DRAFT WORKING PAPER:
COMMENTS WELCOME

Public transportation and infectious diseases:
A review of the public health literature concerning the role of public transit in spreading COVID and the interventions that minimize the risks of contagion on public transit

Authored by:
Hao Ding, Doctoral student researcher

With contributions from:
Maya Desai, Undergraduate student researcher

September 2020

This paper was prepared as part of UCLA Institute of Transportation Studies' Monitoring Adjustments to Transit Services During a Pandemic Rapid Research Project, generously funded by the University of California Statewide Transportation Research Program. For more information, please visit https://www.its.ucla.edu/covid

Contents

Introduction

The Covid-19 pandemic has changed how people travel and how transportation functions, at least temporarily. Several recent studies in Europe and Australia have found that while people are generally making fewer and shorter trips during the pandemic, they are traveling more on private automobiles and active transportation like biking and walking and less on public transit (de Haas, Faber, and Hamersma 2020; Molloy et al. 2020; Beck and Hensher 2020). This shift in travel mode choice and preference may be largely due to fear of infection during outbreaks of communicable diseases because public transit hosts large volumes of people in dense and enclosed environments (Beck and Hensher 2020; Hotle, Murray-Tuite, and Singh 2020; Meyer and Elrahman 2019). To lower the risk of infection in the transit system and help reduce the spread of Covid-19, transit agencies worldwide have implemented various measures including increased cleaning and disinfecting, modifications of seating and boarding protocols to ensure physical distancing, route and service modifications, and sometimes partial or complete suspensions, mask-wearing requirements, temperature screening, etc. (WSP 2020).

Guiding people's avoidance behaviors and transit agencies' various pandemic response measures is the perception that public transportation poses a high risk for the transmission and spread of infectious diseases. However, the scientific evidence, mostly from the public health literature, presents a mixed rather than conclusive, and also more nuanced case about the role of public transportation in the transmission and spread of infectious diseases. This paper will review public health studies that investigate 1) the association between traveling on public transit and risk of infection, and 2) the role of public transportation in spreading infectious diseases. This paper will also consider the experience of countries that have been more successful in responding to the current pandemic but have adopted very different measures about travel and transportation, notably China and South Korea but others as well, in order to draw lessons on what public transportation can and should do amid outbreaks of infectious diseases.

Travelling on public transit and risk of infections

Infection on public transportation usually becomes a concern when there is an outbreak of communicable diseases caused by viruses that can be transmitted by direct and indirect contact and by airborne droplets and/or aerosols. These are often respiratory diseases such as influenza, SARS, MERS, and Covid-19. The risk of infection in the public transit system is thought to be high because virus concentration may be high on surfaces that are frequently touched by passengers and in the air during peak hours when volume and density of passengers are high (Meyer and Elrahman 2019). Thus, during an outbreak of a pandemic, public health guidance regarding public transit often emphasizes the need to increase cleaning and disinfecting, promote physical distancing, and discourage non-essential travel (ibid.). The perception that public transportation poses high infection risks may result in fear and thus avoidance of public transit among the public, which may continue even after infection cases decline, and the actual risk is reduced, resulting in a slow and lagging recovery of transit ridership (Wang 2014). However, may this perception be misguided? In other words, how high is the risk of infection on public transportation? This section reviews public health studies that investigate the relationship between traveling on public transit and the risk of getting infected by respiratory diseases that can spread via airborne transmission.

There is a good amount of research about infection risks on public transportation, though most are simulation studies while only three are observational studies. One case-control study surveyed 72 patients with acute respiratory infection (ARI) and 66 patients with acute non-respiratory infection in Nottingham, U.K. during the 2008/09 influenza season, about their use of bus or tram, and other confounding factors including socio-demographic characteristics and health status factors like pre-existing medical conditions, smoking status, and vaccination history (Troko et al. 2011). The authors found a statistically significant association between ARI contraction and bus or tram use five days preceding the onset of symptoms (ibid.). They also found that ARI risks were higher for occasional riders than for regular riders, suggesting that habitual transit use may help develop immunity, but the lack of statistical significance on this result prevents a reliable conclusion (ibid.). The authors concluded that their findings support public health recommendations during pandemics about exercising good personal hygiene and refraining from unnecessary travel on public transit, but cautioned that suspending mass transit may not be justified because household exposure tends to pose higher infections risks (ibid.).

Another study used Oyster card data (the electronic ticket for public transportation in London) on underground trips and data on influenza-like illnesses (ILI) infections in London to examine the association between underground use and ILI infection rates at the borough level (Goscé and Johansson 2018). The authors found that boroughs with no underground stations have lower ILI infection rates than those with underground stations, though the difference is not statistically significant (ibid.). They also found that boroughs with higher incidence rates are more peripheral, meaning passengers from these boroughs tend to spend more time in the underground system and transfer between lines, thereby getting in contacts with more people (ibid.). The authors then estimated the number of contacts made by passengers during their underground trips, which were found to have a statistically significant correlation with ILI infection rates of the passengers' departing boroughs (ibid.).

