

COVID-19 impacts on mobility, environment, and health of active transportation users

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ARTICLE INFO

Keywords:

COVID-19

Health assessment

Active transportation demand change

Air pollutant change

Built environment modification

ABSTRACT

Active transportation could be an effective way to promote healthy physical activity, especially during pandemics like COVID-19. A comprehensive evaluation of health outcomes derived from COVID-19 induced active transportation can assist multiple stakeholders in revisiting strategies and priorities for supporting active transportation during and beyond the pandemic. We performed a two-step reviewing process by combining a scoping review with a narrative review to summarize published literature addressing the influence of COVID-19 on mobility and the environment that can lead to various health pathways and health outcomes associated with active transportation. We summarized the COVID-19 induced changes in active transportation demand, built environment, air quality, and physical activity. The results demonstrated that, since the pandemic began, bike-sharing users dropped significantly while recreational bike trips and walking activities increased in some areas. Meanwhile, there have been favorable changes to the air quality and the built environment for active transportation users. We then discussed how these changes impact health outcomes during the pandemic and their implications for urban planning and policymaking. This review also suggests that walking and biking can make up for the reduced physical activities during the pandemic, helping people stay active and healthy.

1. Introduction

COVID-19 related mobility restrictions and social-distancing interventions has led to significant changes in active transportation demand (Buehler & Pucher, 2021; Hunter et al., 2021; Nikiforiadis et al., 2020; Pan, Darzi, et al., 2020). Public transport is perceived to be the least safe mode of transportation during COVID-19, leading to a shift to safer alternatives such as bicycling and walking, especially for those with limited access to private automobiles. Meanwhile, with the limited opportunities for physical activities in indoor locations and the shut-down of many outdoor recreational facilities during the pandemic, people may choose to walk or ride a bike more often to stay healthy and cope with the pandemic. Both factors have affected the demand for active transportation during COVID-19 (Fuller et al., 2021; Padmanabhan et al., 2021).

Changes in active transportation trips could both benefit and harm public health outcomes. Physical activity continues to be on top of the national public health objectives and is included in Healthy People 2030 as one of the national priorities in the U.S. (US Department of Health and Human Services, 2014). Physical activity can bring numerous health benefits by reducing the risks of premature death, obesity, cardiovascular diseases, type II diabetes, depression, certain cancers, Alzheimer's disease, and other dementias (Mueller et al., 2015; Weggemans et al., 2018; Woodcock et al., 2011). Walking and bicycling are the most popular and accessible sources of physical activity.

However, pedestrians and bicyclists sharing streets with motorized traffic are often exposed to other traffic risks such as crashes and air pollution. Traffic risks involving non-motorized road users are serious threats that can outweigh the many health benefits in certain locations and populations. Active transportation users are more prone to injuries

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<https://doi.org/10.1016/j.cities.2022.103886>

Received 5 January 2022; Received in revised form 5 June 2022; Accepted 30 July 2022

Available online 3 August 2022

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and deaths when involved in collisions. According to the National Highway Traffic Safety Administration (NHTSA), active transportation user fatalities accounted for 1.9 to 2.3 % of total roadway fatalities between 2008 and 2017 (National Center for Statistic and Analysis, 2019). Factors such as risky driving behaviors are among the significant crash-contributing factors affecting bicyclist safety (Dai & Dadashova, 2021). During COVID-19, reckless driving behaviors were observed to increase, namely, speeding, driving under the influence, and a lower seat belt usage rate (NHTSA, 2021). Such risky behaviors of road users can expose active transport users to higher risks of being involved in crashes and suffering from severe injuries and fatalities from crashes. In fact, the NHTSA report also found that despite the reduction in the number of road crashes, the severity of crashes in the U.S. had increased during COVID-19 (NHTSA, 2021).

Other potential health risks are from exposure to air pollution. However, with the reduced traffic volume during COVID-19, the level of air pollutants may have decreased, reducing their harmful health effect on active transportation users (Li et al., 2020; Ma & Kang, 2020). A pre-COVID-19 systematic review comparing air pollution exposures in active versus passive travel modes in European cities found that pedestrians were the least exposed group for many air pollutants, including particulate matter 2.5 (PM_{2.5}), ultrafine particles (UFP), and carbon monoxide (C.O.), compared to other road users (e.g., cyclist, bus riders, and car users). Only for black carbon (B.C.), pedestrians were exposed more than bus users on average but remained less exposed than cyclists and car users (Nazelle et al., 2017). Although cyclists may be more exposed to air pollution than pedestrians and similarly exposed compared to bus and car users, many studies have shown that the health impacts of cycling, mainly due to increased physical activity, well outweigh the exposure risks to air pollution. In most scenarios, studies concluded that

the benefits of physical activity from active transportation outweigh the risks from air pollutants. Only in cities where air pollution levels are unusually high, physical activity benefits may be offset by the increased risk of air pollution. For example, in Delhi (153 µg/m³ PM_{2.5}), an individual could bike for up to 45 min each day before health risks from air pollution exposure surpassed physical activity benefits (Tainio et al., 2016).

The exposure and safety of active transportation users are heavily dependent on the built environment (e.g., sidewalks, bike lanes, trails, proximate destinations). During COVID-19, various built environment modifications have been implemented, not only to accommodate the demand change for active transportation but also to motivate road users to utilize active transportation more regularly contributing to the changes in active transport demand. Although there have been many publications documenting COVID-19 impacts on transportation and health, no study has synthesized the rapidly accumulating evidence on the impacts of COVID-19 on active transportation users' health outcomes by comprehensively considering travel mode changes, air quality changes, and built environmental responses/modifications.

In this paper, we have used a mixed-method approach by combining the scoping and narrative review methods to collect evidence from published literature to fill in this critical knowledge gap. Fig. 1 illustrates the conceptual framework used for conducting the literature review. It graphically illustrates how the three health pathways due to COVID-19 induced changes in active transportation may impact public health. Increasing active transportation activities during COVID-19 can help improve public health by increasing physical activity. On the other hand, increasing exposure to traffic may negatively affect the health of active transport users by increasing the risks of crashes and air pollution exposures. This framework provides the evidence base to guide future

