to their countries, which is more important during a pandemic. One measure is to check incoming travelers as far from the actual territorial border as possible. When the first cases of COVID-19 were seen in China in January 2020, neighboring Asian countries who had experienced similar respiratory infectious disease outbreaks—such as SARS (2003) and MERS (2012)—took measures immediately. South Korea, Taiwan, and Hong Kong officials boarded planes arriving from Wuhan, China, to screen passengers before allowing them into their countries (*14*). Canada announced that borders were temporarily closed to anyone, including its own citizens, who had COVID-19 symptoms, and they would be prevented from boarding a Canada-bound plane.

The Court of Justice of the European Union agreed that member states have rights and are responsible for public health matters and should decide on any measurement put in place (*15*). This permits closing or restricting borders, testing at border crossings, and requiring people to wear masks at the borders. Regional differences exist within individual member states in terms of the implementation of border measures, and the response for each country differs (*16*); for example, Austria and Bulgaria require persons (with exceptions) entering the country from the Schengen Area to present a medical certificate not older than 3 or 4 days noting their state of health and COVID-19 test results. Finland introduced an internal border control restriction on nonessential travel for the Schengen countries. The Republic of Lithuania screens all persons for COVID-19 symptoms at border crossing points.

Another term derived during the SARS outbreak is *exit screening*, which is considered an effective way to fight outbreaks. However, very little research compares entry and exit screenings and their effectiveness at land ports of entry. Exit screening measures were actively taken during the SARS outbreak in Australia, Canada, and Singapore but did not detect any confirmed cases; however, cases of SARS were noticed in the countries where the screening took place (*17*).

During the Ebola outbreak in West Africa, the Centers for Disease Control and Prevention (CDC) implemented travel and border health measures to prevent the international spread of the disease. CDC staff provided in-country technical assistance for exit screening in countries in West Africa dealing with the outbreak. They also participated in the education and protection of travelers and communities in that region. Although it is difficult to assess, this process might have helped control the outbreak. The disease was spread through population movement along the borders of Guinea, Sierra Leone, Liberia, Senegal, and Mali. Exit screening measures for Ebola covering those countries did not identify any confirmed cases (*17*).

2.4 USE OF TECHNOLOGY AT THE BORDERS

A growing number of countries are implementing technology-based measures to regulate the movement of citizens and slow the spread of COVID-19. For example, Israel announced that "all means" will be used to fight the spread of the virus, including any and all technology thus far not used for the civilian population (*18*). In other words, privacy concerns are not an issue anymore, and the government can track the movements of people testing positive for the virus without asking for consent from the individuals.

The European Union funded a project called iBorderCtrl, which is a way of using artificial intelligence at the borders (*19*). This "virtual policeman" is designed to prescreen incoming travelers by subjecting them to a short interview. The system is strengthened by a lie detector and will be used at airports or land ports of entry.

Before the pandemic hit, some countries were working on installing biometric technology at their borders to allow arriving and departing passengers to move through customs without their travel documents being inspected by an officer. Instead, the body itself becomes the ticket and passport of an individual. Dubai International Airport has already conducted a pilot test of the technology. Passengers are asked to pass through a smart tunnel that identifies each person with special scans (*19*). This technology is also promising in its ability to detect symptomatic sick people.

Another way to detect symptomatic sick people is to employ mass thermal screenings by camera. Although these cameras were designed for military use, since the systems can sense elevated skin temperature, they are widely used to screen people at airports. However, there are three issues with this technology: first, the system is still not precise enough to identify all people who have a fever; second, many people with COVID-19 infection do not actually have fevers; and third, the system cannot detect sick people with fever who took medicine to lower their temperature. Although scanners were in use across airports in Asian countries during the SARS outbreak in 2003 (*20*), the technology has not proven itself yet (*21*). Scanning systems and thermal cameras perform better with the use of artificial intelligence combined with image processing and machine learning algorithms. A cloud-based centered system may drastically reduce the number of public health staff requirements at the screening points (*22*).

Although thermal screenings are generally implemented at international airports, Singapore has employed thermal screenings at some land ports of entry. Thermal screenings were implemented at Woodlands and Tuas checkpoints in January 2020 to check arriving travelers from Malaysia.

Suspect cases were referred to hospitals for further assessment. The screenings will resume once the border closures are lifted (*23*).

2.5 EL PASO–CIUDAD JUAREZ BINATIONAL CHALLENGES ON COVID-19

El Paso (United States) and Juarez (Mexico) form the second largest binational metro area along the U.S.-Mexico border after San Diego–Tijuana. The El Paso–Juarez corridor is the busiest border crossing in Texas, with its unique location encompassing a binational conurbation of two large cities, one on each side of the border. This corridor supports major binational manufacturing, warehousing, and transportation industry. Similar to the rest of the world, COVID-19 hit the El Paso–Juarez border region hard. Border crossings were restricted to essential travelers only on March 21, 2020, resulting in a drop in personal vehicle crossings of more than 60 percent. Still, the spread of the disease could not be controlled. Currently, El Paso has nearly 20,000 confirmed cases of COVID-19, with close to 400 deaths (*2*), while Juarez has reported nearly 5,000 confirmed cases and 700 deaths. Furthermore, Juarez accounts for the majority of the confirmed cases (9,000) and deaths (1,000) in Chihuahua (*3*).

After agreement between the United States and Mexico, border crossings have been limited in the El Paso–Juarez region (*7*). The United States does not allow nonessential travelers to enter the country, excluding citizens and permanent residents, but has not taken any other special measures. On the Mexican side of the border, during the first days of spread, Mexican police officers logged the temperature of visitors entering Mexico (*24*). Entry to Mexico was denied if the temperature of an individual was high. In addition, in Juarez, citizens were fined if more than two people older than 18 years rode in the same vehicle. Therefore, Mexican police officers at the border were also screening the number of people in each car crossing to Mexico (*24*). These restrictions in Juarez lasted until May; since then, no filters have been applied at the border to enter the country.

One of the main objectives of this study was to understand the effects of border crossings on the spread of an infectious disease. The El Paso–Juarez region was selected as the case study since it has extensive numbers of border crossings of all modes and is an urbanized binational region. Although borders are closed to nonessential travel, thousands of people still cross the border daily. Available data are limited in terms of the origin of the COVID-19 positive individuals. Therefore, researchers aimed to understand the direct effects of daily crossings on the speed of the spread for both sides at the micro level.

CHAPTER 3. MODEL DEVELOPMENT

Researchers classified the models into two levels: (a) macro-level models, and (b) micro-level models. The studies were conducted for each country. Macro models were developed for the econometric analysis of the larger-scale data, which were county level for the United States and state level for Mexico. Researchers also conducted an extra analysis using Mexico data at the city level for the states that have border crossings to the United States. The micro-level model development, on the other hand, focused on the El Paso–Juarez binational region by linking the daily crossings, the mobility of the community, and the number of cases.