Apart from these two studies that focused on influenza, there were more studies done earlier that focused on tuberculosis (TB), which can also spread via airborne transmission. An earlier study reviewed 12 studies, mainly contact investigations, of TB transmission among passengers of the train, long hour bus, school bus, and commuter van (Edelson and Phypers 2011). Among the 12 studies, 8 found between 8.7% to 55% infection rates among tested passengers, while 6 reported identifying between 1 to 24 active TB cases through contact tracing (ibid.). Thus, the review concluded that there exists a risk of TB transmission on buses or trains, but this risk has yet to be quantified (ibid.).

Overall, these observational studies confirm the existence of infection risks on public transportation but fail to offer more insights on the magnitude of this risk. In contrast, studies that simulate an outbreak of infectious diseases in an urban setting can compare infection rates on public transportation to infection rates in other settings such as school, workplace, and household. One such study simulated interactions of subway riders with their workplaces, schools, households, and community activities in New York City during an influenza outbreak, using data from the 1957-1958 influenza pandemic and NYC travel surveys (Cooley et al. 2011). The simulation shows that subway use only contributes to 4.4% of total cumulative infections, of which commuters account for 3.6% while non-commuters account for less than 1% (ibid.). However, this result does not necessarily indicate a low infection risk. The simulated risk factor for subway commuting is 78.73 per 1,000 individuals, which is comparable to workplace interactions (79.1 per 1,000) but smaller than households (99.03 per 1,000), community activities (106.78 per 1,000), and schools (438.15 per 1,000) (ibid.). Simulations of various interventions also show that intervention targeting the subway system is far less effective than contact-reducing interventions targeting the entire community and vaccination programs (ibid.)

Similar results were also obtained in a different study that simulated an outbreak of smallpox, which can be transmitted through respiratory droplets, in Hong Kong (Zhang et al. 2018). The simulation shows that, among all settings, household accounts for the biggest share of infections (59.6%), followed by office (18.1%), school (13.4%), restaurants (7%), hospitals (1%), and public transportation (0.9%) (ibid.). The authors suggested that the high percentage of household infections might be explained by the fact that people generally spend most of their time at home, whereas high percentages of office and school infections might be explained by high population density (ibid.). However, the authors also noted that hospitals, despite accounting for only 1% of total infections, have the highest infection probability due to the high concentrations of infected cases (ibid.). Another key simulation result shows that improving ventilation helps reduce infection probability (ibid.)

Another recent study simulated an outbreak of H1N1 influenza in Changsha, China, using geospatial data on traffic and infection dynamics and spreading characteristics (Mei et al. 2015). This study simulated scenarios in which public health interventions including vaccination of 10% of the total population, seven-day isolations of close contacts with confirmed cases, and seven-day suspension of office work are activated on the 4th and the 5th day of the outbreak (ibid.). While the main finding was that activating these interventions one day earlier can reduce the maximum total infected cases from approximately 6,800 by more than half to about 3,100, the authors noted that about 19% of patients get infected at public transit and transfer points (ibid.). While this percentage seems significantly higher than simulations from other studies, it may be because that vaccination, quarantine, and office closure as simulated in this study have reduced infections in other settings.

Thus, it seems that the percentage of infections in a particular setting without public health interventions is affected by at least four factors, namely duration of time spent, population density, the concentration of infected people, and degree of ventilation or concentration of virus in the air. The interplay of these factors may help explain the low infection risks on public transportation as suggested by both simulations: while population density tends to be high on public transit especially during peak hours, time spent on public transit tends to be shorter. The concentration of infected people on public transit would vary depending on many different factors such as the extent of testing and contact tracing and the degree of compliance of self-quarantine. Moreover, improved ventilation on buses and trains, sometimes by simply keeping windows open, can lower the concentration of viruses in the air.

Making public transit safer

A number of studies also investigate measures to make public transit a safe environment during an infectious disease outbreak. One study simulated the spread of an infectious disease in and through the public transportation systems and found that increasing transportation efficiency (how quickly passengers reach destinations), improving sanitation and ventilation, discouraging non-essential travel overall, and limiting travel by infected individuals, in particular, can lower the risk of infection on public transportation (Xu, Connell McCluskey, and Cressman 2013). Similarly, a recent study that specifically simulated transmission of the SARS-Cov-2 virus via aerosols in indoor environments showed that public transportation and other crowded public indoor spaces should focus on controlling passenger densities and improving ventilation to lower infection risks, while passengers should practice physical distancing and ensure minimal time spent in such spaces (Vuorinen et al. 2020).

One earlier study also focused particularly on the importance of ventilation by specifically simulating the airborne transmission of influenza in bus microenvironments equipped with different ventilation methods (Zhu et al. 2012). Simulations show that air-recirculation ventilation mode using high-efficiency filtration has similar performance in lowering infection risk to a non-air-recirculation mode that uses 100% outdoor air supply, indicating the benefits of filtration (ibid.). Moreover, the study also found that displacement ventilation systems that replace polluted air with fresh air perform better in reducing infection risk than mixing ventilation systems which dilute polluted indoor air with fresh air (ibid.).

