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Fourteen pathways between urban transportation and health: A conceptual model and literature review

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ABSTRACT

Introduction: Transportation is an integral part of our daily lives, giving us access to people, education, jobs, services, and goods. Our transportation choices and patterns are influenced by four interrelated factors: the land use and built environment, infrastructure, available modes, and emerging technologies/disruptors. These factors influence how we can or choose to move ourselves and goods. In turn, these factors impact various exposures, lifestyles and health outcomes.
Aim and methods: We developed a conceptual model to clarify the connections between transportation and health. We conducted a literature review focusing on publications from the past seven years. We complemented this with expert knowledge and synthesized information to summarize the health outcomes of transportation, along 14 identified pathways.
Results: The pathways linking transportation to health include those that are beneficial, such as when transportation serves as means for social connectivity, independence, physical activity, and access. Some pathways link transportation to detrimental health outcomes from air pollution, road travel injuries, noise, stress, urban heat islands, contamination, climate change, community severance, and restricted green space, blue space, and aesthetics. Other possible effects may come from electromagnetic fields, but this is not definitive. We define each pathway and summarize its health outcomes. We show that transportation-related exposures and associated health outcomes, and their severity, can be influenced by inequity and intrinsic and extrinsic effect modifiers.
Conclusions: While some pathways are widely discussed in the literature, others are new or under-researched. Our conceptual model can form the basis for future studies looking to explore the transportation-health nexus. We also propose the model as a tool to holistically assess the impact of transportation decisions on public health.

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1. Introduction

Transportation allows us to move around, partake in the activities that compose our daily routines, and access people, education, jobs, services, and goods (Litman, 2018). The choices that determine how transportation will facilitate the movement of people and goods is a reflection of transportation demand – the derived need for transportation based on the economies, societies, and technologies of a city or region (Litman, 2015). Transportation also promotes the growth of cities (Marshall, 2000), and catalyzes the transfer of knowledge and the exchange of cultures and ideas (Dvir and Pasher, 2004; Glaeser, 2000; Marshall, 2000). However, despite the convenience and connectivity transportation can provide, there are by-products of transportation systems that pose significant public health risks. For instance, road crashes are the eighth leading cause of death worldwide (World Health Organization, 2018a), transportation-related air pollution (TRAP) is conservatively estimated to result in nearly 200,000 premature deaths annually (Bhalla, 2014), and transportation noise produces a burden of disease similar to that of second-hand smoke (Hänninen et al., 2014). Other health risks occur as a result of stress, urban heat islands, contamination, restricted green space, blue space, and urban aesthetics, climate change, community severance, and the inequitable distribution of benefits and harms, which further contribute to existing health inequities. The subsequent sections of the introduction detail our attempt to holistically develop a conceptual model which links transportation and public health and outline the potential uses for such a model.

Abbreviations

AV	Autonomous Vehicle
BMI	Body Mass Index
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
DALY	Disability-adjusted life year(s)
dB	Decibel
EMF	Electromagnetic Field
EV	Electric Vehicle
FIA	Federation Internationale de l'Automobile
GHG	Greenhouse Gas
GT	Gigatons
ICEV	Internal Combustion Engine Vehicle
O_3	Ozone
PAH	Polycyclic Aromatic Hydrocarbon(s)
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter less than 2.5 μm in diameter
QOL	Quality of Life
TRAP	Traffic-Related Air Pollution
UHI	Urban Heat Island
UK	United Kingdom
VIA	Visual Impact Assessment
VMT	Vehicle Miles Traveled
WHO	World Health Organization
WPT	Wireless Power Transfer