3.1 MACRO LEVEL

3.1.1 Study Data

Exploring the socioeconomic, transportation, and COVID-19 related data to see the effects on the speed of spread helps researchers understand and focus on the most significant parameters. This chapter introduces the data, along with their sources, and the methodology to examine the data. The first goal of this research was to understand the effects of transportation and border-crossing-related parameters on the speed of spread. The speed of spread was defined as the average number of daily cases in a region after the 100th case was experienced. Based on the availability of the data, the regions were selected at the county level for the United States and state level for Mexico. Since the data resources were different, researchers did not merge the two datasets (U.S. and Mexico) in order to prevent any bias and analyzed each country's models independently.

3.1.1.1 United States

In the United States, there are 3,141 counties or county equivalents in the 50 states and the District of Columbia (*25*). By the time data collection started, there were 687 counties in the United States that had more than 100 cases. To develop macroscopic regression models with a population size of 3,141, the sample size to give a 99 percent confidence level with a 5 percent margin for error was 550. Therefore, researchers kept those 687 counties for the model development.

The variable descriptions and data sources are listed in Table 1. Because the data were taken from different sources, it is necessary to explain how certain variables were determined.

- The area, population, household income, poverty rate, employment rate, uninsured population rate, rate of driving residents, rate of carpool users, and rate of public transit users were all collected from the U.S. Census Bureau based on the latest available data for each county.

- The number of cases was used to calculate the speed of spread. Researchers recorded July 15, 2020, as the last day of the study.
- The number of tests was directly gathered from the county health departments in cases where they publish this information. For the ones that do not provide this information, the state average (tests/population) was used to extrapolate the number of tests at the county level.
- For airport and border crossings, two categories were created: "yes" and "no." Researchers selected "yes" if the county has an airport or a land port of entry.
- Researchers recorded the effective starting and ending dates for stay-at-home and nonessential business closures to calculate the length of the orders. If the orders have not yet been lifted, the last day of the analysis was taken as the last date.
- The average temperature was the mean of daily temperatures recorded between April 1, 2020, and July 1, 2020, at the county level.
- Social distancing scoreboard was a letter grade given to counties by a third-party organization using various parameters, including change in average distance traveled and visitation to nonessential venues compared to the pre-COVID-19 period.
- Google retail, transit stations, workplaces, and at home indexes are all released freely by Google in its Community Report using aggregated, anonymized sets of data from users who have turned on their location history. The data show how time spent in categorized places changes compared to baseline days (median value from the 5-week period from January 3 to February 6, 2020). These data provide daily mobility changes at the county level. Researchers took the average for each index between April 1, 2020, and July 1, 2020.
- The Apple mobility index is another publicly available data source provided by Apple that focuses on the daily changes in requests for directions by transportation type for all counties in the United States. Researchers took the average of daily values between April 1, 2020, and July 1, 2020, for model development. January 13, 2020, was selected as the baseline, and all counties' and states' relative volume changes since that time were used to calculate the index that considered the seasonal effects.

Table 1. Model Variables

Name	***Value and Unit***	***Reason***	***Reference***
Area	Land area in square miles	To see the effect of the larger regions and a possible interaction with population	U.S. Census (*26*)
Population	Number of people	To see the effect of the population	U.S. Census (*26*)
Household income	Median household income in dollars	To see the effect of income level	U.S. Census (*26*)
Poverty rate	Rate of population who live under poverty threshold	To see the effect of poverty rate	U.S. Census (*26*)
Employment rate	Rate of population who actively work	To see the effect of number of workers	U.S. Census (*26*)
Population above 65 years old	Rate of population above 65 years old	To see the effect of senior population	U.S. Census (26)
Households	Number of households in the region	To see the effect of population per household	U.S. Census (*26*)
Uninsured population	Rate of uninsured population	To see the effect of uninsured population	U.S. Census (*26*)
Drove alone	Rate of commuters who drive to work	To see the effect of drive-alone preference	U.S. Census (*26*)
Carpool	Rate of commuters who carpool to work	To see the effect of carpool preference	U.S. Census (*26*)
Transit	Rate of commuters who use transit to work	To see the effect of transit preference	U.S. Census (*26*)
Number of cases	Number of COVID-19 cases on July 15, 2020	To calculate the speed of spread	USAFacts (*2*)
Number of tests	Number of COVID-19 tests reported by local agencies	To see the effect of testing (the state average per population was used for the cases counties do not report)	County & state health departments
Airport	1 if Yes 0 if No	To see the effect of having an airport	Bureau of Transportation Statistics (BTS) (*27*)
Border crossing	1 if Yes 0 if No	To see the effect of having at least one land port of entry	BTS (27)
Stay-at-home order length	Number of days stay-at-home order was in effect	To see the effect of longer stay-at-home orders	Institute for Health Metrics and Evaluation (IHME) (*6*)
Nonessential business closure length	Number of days nonessential business closure order was in effect	To see the effect of longer nonessential business closure orders	IHME (*6*)
Social distancing scoreboard	1 if F grade 2 if D grade 3 if C grade 4 if B grade 5 if A grade	To see the effect of social distancing	Unacast (*28*)
Average temperature	Average April-May-June temperature in °F	To see the climate influence	National Centers for Environmental Information (*29*)

Name	*Value and Unit*	*Reason*	*Reference*
Google retail	Time of stay change at retail places, average rate in April-May-June	To see the effect of people density at retail places	Google (*30*)
Google transit stations	Time of stay change at transit stations, average rate in April-May-June	To see the effect of people density at transit stations	Google (*30*)
Google workplaces	Time of stay change at workplaces, average rate in April-May-June	To see the effect of people density at workplaces	Google (*30*)
Google at home	Time of stay change at residential units, average rate in April-May-June	To see the effect of people density staying at home	Google (*30*)
Apple mobility index	Daily changes in requests for directions, average rate in April-May-June	To see the effect of people's mobility	Apple (*31*)

For each variable within the U.S. dataset, the descriptive statistics were calculated and are shown in Table 2.

Table 2. Descriptive Statistics of U.S. Data

Name	*Mean*	*Std. dev.*	*Min.*	*Max.*	*Median*
Area (square miles)	925.5	1,597.0	15.0	20052.0	576.1
Population	360,772	638,133	5,812	10,098,052	174,202
Household income ($)	60,744	17,019	21,093	136,268	57,333
Poverty rate (%)	14.3	6.0	3.5	43.6	13.5
Employment rate (%)	58.7	7.0	22.5	77.1	59.5
Population above 65 years old (%)	15.5	3.9	6.1	55.6	15.1
Households	132,368	221,794	126	3,306,109	65,645
Uninsured population (%)	9.1	4.3	2.0	30.5	8.6
Drove alone (%)	79.6	8.8	6.0	91.0	81.3
Carpool (%)	9.3	2.3	1.9	23.1	8.9
Transit (%)	2.5	6.0	0.0	61.4	0.8
Number of cases	4,419	10,190	135	143,009	1,507
Speed of spread (average daily cases)	**39.8**	**86.1**	**0.4**	**1190.9**	**14.5**
Number of tests	53,511	103,549	1,000	1,559,384	24,255
Airport	0.30	0.46	0.00	1.00	N/A
Border crossing	0.02	0.13	0.00	1.00	N/A
Stay-at-home order length (days)	44.5	29.3	0.0	118.0	39.0
Nonessential business closure length (days)	35.7	30.8	0.0	118.0	40.0
Social distancing scoreboard (1 to 5)	1.18	0.45	1.0	3.0	1.0
Average temperature (°F)	63.6	7.3	40.9	81.5	62.3
Google retail	(17.9)	10.1	(62.8)	8.3	(16.9)
Google transit stations	(18.6)	15.2	(64.0)	29.0	(15.7)
Google workplaces	(27.4)	6.3	(50.6)	4.0	(27.0)
Google at home	10.2	3.2	(1.4)	22.4	9.9
Apple mobility index	11.3	24.2	(73.0)	215.4	11.5