Another study focused particularly on virus transmission via frequently touched surfaces(von Braun, Thomas, and Sax 2015). This study collected a sample of 49 swabs from frequently touched surfaces in public transportation vehicles, ticket and coffer vending machines, as well as from high-touch surfaces in a hospital and a medical school in Geneva, Switzerland during the peak of the 2009 H1N1 pandemic to test if H1N1 virus may be detected (ibid.). Only one specimen collected from the bedrail of an infected patient tested positive for the virus (ibid.). The authors suggested that such surfaces in public transportation had low virus quantity because acutely infected patients might be less likely to use public transit, while increased public alert regarding hand hygiene may also result in less virus transmission through surface contacts (ibid.). The author also suggested that high frequency of touches might have reduced the virus concentration on these surfaces (ibid.). But this does not necessarily lower risk of infection. The authors also did not report or consider the effects of cleaning and disinfecting.

Thus, the risk of infections on public transportation can be reduced with targeted policies and procedures. To reduce virus transmission via surfaces, transit agencies can increase their cleaning and disinfecting efforts; to reduce virus transmission via air, transit agencies can improve ventilation systems in their vehicles and stations as well as enforcing various policies such as physical distancing and mask-wearing. As noted earlier, during the Covid-19 pandemic, many transit agencies are taking these measures to reduce infection risks while continuing their operations to provide service for those relying on public transportation (WSP 2020). These measures were also included in national guidance on pandemic planning and response for public transit agencies published in 2014 (National Academies of Sciences, Engineering, and Medicine 2014). However, the extent to which these measures are implemented will likely vary across transit agencies because there exist considerable variations among them concerning system sizes and amounts of resources available. Moreover, the effectiveness of these measures taken by transit agencies will also likely vary because it may depend greatly on the degrees of the spread of the disease.

The role of public transportation in the (geographical) spread of infectious diseases

Apart from the risk of infections on public transportation, another concern about public transportation in a pandemic may be the spread of infectious diseases from one place to another as people travel between different places via public transportation. The role of transportation in spreading infectious diseases geographically has been studied by many, although past studies have primarily focused on the role of air travel. A recent review of studies about respiratory virus spread in and via transportation systems concluded that the weight of the empirical evidence suggests that air travel accelerates the spread of the virus to new areas and that inflight transmission, as well as transmission in airports, can occur (Browne et al. 2016). Browne et al. also found that the virus can spread on cruise ships and have historically spread to new areas via sea travel but there is no evidence of such transmission in modern-day pandemics (ibid.). Regarding ground transportation, Browne et al. found that long-distance or inter-region buses and trains can spread the virus to new areas, but they found very few evidence for intra-region spread through public transportation and virus transmission aboard buses and trains (ibid.). This paper thus far has reviewed studies on virus transmission and risk of infections on public transportation, and now turns to the intra-region spread of disease via public transportation.

Studies on the geographical spread of disease via public transportation are mostly simulations rather than observational studies. These studies simulate how an outbreak of infectious disease spread within a metropolitan area via the public transportation system, as well as the effect of travel restrictions on containing the spread of the outbreak. One study used travel survey data containing data on travel modes and residential locations to simulate a pandemic influenza outbreak in metropolitan Tokyo (Ohkusa and Sugawara 2007). The simulation assumed that an individual contracted the virus from abroad and returned to Tokyo on day 1, and consulted the doctor on day 5 when symptoms started to show, and public health interventions started on day 6 (ibid.). This simulation showed that the disease has already spread too much of the metropolitan region by day 7, which, as the authors argued, indicated that quarantine or lockdown of particular areas within the metropolitan region where active cases are found might not be effective (ibid.). The author noted the important role played by commuter trains in spreading the virus throughout the metropolitan area, which may be less relevant in regions where residents do not rely as heavily on trains for transportation as those in Tokyo (ibid.).

Another study also simulated the spread of an influenza outbreak in Tokyo, but with a focus on its suburban commuter towns along rail lines (Yasuda et al. 2008). The study compared scenarios of where the first patient is, and found that commuting via the train plays a bigger role in the local spread of infection if the first patient is in Tokyo, whereas infection among school children plays a bigger role if the first patient is in the local town (ibid.). The study also tested the effects of interventions like traffic suspension, school closure, and vaccination of school children, and found that traffic suspension has no effect on the number of infected individuals after the influenza reaches the suburban town, but can delay the spread if implemented early enough, while the other two measures are more effective (ibid.).

Similarly, one study models the transmission of TB in an urban setting where individuals of a town either commute daily via public transportation to other parts of the urban area or interact within the town community (Pienaar et al. 2010). This similar simulation setup also helps to investigate the role of intra-city travel on public transportation in spreading infectious diseases. Simulation over a 20-year period shows that the infectious fraction of a town’s population of which 90% are commuters is nearly twice of the infectious fraction in a town with 30% of commuters, suggesting that a higher percentage of commuters can significantly increase TB infection in the community (ibid.). Simulations also show that behavioral interventions that can reduce disease transmission through infectious particles such as mask-wearing can effectively contain infection levels, but the effectiveness of such measures depends considerably on the degree of compliance (ibid.).

