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BRIEF REPORT

Interstates of Infection: Preliminary Investigations of Human Mobility Patterns in the COVID-19 Pandemic

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Abstract

Purpose: The COVID-19 pandemic has illuminated various heterogeneities between urban and rural environments in public health. The SARS-CoV-2 virus initially spread into the United States from international ports of entry and into urban population centers, like New York City. Over the course of the pandemic, cases emerged in more rural areas, implicating issues of transportation and mobility. Additionally, many rural areas developed into national hotspots of prevalence and transmission. Our aim was to investigate the preliminary impacts of road travel on the spread of COVID-19. This investigation has implications for future public health mitigation efforts and travel restrictions in the United States.

Methods: County-level COVID-19 data were analyzed for spatiotemporal patterns in time-to-event distributions using animated choropleth maps. Data were obtained from *The New York Times* and the Bureau of the Census. The arrival event was estimated by examining the number of days between the first reported national case (January 21, 2020) and the date that each county attained a given prevalence rate. Of the 3108 coterminous US counties, 2887 were included in the analyses. Data reflect cases accumulated between January 21, 2020, and May 17, 2020.

Findings: Animations revealed that COVID-19 was transmitted along the path of interstates. Quantitative results indicated rural–urban differences in the estimated arrival time of COVID-19. Counties that are intersected by interstates had an earlier arrival than non-intersected counties. The arrival time difference was the greatest in the most rural counties and implicates road travel as a factor of transmission into rural communities.

Conclusion: Human mobility via road travel introduced COVID-19 into more rural communities. Interstate travel restrictions and road travel restrictions would have supported stronger mitigation efforts during the earlier stages of the COVID-19 pandemic and reduced transmission via network contact.

KEYWORDS
COVID-19, mobility, rural–urban, spatiotemporal, time-to-event

Investigations of the spatiotemporal distribution of Coronavirus Disease 2019 (COVID-19) are critical to modeling its epidemiological potential, allocating resources, and developing effective, scalable mitigation policies. As of January 2021, more than 25,000,000 COVID-19 cases and more than 421,000 deaths have been reported among the 3108 counties and county-equivalents in the coterminous United

States.[1] Given its clinical features—mean R_0 of 2.2 individuals,[2] median incubation period of 5.1 days,[3] and presymptomatic transmission period[4]—COVID-19 has demonstrated substantial penetrance into communities—rural and urban alike.[1,5] Early cases of COVID-19 were imported into the United States.[6,7] Initially, COVID-19 appeared to be limited to urbanized areas, but cases emerged in rural areas, and several of them developed into national-level hotspots of prevalence.[1,5] COVID-19 has been detected among every class of county along the rural–urban continuum.[1,8] Clearly, it is not limited to urbanized areas.

Current research on rural–urban differences in infectious diseases pandemic epidemiology is sparsely available due to the novelty of the virus and its infections. COVID-19 affords a unique opportunity to investigate these differences. Souch and Cossman[9] previously reported on state-level rural–urban disparities in COVID-19 testing rates and found that states with higher prevalence of risk factors—which tend to be rural—were testing their populations at lower rates and reported higher test-positivity than their healthier, more urban counterparts. It remains largely unknown which mechanisms contributed to the emergence of COVID-19 in rural areas—with lower population densities and other epidemiologically favorable[10] conditions. Rural and suburban areas have been described as conducive for social distancing and at an advantage in the mitigation of COVID-19.[11,12]

Public transportation and private travel are known to be major factors in community transmission of infectious diseases.[13,14] While public transportation tends to be concentrated in urbanized areas, commuter travel often requires traveling through rural areas. Infectious diseases have been associated with elevated incidence in proximity to major roadways. As a result, major roadways have been implicated in the transmission of infectious diseases like AIDS in Africa,[15] syphilis in rural North Carolina,[16] and H1N1 in China,[13] via network contact—among other examples. It is important to apply the same analyses to COVID-19. In the United States, despite travel restrictions, residents of the South and Midwest tended to travel at similar or greater levels than before travel restrictions went into effect.[17] By extension, it becomes apposite to investigate the role of human mobility in the manifestation of the COVID-19 pandemic in the United States. In this preliminary brief report, we explore the role of the interstate highway system and rural–urban differences in the arrival and community transmission of COVID-19.

