sustainability

Review

Health Impacts of COVID-19 through the Changes in Mobility

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Abstract: Understanding the wider effects of the COVID-19 pandemic on public health is needed to respond sufficiently to the impacts and facilitate recovery. We studied the secondary health impacts of COVID-19 through the changes in transportation using a ripple effect mode. Three ripples are defined to reflect the impacts of COVID-19 on (1) transportation and the systems behind it, (2) transportation-related health risk factors, and (3) public health. COVID-19 impacts on transportation are synthesized through six areas: transportation demand, transportation mode, traffic safety, land use and built environment, transportation jobs, and transportation equity. These changes are further associated with decreased transportation-related air pollution, greenhouse gases, noise, heat, and stress. Higher rates of road casualties were observed in the area of COVID-19. Social exclusion and limitations in accessibility to healthcare and healthy food were identified as negative consequences of changes in transportation. There are uncertainties in the rate of active transportation (i.e., walking and cycling) and related crashes that require further investigation. The findings of this study uncover the complex and relatively unknown impacts of COVID-19 on public health through changes in transportation.

Keywords: COVID-19; transportation; modal shift; active transportation; equity; traffic safety; sustainable transportation

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1. Introduction

The COVID-19 outbreak was a health crisis that caused unprecedented deaths. Numerous scientific research has been conducted on the direct health impacts of COVID [1]. However, the impacts of the COVID-19 global pandemic go beyond killing people, where some indirect health impacts—namely, causing mental health issues [2,3], increasing substance abuse disorders [4,5], and hindering access to primary health care [6,7]—were observed. This urged international, federal, and local agencies to develop pandemic preparedness and responses to curb the indirect (second order) impacts. Transportation agencies are no exception and should identify the COVID-19 health implications through the changes in transportation systems to support planning, decision-making, and innovation as we move from crisis to recovery.

The transportation system, particularly public transit and shared mobility, is responsible for a portion of the COVID-19 outbreak [8–11]. On the other hand, the global pandemic has drastically affected mobility and transportation systems, mainly stemming from pandemic-related mobility restrictions [12], teleworking and teleshopping possibilities in the era of a global pandemic [13], and changes in users' preferences with respect to the mode of transportation [14,15].

Although the impacts of COVID-19 and the global pandemic on mobility and transportation have been studied in the past [16,17], the discussion about the indirect health impacts of COVID-19 through the changes in transportation is in its infancy. The objective of this work is to provide information for decision-makers in the area of urban transportation to better address the wider effects of the COVID-19 pandemic. We explore the secondary impacts of COVID-19 on public health through the changes in transportation based on the ripple effect concept. The "ripple effect" explains the sequentially spreading effects of events, which have been adopted in many fields to understand the wider impacts of COVID-19, including in economics [18], supply chain [19–21], and psychology [22,23]. Figure 1 illustrates the designed ripple effect model in this study. COVID-19 is placed in the center of the graph to reflect the source of the sequential effects. Inspired by [24], The first ripple contains six interconnected areas through which the transportation sector has been impacted by COVID-19: traffic safety, transportation jobs, mobility demand, transport mode, transportation equity, and land use. The second ripple finds the impacts of the sequential source (COVID-19) on transportation-related health risk factors. Transportation, and the systems behind it, are believed to be linked to public health in the literature [25–29]. Glazener et al. [30] identified fourteen pathways through which transportation can affect public health. Among those, twelve transportation-related health risk factors are used in this study to uncover the indirect impacts of COVID-19. The third ripple translates the correlation of the second ripple to health implications. There is extensive literature about the associated health outcomes of transportation-related health risk factors [30]. To achieve the objective of this research, we synthesize the previous findings of the COVID-19 impacts on transportation and transportation-related health risk factors (first and second ripple effects). Hence, this study does not elaborate on the third ripple. Readers are referred to [24,30] for further information about the health outcomes of transportation-related health risk factors.

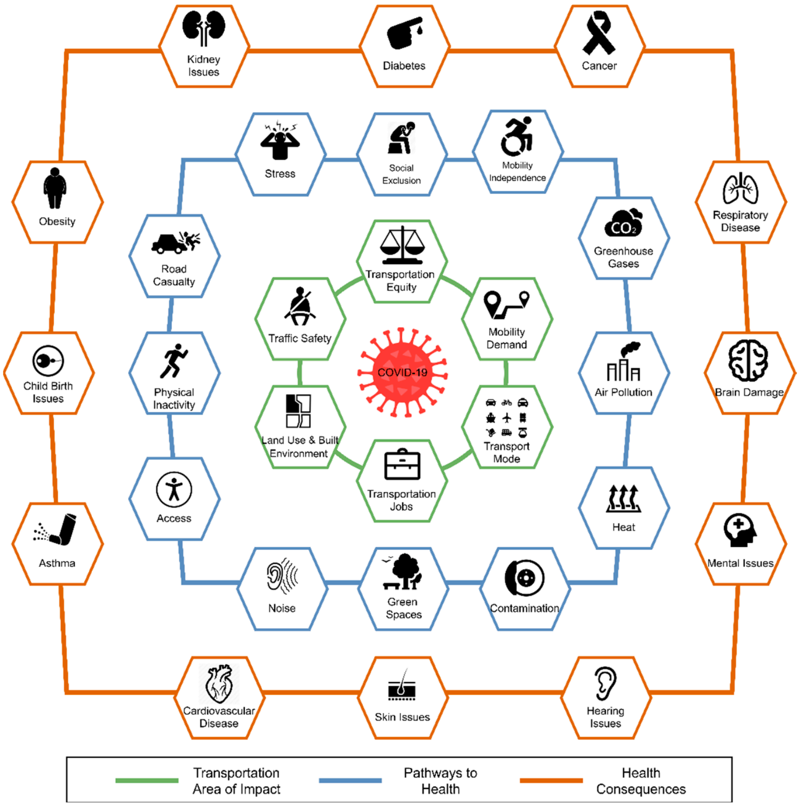

Figure 1. Ripple effects of COVID-19 outbreak through the changes in transportation.

This paper does not aim to conduct a systematic review of the literature or be exhaustive but rather follow a system thinking approach to systematically identify the secondary health impacts of COVID-19 through the changes in transportation. The remainder of this paper is structured based on the ripples of the proposed model. Section 2 addresses ripple one and summarize the impacts of COVID-19 on mobility and transportation systems. The discussion about the second ripple is reported in Section 3. Finally, we concluded the paper and discussed the future directions in Section 4.

2. Ripple 1: COVID-19 Impacts on Transportation

2.1. Mobility Demand

COVID-19 has affected mobility demand, how we choose to travel, and how people work across the country and the world. An analysis of the subway ridership system in New York showed a 90% reduction from the 5.5 million trips at the beginning of March 2020, with an average of 500,000 daily trips [31]. The ridership of the Bay Area Rapid Transit (BART) in the San Francisco Bay Area has dropped by over 90 percent compared to similar time periods in 2019 [32]. An analysis of the 113 county-level transit systems in 63 metro areas and 28 states across the United States from 15 February to 17 May 2020, showed that mobility demand dropped by 73% after the pandemic started [33]. Metrorail ridership was also less than 10% of its normal level, and bus ridership decreased by 75% in the State of Washington by 29 March 2020 [33]. The observation of a decreasing trend in public transportation usage is not limited to the United States. To name a few, a study in China found that 40% of public transport users switched to motor vehicles, and 34% maintained their original transportation mode after resuming work [34]. A study in Tampere, Finland, observed a 70% decrease in the number of public transport passengers during the spring of 2020 [35].