A more recent study simulated the spread of an outbreak of airborne infectious disease in Beijing and compared the relative effectiveness of suspending subway, bus, and taxi in containing the spread of the disease (Zhang et al. 2016). Simulation results showed that suspending the subway can significantly delay and reduce the peak of infected cases, suspending bus can also reduce the peak number but is less effective in delaying the peak, and suspending taxi had a minimal effect (ibid.). The authors suggested that the reason for the subway to have the biggest effect among all three modes considered may be its high population density and passenger flow (ibid.). In addition, simulation also showed that suspending office work can also reduce the peak number of infections but is also less effective than suspending the subway in delaying the peak (ibid.).

Some studies also investigate the effect of travel restrictions overall instead of suspending public transportation on controlling an infectious disease outbreak. One study simulated an outbreak of an infectious disease in Sweden with the origin of the outbreak in Stockholm and tested the effect of banning travels over 50 and 20 kilometers on containing the outbreak (Camitz and Liljeros 2006). Simulations of the no-restriction, 50km travel restriction, and 20km travel restriction scenarios showed that both travel restrictions can drastically reduce the speed and geographical spread of the outbreak, even if not 100% compliant by the public (ibid.). Moreover, while a 50km travel ban can effectively limit the spread of the disease within Stockholm and a small number of other large cities, a 20km travel ban can limit the spread within Stockholm and it surrounding small cities (ibid.).

A few latest studies on the current Covid-19 pandemic also reveal the effect of travel restrictions. One study modeled the spread of the disease in London and compared scenarios with different levels of interventions (Goscé et al. 2020). Simulation results suggest that in the absence of a vaccine, a combination of non-pharmaceutical interventions including universal testing and case isolation, contact tracing and isolation, and mask-wearing in a continued lockdown can minimize infections and deaths (ibid.). Such an approach can eliminate the infection in London over four to six months, after which lockdown can be lifted but with sustained efforts to prevent imported cases and contain mini-outbreaks until a vaccine becomes available (ibid.). In contrast, if lockdown is lifted, interventions such as universal testing, social distancing, use of face covers, and isolation of individuals over 60-year old can reduce infections and deaths to some extent but not as effective as the continued-lockdown approach (ibid.).

Another study modeled the propagation of the outbreak in Wuhan using data on Covid-19 cases to estimate how transmission rates varied (Kucharski et al. 2020). The model estimates showed that transmission of the disease likely declined in Wuhan during late January, which coincides with the implementation of travel restriction measures (ibid.). However, the authors also noted that the transmission rate had already declined before the enforcement of travel restrictions, which might reflect the effect of other public health interventions and growing public awareness (ibid.).

The evidence reviewed thus far seems to suggest that in the absence of a vaccine, behavioral interventions, albeit sometimes being drastic, can effectively limit the spread of infectious diseases and reduce infections and deaths. However, it has been argued that such measures may result in lower welfare relative to the scenario with decentralized individual decision making and no public intervention at all (Fenichel 2013). While individuals' decentralized decision making may lead recovered individuals to undersupply contacts with other individuals and lead infected and susceptible individuals to oversupply such contacts, society-wide behavioral interventions such as non-targeted social distancing may induce recovered individuals to further undersupply contacts (ibid.). This undersupply of contacts by recovered individuals represent a welfare loss because more contacts by recovered individuals can reduce the probability of susceptible individuals contacting infected individuals and allow more contacts (with recovered individuals) for susceptible and infected individuals without raising infection probability (ibid.).

Lessons from other parts of the world and from past pandemics

During the current Covid-19 pandemic, debates on whether governments should implement drastic measures such as lockdowns and traffic suspensions often refer to the contrasting approaches of China and South Korea in responding to the pandemic. While both countries have been more successful in containing the spread and reducing infections and deaths than many other countries around the world, their public health interventions have been very different, as China adopted lockdowns and other drastic measures whereas South Korea did not. What also makes the comparison of China and South Korea interesting is that they both experienced past pandemics like SARS and MERS and these past experiences have informed their response to the Covid-19 outbreak. Such a comparison may also generate some insights on the effectiveness of travel restrictions as a public health intervention during a pandemic.

One latest study compares China's responses to the 2003 SARS outbreak and the 2020 Covid-19 outbreak (Yang et al. 2020). The authors noted that one of the key lessons learned from the 2003 SARS outbreak was aggressive quarantine and contact tracing, which was also implemented as part of the Covid-19 response (ibid.). Thus, public transportation may be suspended as part of the aggressive quarantine efforts (ibid.). The authors also noted other measures relevant to public transportation such as mask-wearing in all public spaces including transit, and temperature screening at key transportation hubs including subway stations (ibid.). Wilder-Smith and Freedman (2020) also pointed out that while China learned from the experience with SARS and implemented isolation, contact tracing, and quarantine with medical observation relatively quickly, the exceptionally high number of cases and the greater transmissibility of Covid-19 as compared to SARS meant that the more drastic measure of community containment or lockdown, which encompassed suspension of public transportation, had to be implemented.