Of primary interest was to estimate the time of arrival of COVID-19 at the county level. COVID-19 was first reported in the United States on January 21, 2020, in Snohomish County, WA.[1] According to the CDC, the patient was known to have recently traveled to Wuhan, China.[7] Just 3 days later, COVID-19 was reported in Chicago, IL. During that same week, cases started appearing in Orange County, CA; Los Angeles County, CA; and Maricopa County, AZ.[1] Approximately 1 month later (February 20, 2020), the virus was reported in Humboldt County, CA—the first rural county.[5] On March 2, 2020, COVID-19 appeared in Grafton County, NH, where nearly 70% of the population is rural.[5,8] Retrospective analyses suggest that COVID-19 arrived in the United States much earlier than previously thought.[18] For example, the first death was originally thought to occur in Snohomish County, WA, on February 29, but a recent autopsy report indicated that the earliest death occurred 3 weeks earlier, shifting the timeline of exposure and transmission to earlier dates.[7,18]

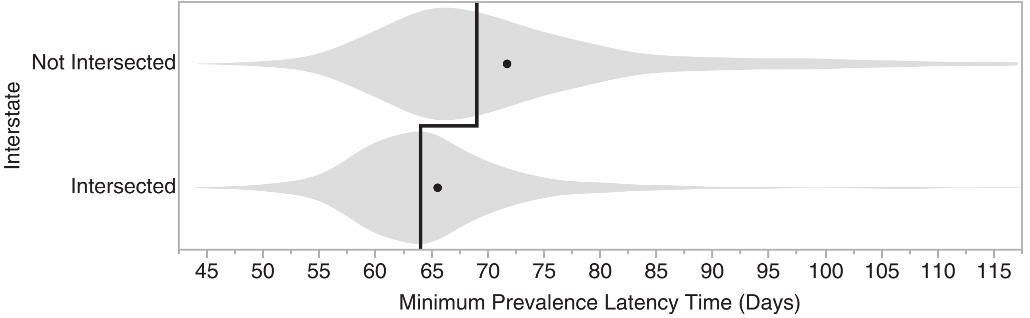
METHODS

Previous research has relied on using the first case in each geographic entity (county, state, prefecture, etc.) to estimate the arrival time of infectious diseases.[13,14] However, given state-level and county-level lags in testing availability and the dynamic nature of test eligibility criteria, we elected to estimate arrival time using a different measure. We contend that counties that attained a similar prevalence rate around a similar time were also exposed around the same time. Furthermore, if the values are similar along major roadways, it suggests that road travel contributed to community transmission.