By the end of March 2020, global road transport activity was down by around 50% compared to the 2019 average [36]. Additionally, there was a 44.67% reduction in transit routing requests, a 17.13% rise in walking routing requests, and a 27.71% rise in driving from 13 January 2020, to 8 September 2020 [37].

The decrease in mobility demand during the pandemic can lead to fewer vehicles on toads, and, consequently, fewer miles traveled (VMT). A study in Beijing, China, reported a 70% reduction in road traffic in spring 2020 within the city boundary after the pandemic compared to spring 2019. Similar changes in traffic volume between 2019 and 2020 were observed at selected intersections located in Gliwice, Poland [38]. According to the motor vehicle traffic data (2009–2021) evaluated by the National Highway Traffic Safety Administration (NHTSA) [39], the VMT decreased by 14.9 billion miles in the first quarter of 2021, a 2.1% decrease from that of 2020. A second report from NHTSA reveals that overall, the VMT decreased by about 430 billion miles(13.2%) in 2020. Specifically, from March to May 2020, the VMT decreased drastically. The daily trips extracted from the Bureau of Transportation Statistics (BTS) website also confirm this sharp decrease between March to May 2020, as shown in Figure 2.

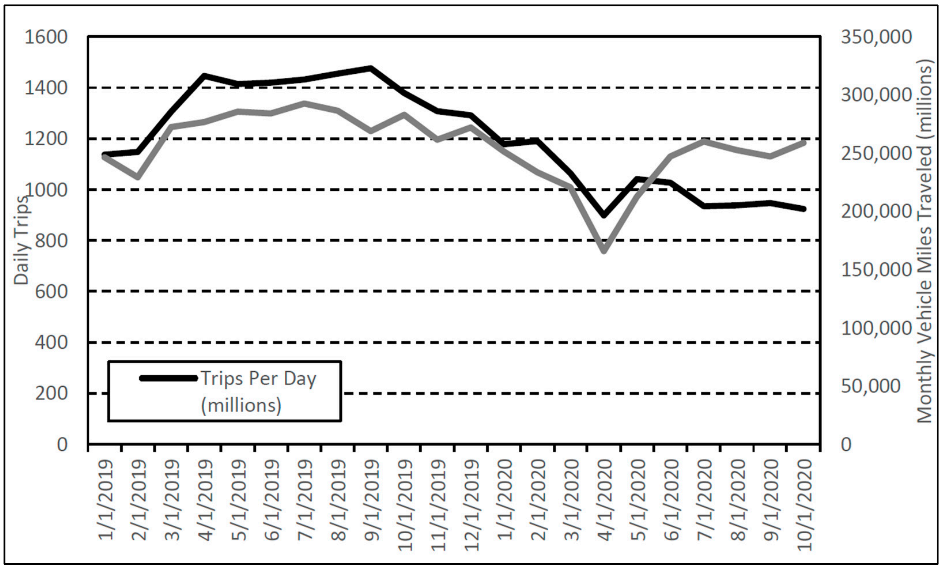

Figure 2. Number of Daily Trips and Monthly VMT Counts [40].

2.2. Transportation Mode

The emergence of COVID-19 has caused a behavioral shift in people's daily lives, including their mode choice: private car, public transit (bus, train, and metro), cycling, walking, and ridesharing/ride-hailing. Concerns over cleanliness and social distancing altered the preferred modal choices of users. The Bureau of Transportation Statistics reported the average reduction in number of people who took trips by bus, rail, or rideshare reduced by 73% and 64% from 19 August to 31 August 2020, and 17 March to 29 March 2021, respectively [40]. In a cross-sectional study conducted in Philadelphia, factors influencing preferred commute modes were studied [41]. The results indicate that 48.2% of respondents shifted their mode choices due to COVID-19 [41]. In another study, a global survey was conducted to evaluate the shift of transportation modes for primary outdoor trips before and after COVID-19; for this purpose, a descriptive analysis was conducted using the data from 1203 respondents that showed a 23% decrease in public transportation usage and a 7% increase in private car usage and walking for primary outdoor trips. It appeared that respondents prioritize safety regarding the spread of infection rather than previously effective factors, such as travel time, comfort, and cost [42]. Another paper that examined the effects of COVID-19 on biking in New York, Boston, and Chicago showed a statistically significant negative correlation between the number of COVID-19 cases and the number of bike-share trips [43]. A positive correlation between the number of cases and average trip duration was found, with the strongest being in New York [43]. The daily bike ridership in New York increased from 9 March through 11 (2020) and then fell significantly throughout March, reaching an average of 15,000 trips by the end of the month, a 71% reduction compared to early March [31]. In addition, the average daily duration of bike trips in March 2020 saw a 39% increase compared to February 2020, and a 34% increase compared to March 2019 [31]. The study also found a statistically significant association between the average duration of bike trips and the number of daily new COVID cases [31]. A study conducted by the Pew Research Center during 13–19 October 2020, randomly selected a sample of 5858 U.S. adults who work either part-time or full-time [44]. The survey found that 71% of the sample were working from home for the entire or most of the time, a 51% increase preceding the pandemic outbreak [44].

One study specifically focused on the effects of COVID-19 policies on walking behavior in U.S. cities and found a decrease in walking activity in areas with a high amount of public transportation [45]. The researchers theorized that the sharp decline in walking behavior could reduce walking trips to public transportation stations. A comparison of COVID-19 impacts on walking behavior in Houston and Seattle showed that in Houston, only one location saw a statistically significant increase in pedestrian counts, whereas, in Seattle, the trend varied in different studied locations [46].

In the first quarter of 2020, Uber had 103 million monthly active users [47]. By the second quarter, after the pandemic had seriously picked up, there were only 55 million users, as seen in Figure 3 [47]. In response to the pandemic, Uber encouraged riders to stay home and provided sanitation supplies to its drivers [47]. Despite the lockdowns in the second quarter of 2020, by the third quarter, the number of monthly active users increased to 78 million, and then to 93 million in the fourth quarter, only 10 million lower than the pre-pandemic period (Figure 3). The same pattern can be observed for Uber trips as well, with the 2020 first quarter boasting 1.66 billion trips, while the second quarter only had 737 million. In the fourth quarter of 2020, the number of trips was inverted to 1.44 billion, parallel to the first quarter [47]. It is important to realize that Uber alone takes in 68% of ride-sharing spending as of January 2021 in the U.S., so the same pattern was repeated in smaller ride-sharing businesses, such as Lyft, which accounts for the other 32% share of trips [47].