Several studies have attempted at evaluating the effectiveness of such aggressive quarantine measures. Shen et al. (2020) evaluated the effects of metropolitan-wide quarantine on the spread of Covid-19 in public spaces including transit and households. Their model estimates suggest that the quarantine strategy may have reduced more than 70% of infection compared to a no-quarantine scenario, and the effect is greater for public space infections than household infections, as public space infections account for about 30% of all infections under the quarantine scenario but about 48% under the no-quarantine scenario (ibid.). Peng et al. (2020) assessed the effectiveness of various medical and non-medical measures and found that medical treatments in the absence of a vaccine only had moderate success, whereas the enforcement of drastic quarantine measures including suspension of public transportation may have played the bigger role. The authors further suggested that the early implementation of quarantine measures is critical as it reduces the likelihood of resource depletion (ibid.). Tian et al. (2020) examined the effectiveness of travel restricting and social distancing measures on controlling the spread of Covid-19 during the first 50 days of the outbreak. Their regression models show that cities that suspended public transit, closed entertainment venues, and/or banned public gatherings had fewer cases in the first week of their outbreaks, while cities that adopted such measures sooner also had fewer cases (ibid.).

While these studies suggest that aggressive quarantine strategies such as lockdowns and traffic bans are effective in controlling the outbreak, South Korea’s experience seems to suggest that the outbreak may be controlled without such drastic measures. South Korea’s response measures include avoiding mass gatherings, mask-wearing, voluntary physical distancing, limiting operations of crowded indoor places, collecting visitor logs, delaying school openings, and the 3T strategy (Test, Trace, and Treat), but does not include any business bans, lockdowns, or suspension of public transportation ((S. Kim and Castro 2020). Kim and Castro suggested that the most important lesson that South Korea learned from the 2015 MERS outbreak was aggressive contract tracing, which informed the country’s response to the Covid-19 outbreak (ibid.). They also noted that the MERS experience led to amendments to South Korea’s Infectious Disease Control and Prevention Act to enact the government’s authority to collect credit card, mobile phone, and other data from confirmed patients and reconstruct their travel trajectories which are then shared on social media to facilitate contact tracing (ibid.).

Although South Korea did not suspend public transportation, transit ridership did decline during both MERS and Covid-19 outbreaks due to fear of infection. One study that examined the effect of public fear of MERS on travel behavior found that transit trips declined by 11.8% between the start of the outbreak on May 20th to June 10th when public fear was at its height, while trips to traffic analysis zones with potential MERS hotspots dropped by 13.88%, more than trips to those without hotspots (8.8%) (C. Kim et al. 2017). The authors also found that the flexibility to alter travel behaviors differed for different population groups, as kids and the elderly reduced transit use much more than adults and youths who had work and school responsibilities, while off-peak trips dropped much more than peak-hour trips (ibid.). Park (2020) examined the changes in subway ridership in Seoul during the Covid-19 outbreak using ridership data between January 1st and March 31st, 2020, and found a similar effect of fear on subway ridership. The study showed that ridership declined only slightly after the alert level raised on January 27th, but then dropped dramatically to about 60% of normal ridership level in late February after the first death and mass infection, and started to increase very slowly in March (ibid.). The author suggested that the very slow recovery of ridership could be due to the combination of decreasing levels of risk perception on the one hand and continued practice of voluntary social distancing on the other (ibid.).

Several other studies have explored the experience of other countries that have experienced past pandemics but discuss the public health response in general instead of addressing the public transportation sector specifically. For example, Teo et al. ((2005) discussed the effectiveness of Singapore's SARS response and mentioned a broad range of interventions including quarantine and contact tracing, temperature screening in public spaces, more frequent disinfection of public spaces, school closures, and educational campaigns about personal hygiene and precautions. The authors did not mention measures specific to public transportation, though temperature screening and more frequent disinfections were likely implemented on public transportation since public spaces should include public transit. The authors characterized Singapore's response strategy as draconian but noted that these measures received widespread support among citizens which may be due to the strong social discipline and the crisis mentality of Singaporeans (ibid.). Another study also emphasized the importance of societal learning in terms of rapid detection, alerting public health officials, and aggressive education and communication efforts targeting the general public at the start of the SARS outbreak in Singapore (Drake, Chew, and Ma 2006). A study about Canada's experience with SARS and H1N1 discussed actions taken regarding international air travel and screening and quarantine at key airports, but did not mention measures for public transportation (Baldwin 2018). The author noted that the most important change in Canada after SARS was the establishment of the Public Health Agency of Canada in September 2004 to coordinate a response to infectious disease outbreaks at the federal level (ibid.).

In addition to government interventions, the degree of compliance among the general public also matters. One study surveyed people in Argentina, Japan, Mexico, the U.K., and the U.S. about whether they adopted various personal protective behaviors, social distancing behaviors, and got vaccinations during the H1N1 pandemic (SteelFisher et al. 2012). The survey found that respondents were more likely to adopt personal protective behaviors than social distancing behaviors in all five countries, although the degrees to which people in each country do so vary (ibid.). For example, Mexicans were the most likely to avoid travel, followed by Argentinians, Japanese, Americans, and the British, whereas Americans and the British were much less likely to wear masks than the other countries (ibid.).