3.1.1.2 Mexico

The collection of available data for the Mexican side of the border was more challenging; some of the parameters are not available, and others are at a more aggregated level. For example, the mobility indexes provided by Google and Apple are provided at the state level. Therefore, researchers followed the same approach with the U.S. county-level data collection to develop a macroscopic model for Mexico at the state level, and a special data exploration was done on the city level for the border states.

Only official and reliable data sources were used to gather information for developing the dataset for Mexico. Information related to census data was acquired using the official data provided by the National Institute of Statistics and Geography (INEGI) (*32*). Poverty-rate data were provided by the National Council for the Evaluation of Social Development Policy (CONEVAL) (*33*), and COVID-19-related data were gathered from the official website prepared for COVID-19 by the federal government of Mexico (*3*). Unlike the United States, the number of COVID-19 tests is not documented in Mexico, but the speed of spread was calculated in the same form as the U.S. dataset. Mexico does not have travelers' mode choices for when commuting to work. Therefore, related parameters were removed from the dataset; instead, researchers found information on the registered number of vehicles in each state and added it to the dataset as a parameter. All the educational facilities were closed on March 20, 2020, and have remained closed. Nonessential businesses were closed on March 30, 2020, and reopened on June 1, 2020 (*34*). On the other hand, the Mexican government never imposed a stay-at-home order; the government encouraged residents to stay at home, but it was never mandatory that people not leave their residences. Any order given in Mexico was effective for the entire country, so researchers did not pick related parameters for the model development. The mobility index parameters were obtained by calculating the average from mobility documents provided by Google and Apple. Table 3 shows the descriptive statistics of the collected data for Mexico.

Table 3. Descriptive Statistics of Mexico Data

Name	*Mean*	*Std. dev.*	*Min.*	*Max.*	*Median*
Population	3,735,336	3,144,135	711,235	16,187,608	2,906,637
Household income ($)	8,832	2,186	4,766	14,217	8,643
Poverty rate (%)	39.9	15.1	14.5	76.4	39.1
Employment rate (%)	50.6	4.4	42.0	59.0	51.1
Population above 65 years old (%)	10.1	1.5	6.2	14.3	10.1
Households	998,428	827,042	205,243	4,168,206	807,756
Uninsured population (%)	15.7	3.4	10.2	25.6	14.9
Number of cars	1,009,108	1,245,873	160,974	5,530,839	570,982
Number of cases	10,126	12,130	1,051	60,474	7,242
Speed of spread (average daily cases)	**384.4**	**618.4**	**14.2**	**3,177.6**	**183.4**
Airport	0.94	0.25	0.00	1.00	N/A
Border crossing	0.16	0.36	0.00	1.00	N/A
Average temperature (°F)	72.5	6.4	60.1	82.6	72.3
Google retail	(52.6)	7.0	(68.9)	(41.9)	(51.6)
Google transit stations	(52.6)	9.3	(81.7)	(35.9)	(51.7)
Google workplaces	(36.5)	6.0	(52.8)	(26.0)	(35.2)
Google at home	17.7	3.2	12.5	27.2	16.9
Apple mobility index	(37.4)	15.6	(74.2)	(1.0)	(36.6)

In the macro-level model development, the U.S. dataset had 687 data points, whereas Mexico had only 32. For this reason, researchers conducted a more detailed analysis focused on six Mexican states (Baja California, Coahuila, Chihuahua, Sonora, Tamaulipas, and Nuevo Leon) that border the United States. These states contain 276 cities, 23 of which have border crossings to and from the United States. Since the data were limited at the city level, researchers only explored the effects of being a border city by developing graphs and using mapping techniques. Some major statistics of the city-level dataset are shared in Table 4 with the state-level grouping.

Table 4. Mexico City-Level Data Summary

Name of the State	*No. of Cities*	*Total Population*	*No. of Border Cities*	*Population of Border Cities*	*Number of Cases (July 15)*	*Total Cases per 1 Million Population*
Baja California	5	3,315,766	3	2,732,393	12,313	3,713
Coahuila	38	2,954,915	3	323,075	9,722	3,290
Chihuahua	67	3,556,574	4	1,449,458	4,783	1,345
Sonora	72	2,850,330	6	534,267	16,154	5,667
Tamaulipas	43	3,441,698	6	1,736,096	12,667	3,680
Nuevo Leon	51	5,119,504	1	18,194	12,472	2,436
Total	**276**	**21,238,787**	**23**	**6,793,483**	**68,111**	**3,207**

3.1.2 Methodology

For both macro-level datasets (U.S. and Mexico), STATA Special Edition Version 16 (*35*) software was used to perform fitting of the models. The stepwise backward elimination technique was employed to select the independent variables, using the criterion $|t| \geq 1.96$.

Both models have a dependent variable, *speed of spread*. The speed of spread is defined as the average number of cases after the 100th case was seen in a region. The possible independent variables are listed in For each variable within the U.S. dataset, the descriptive statistics were calculated and are shown in Table 2.

Table 2 and Table 3 for the U.S. and Mexico model development, respectively. Since the dependent variable should have a positive value, Tobit regression analysis was used to fit the model. Tobit regression was first developed by Tobin (*36*) in 1958. It is a specified linear regression model with a dependent variable censored by an upper and/or lower limit. In this case, researchers limited the lower limit to zero and ran the model without an upper limit.

3.2 MICRO LEVEL

The previous section introduced the model development at the macro level to understand the parameters that have a significant effect on the speed of spread. This section describes how the researchers conducted their analysis at a micro level with a focus on the El Paso–Juarez binational region, where thousands of daily border crossings occurred even after the border restrictions were in place.

3.2.1 Study Data

For the micro-level model development, researchers focused on the daily border crossings and their effects on the daily cases. Since testing is not conducted every day and the results fluctuate day to day, researchers used the 7-day average for all parameters. The availability of the data was limited for the model development. Researchers contacted Fideicomiso de Puentes Fronterizos de Chihuahua, the agency that operates the international bridges in Chihuahua, to obtain the pedestrian and passenger vehicle traffic counts going northbound to the United States. The daily northbound crossings of two major international bridges (Paso del Norte and Zaragoza) were gathered and aggregated. Although these data did not cover all the border crossings, researchers used the information collected for the model development purposes (to understand the significance of the parameter).