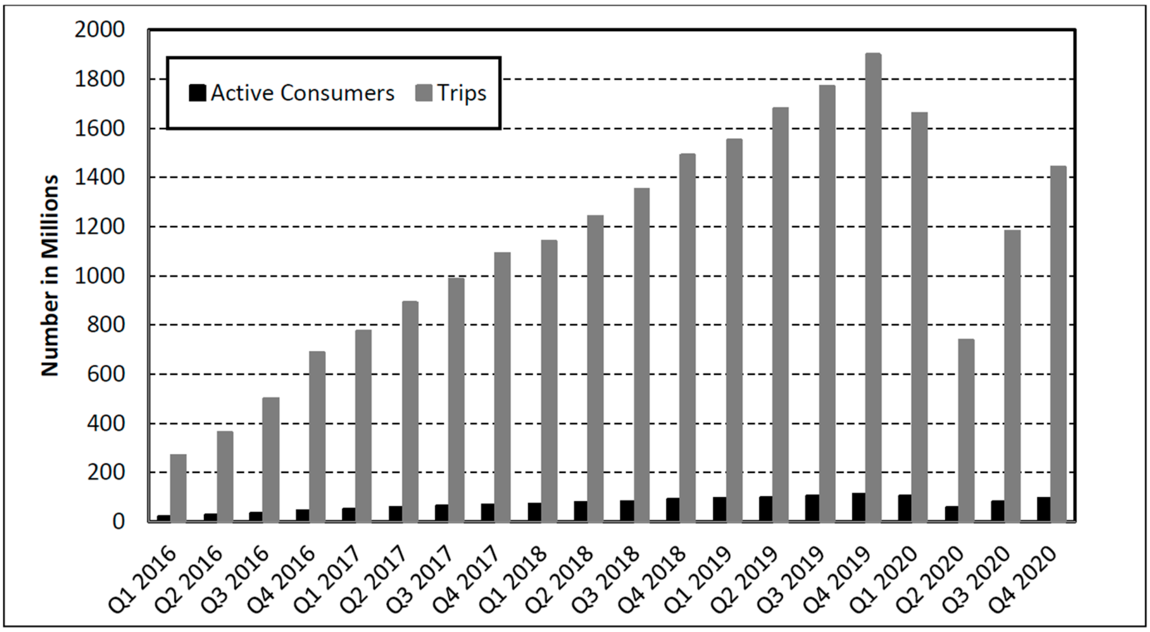

Figure 3. Uber trip statistics between 2016 to 2020 [47].

2.3. *Traffic Safety*

During the pandemic, the changes in travel demand, road traffic, and VMT affected traffic safety by reducing exposure to road crashes. The National Highway Traffic Safety Administration (NHTSA) conducted a comparative analysis of road crashes and showed a lower number of crashes during the pandemic [39]. The rates of motor vehicle crashes per emergency medical services (EMS) activation were compared between 2019 and 2020 [39]. A similar trend was observed in Connecticut, the US [48], Tarragona, Spain [49], Greece, and the Kingdom of Saudi Arabia [50].

Data from the U.S. shows that even though fewer crashes were observed during the global pandemic, road fatalities increased by 7% between 2019 to 2020 (Figure 4) [39]. The percentage of all patients severely injured in motor vehicle crashes increased significantly in the 10th week of 2020 when the COVID-19 public health emergency was declared [51]. The increase in crash severity is linked to changes in driving behavior during the global pandemic. The NHTSA studied the rates of ejections from vehicles per EMS activation (as an indicator of seat belt usage) and demonstrated an increase in ejection rates, mostly after week 10 of the year 2020 [51]. The comparison between the number of drivers with a positive drug test in the fourth quarter of 2019 and 2020 demonstrates a 5% increase in drug usage (at least one category) among drivers during the global pandemic and a 13% increase among motorcyclists [51]. According to data analysis, traffic speed, which was a major contributor to the increased severity of crashes, rose during the global pandemic [51]. A survey of 3000 respondents in the U.S. and Canada assessed the likelihood of engagement in risky driving behavior during the pandemic and compared that with the pre-COVID-19 period [52]. Results revealed that notable proportions were more likely to engage in risky driving behaviors during the pandemic than before the COVID-19 outbreak [52]. Respondents admitted to being engaged in speeding more than usual (7.6%) and drinking while driving (7.6%) in the U.S., and speeding (5.5%) and distracted driving (4.2%) in Canada during the global pandemic [52].

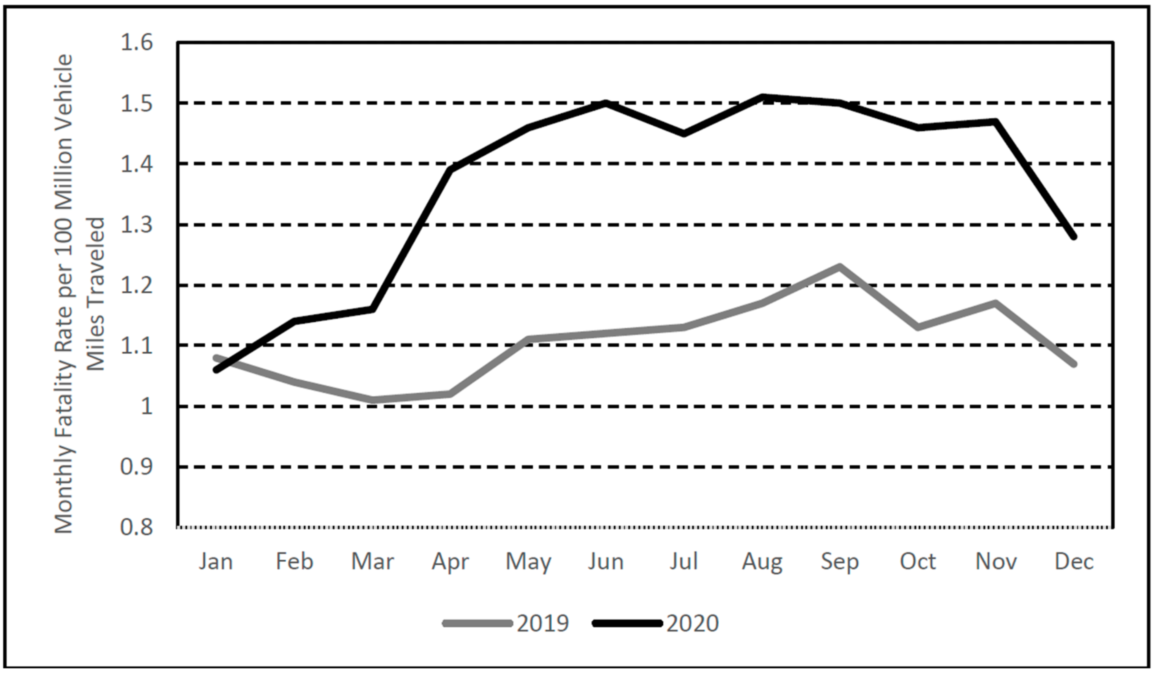

Figure 4. Monthly fatality rate per 100 million vehicle miles traveled [35].

Few studies explored the changes in non-motorized crashes after the COVID-19 outbreak. NHTSA analysis found that pedestrian injuries decreased, with the lowest record being observed in December 2020, a 1.2% decrease compared to a similar occurrence in 2019 [51]. Another study found an inverse relationship between the number of COVID-19 cases and e-bike fatalities and injuries in China's province-level e-bike safety analysis [53]. On the other hand, NHTSA analysis showed a higher number of drug users among pedestrians after the global pandemic [51], which is associated with higher levels of non-motorized crashes and injuries. A descriptive analysis of data from Franklin County in the state of Ohio showed a higher share of pedestrian and bike crashes (from all crashes) in 2020, both before and after the lockdown [54].

A study conducted by the Department of Transportation Planning and Engineering at the National Technical University of Athens revealed a 41% reduction in the total number of road accidents during March 2020 in Greece and the Kingdom of Saudi Arabia, when most preventative measures for COVID-19 took place [50]. A large increase in highway fatalities per 100 million VMT (based on quarterly data) has occurred since the pandemic started spreading in the second quarter of 2020. It was shown that a decrease in traffic volumes due to the lockdown led to an increase in road speeds by 6% to 11%, along with more frequent harsh acceleration and harsh braking events. Higher rates of mobile phone use (up to 42% increase) were observed during March and April 2020 COVID-19 spread peak period.