Thus, the experience of China and South Korea and other countries in responding to the current Covid-19 outbreak as well as past pandemics all seems to suggest that public transportation may not be the most important target area for interventions. On the one hand, countries like South Korea did not suspend public transportation or implement other measures specific to public transportation. On the other hand, even in countries like China where public transportation was suspended, the suspension was part of a wider lockdown effort in which many other, if not all, activities were suspended. In other words, merely targeting the public transportation sector in a pandemic response is not likely to yield much success in controlling the spread of the disease. What matters more is the society-wide public health response, as well as the degree of compliance among the general public.

Conclusion

We have reviewed studies, primarily from the public health literature, on public transportation and infectious disease outbreaks, focusing on three main issues: 1) risk of infections on public transportation, 2) role of public transportation in the spatial spread of infectious disease, 3) what can be learned about public transportation from successful experiences in responding to pandemics. The weight of the empirical evidence suggests that there is an association between traveling on public transportation and infection, but the risk of infections on public transportation tends to be lower than in other settings. This is because while population density on transit tends to be high during peak hours, people generally spend a shorter time on transit and thus are exposed to less virus as compared to other settings like school, workplace, and home. This exposure can be further reduced by improving ventilation in the transit system as well as implementing aggressive contact tracing and quarantine in the entire community.

Many simulations suggest that intra-city or intra-region travel via public transportation can spread the disease across metropolitan areas, and travel restrictions such as suspending public transportation can delay the spread and/or reduce infections, provided that they are implemented early enough. However, simulations also suggest that other measures such as school closure and working from home that target higher-risk settings may be more effective than measures that target public transportation. Such findings from simulation studies seem to be supported by studies that examine the public health response to pandemics in China, South Korea, and other countries. The experiences of these countries in responding to the past and current pandemics indicate that public transportation need not be the most important target area of interventions. Instead, the more effective pandemic response focuses on society-wide quarantine and contact tracing, cleaning and disinfecting of all public spaces, education, and communication about the disease and precautions, etc. In other words, if the society-wide public health response were effective, public transportation need not take specific measures to address the outbreak; but if the society-wide public health response were not effective and the outbreak was not controlled, what public transportation can do to help contain the spread of the disease may be relatively limited.

References

Baldwin, G. 2018. “The Future of Canada’s Transportation System: Has Canada Learnt From Its Experiences with Outbreaks Such As SARS, Ebola, H1N1 and MERS?” In . https://trid.trb.org/View/1667753.

Beck, Matthew J., and David A. Hensher. 2020. “Insights into the Impact of COVID-19 on Household Travel and Activities in Australia – The Early Days under Restrictions.” *Transport Policy* 96 (September): 76–93. https://doi.org/10.1016/j.tranpol.2020.07.001.

Braun, Amrei von, Yves Thomas, and Hugo Sax. 2015. “Do High-Touch Surfaces in Public Spaces Pose a Risk for Influenza Transmission? A Virologic Study during the Peak of the 2009 Influenza A(H1N1) Pandemic in Geneva, Switzerland.” *American Journal of Infection Control* 43 (12): 1372–73. https://doi.org/10.1016/j.ajic.2015.07.012.

Browne, Annie, Sacha St-Onge Ahmad, Charles R. Beck, and Jonathan S. Nguyen-Van-Tam. 2016. “The Roles of Transportation and Transportation Hubs in the Propagation of Influenza and Coronaviruses: A Systematic Review.” *Journal of Travel Medicine* 23 (1). https://doi.org/10.1093/jtm/tav002.

Camitz, Martin, and Fredrik Liljeros. 2006. “The Effect of Travel Restrictions on the Spread of a Moderately Contagious Disease.” *BMC Medicine* 4 (1): 32. https://doi.org/10.1186/1741-7015-4-32.

Cooley, Philip, Shawn Brown, James Cajka, Bernadette Chasteen, Laxminarayana Ganapathi, John Grefenstette, Craig R. Hollingsworth, et al. 2011. “The Role of Subway Travel in an Influenza Epidemic: A New York City Simulation.” *Journal of Urban Health* 88 (5): 982. https://doi.org/10.1007/s11524-011-9603-4.

Drake, John M., Suok Kai Chew, and Stefan Ma. 2006. “Societal Learning in Epidemics: Intervention Effectiveness during the 2003 SARS Outbreak in Singapore.” *PLOS ONE* 1 (1): e20. https://doi.org/10.1371/journal.pone.0000020.

Edelson, Paul J., and M. Phypers. 2011. “TB Transmission on Public Transportation: A Review of Published Studies and Recommendations for Contact Tracing.” *Travel Medicine and Infectious Disease* 9 (1): 27–31. https://doi.org/10.1016/j.tmaid.2010.11.001.

Fenichel, Eli P. 2013. “Economic Considerations for Social Distancing and Behavioral Based Policies during an Epidemic.” *Journal of Health Economics* 32 (2): 440–51. https://doi.org/10.1016/j.jhealeco.2013.01.002.