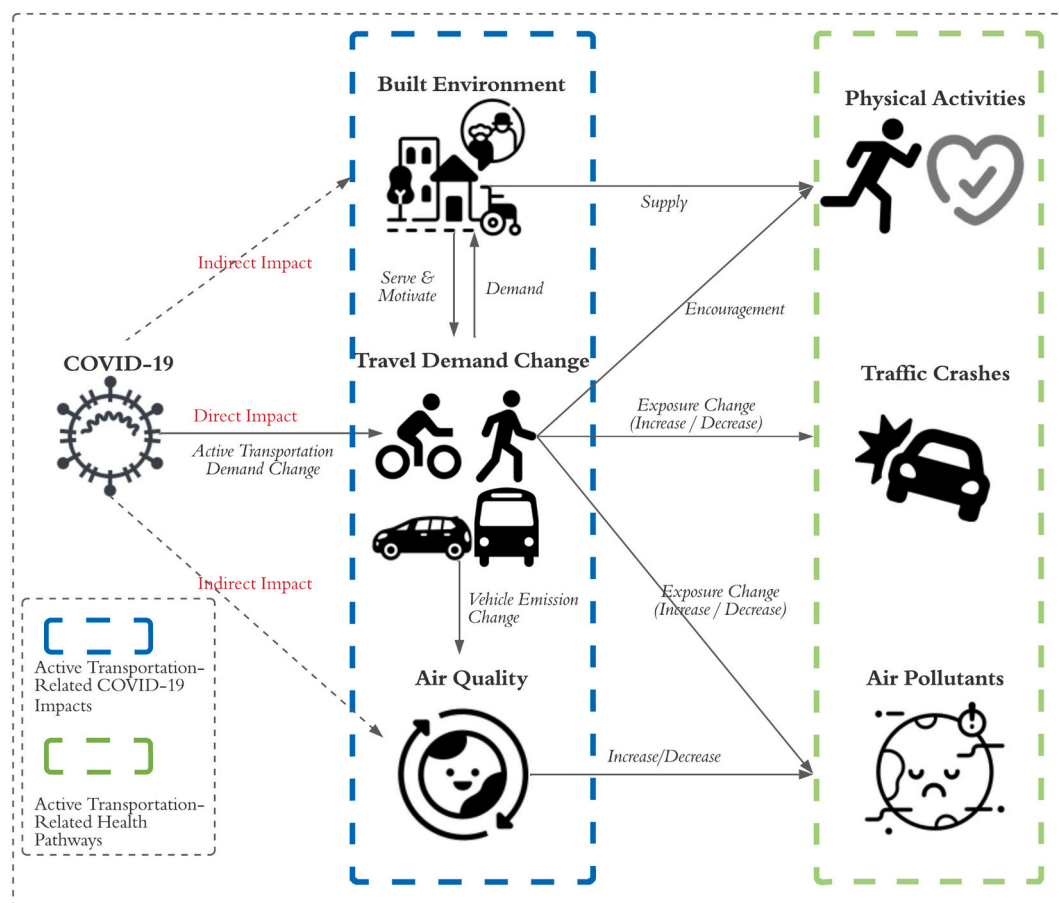


Fig. 1. Conceptual framework of the health pathways for COVID-19 induced changes in active transportation.

decision-making responding to the increasing demand changes and promoting active transportation toward creating a healthy and sustainable built environment.

The remainder of this paper is organized as follows: In [Section 2](#), we describe the review methodology. [Section 3](#) presents the findings of COVID-19 induced changes from the scoping review and the inferences of potential health consequences associated with these changes on active transportation users from the narrative review. In [Section 5](#), we summarize the key findings and further discuss the implications for urban planning or policymaking, limitations, and future research.

2. Method

2.1. Two-step review procedure

This study aims to assess the potential changes in health outcomes resulting from COVID-19 induced active transportation activities through three health pathways: physical activity, traffic crashes, and air pollution-related health concerns. The literature search was performed in March 2021. At the time of the search, no study was found directly reporting on the changes in health-related outcomes associated with active transportation (e.g., diseases caused by air pollution or injuries and fatalities for pedestrians and cyclists) induced by the pandemic. Therefore, we proposed a two-step review procedure by combining a scoping review with a narrative review to collect evidence from existing research works, as shown in [Fig. 2](#).

We first performed a scoping review by conducting a systematic literature search and summarized the observed and estimated changes in active transportation demand, air quality, and built environment during the pandemic from published research works. Then, we performed a narrative search to identify relevant publications to support the inferences about the potential impacts of COVID-19 induced changes on active transportation users' health through the three specified pathways: physical activity, air pollution-related health concerns, and traffic crashes.

- **Scoping review:** Scoping review is commonly used to examine emerging evidence through a systematic search and facilitate the discussion on a broad question ([Munn et al., 2018](#)), which works well for summarizing COVID-19 induced changes in active transportation demand, built environment, and air quality. We adopted a scoping review framework proposed by [Arksey and O'Malley \(2005\)](#), which includes four steps: identification, screening, eligibility, and inclusion.
- **Narrative review:** Narrative review has been widely adopted to obtain a broad perspective on a topic of interest. It often involves general discussions of a topic with no pre-stated hypothesis. Instead of locating all relevant literature, it usually searches for pivotal papers known to the subject expert ([The University of Alabama at Birmingham, 2022](#)). It fits the goal of finding supporting publications aiding in the inferences and discussions on the potential health consequences of COVID-19 induced changes on active transportation users.

Note that in this paper, health consequences are defined as the secondary health outcomes of COVID-19 through transportation, which does not include the direct impacts of COVID-19, such as the number of transmissions and dead patients.

2.2. Literature databases

This study retrieved relevant research evidence primarily from the five research databases, including Google Scholar, Web of Science, Embase, EBSCO, and Transport Research International Documentation (TRID). Google Scholar (scholar.google.com) is a widely used web search engine, which indexes the metadata of scholarly literature across multiple disciplines and provides access to full text in different publishing formats. Web of Science (webofscience.com) is a publisher-independent research database sponsored by the Institute of Scientific Information. This database covers more than 79 million records from several areas, such as life sciences, biomedical sciences, engineering, social sciences, health sciences, engineering, computer science, among others. Embase (embase.com) is a leading biomedical literature

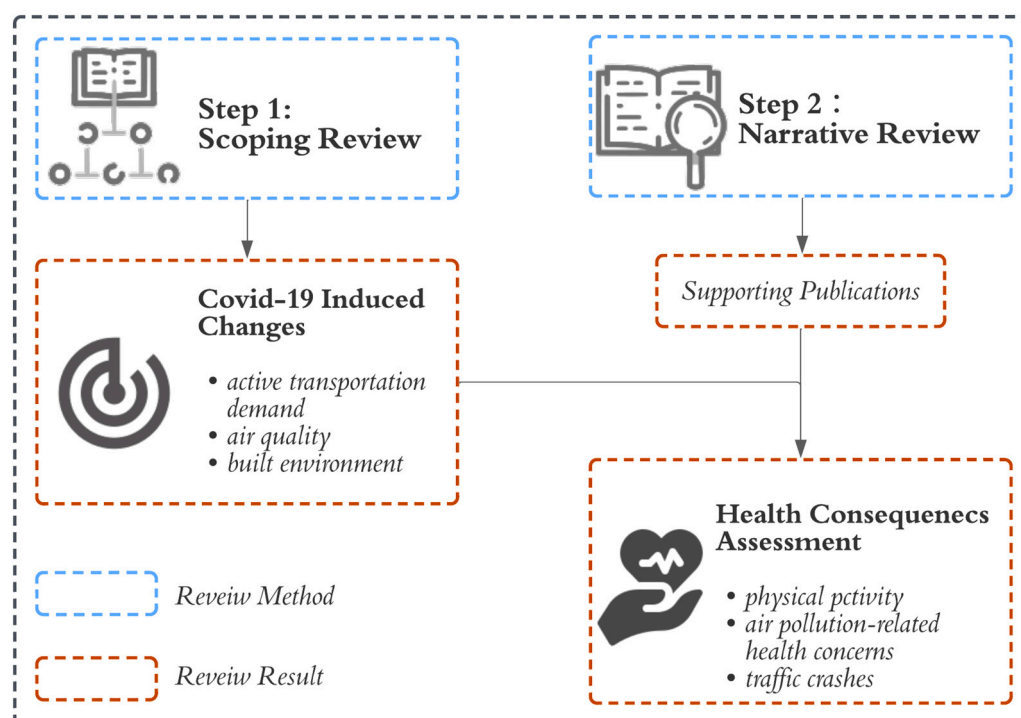


Fig. 2. The proposed two-step review procedure.