Figure 1 demonstrates the total number of border crossings northbound between March 1 and July 1, 2020. As the figure shows, the number of daily crossings declined sharply after the border restrictions were implemented. The average number of daily crossings was 13,164 vehicles before the restrictions, which declined to 5,148 on average for the rest of March. The numbers stayed steady during the month of April, with an average of 5,052 vehicles crossing the border daily. The numbers increased in May and June, with monthly averages of 7,056 and 8,071 vehicle crossings per day, respectively.

For pedestrian crossings, the trend was similar to vehicle crossings. The total daily average of northbound pedestrian crossings was reported as being 13,591 in March before restrictions took place. The average went down to 3,244 for the rest of the month, stayed steady in April with an average of 3,099, and was followed by 4,581 and 5,980 daily crossings in May and June.

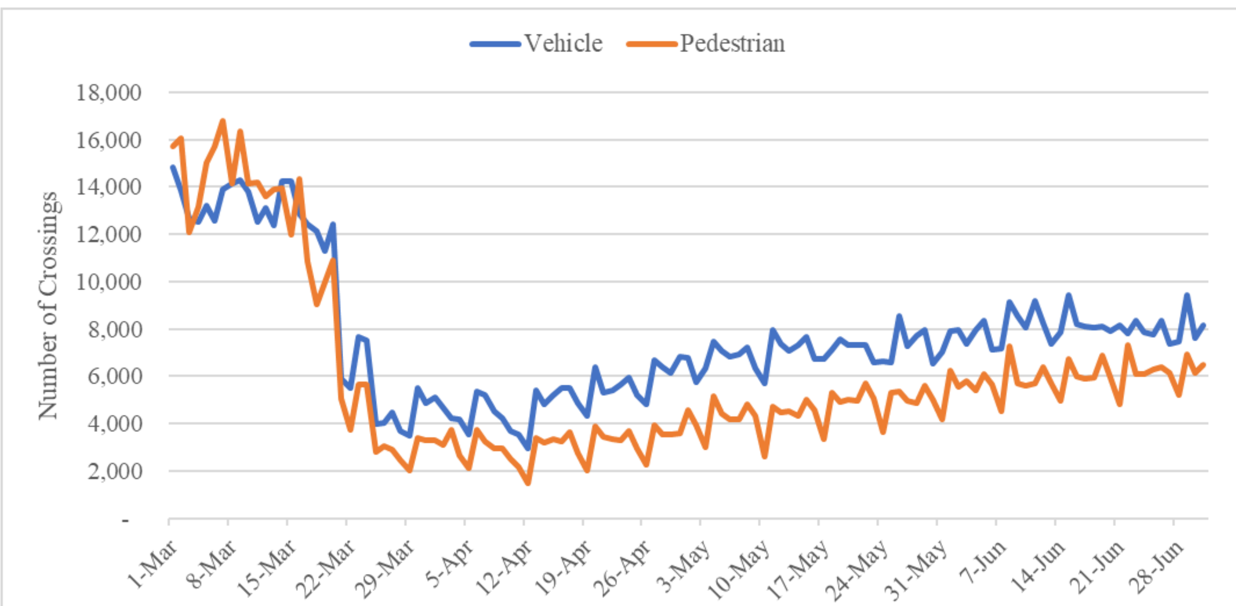

Figure 1. Number of Daily Vehicle and Pedestrian Crossings

Researchers were able to gather daily crossings for only the northbound traffic. The southbound traffic is as important as the northbound, especially when considering the spread of disease in Mexico. For micro-level model development purposes, researchers assumed that southbound had the same amount of border crossings as northbound. The idea supporting this assumption was that the micro-level study was not detailed at the port-of-entry level, and only essential travel was allowed after border restrictions. In other words, people who needed to cross the border for work (essential workers) crossed back at the end of the day, and it was not important which port of entry they used since the study considered the entire El Paso–Juarez ports of entry as one single border crossing. Two other potential independent variables that may affect the spread of the disease are *Apple mobility index*, and *Google workplaces*. Researchers were able to gather daily information for El Paso County and Chihuahua for both variables.

Figure 2 demonstrates the 7-day average of daily mobility trends at the border cities. Since Apple and Google introduced the baseline in different ways, the variation in the numbers is quite different. On the other hand, the overall trends have a similar pattern—a sudden decrease after the border restrictions, a steady rate for a month, and an increasing recovering trend for the duration. One interesting finding illustrated by this graph is that the sister cities had nearly the same trend.