2.4. *Transportation Jobs*

Reductions in mobility due to COVID-19 restrictions and stay-at-home orders reduced the demand for jobs in the transportation sector [55]. A study analyzing data from the Current Population Survey found that employees in the transportation sector were 20.6% more likely to be unemployed than workers in non-transportation industries [55]. Other studies tried to associate unemployment with the ability to telework. Dingel and Neiman (2020) reported that the percentage of transportation and material moving occupation jobs that could be done from home was only 0.03. According to the data for all transportation and material moving occupations from the Bureau of Labor Statistics, there was a 167.4% increase in the unemployment level from 2019 to 2020. Globally, aviation jobs decreased by 52.5% from the pre-COVID-19 era [55]. According to the Bureau of Labor Statistics, the employment level for bus drivers, transit, and intercity jobs decreased by 9.2%.

Interestingly, employment for subway and streetcar operators and light truck drivers increased by 6.8% and 0.9%, respectively, from 2019 to 2020. Based on this information, COVID-19 did not impact the unemployment rate of different transportation modes in the same way. The reductions in mobility could be driven more so by the unemployment of drivers in ride-hailing and ridesharing companies rather than those involved with the transportation of goods and services [56].

2.5. Land Use and Built Environment

Due to the rapid spread of COVID-19 in March 2020, many public health safety measures were taken to combat the spread of the disease, one being social distancing. These measures and the closure of many schools and non-essential businesses limited human mobility. In New York City, transportation-related land showed a 70% decrease in usage by the middle of March 2020 [57]. Another study compared the different types of land and the usage of bikes in 2019 and 2020 [58]. Their findings indicated that the proportion of industrial lands had a significant negative relationship with average bike pickups, while open spaces and average bike pickups showed a significant positive relationship. A negative relationship was observed for residential lands in 2019. In contrast, a positive relationship was observed in 2020. These results are mainly attributed to stay-at-home orders and the increasing restriction of movement. The National Association of City Transportation Officials (NACTO) shared emerging strategies that different cities implement for pandemic response and recovery [59]. In Brookline, Massachusetts, cones, and signs were used to extend sidewalks and bike lanes along high-traffic streets. In Philadelphia and Minneapolis, some roads and parkways were closed off to motor vehicles around March 2020 [60]. To encourage social distancing, Denver officials increased the number of lanes dedicated to cycling and walking [60]. Using statistical analysis, one study examined how pedestrian activity in Salt Lake City, Utah changed with surrounding land use and the built environment [61]. Areas with more commercial land and employment density saw a greater relative decrease in pedestrian activity after initiated lockdowns [61]. Traffic signals near more transit stops had significantly low levels of pedestrian activity starting in April 2020 [61]. Pedestrian activity did not decline considerably in residential areas within a quarter mile of a park [61].

2.6. Transportation Equity

Since the start of the COVID-19 pandemic, there have been changes in transportation equity or accessible and affordable transportation for everyone in the community. These changes in equity stem from many different factors affected by the pandemic, mainly the difference in income, age, education, and residential areas. There were already inequities in the transportation sector before the pandemic; however, new inequities arrived, and the existing ones have grown more prevalent due to the pandemic.

A comparison between trips in low, middle-, and high-income communities in Columbus, Ohio using cell phone location data from 15 March to 30 April 2020 (early days of the lockdown order in Ohio) and the same period in 2019 showed a reduction in the number of trips, with a more significant decrease in low-income communities compared to high and middle-income communities [62]. A survey of 4000 transit riders in the cities of Toronto and Vancouver, Canada, explores the impacts of the COVID-19 pandemic on inquiry in transportation [63]. Women and people with challenging health conditions were more likely found to report difficulties while avoiding public transit (and exposure to virus spread) during the COVID-19 pandemic. A report from the Connecticut Department of Transportation analyzed three cities: New Haven, Stamford, and Hartford, and how their transportation systems were affected by the pandemic [64]. All three cities experienced an initial overall drop in ridership during the pandemic; however, many predominantly Black neighborhoods within these cities observed positive average changes in ridership, especially in Stamford and Hartford [64]. These neighborhoods consist of populations that work more service jobs, were labeled "essential workers" during the pandemic, and could not work from home. As a result, they were forced to put themselves at risk by using public transportation during the pandemic.

3. Ripple 2: Transportation-Related Health Risk Factor

3.1. Air Pollution

With a reduction in transportation on the roads during the pandemic, lowered air and noise pollution are expected. According to the report from the Alliance for Transportation Electrification, the unprecedented reduction in road traffic that occurred during the first few months of social distancing in the United States provided a rare opportunity to collect data on the short-term air quality impact of sharply reduced tailpipe emissions [65]. Data collected by the National Aeronautics and Space Administration (NASA) demonstrated a notable drop in atmospheric nitrogen dioxide (NO_2), a criteria pollutant emitted primarily from the burning of fossil fuels for transportation and is often used as an indicator of changes in human activity [66]. March 2020 had the lowest monthly atmospheric nitrogen dioxide levels on NASA's record. In particular, the data showed that nitrogen dioxide levels in March 2020 were about 30% lower on average across the regions from Washington, D.C. to Boston, Massachusetts, compared to the mean March months from 2015 to 2019. Satellite data demonstrate that in March 2020, when road traffic was around 40% lower compared to pre-pandemic levels, the levels of NO_2 were the lowest of any March going back to even 2005. During March and April, NO_2 and other air pollutant concentrations dropped by 30% in major metropolitan regions, including New York and Los Angeles [65].

Five major air pollutants regulate air quality [67]. These pollutants include particle pollution (particulate matter $PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), ground-level ozone (O_3), carbon monoxide (C.O.), and sulfur dioxide (SO_2). These five pollutants also calculate the Air Quality Index (AQI), whereas a higher AQI represents higher levels of pollution. A significant reduction of NO_2 was noted after the worldwide lockdown, which mainly occurred due to the reduction of traffic emissions in urban cities. The same study selected the ten most polluted cities based on AQI: Delhi, Mumbai, New York, London, Los Angeles, Madrid, Seoul, Rome, São Paulo, and Wuhan. The study compared the change in air pollution levels before and during the pandemic due to a reduction in transportation. The results showed that the average C.O. concentration decreased in all ten cities after the COVID-19 lockdown. There was a momentous drop in average NO_2 concentration during the lockdown in Delhi (−65%), New York (−52%), Los Angeles (−60%), Madrid (−66%), São Paulo (−50%), and Wuhan (−59%) compared to pre-lockdown conditions. Moreover, the average $PM_{2.5}$ concentration decreased in nine out of the ten selected cities. A reliable reduction in average PM_{10} concentration was observed in New York, London, Los Angeles, Madrid, and San Paulo during the lockdown, and 9 out of 10 cities saw a reduction in average PM_{10} concentration.

An analysis of hourly traffic, air pollutants, and meteorological data collected five weeks before and ten weeks after the stay-home order was enacted (17 February through 31 May 2020) on a major freeway in downtown Seattle, Washington showed that median traffic volume decreased by 37%, and road occupancy decreased by 52% [57]. The median B.C. and $PM_{2.5}$ levels decreased by 25% and 33%, while NO_2 and C.O. decreased by 29% and 17%, respectively [57]. The COVID-19 responses were associated with significant decreases in median levels of traffic-related pollutants by controlling for meteorological conditions [57].