1.1. Purpose of the conceptual model

The ideas we discuss in this paper build on existing work in a growing field focusing on how transportation is linked to public health and health inequalities. In this paper, we frame the discussion around the ability of the transportation system to enable the movement of people and goods. Transportation—and the systems, technologies, activities, land use and infrastructure behind it—impacts health in numerous ways, particularly in urban areas (Khreis et al., 2016). We limit our discussion to urban areas because estimations project the global urban population will account for nearly 68% of the worldwide population by 2050 (United Nations, 2018), exposing more people to the adverse health impacts associated with urban transportation. The dynamic and evolving nature of transportation, partly due to emerging technologies often referred to as disruptors, paired with growing public health concerns, requires thorough analysis to holistically frame the specific adverse health outcomes that result from transportation decisions, and consider strategies to mitigate those. Understanding and formulating the numerous ways by which transportation decisions affect public health will help in studying the transportation and health nexus in a holistic manner and support policy and decision-making that prioritize health in cities. Also, by providing a conceptual model, the authors aim to aid practitioners in their evaluation of transportation impacts on health, highlight research gaps, and make recommendations for both future research and practice.

The intersection of transportation and public health is a complex and multidisciplinary area. It requires drawing information from multiple fields to contextualize the relationship in an assessment framework. The first report to link a wide range of health outcomes to transportation was *Health on the Move*, a 1991 report from the United Kingdom (Hannah et al., 1991). This was updated in 2011, including an even broader range of pathways affecting health: access, physical activity, injury, pollution, stress, climate change, loss of land and planning blight, community severance, and danger. We include each of these pathways in this paper and integrate the impacts of "loss of land and planning blight" and "danger" into pathways we label "green space and aesthetics" and "social exclusion".

In 2015, Dannenberg and Sener examined the relationship between transportation and health, through five pathways, namely: safety (motor vehicle crashes), air quality, physical activity, equitable access, and noise (Dannenberg and Sener, 2015). Similarly, Lyons et al. (2014) developed a conceptual model based on four pathways: (physical) activity, safety, air quality, and access, to holistically integrate public health benefits within existing state transportation systems in the United States (Lyons et al., 2014). Widener and Hatzopoulou (2016) identified seven pathways: noise, air pollution, motor vehicle crashes, stress, physical activity, access, and interpersonal contact (Widener and Hatzopoulou, 2016), while van Wee and Ettema (2016) conceptualize the relationship between transportation and health through four pathways: physical activity, exposure to air pollution, casualties, and subjective well-being (van Wee and Ettema, 2016). Additionally, Götschi et al. (2017) developed a conceptual model identifying the behavioral considerations that determine the utility of active travel modes, citing health benefits as a key determinant in mode choice considerations, although references to specific health outcomes as a result of active travel is missing (Götschi et al., 2017). The recurrence of several pathways (motor vehicle crashes, access, air pollution, noise, stress, and physical activity) justified their inclusion in this paper.

More recently, Frank et al. (2019) developed a model linking built environment and transportation decisions to health through six pathways that fall under the two categories of behaviors and exposures. Behavior refers to encouraging or discouraging certain behaviors in ways that affect human health and this category includes the pathways of dietary intake, physical activity, and social interaction. Exposures refer to human exposures to harmful substances and stressors and this category includes the pathways of air pollution, traffic safety and crime, and noise (Frank et al., 2019). Frank et al. (2019) outlined that these pathways lead to biological responses including increased body mass index, systemic inflammation and stress, which in turn lead to chronic physical and mental diseases that increase healthcare utilization and cost. Nieuwenhuijsen (2020) published a conceptual model exploring transportation's role in creating "carbon-neutral, livable, and healthy" cities and suggested that urban design elements such as density, diversity, distance, and design, lead to specific mode choices such as using the car, cycling, and walking, which in turn have significant impacts on morbidity and mortality. The public health impacts occur through a number of possible pathways such as air pollution, noise, temperature, UV, stress, social contacts, and physical activity (Nieuwenhuijsen, 2020). He suggested that multidisciplinary and systemic approaches are needed to reduce the detrimental health effects of the different pathways (Nieuwenhuijsen, 2020).