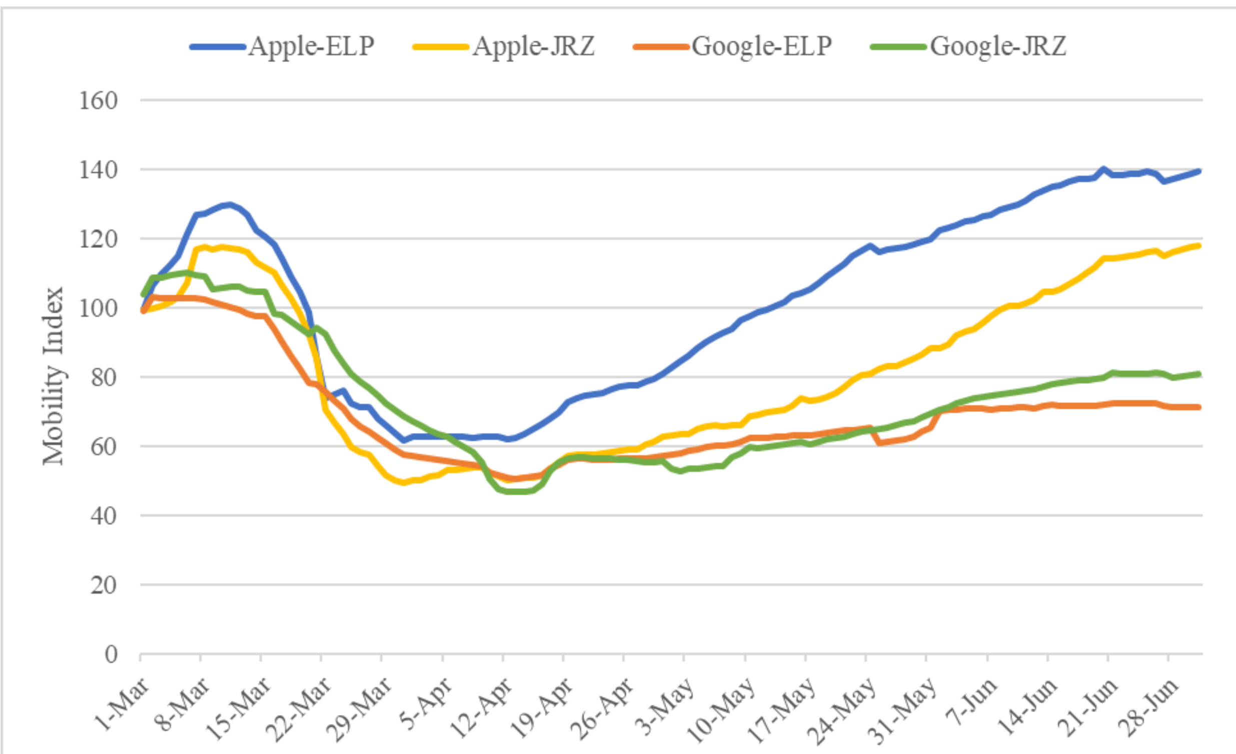

Figure 2. Daily Mobility Trends

3.2.2 Methodology

To develop the micro-level models, researchers needed to have the total amount of traveler data, which is determined by the number of passengers in each vehicle. Unfortunately, daily border crossing data do not provide that information. To calculate the average number of persons per vehicle, researchers checked the BTS border-crossing/entry data (*27*), which provide summary statistics for inbound crossings at the U.S.-Mexico border at the port level. It was found that the average persons per vehicle number decreased from 1.69 to 1.34 after the border restrictions. Researchers used those numbers to convert the number of vehicles to number of passengers. The total number of travelers crossing the border was calculated using the following equations:

$$Before\ restrictions = 1.64\ (No. of\ vehicles) + (No. of\ pedestrians)$$

$$After\ restrictions = 1.39\ (No. of\ vehicles) + (No. of\ pedestrians)$$

After calculating the total number of people crossing the border using the equations above, the researchers updated Figure 1 with the daily number of people crossing. Then, 7-day averages were calculated and are demonstrated in Figure 3. The average number of crossings was calculated as 35,839 persons during the first 20 days of March before the restrictions; the number declined to 10,536 for the rest of the month. The numbers slightly increased after that and had an average of 14,036 in May and 16,796 in June. Other variables in the model development (*Google workplaces* and *Apple mobility index*) are both indexes that take a base number and set it to 100. Similarly, researchers set the average number of crossings before border restrictions to 100 and introduced the border mobility index as an input for the micro model. In Figure 3, the secondary vertical axis demonstrates how the border mobility index changed during the study period.

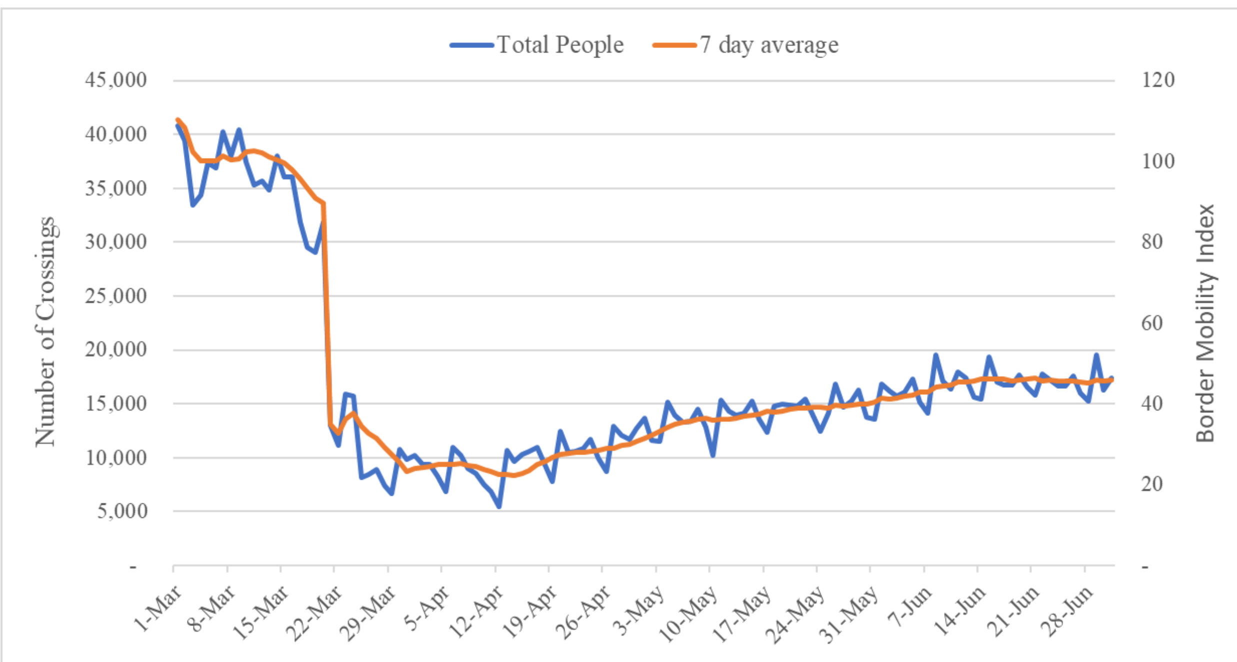

Figure 3. Total Number of Daily Crossings

According to CDC quarantine guidelines, people who have been in close contact with someone who has COVID-19 need to quarantine for 14 days. Based on that fact, researchers used the 14-day lag for the number of cases in the dependent variable. In other words, the independent variables that were believed to have an effect on the number of cases were assumed to show their effect on the 14th day on the number of cases. Moreover, to cover the daily fluctuations because of delays in testing results, or daily border-crossing variations, researchers used the average numbers of the last 7 days for all parameters (independent and dependent) in the study.

Besides the number of available parameters for model development, one other important challenge at the micro level was to make sure the independent parameters were not highly correlated. As Figure 2 and Figure 3 demonstrate, all the parameters showed similar trends. Therefore, researchers conducted a multicollinearity check for the variables, and a matrix showing the collinearity between each parameter was developed (see Table 5). One key aim of regression analysis is to isolate the relationship between each independent variable and the dependent variable, and multicollinearity reduces the precision of the estimates and weakens the statistical power of the regression model. Due to the high collinearity observed, researchers kept only one parameter to test the level of significance and develop multiple models.

Table 5. Collinearity Matrix of Independent Variables

Variable	*Border Mobility*	*Google Workplaces*	*Apple Mobility*
Border Mobility	1.00	0.96	0.51
Google Workplaces	0.96	1.00	0.58
Apple Mobility	0.51	0.58	1.00

CHAPTER 4. MODEL RESULTS

4.1 MACRO LEVEL

This section focuses on the results of the macro-level datasets. Researchers collected county-level information for the United States using 687 data points and state-level information for Mexico using 32 data points. Because of the differences in testing and reporting for each country, researchers developed two regression models individually for the United States and Mexico. Moreover, since the number of data points for Mexico was very limited, researchers conducted a more detailed analysis at the city level for the Mexican states that border the United States. This follow-up analysis did not include the development of a model.