database covering 37.2 million records from 8100 journals. EBSCO ([ebsco.com](https://www.ebsco.com)) is an intuitive online research platform used by thousands of institutions and millions of users covering a variety of research databases, eBooks, and journals. TRID database (trid.trb.org) is a mainstream transportation research database, collecting and storing research works from the Transportation Research Board's Transportation Research Information Services which is solely focused on transportation research and covers more than 1.25 million records worldwide. In addition to these databases, we also added articles from a COVID-19 special issue in the Journal of Transportation Research Interdisciplinary Perspectives (<https://www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives/special-issue/10QQ201V2HM>).

Many studies have shown that Google Scholar, Web of Science, and Scopus are among the most comprehensive research databases, which are also highly overlapped (Harzing & Alakangas, 2016; Martín-Martín et al., 2018). Among these three databases, Google Scholar has the broadest coverage, including both scientific and grey literature (e.g., reports, blog posts, proceedings produced by government agencies, institutes, and researchers.) Web of Science provides similar results to Scopus but covers more “high-impact” publications (Martín-Martín et al., 2018). It is worth noting that some public agencies and experts usually post their research findings as “grey literature,” which are usually available online much faster than traditional journal articles and have become a valued source in many disciplines, especially for studying public health emergencies, such as COVID-19. By combining Google Scholar, Web of Science, and three discipline-specific databases (i.e., Embase, EBSCO, and TRID), we believe it could cover a broad enough range of disciplines and obtain a comprehensive and less redundant collection of relevant publications. Therefore, we excluded Scopus and

other databases from the literature searching process.

2.3. Article inclusion criteria

This study performed the following criteria to select noteworthy publications:

- Language: In this study, we only included the publications written in English to ease the burden of translating non-English publications.
- Publication time: All the reviewed articles and reports were published in 2020 and 2021.
- Content: The selected studies need to address the impacts of COVID-19 on active transportation volume/demand change or on active transportation users through the three proposed health pathways, as illustrated in Fig. 1.

3. Results

This section contains two parts of the review results. As discussed earlier, we first present the scoping review results documenting the changes observed or estimated by published works in active transportation demand, air pollutants, and built environment during COVID-19. Then we link these changes with supporting publications identified through the narrative review to discuss the potential consequences of COVID-19 induced changes on active transportation users' health through the three pathways: physical activity, air pollution-related health concerns, and traffic crashes.

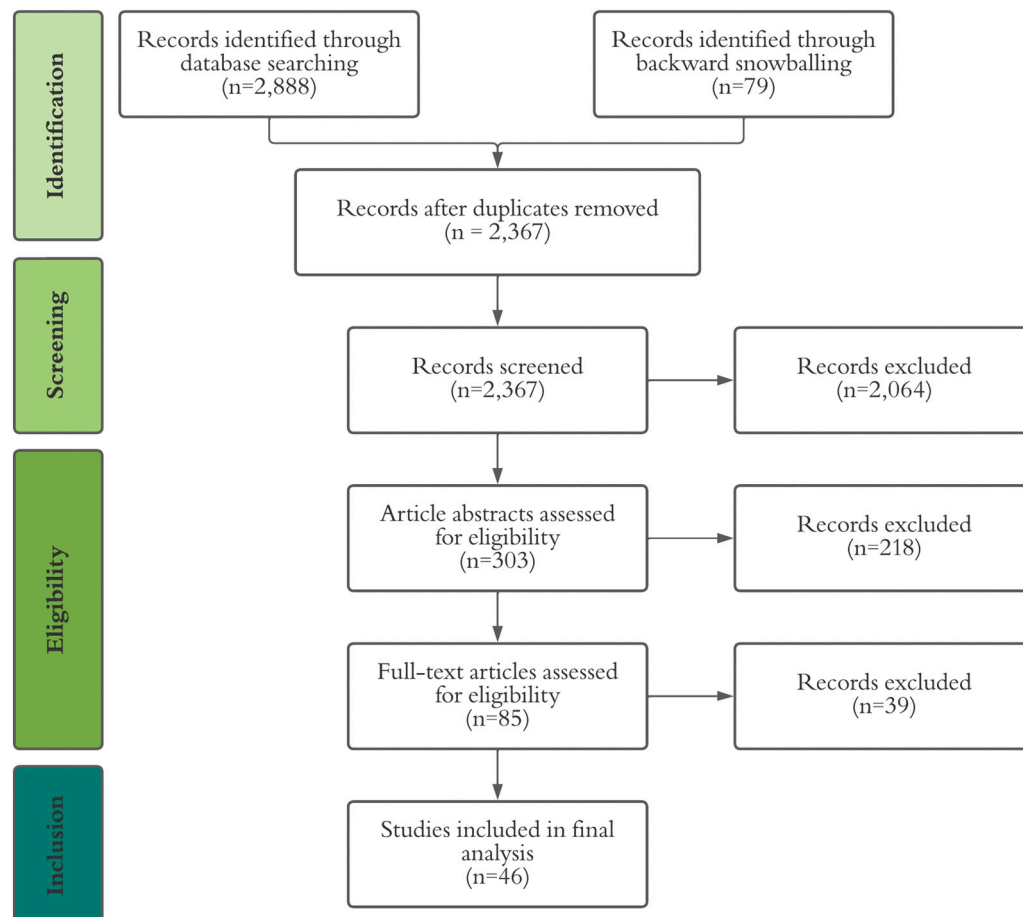


Fig. 3. Scoping review procedure for literature identification and inclusion.

3.1. Scoping review results on COVID-19 induced changes

3.1.1. Literature search results

The scoping review process included four steps: identification, screening, eligibility, and inclusion (see Fig. 3).

First, a professional librarian conducted the search based on the proposed keywords from the five selected databases. This search was performed in March 2021. A total of 2888 publications were identified. Note that identified publications contain a small group of review papers, which were then used as a “start set” to perform the backward snowballing method (Lagorio et al., 2016), resulting in 79 additional articles and bringing the number of initially identified articles to 2967. After identification, duplicated articles were removed, resulting in 2367 articles kept after this step. Next, two reviewers independently performed a more thorough screening process. They went through the titles and abstracts of the 2367 articles independently and labelled each article as “Relevant”, “Irrelevant”, or “Maybe”. After this process, we included articles labelled as “Relevant” by both reviewers and excluded articles labelled as “Irrelevant” by either reviewer. A third reviewer screened the articles labelled as “Maybe” to make the final decision. After this process, 303 articles were selected. In the next step, the reviewers carefully read the abstract of each article and further selected 85 articles that met our eligibility criteria. Two reviewers reviewed the full text of the selected 85 articles independently to assess their relevance to the scope of the paper. Finally, 46 were included in this review.