Other countries have also seen an improvement in air quality during the pandemic. Stringent travel restrictions that began on 25 January 2020, have been linked to improved air quality and decreased mortality in China [68]. The study obtained daily concentrations of nitrogen dioxide and $PM_{2.5}$ in 367 Chinese cities from 1 January 2016, to 14 March 2020, and demonstrated that NO_2 dropped by 12.9 ug/m^3 in China due to the quarantine measures, and $PM_{2.5}$ dropped by 18.9 ug/m^3. Researchers estimated that improved air quality during the quarantine period avoided a total of 8911 NO_2-related deaths, 65% of which were linked to cardiovascular and chronic obstructive pulmonary (COPD) problems [68]. The reduction in $PM_{2.5}$ during the quarantine period avoided a total of 3214 $PM_{2.5}$-related deaths in China, 73% of which were from cardiovascular diseases and COPD [68]. Satellite data from the European Space Agency depicted that nitrogen dioxide levels across eastern and central China have been 10–30% lower than normal [69]. In Italy, since the country went into lockdown on 9 March 2020, the NO_2 level in Milan and other parts of northern Italy decreased by about 40% in approximately two weeks [69]. In Bari, a city in the Apulia Region in southern Italy, the average NO_2 concentration decreased to 48.2 ug/m^3 compared to 62.2 ug/m^3 in March 2019 [69].

3.2. Contamination

Traffic volumes have generally seen a decrease worldwide during the pandemic through previous literature reviews. Therefore, we may expect contamination associated with traffic to decrease as well. Common types of contamination may include tire wear, vehicle wear, and road dust [30]. There is evidence in the literature that traffic-related contamination is negatively associated with public health [30], However, the authors did not find studies that researched the change in traffic contamination caused by the COVID-19 pandemic.

Particles generated by brake use that remain on a road's surface could eventually seep into underground water during rainfall. A study from the Chemistry Department at the University of Otago in New Zealand discovered heavy metals in road debris collected in urban areas and the suspended sediment component of runoff from two stormwater drains in Dunedin, New Zealand [70]. Road dust consists of solid particles generated by any mechanical processing of materials. When this dust becomes airborne, primarily by the friction of tires moving on unpaved dirt roads and dust-covered paved roads, it is called road dust. Road dust brings severe health impacts. Lead and chromium compounds in road dust were present in human body fluids, which may cause deficits in neurobehavioral and cognitive development in childhood [71]. Lead may also cause dysfunction of the reproductive system and microcytic anemia, resulting in hypertension and chronic renal failure [72]. Heavy metals may also lead to health issues. Heavy metal toxicity may lower energy levels and damage the functioning of the brain, lungs, kidneys, liver, and blood composition. Long-term exposure can lead to physical, muscular, and neurological degenerative processes that imitate multiple sclerosis, Parkinson's Disease, Alzheimer's Disease, and muscular dystrophy. Repeated long-term exposure to metals may even cause cancer [73].

3.3. Noise

Following a drop in air pollution and greenhouse gas emissions, traffic noise also decreased significantly during COVID-19 pandemic. A study conducted by Boston University measured sound levels in three urban protected areas in metropolitan Boston during three time periods: in the fall and summer pre-pandemic, after the lockdown in March 2020, and during the beginning of reopening in June 2020 [74]. The study found that regardless of the time, the sound levels were highest near major roads and decreased significantly with a logarithmic increase in distance from the roads. For the first two protected areas closest to the city center, sound levels averaged 1–3 dB lower during the lockdown. However, at the third protected area transected by a major highway, sound levels were 4–6 dB higher during the pandemic. It is speculated that, although there was reduced traffic, it led to higher speeds and more noise by the fewer drivers who were on the roads. The study found that altered levels of traffic and transportation can have significant and unexpected effects on the level of noise pollution in protected areas. The study proves that vehicular traffic volume is not a linear predictor of noise pollution in protected areas. Additionally, changes in noise pollution do not always correspond to reductions in noise levels.

Changes in noise pollution caused by lockdowns and traffic changes brought by the COVID-19 pandemic also occurred in other countries. A study investigated sound levels in Dublin, Ireland, before and after the lockdown due to the pandemic [75]. A significant reduction in average hourly sound and hourly minimum sound levels was observed at all 12 noise monitoring stations between January and May 2020, which can be attributed to reductions in road and air traffic movements. In addition, for 10 of the 12 stations, sound level is associated with traffic volume.

A study in Bochum, Germany, compared sound pressure levels before and during the pandemic [76]. The study period includes five weeks before and during the pandemic-induced lockdown on 16 March 2020. Data were stratified by the land use category, and it was found that the overall noise was reduced by 5.1 dB, with noise reductions occurring in every LUC. The weakest noise reductions were found in the "main street" (3.9 dB) and the strongest in the "urban forest", "green space", and "residential area" (5.9 dB each). These reductions may be attributed to the marked decrease in federal road traffic during the lockdown period. In March 2020, there was an 18.6% decrease compared to February 2020, and a decrease of 20.5% compared to March 2019. Traffic volume right after the lockdown declined by 30% compared to the same period in 2019 for the Ruhr region of Germany. Air traffic and rail traffic also saw a sharp decrease.

3.4. Heat

When an area of land is covered with pavement or other structures that retain heat, urban heat islands occur [77]. With restricted movement and limited automobile movement during the pandemic, the effect on Surface Urban Heat Island Intensity (SUHII) due to this shift was investigated. In the United Arab Emirates, SUHII declined by 19.2% compared to 2019 [78]. Another study conducted in 21 metropolitan cities in the Middle East reported similar findings [79]. Currently, there is no literature examining the change in urban heat islands during the COVID-19 lockdowns in the United States due to transportation.

3.5. Greenhouse Gases

Forced lockdowns and restrictions limited human activity on roads. The Environmental Protection Agency's reports show that the transportation sector accounted for the largest portion (29%) of all greenhouse gasses (GH) in 2019. Out of the 29%, light-duty vehicles, such as personal vehicles, make up the majority. According to the International Energy Agency, the pandemic led to a reduction of 14.5% in global CO_2 emissions relative to 2019 by April [80]. The transportation sector reportedly accounted for 50% of the global drop [80]. However, the decline in CO_2 emissions did not last long, because as of December 2020, CO_2 emissions were 2% higher than in 2019, with road transport activity being one of the main reasons for the rebound [80]. Another study reported a reduction of 4.5 gigatons of CO_2 equivalent (one billion tons of carbon dioxide) during the lockdown (Stoll 2020). The latter paper also examined the GHG level for different transportation modes. There was a 50% reduction in the GHG level due to passenger vehicles, specifically work-related commutes, and an 80% reduction in the GHG level due to business-related air travel after the pandemic. Since surface transport contributed to nearly half of the decreases seen in the emissions during the lockdown, maintaining active travel methods, such as walking and cycling, could help cut back CO_2 emissions [81].

The results of tracking the real-time energy and emission implications of the pandemic showed that the United States saw a 10.3% drop in greenhouse gas emissions in 2020 [82]. Transportation sector emissions between 2019 and 2020 dropped by 14.7%, the steepest demand among emitting sectors, compared to the 7% decrease in industrial emissions and a 10.3% decrease in power sector emissions. As a result of sharp declines in passenger vehicle travel due to shelter-in-place orders and lockdowns across the country, the transportation sector, which accounts for 31% of net U.S. emissions, dropped 273 million metric tons compared to 2019. Figure 5 illustrates the yearly United States Greenhouses Gas emissions by sectors from 2018 to 2020.