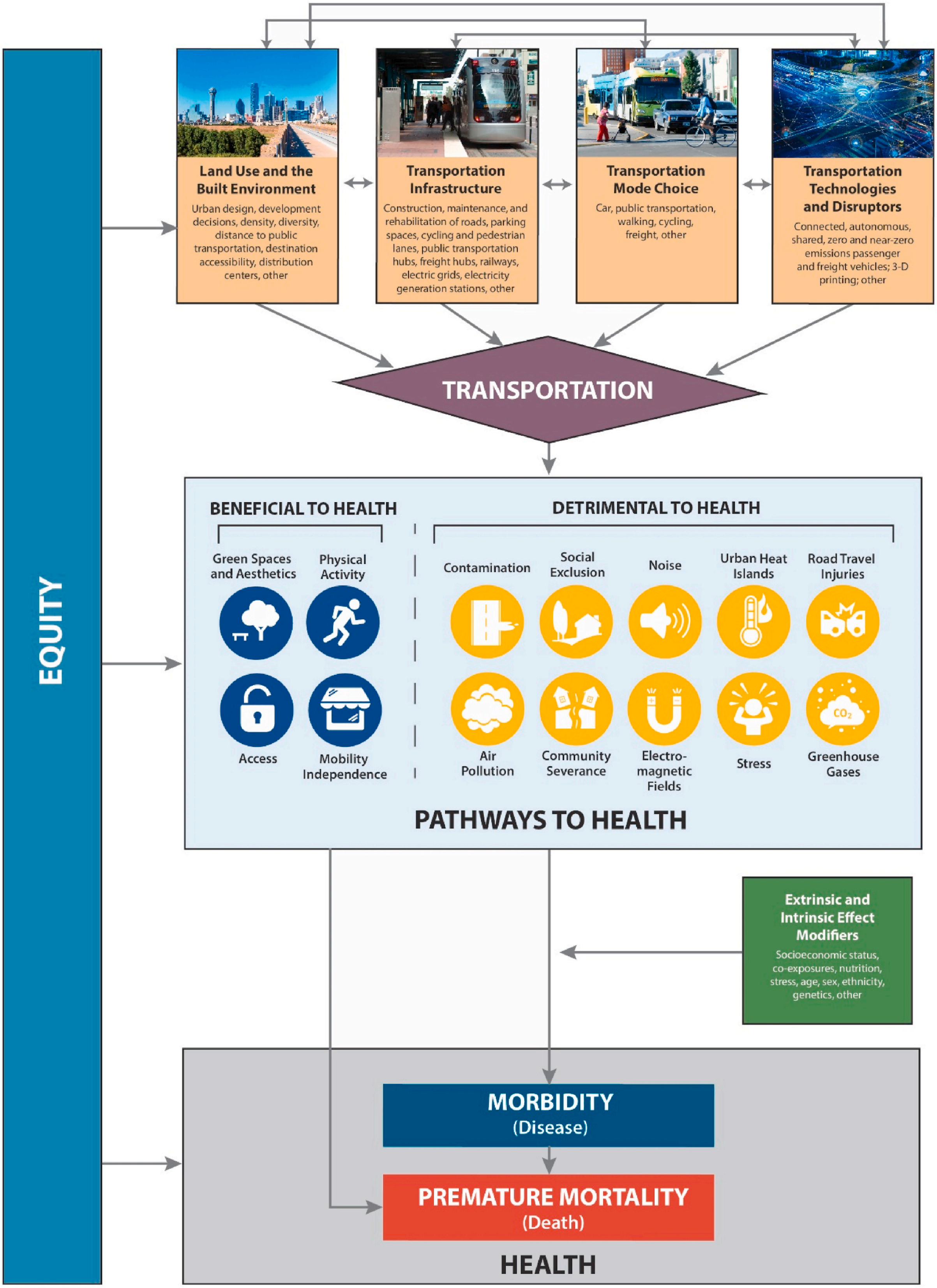
The work reported in this paper largely expands on the conceptual model developed by Khreis et al. (2017a), which is a development of a previous effort reported in Khreis et al. (2016). Khreis et al. (2017a) identified nine pathways linking transportation to public health. These were: motor vehicle crashes; air pollution; noise; heat islands; lack of green space and biodiversity loss; physical inactivity; social exclusion; community severance; and climate change (Khreis et al., 2017a). In this paper, we ultimately included 14 interlinked pathways that connect transportation to various public health outcomes: green space and aesthetics, physical activity, access, mobility independence, contamination, social exclusion, noise, heat, road travel injuries, air pollution, community severance, electromagnetic fields, stress, and greenhouse gases. In a non-systematic literature review, we also researched and listed the health outcomes related to each of these pathways as they occur in the literature.