Fig. 4 illustrates the distribution of study areas for the selected 46 articles. Among them, 14 specifically examined the COVID-19 impacts on active transportation in Europe, 12 in North America, nine in Asia, two in South America, and one in Australia. Meanwhile, eight of the reviewed articles assessed the COVID-19 impacts at the international level across multiple countries.

3.1.2. Impacts on active transportation demand change

Numerous studies have been conducted to examine the influence of COVID-19 on people's engagement in active transportation, concentrated around walking, cycling, and shared biking. After performing the article screening process, 20 most relevant research works were included, out of which eight were related to examining the changes in bike-sharing systems (BSS), ten in walking, and nine in cycling (Table 1). Since there were a considerable number of studies specifically targeting the BSS changes, we separated BSS from biking in this review. Two types of active transportation demand changes were examined by the selected

research works, including model share change and volume change. This section documents both changes observed by existing studies.

For BSS, the reviewed eight studies only reported on the volume change, in which 75 % of them (six out of eight) observed a drop in the volume of BSS users (Bucsky, 2020; Chai et al., 2020; Firestine, 2021; Padmanabhan et al., 2021; Teixeira & Lopes, 2020; Tokey, 2020), especially during the peak of the first wave of confirmed COVID-19 cases and when the stay-at-home orders were in effect. A survey conducted by Nikiforiadis et al. (2020) in Thessaloniki, Greece, indicated that COVID-19 did not significantly influence BSS use. A survey conducted by Jobe and Griffin (2021) in San Antonio indicated that 47.8 % of their respondents did not change their BSS usage, while 26.1 % increased their BSS trips, and 21.7 % decreased or even stopped their BSS usage during the pandemic.

Among the ten walking-related articles, seven of them reported on the volume change only, two reported on the modal share change only, and one examined both changes. Five studies (50 %) observed a clear decrease in the volume of pedestrians since the COVID-19 began (Bucsky, 2020; Ehsani et al., 2021; Hunter et al., 2021; Shakibaei et al., 2021; Szczepanek, 2020). Although the volume decreased, the modal share of walking was observed to increase in all three modal shift-related studies (Abdullah et al., 2020; Anke et al., 2021; Bucsky, 2020). Some studies also suggested that the volume changes in walking also vary across different population groups and locations. For example, Yang and Xiang (2021) found that low-income households increased walking activities during the pandemic. Matson et al. (2021) found an increased number of walking trips from frequent walkers. Zecca et al. (2020) observed that the pedestrian flows were almost completely zeroed in the residential areas, while the pedestrian intensity increased considerably in places close to essential services.

Regarding the changes of cycling, two studies specifically examined the modal share change of cycling during COVID-19; both found the modal share of cycling had increased (Anke et al., 2021; Bucsky, 2020). Eight studies examined the cycling volume and frequency changes, in which only one study (Bucsky, 2020) clearly mentioned an observed 23 % decrease in the cycling volume; three studies reported no obvious change before and during the COVID 19 (Abdullah et al., 2020; Ehsani et al., 2021; Shakibaei et al., 2021). For the other four studies, Kurkcu et al. (2021) found spatial differences in changes in biking trips. They observed a considerable decrease in biking among older adults and people living in high-income areas. Fuller et al. (2021) found that 63 % of their respondents increased cycling, but different trip purposes led to



Fig. 4. Distribution of student areas for the selected articles in the scoping review.

Table 1

Summary of COVID-19 impacts on travel mode change from reviewed studies.

Author (year)	Country of origin	Spatial scale	Examined data	Active transportation modes		
				BSS	Walking	Cycling
Abdullah et al. (2020)	International	International	Survey responses		Modal share increased	No significant change
Anke et al. (2021)	Germany	Country-level	Survey responses	Volume decreased (−2 %)	Modal share increased	Modal share increased
Bucsky (2020)	Hungary	City-level	Volume observations		Volume decreased (−50 %)	Volume decreased (−23 %)
					Modal share increased	Modal share increased
Chai et al. (2020)	China	City-level	Volume observations	Volume decreased (−64.8 %)		
Ehsani et al. (2021)	United States	Country-level	Survey responses		Volume decreased (−10.15 %)	No significant change
Firestone (2021)	United States	City-level	Volume observations	Volume decreased with stay-at-home orders in effect		
Fuller et al. (2021)	Australia	Country-level	Survey responses			63 % of respondents increased biking frequency
Habib and Anik (2021)	International	International	Twitter posts (tweets)			Bike sales increased
Hunter et al. (2021)	United States	City-level	Volume observations		Volume decrease (−70 %)	
Jobe and Griffin (2021)	United States	City-level	Survey responses	Uncertain change		
Kurkcu et al. (2021)	United States	Neighbourhood-level	Volume observations			Spatially varying change in volume
Matson et al. (2021)	United States	City-level	Survey responses		Increased for frequent walkers	Uncertain change
Nikiforiadis et al. (2020)	Greece	City-level	Survey responses	No significant change		
Padmanabhan et al. (2021)	United States	City-level	Volume observations	Volume decreased		
Shakibaei et al. (2021)	Turkey	City-level	Survey responses		Volume decrease (−42 %)	No significant change
Szczepanek (2020)	Poland	City-level	Volume estimates		Volume decrease (−33 % to −85 %)	
Teixeira and Lopes (2020)	United States	City-level	Volume observations	Volume decreased (−71 %)		
Tokey (2020)	United States	City-level	Volume observations	Volume decreased (−50 %)		
Yang and Xiang (2021)	United States	Country-level	Survey responses		Change by population groups	
Zecca et al. (2020)	United Kingdom	Neighbourhood-level	Volume observations		Spatially varying change in volume	

Four types of spatial scales were used to classify the reviewed studies.

Neighbourhood-level: data were collected within some local communities or districts; City-level: data were collected city-wide from multiple sites; Country-level: data were collected nationwide; International: data were collected from multiple countries.

different levels of change. For example, their study observed that biking trips increased for exercise and wellbeing (recreational) but not for commuting purposes. Matson et al. (2021) indicated that the change of cycling is strongly related to the cyclists' biking frequency and attitudes toward COVID-19. They observed a decrease in cycling for infrequent cyclists; however, the frequent cyclists even increased biking trips since the pandemic began. Habib and Anik (2021) indicated that people make more recreational bike trips during the pandemic to improve their physical and mental health, leading to an increase in bike sales.

It is worth noting that some studies revealed an evident shift from public transportation to active transportation to lower virus exposure (Anke et al., 2021; Bucsky, 2020; Habib & Anik, 2021).