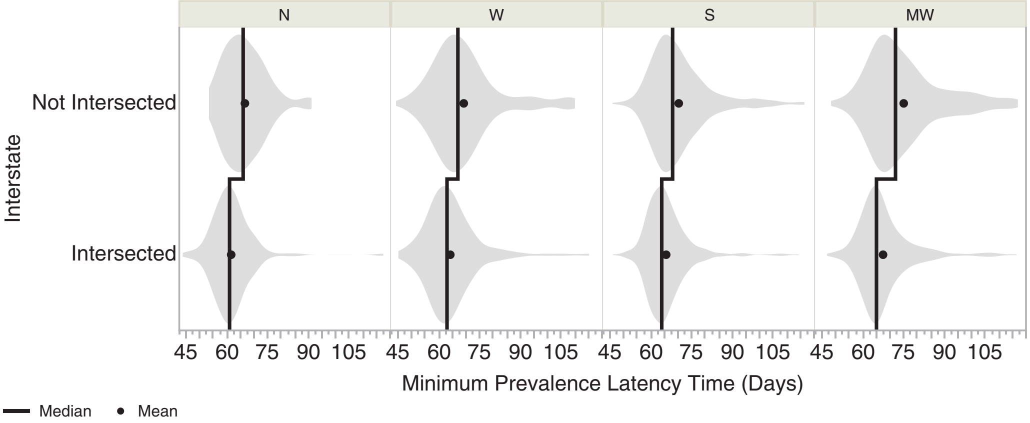
As of this writing, all 2887 analyzed counties reported a prevalence rate of at least 3 cases per 100,000 population. This prevalence rate is called the minimum prevalence (MP) for our purposes. JMP Pro[19] 14 was used to extract the event date that each county attained MP. The time-to-event (in days) was calculated for all affected counties, relative to the first national case (January 21, 2020). Prevalence rates were calculated using data from *The New York Times*' county-level dataset and US Census Bureau 2019 population estimates.[20,21] Rural-Urban Continuum Codes (RUCC) were merged with the data table. This data table was geo-coded using QGIS[22] (Version 3.12) and joined with several TigerLine Shapefiles[23] from the US Census Bureau. A spatial query identified all counties intersected by interstates and encoded the result as a binary indicator. An Albers-equal area conic projection (ESRI 102003, Redlands, CA) was employed to generate choropleth maps showing values of MPLT using natural breaks (Jenks) classification methods. Animated choropleth maps of county-level MPLT and time-to-event of county-level first cases are available in the online Supplementary Materials. Violin plots of time-to-event distributions of MPLT were also generated across levels of RUCC, geographical region, and interstate intersection status.

RESULTS

Of the 3108 counties and county-equivalents, 2887 (93%) reported at least one case of COVID-19 as of May 17, 2020. According to RUCC, there are 1160 metro or urban counties (RUCC 1 through 3) and 1948 nonmetro or rural counties (RUCC 4 through 9). Of all nonmetro counties, 89% reported at least one case of COVID-19. In contrast, 99% of all metro counties reported at least one case of COVID-19. Lower values of MPLT correspond to earlier estimated times of arrival. Fifty percent of all affected counties attained MP on or before March 27, 2020. Figure 1B shows regional differences in COVID-19 arrival time. The North ($N = 213$) had the lowest median MPLT value of 62 days (corresponding to March 23), followed by the West ($N = 353$) with a median MPLT of 65 days, the South ($N = 1369$) with a median MPLT of 66 days, and the Midwest ($N = 952$) with a median MPLT of 68 days. Table S1 provides a descriptive statistics summary of MPLT subset by region.



(a) Violin Plots of MPLT by Interstate Intersection Status



(b) Violin Plots of MPLT by Region and Interstate Intersection Status

FIGURE 1 **Violin plots of MPLT values.**
Source: New York Times and US Census Bureau. Note. Data are current as of May 17, 2020. Only counties of the coterminous United States are included in this analysis. Regions included are North (N), West (W), South (S), and Midwest (MW) and are in order of ascending MPLT value

Of the 2887 affected counties, 1368 were intersected by interstates. A Wilcoxon–Mann–Whitney U test demonstrated that counties intersected by interstates ($Mdn = 64$) had significantly lower MPLT values than their non-intersected counterparts ($Mdn = 69$), $Z = -16.31$, $p < .0001$, $r = .30$. Figure 1A shows the effect of interstate intersection on MPLT. This significant difference suggests that interstate-intersected counties were exposed to COVID-19 earlier than non-intersected counties. The difference in MPLT was greatest for the most rural counties (RUCC equal to 9), as shown in Figure 2. Table S2 provides a descriptive summary of MPLT subset by RUCC. The combination of these results indicates that community transmission occurred earlier in urbanized areas and spread to rural areas via primary roadways.