While many of the pathways in this paper have been included in previous conceptual models, we add three pathways that have not been identified in previous works: contamination, electromagnetic fields, and mobility independence. We define and describe these linkages, and for each pathway, we list its associated health outcomes, which is another addition to the literature. We note the influence of intrinsic and extrinsic factors which can modify associated health outcomes, and the severity of these outcomes within a community. Issues of inequity also influence the relationship between transportation and health. We have added an equity component to our model to communicate the relevance of equity and its influence on urban transportation such as the unequal distribution of transportation infrastructure, transportation-related exposures, and associated health outcomes. Finally, we conclude by making recommendations for future research and practice. The conceptual model we present in this paper is an up-to-date and holistic model linking transportation to health, with a focus on urban transportation and urban areas.

1.2. Application of the conceptual model

The conceptual model is meant to detail how transportation factors influence health through numerous beneficial and detrimental interlinked pathways, which are recognized in the literature to different extents. By highlighting the complex intersectionality of transportation and health, and the wide range of pathways and health outcomes associated with transportation, this model is intended to:

o Guide future research to further explain and understand the health outcomes of transportation.
oEvaluate the impact of transportation on public health.
oGuide future practice and policy to consider and address these issues holistically.
oPromote awareness and increase the focus on pathways and health issues associated with transportation.
oPromote cross-disciplinary education, training, and workforce development across transportation and health.
oHighlight the importance of cross-disciplinary approaches to prepare researchers, practitioners, and policymakers to resolve transportation-related health issues.



(caption on next page)

Fig. 1. A conceptual model of the linkages between transportation and health.

oHighlight the necessity of systemic reforms to transportation and health rather than a "one exposure-one outcome-one intervention" approach, which often fails to account for the entirety of public health issues or introduces narrow focuses and negative consequences.
oFoster research in the area of cumulative risk assessment which seeks to elucidate the health impacts of complex exposures to chemical or physical hazards and non-chemical or social stressors.

2. Methods

Our methods for developing the transportation-public health conceptual model started with examining existing conceptual models that detailed transportation's impact on health, as referenced in section 1.1, to frame the concept of transportation and identify potential pathways between transportation and health for our own model. Pathways that were included from preexisting models include: road travel injuries, air pollution, noise, heat, green space, physical inactivity, stress, social exclusion, community severance, greenhouse gases, and access. Following this, we conducted a literature review, providing a "bottom-up" perspective on pathways as they occur in the literature, using pathways from existing models as keywords to expand on existing work. Lastly, we solicited input from experts, some of whom were included on this paper and some not, providing a "top-down" perspective on framing the issues, to assess the linkages between transportation and public health. Consultation with experts led us to include other pathways such as contamination and mobility independence. The electromagnetic fields pathway was included after reviewing literature related to emergent and disruptive transportation technologies. The literature review and expert consultation were conducted in parallel, with multiple iterations. Our approach ensured that the most relevant and recent sources contributed to a broad evaluation of these pathways and their impacts on health. The following describes our approach in more detail.

2.1. Framing key concepts of transportation and the relationship with public health

Four key factors, which are not mutually exclusive, affect transportation. The existing conceptual models that were reviewed often discuss transportation as a result of mode choice and urban design. We expand upon these conceptions by further distinguishing land use and the built environment from transportation infrastructure and mode choice, as well as including the impact of emergent and disruptive transportation technologies; an issue of increasing relevance with potentially large impacts on the future transportation landscape. These factors are shown in Fig. 1 and are described next:

1. Land Use and Built Environment: Patterns of land use and the built environment, including, but not limited to density, land use diversity and mix, distance to public transportation, and destination accessibility, affect the viability and desirability of different transportation modal options. Land use policies that encourage density and accessibility can contribute to the production of certain transportation infrastructures when coupled with investment (McFadden et al., 2014). Land use and the built environment can incentivize the development and adaptation of emergent and disruptive technologies. For example, car-oriented cities with low-density and urban sprawl may have more interest in technologies meant to improve automobile travel such as connected and autonomous vehicles (Bansal et al., 2016) or ride-hailing services (Clewlow and Mishra, 2017). In urban areas where alternative modes of transportation are supported by land use and the built environment, for example, heterogenous land use mix and dense and compact development, electric bikes or scooters and bike and scooter sharing may be sought after.
2. Transportation Infrastructure: This category accounts for the design, construction, and maintenance of various transportation infrastructure including roads, parking spaces, cycling lanes and parking, pedestrian sidewalks, public transportation and freight hubs, railways, and electric grids amongst others. The presence and quality of transportation infrastructure impact modal choice and the viability of modal options. Further, in the long term, it can alter land use and built environment characteristics such as increasing urban sprawl. Transportation infrastructure decisions can also make emergent and disruptive transportation technologies more or less desirable and viable.
3. Transportation Mode Choice: Transportation mode refers to the way humans and goods move around, including by walking, cycling, using public transportation, private vehicles and taxis (both cars and powered two-wheelers), freight vehicles, or a combination thereof. New transportation modes include scooters and electric scooters. Transportation mode also includes the choice of vehicle type and 'last mile' connections to and from public transport. While motor vehicles are the prominent mode of transportation in many high-income regions, mode choice is determined by the safety, convenience, availability, affordability, feasibility, and accessibility of modal options (for example, distance and travel time) (Simons et al., 2013), as well as perceptions and attitudes towards different modes (Handy et al., 2005). Transportation mode choice further impacts the adaptation of and investment in transportation technologies and infrastructure. In the long term, transportation mode choice can result in altered land use and built environment, for example, urban sprawl.
4. Transportation Technologies and Disruptors: This category includes emergent and disruptive transportation technologies such as autonomous, connected, electric, and shared vehicles. These technologies, in addition to innovations in other fields, such as 3D printing and drones, are influencing transportation and the factors that affect it. These technologies can encourage or discourage the use of a certain transportation mode; increase or decrease the necessity for specific types of transportation infrastructure; create

the need for a new kind of transportation infrastructure; and in the long term, dictate land use and built environment characteristics.

Public health broadly pertains to the protection and improvement of people's health and the communities they live in (Centers for Disease Control and Prevention, 2020a). The relationships between the social, cultural, and physical environments an individual lives in and that individual's characteristics and choices influence health outcomes (World Health Organization, 2017). Each of the transportation factors detailed previously is influenced by the environments people live in and their preferences. Transportation has, therefore, become an inherent factor in shaping health outcomes.

2.2. Literature review

The foundation of this paper is a literature review covering 294 published articles and papers related to transportation and public health as identified from the Transportation Research Board (TRID) and Google Scholar databases. These articles were screened and shortlisted from searches using the following keywords: "transportation", "transport", "mobility", "public health", and "active transportation" in conjunction with "motor vehicle crashes", "road travel injury", "air pollution", "noise", "green space", "aesthetics", "physical activity", "community severance", "social exclusion", "electromagnetic field", "greenhouse gases", "urban heat island", "accessibility", "contamination", "independence", and/or "stress" and subsequent references found within those papers; essentially we used our conceptual model to guide our literature review of each pathway. The findings from the reviewed literature, and references within those papers, included health outcomes that allowed us to populate a table containing the known health outcomes associated with each pathway. We do not report the results systematically but focus on systematic reviews, meta-analyses, and articles published between January 1, 2013 and October 19, 2020 to provide up-to-date information and add value to previously published conceptual models. Thirty-nine papers, articles, and reports from 2018, sixteen from 2019, and eighteen from 2020 were included in this paper. We use older articles if they represent seminal or unique research; are necessary to understand recent findings; or if there is a lack of recent research.