3.1.3. Impacts on air pollutants

Active transportation is commonly defined as any self-propelled, human-powered mode of transportation. Therefore, while active transportation users do not produce emissions, they are exposed to environmental pollutants. Exposure to pollutants like Nitrogen Dioxide (NO₂), Particulate Matter (PM), Sulphur Dioxide (SO₂), Ozone (O₃), Black Carbon (B.C.), and Carbon Dioxide (CO₂) is determinantal to human health. The World Health Organization (WHO) recently reviewed the literature on air pollution effects on human health and accordingly updated its air quality guidelines, bringing the air pollution thresholds down to reflect the latest evidence (WHO, 2021). Air pollution from

traffic has been associated with all-cause mortality and a wide spectrum of diseases include but are not limited to cardiovascular disease, lung cancer, diabetes, adverse birth outcomes, congenital anomalies, neurological disorders, pregnancy-induced hypertensive disorders and pre-eclampsia, and adverse respiratory outcomes (Khreis et al., 2020). O₃ exposure, although not a primary traffic-related pollutant, can cause coughing and sore or scratchy throat, making people difficult to take a deep breath. It also inflames and damages the airways, making the lungs more susceptible to infection and aggravating lung diseases such as asthma, emphysema, and chronic bronchitis, and increasing the frequency of asthma attacks (US Environmental Protection Agency, 2021). Due to the increased ventilation rate during walking and biking, the inhaled dose of air pollutants can increase; hence these pollutants can have determinantal impacts on the health of active transportation users with prolonged exposure to traffic pollution. Therefore, exploring the impact of air pollutants on active transportation user health has gained increasing attention in the literature. For the purposes of this study, we reviewed the studies on impacts of COVID-19 on air pollution, to make an inference on how these changes may impact the active transport users' health.

In this scoping review, we included a total of 19 articles that estimated changes in air quality by comparing certain pollutants before and during COVID-19. The typical pre vs. during COVID-19 threshold in these studies is the implementation of lockdown policies in the

geographical location of each study. Fig. 5 illustrates the percent changes of eight air pollutants observed by the reviewed articles, including B.C., CO₂, NO₂, NO_x, O₃, PM₁₀, PM_{2.5}, and SO₂. Each violin plot represents the median value (black line in the bar), the interquartile range (the black bar in the centre), and the probability density distribution (the plot shape) of changes for each pollutant. The wider the plot around a value, the more articles report pollutant percent changes at that value. Black dots represent the mean values of changes reported by each article.

Among the eight pollutants, the selected studies mainly discussed the changes in NO₂ and PM_{2.5}. A total of 14 articles assessed PM_{2.5} changes, with 13 observing decreases ranging from 3.6 % to 64.11 % and one observing increases ranging from 3 % to 7 %. A total of 14 articles examined NO₂ changes, and all of them reported decreases ranging from 5 % to 78 %, with a mean value of around 40 %. Meanwhile, with the implementation of lockdown policies, studies also observed apparent decreases in the levels of B.C., CO₂, NO_x, PM₁₀, and SO₂. Five articles examined the changes in PM₁₀, reporting decreases in PM₁₀ levels with a mean value of 39.5 %. Five articles observed decreases in SO₂ levels in their study areas with a mean value of 20.35 %. Two articles examined NO_x changes; one observed decrease ranging from 29 % to 47 %, and another observed a 54 % decrease. Two articles studied B.C. level changes and reported decreases (45 % to 51.1 %) in their studies. Only one of the reviewed articles examined CO₂ changes at the global level and observed a 17 % decrease in CO₂ levels. Unlike the aforementioned pollutants, an opposite trend of changes was observed from the seven identified articles reporting the O₃ changes. Six observed increases in O₃ from their study sites; one of them reported an extremely high rise (200 %). Only one study reported a decrease with a value of 8.08 %. Studies claimed that the decrease in nitrogen oxides level could directly lead to an increase in O₃ (Dantas et al., 2020; Mahato et al., 2020). More details of pollutant changes in the reviewed articles can be found in Table 2.

If the article reports different values for a pollutant level change, we document the maximum and minimum values written in the parenthesis.

City-level: data were collected city-wide from multiple sites; Regional: data were collected from several neighbouring cities; Country-level: data were collected nationwide; International: data were collected from multiple countries.

3.1.4. Impacts on the built environment

Many planning organizations adapted contingency plans to accommodate the changing demand for active transportation. Some of the practices were documented in the reviewed studies. Five studies addressed built/natural environmental strategies responding to COVID-19. These studies extended their discussions from the regional (e.g., England and Wales) and national (i.e., Italy) level to the global perspectives, highlighting the shifting or renewed roles of the urban environments amidst COVID-19. Given the small number of articles addressing the built environment and the unique focus of each article, we provide our review of each study separately for these articles.

Capolongo et al. (2020) explored the broad inquiry on ways to better integrate pandemic-responsive public health strategies into contemporary urban planning practices. They proposed shorter-term action items such as “plan a smart and sustainable mobility network” and “re-think the accessibility to the places of culture and tourism,” and longer-term strategies such as “re-think building typologies, fostering the presence of semi-private or collective spaces,” “integrate the existing environmental emergency plans, with those related to the health emergencies,” and “improve stakeholders’ awareness of the factors affecting public health in the cities.”

Two studies addressed mobility responses to COVID-19. One study addressed specific local strategies implemented in large cities in Italy (Barbarossa, 2020), and the other study inventoried and analysed a comprehensive list of mobility measures from around the world (Combs & Pardo, 2021). Barbarossa (2020) discusses Italian examples of COVID-19 mobility responses employed by their 10 most populated cities. Their responses covered a wide range of built environment interventions to accommodate the increased demand for walking and cycling, such as temporary and permanent bike lanes, pedestrian and public spaces, restricted areas, and traffic calming zones. The scale of these interventions varied from 22 km of temporary/permanent bike lanes in Florence to 150 km of temporary bike lanes in Rome. Combs and Pardo (2021) developed a database containing 1109 COVID-19 mobility responses from multiple data sources at a global scale. Most of the COVID-19 mobility strategies involved physical modifications to existing streets. Popularly implemented strategies were re-allocation of vehicular lanes to walking and cycling (13.2 %, 146 applications), partial street closure (11.0 %, 122), and full street closure (11.0 %, 122) to