4.1.1 United States

The results of the Tobit regression analysis are presented in Table 6. The significant independent variables—*population*, *households*, *uninsured population*, *transit*, *border crossing*, *stay-at-home order length*, and *Google workplaces*—were identified. The independent variables presented here were all statistically significant, with $|t| \geq 1.96$. The regression model results produced a root mean squared error (RMSE) of 49.2. As Table 6 shows, some parameters have positive coefficients, as explained below:

- *Population:* If the county has a higher population, the speed of spread is expected to be significantly higher.
- *Uninsured population:* If the county has a higher rate of uninsured population, the speed of spread is expected to be higher.
- *Transit:* Based on the latest American Community Survey, if the county has more transit users, the speed of spread is expected to be higher.
- *Border crossing:* If the county has at least one land port of entry, the speed of spread is expected to be significantly higher.
- *Google workplaces:* Based on the Google data, if the rate of the residents who are at workplaces is higher, the speed of spread is expected to be higher.

On the other hand, two parameters have negative coefficients:

- *Household:* If the number of households is higher, in other words, if the number of persons per household is lower, the speed of spread is expected to be significantly lower.
- *Stay-at-home order length:* For an increased number of days of the stay-at-home order, the speed of spread is expected to be lower.

Table 6. Results of U.S. Macro-Level Model

Variable	*Coefficient*	*Std. error*	*t-values*	*95% confidence intervals*	
Population	0.0000684	0.0000034	20.35	0.0000618	0.0000750
Households	−0.0000119	0.0000039	−3.05	−0.0000197	−0.0000043
Uninsured population	167.4307	17.8951	9.36	132.2937	202.5677
Transit	95.7296	21.6916	4.41	53.1381	138.3210
Border crossing	21.5689	9.6497	2.24	2.6218	40.5160
Stay-at-home order length	−0.1661	0.0340	−4.89	−0.2329	−0.0994
Google workplaces	0.4646	0.0944	4.92	0.2793	0.6498
Number of observations	687				
Log-likelihood	−3123.56				
p-value	0.0000				

4.1.2 Mexico

Similar to the U.S. dataset, Tobit regression was applied to the Mexico dataset. The findings of the analysis are presented in Table 7. The significant independent variables—*population*, *households*, *poverty rate*, *border crossing*, and *Apple mobility index*—were identified. Except for *border crossing*, the independent variables presented here were all statistically significant, with $|t| \geq$1.96. Researchers kept the *border crossing* parameter to show the significance level ($|t| =$1.83). The regression model results produced an RMSE of 568.

Table 7. Results of Mexico Macro-Level Model

Variable	*Coefficient*	*Std. error*	*t-values*	*95% confidence intervals*	
Population	0.0002233	0.0000136	16.41	0.0001953	0.0002513
Households	−0.0001557	0.0000512	−3.04	−0.0002609	−0.0000505
Poverty rate	5.149919	1.809658	2.85	1.430114	8.869724
Border crossing	149.3221	81.46776	1.83	−18.13728	316.7815
Apple mobility index	5.86807	1.283363	4.57	8.506059	3.230082
Number of observations	32				
Log-likelihood	−200.59363				
p-value	0.0000				

As Table 7 reveals, some parameters have positive coefficients:

- *Population:* If the state has a higher population, the speed of spread is expected to be significantly higher.
- *Poverty rate:* If the state has a higher poverty rate, the speed of spread is expected to be higher.

- *Border crossing:* If the state has at least one land port of entry, the speed of spread is expected to be significantly higher.
- *Apple mobility index:* Based on the Apple mobility data, if the mobility rate is higher, the speed of spread is expected to be higher.

In contrast, one parameter has a negative coefficient:

- *Household:* If the number of households is higher, in other words, if the number of persons per household is lower, the speed of spread is expected to be significantly lower.

Because of a limited number of data points, it was found that the results for Mexico were not as precise as the U.S. results. In addition, the findings did not reflect that the border crossing had a significant effect, as was the case for the U.S. results. Since the available resources did not provide much information for Mexico, to understand the effects for a border city in Mexico, researchers conducted a follow-up study at a more disaggregated level. Six Mexican states having border crossings to the United States were explored at the city level to understand whether being a border city has a significant effect on the speed of spread.

Of the 276 cities in the border states in Mexico, 253 do not provide any border crossings to or from the United States. To better understand the effects of having a border crossing in a city, a comparison was conducted. All the cases were scaled to 1,000 population, and cases per 1,000 population were compared by taking the average and plotting histograms. Figure 4 and Figure 5 show the results.

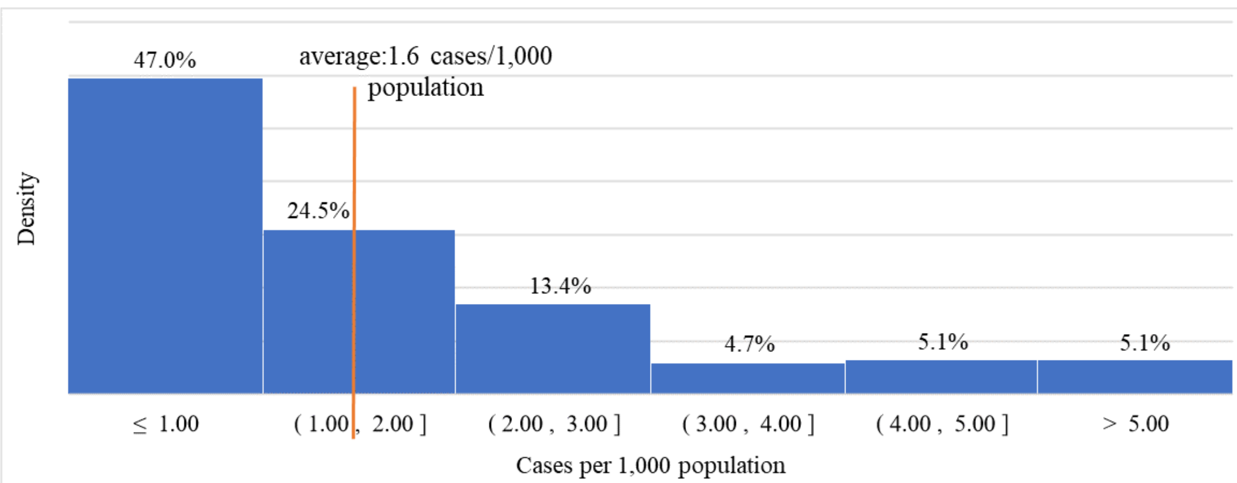

Figure 4. Cities without Border Crossings

As demonstrated in Figure 4, the average number of cases was 1.6 for the cities without border crossings, and 47 percent of the cities had less than 1 case per 1,000 population in those cities. In contrast, cities with border crossings had an average of 3.6 cases per 1,000 population, and more than 30 percent of them had more than 5 cases per 1,000 population (see Figure 5).