Figure 3 shows seven choropleth maps of MPLT values. The first six maps show the progression of COVID-19 over the first 99 days, at the county level. Therefore, superimposition of subsequent maps produces the next iteration of the small multiple maps. The seventh and final iteration—including day 99 through day 117—is shown in the largest map. A histogram shows the natural breaks classes of MPLT and corresponds to the choropleth map legend. Darker values indicate earlier estimated arrival time. Therefore, similarly shaded counties attained MP around a similar time. By extension, similarly shaded counties shared arrival times.

Within the largest map, there are six inset maps highlighting urbanized areas and major interstates. Generally, there was a positive relationship between MPLT and distance to urbanized areas. In Washington State—the location of the first reported case—for example, counties intersected by I-90 had earlier arrival times than counties not intersected by I-90. It is clear that COVID-19 spread from urbanized areas of Washington State—like Seattle—to more rural areas along the interstate. Spatiotemporally, this pattern traces along I-90, as several counties attained MP within the same 11-day period. Similar patterns can be seen in Denver-Aurora, CO; Albany-Schenectady, NY; New Orleans, LA; Atlanta, GA; and in Charleston, WV—among other examples.

The Appalachian Region is perhaps one of the clearest examples of this transmission pattern. West Virginia was the last state to report a single case of COVID-19.[1] Topographically, this region is unique because it is corralled by the Appalachian Mountains and the Ohio River Valley. Due to these features, Appalachia may have been at an advantage in social distancing and limiting community spread.[12] Generally, it appears that the mountainous topography and lower population density limited prevalence and delayed the arrival of COVID-19 in Appalachia. Figure 3 shows that COVID-19 arrived earlier in counties intersected by I-77 in West Virginia. As of this writing, several counties in West Virginia have yet to report a single case of COVID-19. It is likely that commercial and private travel activities along I-77 facilitated the transmission of COVID-19 into the rural areas of the Appalachian Region.

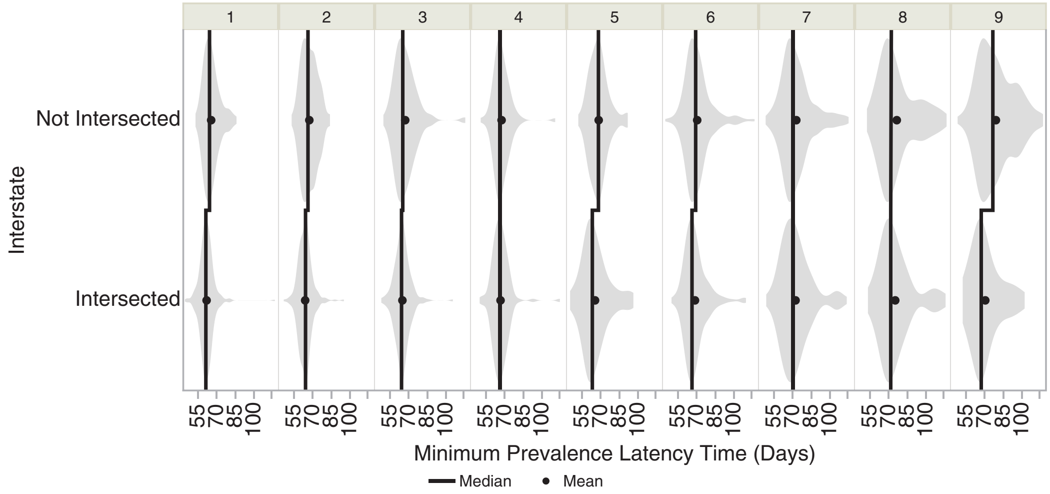


FIGURE 2 **Violin plots of MPLT values by RUCC and interstate intersection status.**
Source: New York Times and US Census Bureau. Note. Data are current as of May 17, 2020. Only counties of the coterminous United States are included in this analysis. Rurality is indicated by higher RUCC values