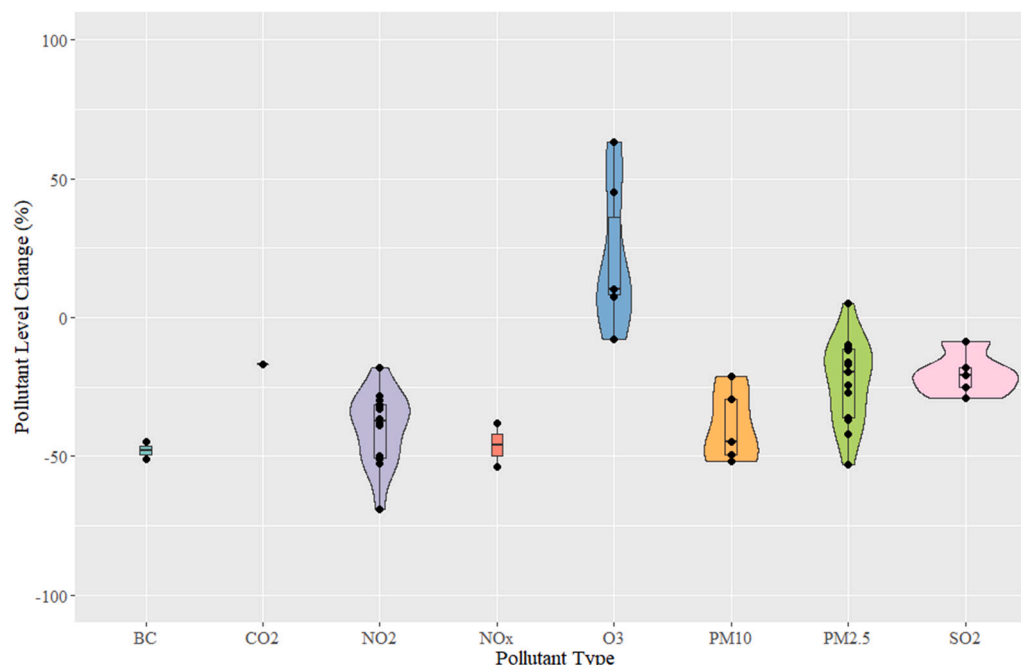


Fig. 5. Changes in air pollutants during COVID-19.

Table 2
Summary of COVID-19 impacts on air pollutants from reviewed studies.

Author (year)	Country of origin	Spatial scale	Air pollutant							
			NO ₂	PM _{2.5}	PM ₁₀	O ₃	NO _x	SO ₂	CO ₂	BC
Connerton et al. (2020)	International	City-level	(−24 % to −39 %)	(−12 % to −37 %)		(−10 % to +30 %)				
Dantas et al. (2020)	Brazil	City-level	(−24.1 % to −32.9 %)							
Dimovska and Gjorgjev (2020)	Macedonia	City-level	(−5 % to −31 %)	(+3 % to +7 %)						
Dobson and Semple (2020)	United Kingdom	Regional	−38.1 %	−19.8 %						
Granello et al. (2021)	Italy	City-level	−33 %	−16 %						
Kumari and Toshniwal (2020)	India	City-level	(−60 % to −78 %)	(−37 % to −49 %)	(−44 % to −55 %)			(−19 % to −39 %)		
Le Quéré et al. (2020)	International	International							−17 %	
Li et al. (2020)	China	Regional		(−27 % to −46 %)			(−29 % to −47 %)	(−16 % to −26 %)		
Ma and Kang (2020)	International	City-level	(−10.4 % to −53.2 %)	(−3.6 % to −29.9 %)						
Mahato et al. (2020)	India	City-level	−52.68 %	−53.11 %	−51.84 %	> + 10 %		−17.97 %		
Menut et al. (2020)	International	International	(−15 % to −45 %)	(−5 % to −15 %)		(−2.7 % to +17.6 %)				
Pan, Jung, et al. (2020)	United States	Regional		−27.25 %		−8.08 %				
Rodríguez-Urrego and Rodríguez-Urrego (2020)	International	International		−12 %						
Silver et al. (2020)	China	Country-level	(−27 % to −50.5 %)	−10.5 %	−21.4 %					
Tobías et al. (2020)	Spain	City-level	−51 %		(−28 % to −31 %)	(+33 % to +57 %)		(−19.4 % to +1.8 %)		−45 %
Toro et al. (2021)	Chile	City-level		−11 %		+63 %	−54 %			
Vultaggio et al. (2020)	Italy	City-level	−50 %		−45 %					
Wang et al. (2021)	China	City-level	(−9.9 % to −64.0 %)	−36.9 %		+200 %		−25 %		−51.1 %
Zangari et al. (2020)	United States	City-level	−51 %							

+ represents increase; − represents decrease.

support walking/cycling. Other environmental measures included automated walk signals, re-allocated curb spaces and street parking, re-allocated sidewalks to commerce, and improved bicycle parking facilities. They also found a number of policy/program responses to mobility challenges during COVID-19, such as reduced/free transit fare, reduced speed limit, subsidized bike purchase/maintenance, and revising/creating mobility plans to respond to COVID-19.

Two studies specifically focused on modelling green spaces in urban communities (Shoari et al., 2020; Ugolini et al., 2020). Shoari et al.'s study of parks and gardens in England and Wales showed that while most people had parks or gardens within a 10-minute walk, disparities existed in terms of accessibility. For example, children had lower levels of accessibility to parks/gardens, and those in high-density living environments (e.g., flat residents) had lower per-capita park/garden spaces. Ugolini et al. conducted online surveys during the early waves of COVID-19 in six countries, including Croatia, Israel, Italy, Lithuania, Slovenia, and Spain. They found that nearby green spaces such as tree-lined streets and small urban gardens became more important during COVID-19 among respondents from Italy, Spain, and Israel, while respondents from Lithuania reported traveling further outside the city to visit green spaces during COVID-19. Urban green spaces were considered important even without the ability to visit them. Respondents recommended those green spaces be better integrated into the neighbourhoods for increased accessibility during pandemics like COVID-19.

3.2. Narrative review results on implications of COVID-19 induced changes on active transportation users' health

As previously mentioned, during the literature search (performed in March 2021), we did not find studies concerning traffic crashes involving active transportation users or the potential impacts of air

pollution changes on active transportation users' health. Therefore, we performed a narrative review to identify relevant studies published since then to support the inferences on the potential health consequences of COVID-19 induced changes (obtained from the scoping review) on active transportation users through the following health pathways: physical activity, air pollution-related health concerns, and traffic crashes.

3.2.1. Physical activity

Two studies, located in the United Kingdom (U.K.) and Japan, looked at the determinants related to physical activity participation during the COVID-19 pandemic. Spence et al. (2021) conducted a 1521-responder survey to examine the impact of the COVID-19 lockdown on the physical activity of U.K. adults and identified potential motivational determinants of behavioral change. Most respondents reported reduced physical activities for commuting to workplaces and activities at recreational facilities compared to the pre-lockdown level. On the contrary, many respondents maintained or increased their physical activities at home and in their local neighbourhoods. Meanwhile, significant increases were observed in sedentary behaviors, including sitting, reclining, and using screen-based devices for working, schooling, and leisure. This study also indicated that most adult respondents did not follow the U.K. guidelines on physical activity, and the prevalence of physical activity was much lower than it was before the pandemic.

This study also modelled the relationship between the physical activity changes and three potential determinants: physical opportunity (access to parks, gyms), social environment (social cues, social support from friends and family, norms), and reflective motivation (willingness). The results indicated that the frequency of physical activity during the pandemic was highly determined by the respondents' physical opportunities and their motivation/willingness. The social environment was

not influential in their model. It suggests the importance of the community environment in promoting physical activity during pandemics like COVID-19 and the significant roles of recreational and active transport facilities such as green space and biking/cycling.