Goscé, Lara, and Anders Johansson. 2018. “Analysing the Link between Public Transport Use and Airborne Transmission: Mobility and Contagion in the London Underground.” *Environmental Health* 17 (1): 84. https://doi.org/10.1186/s12940-018-0427-5.

Goscé, Lara, Professor Andrew Phillips, P. Spinola, Dr Rishi K. Gupta, and Professor Ibrahim Abubakar. 2020. “Modelling SARS-COV2 Spread in London: Approaches to Lift the Lockdown.” *Journal of Infection*, May. https://doi.org/10.1016/j.jinf.2020.05.037.

Haas, Mathijs de, Roel Faber, and Marije Hamersma. 2020. “How COVID-19 and the Dutch ‘Intelligent Lockdown’ Change Activities, Work and Travel Behaviour:

Evidence from Longitudinal Data in the Netherlands." *Transportation Research Interdisciplinary Perspectives* 6 (July): 100150. https://doi.org/10.1016/j.trip.2020.100150.

Hotle, Susan, Pamela Murray-Tuite, and Kunal Singh. 2020. "Influenza Risk Perception and Travel-Related Health Protection Behavior in the US: Insights for the Aftermath of the COVID-19 Outbreak." *Transportation Research Interdisciplinary Perspectives* 5 (May): 100127. https://doi.org/10.1016/j.trip.2020.100127.

Kim, Chansung, Seung Hoon Cheon, Keechoo Choi, Chang-Hyeon Joh, and Hyuk-Jin Lee. 2017. "Exposure to Fear: Changes in Travel Behavior during MERS Outbreak in Seoul." *KSCE Journal of Civil Engineering* 21 (7): 2888–95. https://doi.org/10.1007/s12205-017-0821-5.

Kim, Sun, and Marcia C. Castro. 2020. "Spatiotemporal Pattern of COVID-19 and Government Response in South Korea (as of May 31, 2020)." *International Journal of Infectious Diseases*, July. https://doi.org/10.1016/j.ijid.2020.07.004.

Kucharski, Adam J, Timothy W Russell, Charlie Diamond, Yang Liu, John Edmunds, Sebastian Funk, Rosalind M Eggo, et al. 2020. "Early Dynamics of Transmission and Control of COVID-19: A Mathematical Modelling Study." *The Lancet Infectious Diseases* 20 (5): 553–58. https://doi.org/10.1016/S1473-3099(20)30144-4.

Mei, Shan, Bin Chen, Yifan Zhu, M. H. Lees, A. V. Boukhanovsky, and P. M. A. Sloot. 2015. "Simulating City-Level Airborne Infectious Diseases." *Computers, Environment and Urban Systems* 51 (May): 97–105. https://doi.org/10.1016/j.compenvurbsys.2014.12.002.

Meyer, M. D., and O. A. Elrahman, eds. 2019. "Chapter 8 - Transportation and _______." In *Transportation and Public Health*, 201–53. Elsevier. https://doi.org/10.1016/B978-0-12-816774-8.00008-6.

Molloy, Joseph, Christopher Tchervenkov, Beat Hintermann, and Kay W. Axhausen. 2020. "Tracing the Sars-CoV-2 Impact: The First Month in Switzerland." *Transport Findings*, May, 12903. https://doi.org/10.32866/001c.12903.

National Academies of Sciences, Engineering, and Medicine. 2014. "A Guide for Public Transportation Pandemic Planning and Response."

Ohkusa, Yasushi, and Tamie Sugawara. 2007. "Application of an Individual-Based Model with Real Data for Transportation Mode and Location to Pandemic Influenza." *Journal of Infection and Chemotherapy* 13 (6): 380–89. https://doi.org/10.1007/s10156-007-0556-1.

Park, Jewel. 2020. "Changes in Subway Ridership in Response to COVID-19 in Seoul, South Korea: Implications for Social Distancing." *Cureus* 12 (4). https://doi.org/10.7759/cureus.7668.

Peng, Fujun, Lei Tu, Yongshi Yang, Peng Hu, Runsheng Wang, Qinyong Hu, Feng Cao, et al. 2020. "Management and Treatment of COVID-19: The Chinese Experience." *Canadian Journal of Cardiology* 36 (6): 915–30. https://doi.org/10.1016/j.cjca.2020.04.010.

Pienaar, Elsje, Aaron M. Fluitt, Scott E. Whitney, Alison G. Freifeld, and Hendrik J. Viljoen. 2010. "A Model of Tuberculosis Transmission and Intervention Strategies in an

Urban Residential Area." *Computational Biology and Chemistry* 34 (2): 86–96. https://doi.org/10.1016/j.compbiolchem.2010.03.003.

Shen, Mingwang, Zhihang Peng, Yuming Guo, Libin Rong, Yan Li, Yanni Xiao, Guihua Zhuang, and Lei Zhang. 2020. "Assessing the Effects of Metropolitan-Wide Quarantine on the Spread of COVID-19 in Public Space and Households." *International Journal of Infectious Diseases* 96 (July): 503–5. https://doi.org/10.1016/j.ijid.2020.05.019.