DISCUSSION

Our results indicate that geographic features and the built environment influenced the arrival times of COVID-19 at the county level and warrant further study. Generally, it appears that counties intersected by interstates, counties containing urbanized areas, and metro counties were at greater risk for developing earlier COVID-19 cases. Results also indicate that the virus spread from coastal areas to the interior. The Midwest was the last region to be exposed, per median MPLT value. There was clearly a delay associated with COVID-19 arrival in rural counties, but this effect was diminished for rural counties intersected by interstates. Our preliminary findings support the findings of Fang and associates,[13] which associated counties intersected by interstates with earlier exposure times for H1N1 in mainland China.[13] In their survival analyses, they found that there was a significantly increased risk for developing H1N1 cases for counties intersected by interstates.[13] Travel restrictions varied widely by state in their timing and implementation.[24] It follows that interstate travel restrictions may have afforded communities substantial delays in the arrival of COVID-19 and, by extension, saved lives. Predictive models of COVID-19 infection showed that cases tended to cluster around major interstates, like I-10 and I-5, as lockdown directives were lifted.[24] Lin and colleagues found that statewide stay-at-home directives were effective at reducing the growth rate of COVID-19, flattening the curve in both metropolitan and nonmetropolitan counties.[25]

County-level analyses of COVID-19 are critical to monitoring its spatiotemporal patterns and epidemiological features. This research was limited by the county-level spatial scale, the use of MPLT as an estimate of arrival time, and the use of a binary indicator for the interstate intersection measure. Continuous geographic data were reduced to a nominal variable with two levels to measure interstate intersection. However, there are varying degrees of interstate intersection. There may be counties that were identified as interstate-intersected, but the length and location of the interstate—relative to a given county's geometry—may be negligible. Importantly, this analysis was ecological in its nature and cannot speak to causal relationships. Given the consideration of population density, it is no surprise that large metro areas were found to have earlier and larger infection events. However, it is important to consider the mechanisms of diffusion from urban areas to more rural ones via human mobility patterns. Hotspots of infection have been identified in rural and urban regions alike.[26,27] Hamidi, Sabouri, and Ewing found that counties linked through social and economic ties are the most vulnerable for COVID-19 infection.[28] It is no surprise that social distancing measures were then critical in stopping the spread of COVID-19.[29]COVID-19 has been reported to spread especially effectively in small crowded spaces, but this feature is not limited to urban areas and has led to the conclusion that social connectivity was more of a driving factor for COVID-19 spread than population density alone.[28] These insights can offer explanations as to how rural areas, despite having lower population density, can become hotspots like their urban counterparts via social gatherings and communal events. Despite geographical differences, it has been reported that mortality rates have been similar among small cities, nonmetropolitan areas, and rural communities.[27] Therefore, research has shown that rural areas are not as protected from the spread of COVID-19 as once thought.[9,12] It appears that the degrees of social connection and mobility are the key factors for interstate spread. Our results are also supported by the findings of Shah and associates, demonstrating the crucial role of road travel restrictions in reducing COVID-19 transmission.[30] Clearly, our results and extant research drive us to inquire about more intricate patterns of human interaction and transmission and explanatory measures beyond population density.