2.3. Expert knowledge and assessment

Discussion and consultation with experts in the fields of public health, urban planning, and transportation further informed our findings and validated the nature of the linkages between transportation and public health. These interviews were informal as those consulted are colleagues of the authors. Interviews were not conducted in a systematic manner but occurred as needed when the authors sought additional input about a specific pathway or the overall conceptual model. Experts were later invited to co-author this paper based on their availability and the utility of their input and previous contributions to the field. Five experts who reviewed this model were finally not included on this paper. We also referred to existing conceptual models that defined transportation and public health linkages to inform our conceptual model and pathways. Discussions and multiple iterations amongst the authors' team informed the final conceptual model.

3. Results

Fig. 1 represents the conceptual model we propose to define the relationship between transportation and public health. Land use and the built environment, transportation infrastructure, transportation mode choice, and emergent and disruptive technologies all influence transportation systems and patterns in an urban area. As such, the purple diamond labeled "transportation" is an umbrella term which encompasses the four interrelated factors displayed in the four boxes above it. The distinct framing of "transportation"" is not to suggest that it is a separate entity from those four factors, but rather to communicate that "transportation" is the cumulative result of interactions between these four factors.

Our conceptual model identifies 14 pathways that link transportation to health outcomes of morbidity and premature mortality. The pathways beneficial to health are colored blue on the left side of the dotted line while those detrimental to health are colored yellow on the right side. The model acknowledges the impact of inequity and intrinsic and extrinsic characteristics that influence the exposure to, and/or modifies the severity of transportation-related health outcomes within a community. Table S1 in the supplemental material is a consolidated list of all the health outcomes associated with each pathway that were identified in the non-systematic literature review. Section 3 of the paper defines and discusses each of the pathways independently and lists their associated health outcomes as they are acknowledged in the literature.

3.1. Pathways to health

3.1.1. Green and blue spaces and aesthetics

Green space is land that is partially or completely covered with grass, trees, shrubs, or other vegetation accessible to the public (Environmental Protection Agency, 2017a), and blue space refers to space covered by water, including ponds, streams, rivers, lakes, seas, and oceans (Gascon et al., 2015). Aesthetics refers to the visual integration of transportation facilities into the surrounding landscape (Texas Department of Transportation, 2009). Green and blue space views can be blocked by urban transportation facilities, infrastructure, and construction which can degrade the aesthetics of an area (Texas Department of Transportation, 2009).

Green spaces mitigate the adverse effects of harmful, transportation-related environmental exposures like urban heat islands

(UHIs), air pollution, and noise (de Vries et al., 2013; Hartig et al., 2014). As some cities begin to encourage non-motorized travel, some transportation infrastructures such as highways and parking lots may no longer be necessary and there may be an opportunity to increase green space, such is the case of Hamburg, Germany, where car-free policies are being gradually implemented (Nieuwenhuijsen and Khreis, 2016). The more typical occurrence, however, is that urban growth, which includes the expansion of transportation infrastructure, results in the loss of green space (World Health Organization, 2016).

Additionally, green space and aesthetics may contribute to physical activity through active commuting, (Wahlgren and Schantz, 2014), although it is important to acknowledge that some evidence suggests that the presence of green space alone might not significantly affect physical activity (Hogendorf et al., 2019). Safety and the quality of green space are the most influential factors in determining activity levels (de Vries et al., 2013; Hartig et al., 2014). One systematic review of literature relating nature and health found inconsistent associations between childhood active transportation and green spaces, often due to parental perceptions of safety and park accessibility (Ding et al., 2011). Inconsistent relationships between active transportation and green spaces were shown for older individuals as well (Hartig et al., 2014). Notably, pleasant aesthetics contribute to feelings of safety and comfort (Lovasi et al., 2009).

Views of natural aesthetics have long been associated with improved health, beginning with the seminal report that documented the difference in hospital patients' recovery due to the view of natural aesthetics or brick walls outside their hospital windows (Ulrich, 1984). The United States Federal Highway Administration has produced guidelines for visual impact assessments (VIAs) that measure the impact of highway construction on aesthetics (Federal Highway Administration, 2015). By utilizing a VIA, the adverse visual effects of highway construction, which may include a reduction in green space or increased community severance, are expected to be mitigated or otherwise minimized to avoid negative health outcomes caused by transportation-related construction.