SteelFisher, Gillian K, Robert J Blendon, Johanna RM Ward, Robyn Rapoport, Emily B Kahn, and Katrin S Kohl. 2012. "Public Response to the 2009 Influenza A H1N1 Pandemic: A Polling Study in Five Countries." *The Lancet Infectious Diseases* 12 (11): 845–50. https://doi.org/10.1016/S1473-3099(12)70206-2.

Teo, Peggy, Brenda S. A. Yeoh, and Shir Nee Ong. 2005. "SARS in Singapore: Surveillance Strategies in a Globalising City." *Health Policy* 72 (3): 279–91. https://doi.org/10.1016/j.healthpol.2004.11.004.

Tian, Huaiyu, Yonghong Liu, Yidan Li, Chieh-Hsi Wu, Bin Chen, Moritz U. G. Kraemer, Bingying Li, et al. 2020. "An Investigation of Transmission Control Measures during the First 50 Days of the COVID-19 Epidemic in China." *Science* 368 (6491): 638–42. https://doi.org/10.1126/science.abb6105.

Troko, Joy, Puja Myles, Jack Gibson, Ahmed Hashim, Joanne Enstone, Susan Kingdon, Christopher Packham, Shahid Amin, Andrew Hayward, and Jonathan Nguyen Van-Tam. 2011. "Is Public Transport a Risk Factor for Acute Respiratory Infection?" *BMC Infectious Diseases* 11 (1): 16. https://doi.org/10.1186/1471-2334-11-16.

Vuorinen, Ville, Mia Aarnio, Mikko Alava, Ville Alopaeus, Nina Atanasova, Mikko Auvinen, Nallannan Balasubramanian, et al. 2020. "Modelling Aerosol Transport and Virus Exposure with Numerical Simulations in Relation to SARS-CoV-2 Transmission by Inhalation Indoors." *Safety Science* 130 (October): 104866. https://doi.org/10.1016/j.ssci.2020.104866.

Wang, Kuo-Ying. 2014. "How Change of Public Transportation Usage Reveals Fear of the SARS Virus in a City." *PLoS ONE* 9 (3). https://doi.org/10.1371/journal.pone.0089405.

Wilder-Smith, A., and D. O. Freedman. 2020. "Isolation, Quarantine, Social Distancing and Community Containment: Pivotal Role for Old-Style Public Health Measures in the Novel Coronavirus (2019-NCoV) Outbreak." *Journal of Travel Medicine* 27 (2). https://doi.org/10.1093/jtm/taaa020.

WSP. 2020. "Covid-19 Transit Operations: Public Transit Responses to Coronavirus Situation." https://www.wsp.com/-/media/Insights/Canada/Documents/2020/Transportation_WhitePaper_COVID_Response-v2.pdf.

Xu, Fei, C. Connell McCluskey, and Ross Cressman. 2013. "Spatial Spread of an Epidemic through Public Transportation Systems with a Hub." *Mathematical Biosciences* 246 (1): 164–75. https://doi.org/10.1016/j.mbs.2013.08.014.

Yang, Yongshi, Fujun Peng, Runsheng Wang, Kai Guan, Taijiao Jiang, Guogang Xu, Jinlyu Sun, and Christopher Chang. 2020. "The Deadly Coronaviruses: The 2003 SARS

Pandemic and the 2020 Novel Coronavirus Epidemic in China." *Journal of Autoimmunity* 109 (May): 102434. https://doi.org/10.1016/j.jaut.2020.102434.

Yasuda, Hidenori, Nobuaki Yoshizawa, Mikio Kimura, Mika Shigematsu, Masaaki Matsumoto, Shoji Kawachi, Masamichi Oshima, Kenji Yamamoto, and Kazuo Suzuki. 2008. "Preparedness for the Spread of Influenza: Prohibition of Traffic, School Closure, and Vaccination of Children in the Commuter Towns of Tokyo." *Journal of Urban Health* 85 (4): 619–35. https://doi.org/10.1007/s11524-008-9264-0.

Zhang, Nan, Hong Huang, Marlyn Duarte, and Junfeng (Jim) Zhang. 2016. "Dynamic Population Flow Based Risk Analysis of Infectious Disease Propagation in a Metropolis." *Environment International* 94 (September): 369–79. https://doi.org/10.1016/j.envint.2016.03.038.

Zhang, Nan, Hong Huang, Boni Su, Xun Ma, and Yuguo Li. 2018. "A Human Behavior Integrated Hierarchical Model of Airborne Disease Transmission in a Large City." *Building and Environment* 127 (January): 211–20. https://doi.org/10.1016/j.buildenv.2017.11.011.

Zhu, Shengwei, Jelena Srebric, John D. Spengler, and Philip Demokritou. 2012. "An Advanced Numerical Model for the Assessment of Airborne Transmission of Influenza in Bus Microenvironments." *Building and Environment*, International Workshop on Ventilation, Comfort, and Health in Transport Vehicles, 47 (January): 67–75. https://doi.org/10.1016/j.buildenv.2011.05.003.