Sasaki et al. (2021) examined the impacts of COVID-19 on older adults' physical activities in August 2020 based on a survey of 999 participants. Sasaki et al. analysed associations between several variables such as socioeconomic status, social participation, and physical activity among older populations in northern Japan. The study found that older men in lower socioeconomic status were less likely to be active, while older women with higher social participation (e.g., participating in an exercise program) were more likely to be active during the pandemic. Older adults with a higher socioeconomic status and social participation in pre-COVID19 were more likely to maintain physical activity levels during the pandemic.

3.2.2. Air pollution-related health concerns

Not many studies have explored the effect of COVID-19 related transportation changes on air pollution that affect active transportation users. However, based on the rich evidence from the existing air quality literature, its positive impact can be inferred. Results from our review showed that air pollution levels were reduced up to 78 % for NO₂, 53 % for PM_{2.5}, 55 % for PM₁₀, all of which are regulated air pollutants due to significant adverse health effects. These reductions imply significant health benefits ranging from fewer exacerbations of for example, asthma attacks, hospital admissions and cases of stroke and myocardial infarctions to other important effects such as reducing the rates of chronic diseases and premature mortality if and where these reductions are sustained. Other pollutants from transport such as black carbon (Invernizzi et al., 2011) were also reduced during the pandemic. However, how to maintain the reduced air pollution level beyond the pandemic through other transportation planning measures or policies remains a challenge.

3.2.3. Traffic crashes

The changes in travel demand and vehicle miles travelled during the pandemic affected traffic safety. NHTSA conducted a comparative analysis of road crashes (NHTSA, 2021). The motor vehicle crash rates per emergency medical services (EMS) activation was compared between 2019 and 2020 (NHTSA, 2021). The results showed a decrease in the rate of crashes. This trend was observed in Connecticut, U.S. (Doucette et al., 2021), Tarragona, Spain (Saladié et al., 2020), and Greece and the Kingdom of Saudi Arabia (Katrakazas et al., 2020).

Not many studies explored the changes in non-motorized crashes after the COVID-19 outbreak. NHTSA's analysis found that the pedestrian injury rate decreased where it was the lowest in December 2020, with a 1.2 % decrease compared to a similar time in 2019 (NHTSA, 2021). Another study found an inverse relationship between the number of COVID-19 cases and e-bike fatalities and injuries in a province-level e-bike safety analysis in China (Yan & Zhu, 2021). On the other hand, NHTSA's analysis showed a higher number of drug usage among pedestrians after the global pandemic (NHTSA, 2021), which can be associated with higher levels of non-motorized crashes and injuries. A descriptive analysis of data from Franklin County in Ohio, U.S., showed a higher share of pedestrian and bike crashes (from all crashes) in 2020 both before and after stay-at-home order (Stiles et al., 2021).

Data from the U.S. shows that despite fewer crashes during the global pandemic, road fatality increased by 7 % between 2019 and 2020 (NHTSA, 2020). 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 (NHTSA, 2021). The increased severity of crashes was also partly because of the changes in driving behaviors during the global pandemic. The comparison between the number of drivers with a positive drug test in the fourth quarter of 2019 and 2020 shows a 5 % increase in drug usage (at least one category) among drivers during the pandemic and a 13 % increase

among motorcyclists (NHTSA, 2021). Based on the analysis of data from U.S. roads indicated traffic speed, one of the major contributors to road crash severity, also increased during the pandemic (NHTSA, 2021). In a survey of 3000 respondents in the U.S. and Canada that asked about the likelihood of engaging in risky driving during the pandemic as compared to before COVID-19 (Vanlaar et al., 2021), respondents admitted engaging more in speeding (7.6 %) and drinking and driving (7.6 %) in the U.S., and speeding (5.5 %) and distracted driving (4.2 %) in Canada during the global pandemic (Vanlaar et al., 2021).

4. Discussion and conclusions

This article examined the changes in active transportation related-activities during the COVID-19 pandemic by performing a scoping review, including active transportation demand changes, air pollutant changes, and built environment modifications. It also made inferences by linking the scoping review findings with narrative review findings to discuss potential health implications of COVID-19 induced changes for active transportation users through three pathways: physical activity, air pollution-related health concerns, and traffic crashes.

4.1. Key findings

4.1.1. Active transportation demand change

Since the COVID-19 pandemic began, a significant drop in BBS users was reported in most studies due to issues including mobility restrictions, the closing of businesses, and other safety concerns. While half of the walking-related articles reported a decrease in walking activities, some studies observed an opposite trend indicating that walking activities increased. For the changes in cyclists, half of the selected articles clearly mentioned that the bike trips were significantly increased. However, some studies found the shift of biking trips may vary across population groups and locations. A noticeable trend was that people chose to make more recreational trips on bikes to keep their physical and mental health during the pandemic.

4.1.2. Air quality change

With the implementation of various mobility restrictions, the usage of motor vehicles dropped significantly during the pandemic, leading to an apparent improvement in air quality. Among the eight examined pollutants, seven pollutants' concentrations were decreased compared to pre-COVID-19, including NO₂, PM_{2.5}, BC, CO₂, NO_x, PM₁₀, and SO₂. The only increase was observed in O₃ that might be caused by the decrease of nitrogen oxides level. It indicates that air quality is more favorable for active transportation users during COVID-19, which can lead to increased health benefits of walking or biking.

4.1.3. Built environment modification

Different built environment interventions and modifications have been proposed and implemented to promote the use of active transportation and encourage citizens' outdoor engagements during the pandemic. Some modifications aim to increase the access to active transportation facilities, such as reallocation of vehicular lanes to walking/cycling lanes, street closure to support walking/cycling, improved bicycle parking facilities. Others focused on recreational environments (e.g., increasing the coverage of and access to green spaces in urban communities), improving residents' motivation to engage in physical and recreational activities. Studies also suggested that governments need to better integrate pandemic-responsive public health strategies into contemporary urban planning practices.

4.1.4. Physical activity

The evidence from U.K. and Japan demonstrated that the frequency of physical activities decreased while sedentary-related behaviors increased compared to the frequency before the pandemic. These changes were directly related to the respondents' physical opportunities

and motivation/willingness. Meanwhile, the respondents' socioeconomic status could also influence people's physical opportunities and willingness to participate in and maintain physical activities during the pandemic.

4.1.5. Air quality

The air pollution reductions achieved during the pandemic are unprecedented, beyond what is feasible with more incremental measures. Although not many studies quantified the health impacts of these changes, they are expected to be large and span across reductions in adverse short-term health effects such as the exacerbations of respiratory symptoms to longer-term positive effects such as reduced premature mortality and improved respiratory and cardiovascular health. Further efforts are needed to quantify and document these impacts using methods like health impact assessments.

4.1.6. Traffic crashes

Our review of the literature showed a decrease in the number of crashes after the emergence of the global pandemic. However, the severity of crashes increased, blaming riskier driving patterns and behaviors including speeding, failing to wear seat belts, and driving under the influence of drugs or alcohol, all of which have a significant impact on active transportation users' safety. The understanding of the COVID-19 impacts on non-motorized crashes is still in its infancy and mixed conclusions were drawn in the limited literature. Therefore, this topic requires further investigation to better understand the non-motorized traffic safety in the era of the global pandemic and the underlying mechanism behind the potential associations.