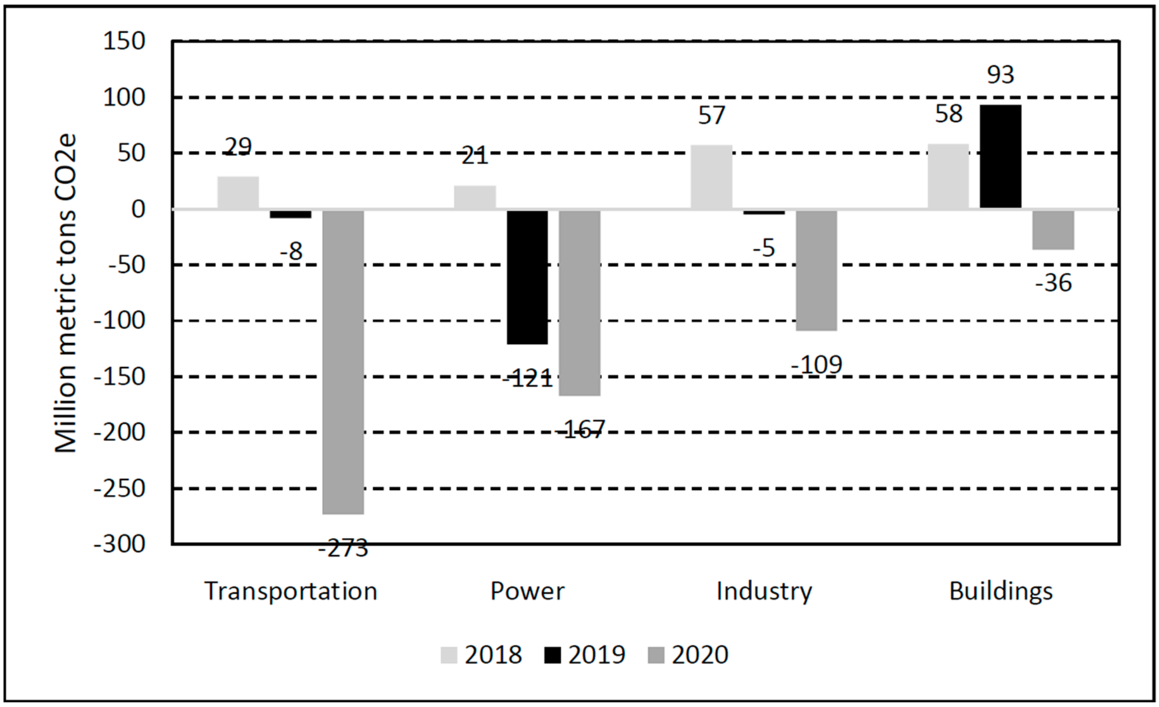

Figure 5. Changes in net US GHG emission by major emitting sectors [82].

3.6. Social Exclusion

The impacts of COVID-19 on social exclusion can be found in the sociology and ethnology literature pointing out the global discrimination against Asian ethnicity [83] and immigrants [84]. The psychological impacts of COVID-19 were also attributed to social exclusion and its health consequences [85]. Although the impacts of the global pandemic have not been directly attributed to accessibility and mobility, and further, social exclusion, the pathway is clear. The barriers in access to mobility modes (e.g., public transit and ride-hail systems) during the pandemic resulted in difficulties in communicating, which can further translate into social exclusion.

3.7. Stress

While the psychological impacts of COVID-19 and its association with anxiety are studied [86], the literature about its impacts and changes in transportation and stress during the global pandemic is limited. Traffic congestion, parking, and fear of road crashes are shown to be associated with stress and related health outcomes [87]. It is expected the decrease in road traffic during the pandemic reduced the stress associated with driving.

3.8. Road Casualties

The majority of relevant studies on the impacts of the global pandemic on road casualties have reached a similar conclusion: While the pandemic reduced crashes due to lower vehicle volume and less travel demand, road-related fatalities increased. The highway fatalities data in the U.S. demonstrates that quarterly highway fatalities have increased steadily since the pandemic (7860 during the first quarter of 2020, 9070 during the second quarter, and 11,300 during the third quarter, respectively) [51]. Figure 6 shows road fatalities over time in the U.S. The literature investigated different factors affecting the fatality rate. A study conducted by the Traffic Injury Research Foundation in Canada and the United States surveyed 1500 drivers in Canada and 1500 drivers in the United States [52]. The study found that traffic volume reduction leads to increases in risky driving behavior. The behaviors most often reported by drivers who admit to being more likely to engage in risky driving behavior during the pandemic were speeding (7.6%), drinking, and driving (7.6%) in the United States, and in Canada: speeding (5.5%) and distracted driving (4.2%), respectively [52].

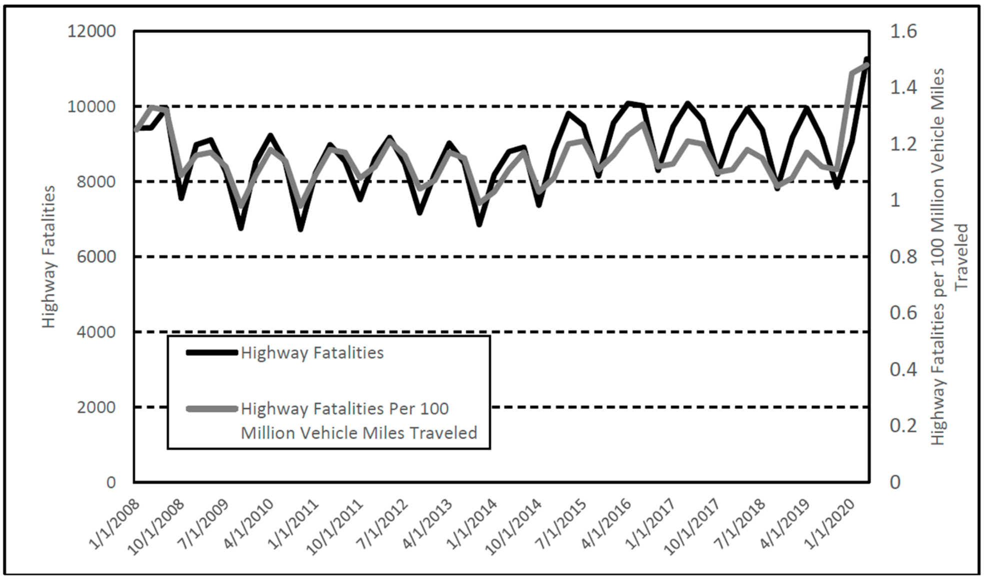

Figure 6. Monthly fatalities increased sharply during April and May of 2020 [47].

Furthermore, the analysis from NHTSA shows that the main behaviors driving the increase in fatality rates included impaired driving, speeding, and noncompliance with wearing a seat belt [39]. NHTSA also examined the prevalence of alcohol and illegal drugs in the blood of seriously or fatally injured drivers and other road user crash victims before and during the pandemic [39]. The study found that drug prevalence was high among roadway users. Drivers had a 64.7% positive test for the use of at least one active drug during the pandemic, compared to 50.8% before the pandemic. Drivers also showed an increase in testing positive for two or more categories of drugs from 17.6% before the pandemic to 25.3% during the pandemic. Pedestrians and passengers' data showed an increase in the prevalence of some drugs. The increase in drug usage for drivers, pedestrians, and passengers during the pandemic is presented in Figures 7–9.