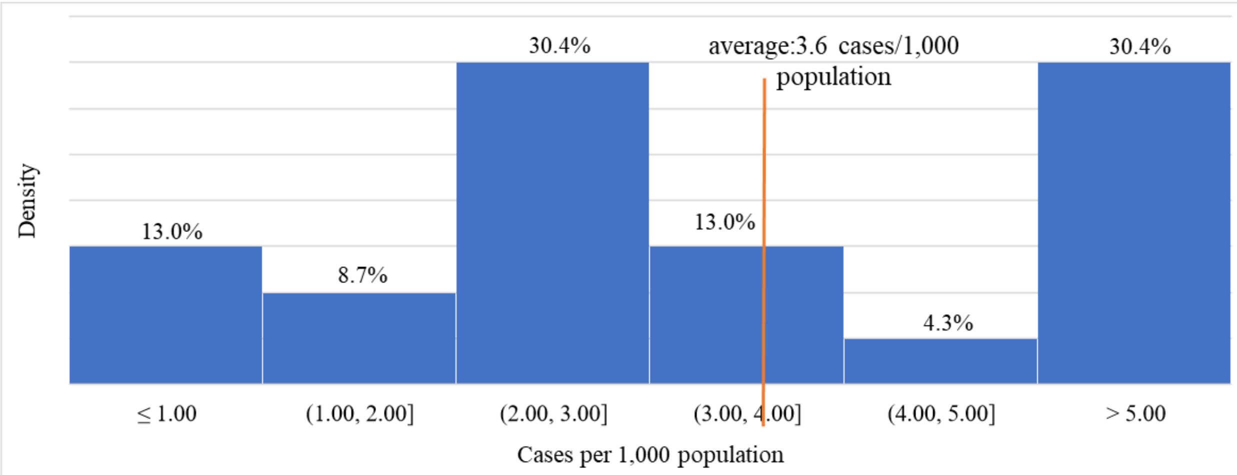

Figure 5. Cities with Border Crossings

In addition to statistical and graphical analysis, researchers conducted a geospatial analysis to demonstrate the case densities on a map. The total number of cases as of July 15 for the cities located in the border states were collected and divided by the population of the cities to find the cases per 1,000 population. The cities having fewer than 100 cases were labeled as "none," and the rest were grouped under six different classes:

- Less than 1 case per 1,000 population.
- Between 1 and 2 cases per 1,000 population.
- Between 2 and 3 cases per 1,000 population.
- Between 3 and 4 cases per 1,000 population.
- Between 4 and 5 cases per 1,000 population.
- More than 5 cases per 1,000 population.

The findings were then mapped and the cities that have border crossings were highlighted using Esri ArcMap version 10.7. As demonstrated in Figure 6, border cities are more likely to have higher case densities.

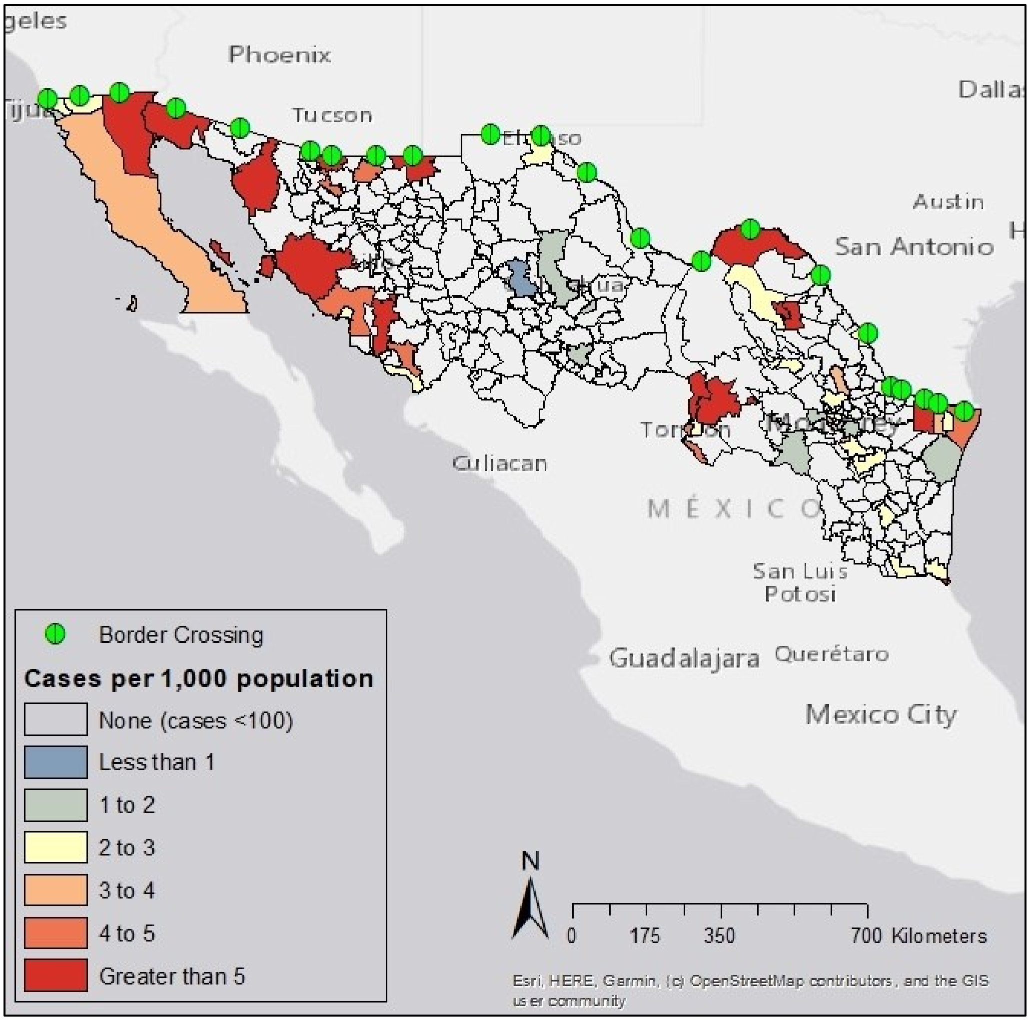

Figure 6. Border States of Mexico Case Densities

4.2 MICRO LEVEL

Macro-level model development allowed researchers to understand that border crossings have a significant effect on the speed of the spread. This section discusses how researchers conducted their analysis at the micro level by focusing on the El Paso–Juarez binational region, which had thousands of daily border crossings occurring even after border restrictions were in place. Since the reporting and testing patterns may differ for each country, two models were developed (U.S. and Mexico). For each model, the same methodology was followed, and researchers tried to understand the effects of the border crossings and the mobility changes on the spread of the infectious disease at the border cities.

4.2.1 United States

Researchers ran the Tobit regression three times, one for each variable, and the results of the analysis are presented in Table 8. All the independent variables were found to be highly statistically significant, with $|t| \geq 1.96$. Because of different considerations for the baselines for each variable, researchers emphasized t-values rather than the coefficients of variables. All the variables showed high significance; the variable with the highest t-value was *Apple mobility*, which includes data on people who cross the border on that day. The findings of the models are explained in the order of highest to lowest significance:

- *Apple mobility:* Based on the Apple mobility data, if the mobility rate is higher, the number of cases is expected to be higher.
- *Google workplaces:* Based on the Google mobility data, if the rate of the residents who are at workplaces is higher, the speed of spread is expected to be higher.
- *Border mobility:* A greater number of border crossings is expected to lead to a greater number of daily cases.