4.2. Implications for urban planning or policymaking

This study brings various broader impacts on public health and urban planning research. It can help to inform the Metropolitan Planning Organization (MPO)s and other policymaking agencies to revisit strategies and priorities for supporting and promoting active transportation. Furthermore, there is an urgent need to assess the health outcomes of COVID-19 induced active transportation demand change, which can help transportation, planning, and public health agencies at multiple governmental levels make informed decisions about the critical needs to accommodate and further support active transportation.

The unprecedented public health challenges of COVID-19 have accompanied unprecedented opportunities to urban planning to revisit and reprioritize its policy objectives to create healthy cities that are more resilient and adaptable to pandemics like COVID-19 in the future. This momentum should be utilized by the policy-makers to promote the active transport in the post-COVID era when the traffic volumes will start increasing to its pre-COVID levels. By surveying policy experts in Switzerland, Büchel et al. (2022) found that timely implemented policy measures may help the traveling population to reconsider their mode choices, and if no policy measures are implemented it is likely that the active transport usage will not increase in the long-run. Most of the recommended policies in this study concern the changes to the built environment such as reducing speed limits on shared streets, installing dedicated bike infrastructure such as separated bike lanes, installing clear pavement markings, broad paths and clear guidance at intersections. Other recommended policies included but were not limited to subsidizing the bike purchase (e.g., e-bikes) and providing online cycling classes in order to keep and attract new cyclists. Nikitas et al. (2021) reported similar best practice approaches that policymakers could take to improve the active transport user experience and keep them in the long run. Hadjidemetriou et al. (2020) also suggested that governments should promote active transportation during the pandemic by reallocating space to support walking and cycling activities. Some short-term and long-term policy recommendations proposed by reviewed studies (Büchel et al., 2022; Hadjidemetriou et al., 2020; Nikitas et al., 2021) are listed in Table 3, which are grouped into four

Table 3

Policy recommendations for promoting active transportation.

Category	Recommendation	Duration
Infrastructure	Add temporary bike lane and sidewalk.	Short-term
	Re-allocate street spaces (i.e., repurpose curb space, on-street parking, outer traffic lanes to bike lane or sidewalk).	Short-term
	Take traffic calming measures (i.e., reduce speed limit, set restricted zones).	Short-term
	Install and improve facilities for bike parking, storage, and e-bike charging.	Long-term
	Add permanent bike lane and sidewalk.	Long-term
	Install automated crossing signals reducing the need to touch the button.	Long-term
	Expand public spaces and green spaces (i.e., create pop-up parks).	Long-term
	Keep open green spaces and parks with trails open during the pandemic.	Short-term
	When the number of visitors is controlled, prioritize the access for vulnerable populations.	Short-term
	Reduce/free entrance fees for parks	Short-term
Accessibility	Keep transit routes available for visiting parks and green spaces during shelter-in-place orders	Short-term
	Subsidize bike and e-bike purchase and maintenance.	Long-term
	Improve bike-sharing service (i.e., reduce fare, offer free use, increase sanitizing, rebalance and optimize station distribution)	Long-term
	Take immediate action. During the pandemic with reduced traffic and increased active transportation need, it is the best time for testing and implementing different interventions.	Short-term
	Improve the engagement of community members and residents in planning and policymaking.	Long-term
Policymaking process	Educate residents about biking (i.e., providing free biking courses, interactive workshops)	Long-term
	Reduce/free the fare for cycling mapping & route planning apps	Short-term
	Educate and disseminate the benefits of active transportation, especially during the pandemic, through media channels.	Short-term
Education & dissemination		

categories: infrastructure, accessibility, policymaking process, and education & dissemination. Short-term recommendations are temporary planned measures and actions for promoting active transportation during the pandemic. Long-term recommendations aim to keep the quick increased active transportation users and improve the walkability and bikeability of cities. We acknowledge this is not a comprehensive list, which only covers the findings from reviewed studies and is meant to be used as a starting point to facilitate the discussion between different stakeholders.

However, the effectiveness of policy and built environmental interventions relies heavily on the physical and population contexts. Both the COVID-19 impacts and the availability/benefits of supportive environmental features are not equally distributed across populations and locations. For example, children and residents of high-density residential communities had lower access to green spaces (Shoari et al., 2020). While collective findings from the reviewed studies suggest the importance of being able to walk and bike safely during the pandemic, it is even more important for those who rely on transit for their daily travel needs, called "captive" transit riders, as transit services became less available and less safe. Planning efforts should consider tailored and targetting approaches to ensure that the programs (e.g., reduced/free transit fare, reduced speed limit, subsidized bike purchase/maintenance) and built environmental modifications (e.g., temporary/ permanent bike lanes and sidewalks, public spaces, traffic calming) are best suited for the local context. Further, more efforts are needed to measure

these planning interventions' health and transportation effects in both the short-term and the long-term (Capolongo et al., 2020).

5. Limitations and future work

We need to acknowledge this work has the following limitations. First, this study only reviewed the articles published from January 2020 to March 2021, which only covers the first wave of COVID-19 pandemic. Therefore, the findings obtained from this study only cover the short-term changes induced by COVID-19, which might be less efficient for researchers who want to explore long-term changes. Second, this study used a narrative review approach to review and discuss the potential health consequences of COVID-19 changes. Although it works properly within the scope and goal of our study, however the findings reported in this paper could be continually improved and updated by incorporating the results of more recent publications. Third, this study primarily documented three COVID-19 induced changes and assessed their potential health consequences on active transportation users through three pathways to health. In fact, COVID-19 has profoundly impacted many aspects of our lives, which might be associated with active transportation health outcomes through a variety of pathways. For example, Glazener et al. (2021) pointed out fourteen pathways linking transportation to various health outcomes.

Future work could improve this study from three perspectives: First, we will expand the time span of the reviewed works, aiming to cover both short-term and long-term changes induced by COVID-19. Second, once there are sufficient available publications, a systematic review is highly recommended to replace the narrative review for comprehensively collecting and documenting the health consequences of COVID-19 induced changes for active transportation. Last, we will attempt to expand the review scope, examining more COVID-19 induced changes and assessing their relationships with different health consequences (e.g., stress, mental health, social exclusion).

CRedit authorship contribution statement

Xiao Li: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Minaal Farrukh:** Investigation, Writing – original draft. **Chanam Lee:** Conceptualization, Writing – original draft, Writing – review & editing. **Haneen Khreis:** Conceptualization, Methodology. **Soham Sarda:** Investigation, Writing – original draft. **Soheil Sohrabi:** Investigation, Writing – original draft. **Zhe Zhang:** Methodology. **Bahar Dadashova:** Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition.

Declaration of competing interest

Authors declare no conflict of interest.

Acknowledgments

The work was supported by the Texas A&M Transportation Institute's Centre for Advancing Research in Transportation Emissions, Energy, and Health, a U.S. Department of Transportation's University Transportation Centre, College Station, TX [69A3551747128].

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