Studies have associated green space with many health benefits including decreased risk of all-cause mortality (Rojas-Rueda et al., 2019), stroke and other cardiovascular diseases, respiratory diseases, premature mortality (Gascon et al., 2016), stress, anxiety (Gascon et al., 2015; Zijlema et al., 2018), type-2 diabetes, and high blood pressure (Twohig-Bennett and Jones, 2018). Green space has also been associated with improved mental health (Zijlema et al., 2018), physical activity (Gascon et al., 2016), improved cognitive function, (Kondo et al., 2018), immune function (Egorov et al., 2017), sleep patterns (Astell-Burt et al., 2013), pregnancy outcomes, and self-reported health (Twohig-Bennett and Jones, 2018). Associations between blue space access, physical activity, and mental health have also been determined to be positive (Gascon et al., 2017; Völker et al., 2018; Völker and Kistemann, 2015). However, urban sprawl is reducing the per capita share of green space in many cities (Fuller and Gaston, 2009). Overall, investment in green spaces is lagging as for example the 100 largest cities in the United States spent a combined $7 billion in 2019 (The Trust for Public Land, 2019) to maintain and enhance park land, a small fraction of the $44.7 billion budget of the United States Federal Highway Administration in the same year (Federal Highway Administration, 2019).

3.1.2. Physical activity

Physical activity refers to body movement requiring energy expenditure. In contrast, physical inactivity refers to a lack of body movement and is considered a public health crisis due to its role in the obesity epidemic and contribution to numerous other diseases (Khreis et al., 2016). Land use policies that promote high-density, connectivity, and active transportation infrastructure can boost physical activity (Panter et al., 2016; Rafiemanzelat et al., 2017). For example, the 'complete street' is a design concept that aims to integrate active transportation in urban spaces that were previously incompatible (Litman, 2015). Modal diversity for transportation can increase physical activity due to the incorporation of active transportation in the daily commute (Costa et al., 2015; Frederick et al., 2018). In a review of 148 United States cities, Frederick et al. (2018) found that modal diversity is inversely associated with obesity and physical inactivity. Populations living in counties with high transportation modal diversity expressed lower obesity rates (25.2% vs 30.8% in automobile-dependent counties), a smaller share of physically inactive residents (19.4% vs 25.9% in automobile-dependent counties), and 1400 fewer years of life lost per 100,000 inhabitants compared to populations in automobile-dependent counties (Frederick et al., 2018). While driving increases the likelihood of a sedentary lifestyle and more disease (Frederick et al., 2018), active transportation contributes to a more physically active lifestyle and lower body mass index (BMI) (Flint and Cummins, 2016; Martin et al., 2015), with minor risks posed by air pollution exposure or motor vehicle crashes (Mueller et al., 2015). Investing in quality active travel infrastructure has been estimated to significantly improve active travel rates. A health impact assessment study of 167 European cities suggested the modal share of cycling could rise precipitously – as high as 25% of all trips – if cycling networks were expanded (Mueller et al., 2018). Furthermore, electric bikes, or "e-bikes" have been found to promote active travel and increase cardiovascular health benefits (Hoj et al., 2018). Trips that are shifted from conventional bicycles to electric bikes typically require less physical activity, however (Bourne et al., 2018). Still, individuals who shift to electric bikes tend to ride further distances than those who use conventional bicycles (Sundfør et al., 2020). This form of emerging technology is beneficial for decreasing transportation time, increasing convenience (and potentially ridership), and limiting physical fatigue compared to traditional bikes (Hoj et al., 2018).

Support for AVs has increased when discussing car-sharing efficiency (Fagnant and Kockelman, 2015) as the ability to perform tasks other than driving while in an AV reduces the cost of using motor vehicles and incentivizes vehicle usage. The potential safety issues presented by AVs, specifically for active transportation users (Sandt and Owens, 2017), are discussed further in section 3.9 (road travel injuries), but a major concern is that AVs may discourage physical activity as AV sensing technology is still being developed and all road users will need to adjust to the operation of AVs in shared street spaces.