Table 8. Results of U.S. Micro-Level Model

Variable	***Coefficient***	***Std. error***	***t-values***	***95% confidence intervals***	
Border mobility	4.290638	0.783303	5.48	2.737832	5.843444
Constant	−57.6563	30.3842	−1.90	−117.8893	2.5767
Number of observations			108		
Log-likelihood			−629.62926		
p-value			0.0000		
Apple mobility	2.641552	0.190313	13.38	2.264279	3.018826
Constant	−165.1129	20.0498	−8.24	−204.8593	−125.3665
Number of observations			108		
Log-likelihood			−587.58063		
p-value			0.0000		
Google workplaces	8.368552	1.035548	8.08	6.315699	10.421410
Constant	−427.0354	65.9702	−6.47	−557.8137	−296.2571
Number of observations			108		
Log-likelihood			−617.32916		
p-value			0.0000		

4.2.2 Mexico

Google and Apple do not provide mobility index data for Ciudad Juarez. All mobility-related available data are at the state level for Mexico. Moreover, the difference in testing and reporting in Mexico did not allow researchers to develop a comprehensive micro-level model. Figure 7 was plotted to illustrate the comparison of the number of daily cases between El Paso County and Juarez. In contrast to El Paso, Juarez numbers started declining after reaching a peak during late May.

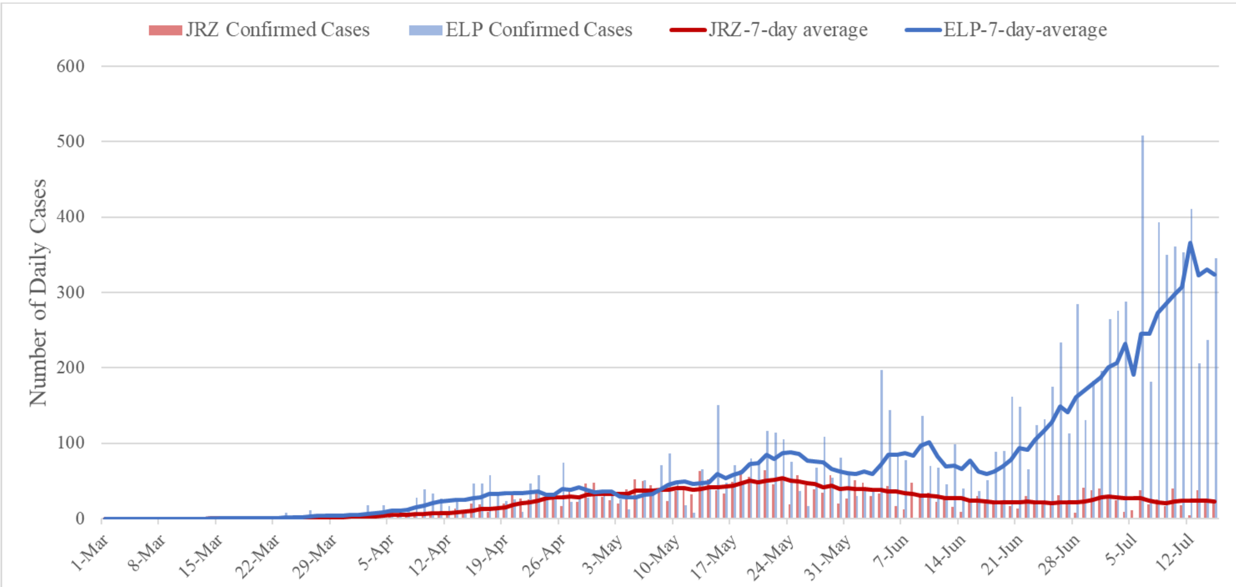

Figure 7. Comparison of Reported Daily Cases

Researchers followed the same methodology and ran Tobit regression analysis for the border mobility to see the effects on the number of daily cases, and the findings of the analysis are presented in Table 9. It was found that border mobility did not significantly affect the number of cases in Ciudad Juarez. Previous models in this study, including the macro-level models for the United States and Mexico and the micro-level model for El Paso County, all demonstrated that border crossings have a significant effect on the spread of disease and the number of cases in a region. Therefore, the results of the Juarez micro-level model were not expected. The difference may be a result of the testing and reporting policy of Mexico. However, a better and more detailed dataset than what was available for this study is required to better elucidate this discrepancy.

Table 9. Results of Mexico Micro-Level Model

Variable	***Coefficient***	***Std. error***	***t-values***	***95% confidence intervals***	
Border mobility	-0.133376	0.151324	-0.88	-0.433526	0.166774
Constant	33.8667	5.5152	6.14	22.9272	44.8061
Number of observations			108		
Log-likelihood			-400.23436		
p-value			0.3790		

CHAPTER 5. FINDINGS AND CONCLUSIONS

COVID-19 is a rapidly spreading infectious disease that was declared a pandemic by WHO on March 11, 2020 (*1*). As of August 20, 2020, more than 20 million cases with more than 800,000 deaths around the world had occurred. From a transportation perspective, understanding the key parameters causing a faster spread of disease is vital for decision-makers. There are different applications in the world in terms of border-crossing precautions, and a growing number of countries are implementing technology-based measures to regulate the movement of citizens and slow the spread of COVID-19. Each application and technique has its advantages and limitations.

To understand the effect of cross-border transportation and other socioeconomic parameters on the speed of spread in the U.S.-Mexico border region, researchers developed two macro models—one for each side of the border. The results for each model showed that *population*, *number of households*, *mobility index*, and *border crossings* have a significant effect on the speed of spread. *Uninsured population rate*, *rate of transit users*, and *length of the stay-at-home order* are the other variables found to be significant for the United States. Mexico model findings showed that *poverty rate* is also significant. Because data were limited for Mexico to only 32 data points found at the state-level model development, researchers conducted a follow-up study to illustrate the importance on the border crossings in states that border the United States. The findings showed that cities with border crossings had 3.6 cases per 1,000 population on average, while cities without border crossings had only 1.6 cases on average.

In micro-model development, researchers focused on the El Paso–Juarez binational metropolitan region. Daily border crossings and their effects on the daily COVID-19 cases were explored. The findings of the El Paso dataset showed that the most significant variable is the mobility of people (*Apple mobility*), followed by the number of people working at their workplaces (*Google workplaces*) and the number of border crossings (*border mobility*). Due to testing and reporting limitations of the Juarez dataset, none of the parameters were found to be significant.

The main contributions of this research are the results of the macro- and micro-level models, which led to understanding the key influencers of infectious disease spread from a transportation- and border-crossing perspective. This research has also established a framework to conduct model developments to determine the significant parameters that can be applied to other infectious diseases.

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