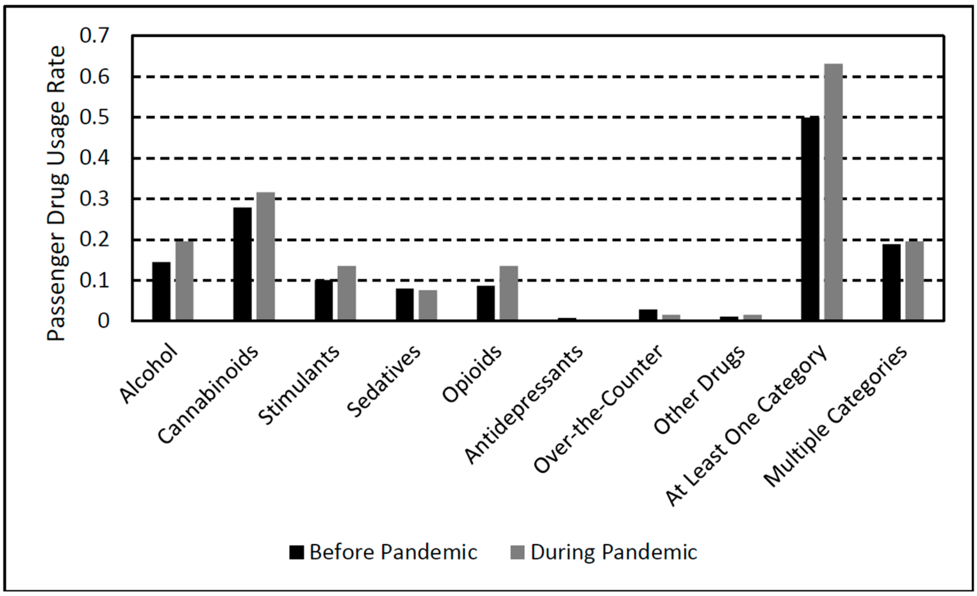

Figure 7. Drug usage of drivers before and after the pandemic [39].

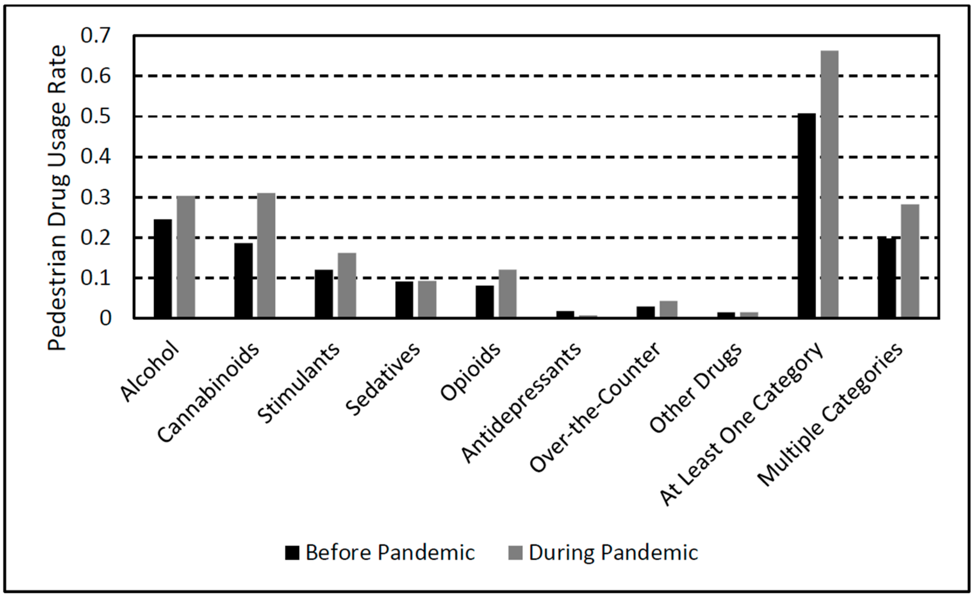

Figure 8. Drug usage of Pedestrians before and after the pandemic [39].

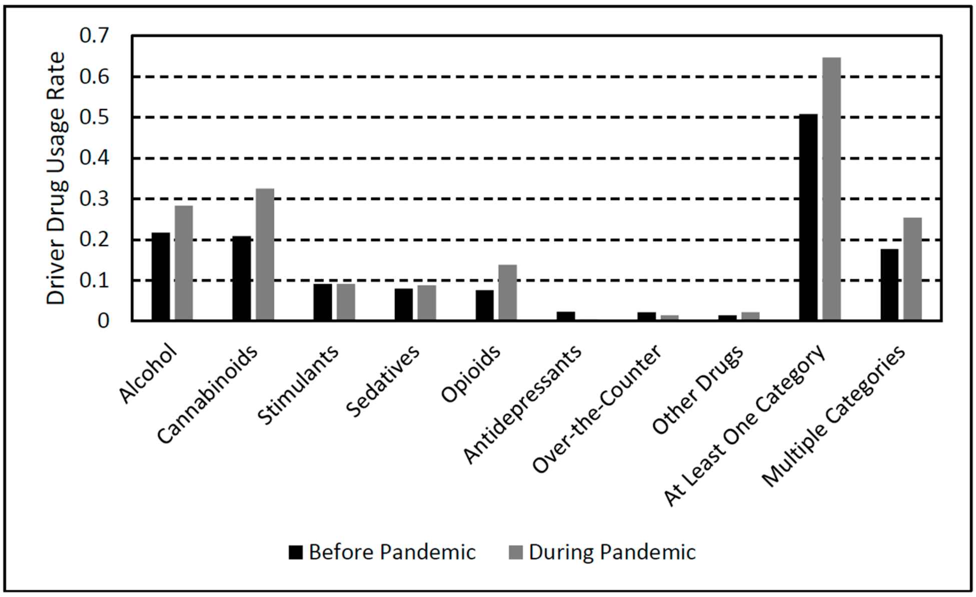

Figure 9. Drug usage of passengers before and after the pandemic [39].

3.9. Physical Inactivity

Increased physical activity is tied to promoting mental and physical health through various pathways [88]. A study investigating the relationship between prolonged physical and social isolation during the COVID-19 pandemic indicates that many emotional disabilities are associated with prolonged physical or social isolation [89]. Several studies have indicated a relationship between active travel and positive emotions, especially after walking and cycling [90]. In a study on walking behavior in U.S. metropolitan cities, 75.5% of the walks taken were utilitarian [45]. However, leisure walks in nature were longer and were not affected as much by the pandemic compared to utilitarian walking.

Moreover, research indicates that areas with high public transportation use had a sharper decrease in pedestrian activity than areas with low public transportation usage [45]. This can most likely be attributed to lower demand for public transportation due to stay-at-home orders or other COVID-19 regulations. Every area had different local guidelines for COVID-19, so physical activity behavior would also vary from region to region. Since some cities saw an increase in bike usage and walking, two main modes of active transportation, it is expected that physical activity in those areas would increase compared to the level of physical activity before the pandemic [46,91]. However, personal vehicle uses also increased due to safety concerns regarding public transportation [92]. Since personal vehicles are a sedentary form of transportation, it is unclear what the overall change in physical activity was before and after the pandemic.

3.10. Green Space

Green space is land that has no built structures and is partly covered by grass or another type of shrubbery [93]. Better health and well-being have been linked to green space through various mechanisms, such as increased physical activity and decreased environmental exposure [94]. While the results are inconsistent, evidence of beneficial associations has emerged [94]. The number of people living in urban areas, where open space is not readily available, is expected to increase to two-thirds of the population [92]. Green spaces could mitigate the common harmful effects of cities [94]. The reduced temperature reduces the urban heat island [94]. Physical activity is also linked to green spaces. In a study analyzing 34 metropolitan cities, walking, and bicycling for transportation-related activities were positively associated with parkland acreage [95]. This contrasts with recreational walking and biking, which showed no significant correlation to the percentage of parklands [95]. Currently, there is no literature that examines the influence of COVID-19 on transportation related to green space. Concerns over the safety and cleanliness of public transit and changes in road traffic made cycling and other active transportation methods more appealing after COVID-19 emerged [41]. Given these changes in commute preference and data indicating an association between parks and walking and bicycling, activity related to active transportation would be expected to increase during the pandemic in areas close to green space.