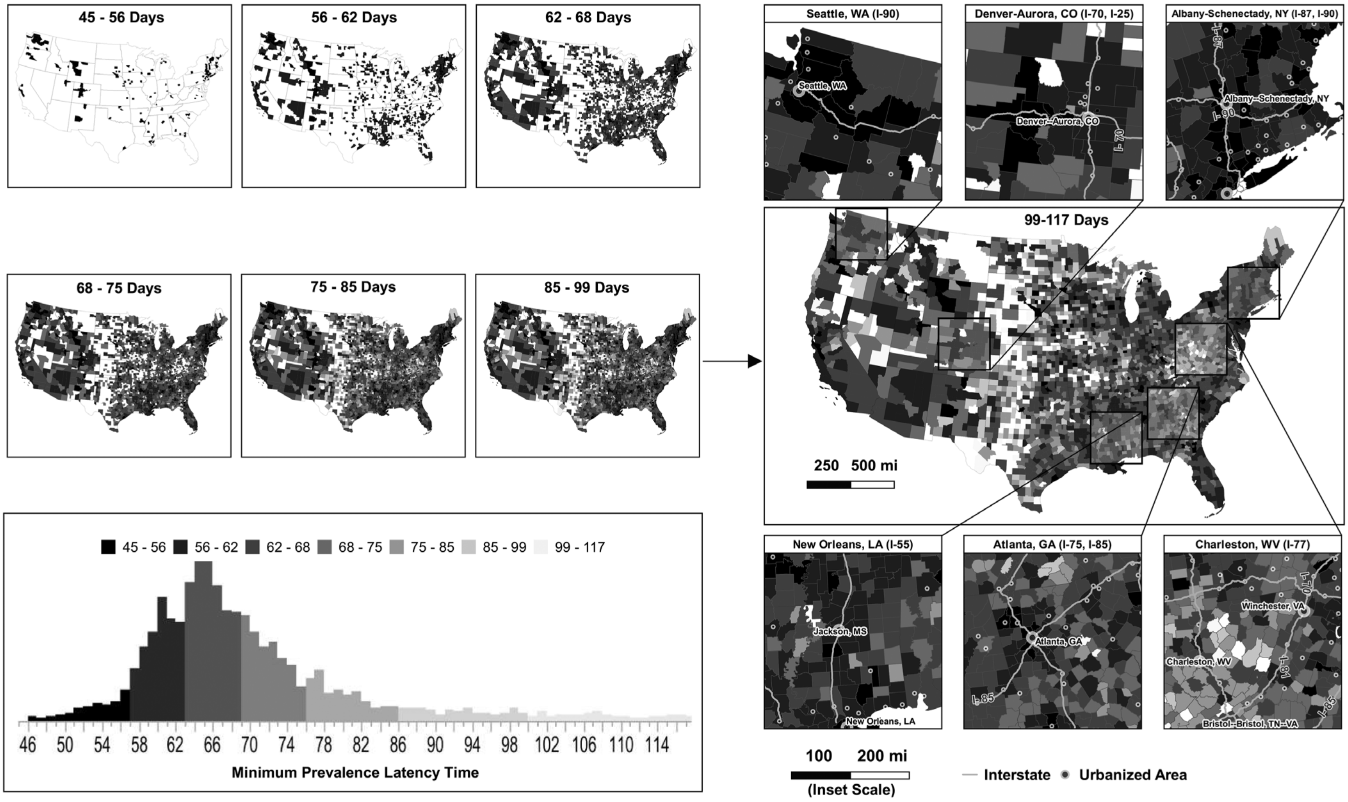


FIGURE 3 Choropleth maps of MPLT values, urbanized areas, and interstates.

Source: New York Times and US Census Bureau. Note. Data are current as of May 17, 2020. Only counties of the coterminous United States are included in this analysis. Only interstates relevant to the discussion are shown for visual clarity. See Online Supplementary Material to see MPLT and all interstates

CONCLUSION

In the future, it will be conducive to adapt the methodology of Fang and associates and conduct proportional hazards survival analyses for the effects of interstate intersection, RUCC, and other human mobility measures on COVID-19 arrival events.[13] Research in this area may support stronger travel restrictions and social distancing directives in the future.[30] Together, these analyses can be used to develop a more robust understanding of the spatiotemporal patterns of COVID-19. Considerations of the role of topographical features, the built environment, and human mobility are critical to any public health endeavor. Application of these methodologies will lead to better public health policies and more effective distribution of medical and economic resources.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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