3.11. Access

Transportation is an important determinant of health care access. A comprehensive study on transportation and access to health care has revealed that structural inequality is a compounding access barrier for low-income socioeconomic groups and, hence, suggests increased partnerships between health and transportation systems in the form of expanded non-emergency transportation services [96]. For access to other major infrastructure, such as airports, planning has continued to make up for the recovery after the pandemic era. In particular, access roads and curb management have been two relevant and critical practices that many airports invested in [97]. Some changes in land use and access restriction have also been apparent due to the COVID-19 pandemic. Many vaccination centers were set up in large parking lots to minimize vaccination waiting time and increase capacity, which led to the temporary closure of the selected parking lots and nearby businesses [98].

3.12. Mobility Independence

The mobility and mode choice of travelers changed drastically during the pandemic. The major shift was the emergence of a large number of remote workers. The change in behavior and culture impacted employees' mental and physical health. For many, abrupt adjustments were necessary to continue their work, and, obviously, the change has its challenges. Another important noticeable change was in public transportation patterns. Passengers avoided using light rails, trams, and even ride-sharing companies, such as Lyft and Uber, during the early months of the pandemic. This impacted the personnel working in this industry and led to mass unemployment, as discussed in the previous sections.

A study in Singapore [99] focused on the imposed restrictions and how they surpass the transmission of COVID-19 on physical activities and sleep patterns, which are important for overall health and well-being. Interestingly, people's time in bed increased by 20 min during the lockdown without an efficiency decrease. Physical activity dropped an average of 42%. Younger and predominantly singles showed the greatest reduction in physical activity during the lockdown with little weekday/weekend differences.

4. Discussion and Conclusions

4.1. Summary and Key Findings

This paper is an attempt to understand the secondary impacts of COVID-19 on public health through various changes in transportation. A ripple effect model was designed to identify the pandemic's impacts. The changes in transportation were studied through six areas: transportation demand, transportation mode, traffic safety, transportation equity, transportation jobs, and land use and the built environment. In the short-term, the global pandemic resulted in changes in transportation demand, and a shift from public transit and shared mobility to private cars was observed. The public transit organizations were also affected by this shift and the sudden change in the sources of revenue for transportation operators, with many experiencing an unexpected shortfall in their finances. The observations regarding the shift to active transportation were not conclusive as it is not clear whether the shift happened in order to satisfy the mobility needs. Teleworking and teleshopping experienced their peak demand during the pandemic. While a lower number of crashes were observed, the severity of crashes increased. The global pandemic's impact on non-motorized crashes is not clear, and mixed conclusions were drawn through the limited available literature. The mobility and accessibility in communities with lower socioeconomic and demographic statuses were negatively affected by the COVID-19 pandemic, mainly due to the reliance of these communities on public transit. Many transportation service jobs diminished due to the changes in transportation demand and the modal shift. Drivers, body shops, and transit system operators are some examples of jobs affected by COVID-19. The various changes in parking needs, bike station demand, and land use are considered long-term impacts of COVID-19 on mobility patterns in cities.

The changes in mobility demand and pattern (and consequently, lower VMT and traffic congestion) resulted in lower air pollution, noise, contamination, greenhouse gases, and heat emissions. The changes in emissions, coupled with the lower outdoor activity of the population, resulted in lower exposure to adverse environmental risk factors, resulting in positive health impacts. Stress levels due to driving and exposure to traffic congestion were alleviated during the pandemic, which led to an improvement in overall public health. Despite the lower number of road crashes during the global pandemic, the increase in the rate of road fatalities and injuries was a caveat to changes in transportation. Difficulties in accessibility and mobility during the pandemic negatively affected access to healthcare and healthy food, particularly for those with lower income and physical/mental disabilities. Moreover, the social interaction of the population through the daily commute was restricted during COVID-19, which is associated with adverse mental health issues. Active transportation (i.e., walking and cycling) incorporated physical activity into daily routines, guaranteeing a myriad of health benefits. However, this global pandemic restricted active transportation which can negatively impact public health. Figure 10 summarizes the findings of this study, the impacts of the COVID-19 pandemic on the first and second ripple (changes in transportation and consequent impacts on transportation-related health risk factors).

4.2. Policy and Research Implications

The global community is seeking actionable solutions (in the form of policies, regulations, and plans) to improve transportation to avoid another negative impact of a future pandemic on public health. The first step toward formulating policies and actions is to identify problems that require attention, decide which issues deserve the most attention, and define the nature of the problem [100]. However, the transportation sector is responsible for identifying the short- and long-term impacts of COVID-19 on transportation, hence, sufficiently responding to the ensuing changes, and facilitating the recovery process.

While researchers need to further investigate the extent of impacts on public health, the government should support such multidisciplinary efforts.

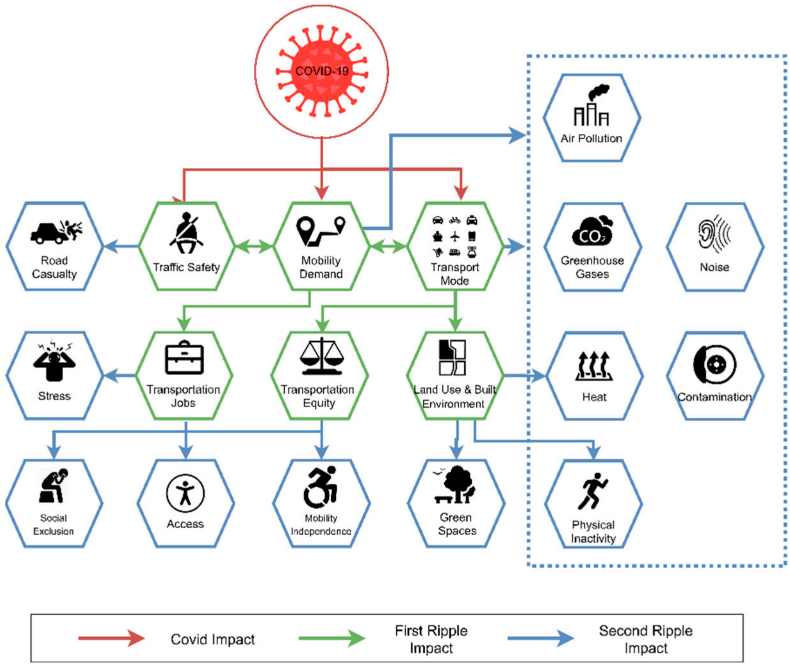

Figure 10. A summary of COVID impacts on transportation and transportation-related health risk factors.

To the knowledge of the authors, this study is the first attempt to systematically identify the secondary impacts of the COVID-19 global pandemic on transportation-related health risk factors. Future research is required to address some of the gaps in understanding the secondary impacts of COVID-19 on public health through the changes in transportation. The global pandemic's impact on non-motorized crashes is not clear, and mixed conclusions were drawn through the limited available literature. Despite the clear linkage between transportation and public health through social interactions and stress, and therefore the potential secondary impacts of COVID-19 on public health through these pathways, the literature is limited and needs further investigation.

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