Additional barriers to physical activity include violence (fear of assault, for example), high-density traffic, poor air quality, and a lack of parks, sidewalks, and recreational facilities (World Health Organization, 2018b). Physical inactivity has been associated with various mental health problems including dementia and Alzheimer's disease (Hamer and Chida, 2009), cardiovascular disease including ischemic heart disease and stroke (Kyu et al., 2016), premature mortality, obesity (Mueller et al., 2015), cancer, diabetes (Kyu et al., 2016), stress (Cohen et al., 2014), and hypertension (Diaz and Shimbo, 2013). Physical inactivity is a leading contributor to global mortality resulting in 3.2 million global deaths annually (World Health Organization, 2018b). Health experts recommend 150 min of moderate exercise per week (or 75 min of vigorous activity weekly), a recommendation that was not met by 28% of adults worldwide in 2016, with higher levels of non-compliance displayed in higher-income countries (World Health Organization, 2018c). On the other hand, physical activity can sustain cognitive capabilities, and improve mental well-being by lowering the risk of depression and anxiety (Anderson and Shivakumar, 2013; Smith et al., 2017).

3.1.3. Access

In this context, access is defined as the ability for individuals to reach jobs, education, goods and services including health facilities and services, public transportation, healthy food, green and/or blue space, social networks (including family), and leisure facilities (Litman, 2018). The ability to access these is a key factor for mitigating social exclusion (Allen, 2008). Several strategies to increase accessibility include built environment and land use interventions, such as complete streets (Litman, 2015), densification, and transit-oriented development (Renne et al., 2016). These strategies may decrease the distance to public transportation and increase active transportation rates, thus reducing morbidity and mortality (Nieuwenhuijsen, 2018). On the other hand, accessibility poverty refers to increased transit time and costs that limit access and may lead to the exacerbation of issues like social exclusion and community severance (Lucas et al., 2016), which in turn lead to adverse health outcomes of their own, including adverse mental health outcomes (Cohen et al., 2014).

In Britain, people with disabilities took 30% fewer trips (one-way course of travel with a single main purpose) than people without disabilities in 2014 (UK Department of Transportation, 2014). Over 80% of people with disabilities noted the most common issue with using buses was getting to the bus stop (UK Department of Transportation, 2014). Further, about 18% and 12% of disabled commuters commented that the most difficult destinations to reach when traveling were the hospital and the doctor, respectively (UK Department of Transportation, 2014). Additionally, 77% of job seekers in Britain do not have regular access to a motor vehicle (Johnson et al., 2014), and 34% of British households indicated poor accessibility to bus and rail services (Heinen and Chatterjee, 2015). Moreover, the cost of public transportation is cited as a barrier for 25% of people age 18 to 24 and 21% of people over age 50 (Johnson et al., 2014). For people aged 65+, participating in activities outside the home can result in higher levels of well-being (Ravulaparthy et al., 2013), so it is beneficial to them when they have the ability to travel to these activities.

The association between travel time and travel distance to healthcare services and patients' health outcomes was investigated in a systematic review of 108 studies (Kelly et al., 2016). The authors concluded that there is an association between living further away from health care and worse health outcomes including survival rates, length of stay in the hospital, and not attending a follow-up appointment (Kelly et al., 2016). Similar transportation barriers were found to impede access to pharmacies for medicine (Syed et al., 2013).

Another concern in this context is related to access to healthy food. "Food deserts" are defined as neighborhoods with low spatial and economic access to healthy and affordable food options (United States Department of Agriculture, 2014). Two studies measured accessibility to healthy food by public transit in Cincinnati, United States (Farber et al., 2014; Widener et al., 2015). They found that accessibility to healthy food could be unpredictable for people dependent on public transportation due to the variability of public transportation services. This leaves individuals who do not live within walking or cycling distance of a grocery store nor have access to a private vehicle vulnerable to inadequate nutrition. Food deserts have been linked to adverse health outcomes including obesity (Ghosh-Dastidar et al., 2014). Furthermore, consumption of fruits and vegetables decreases the risk of several types of cancer (Higdon et al., 2007), cardiovascular disease (Bazzano et al., 2002), and protects against adverse health effects of air pollution (Barthelemy et al., 2020), but access to these foods are limited in food deserts. However, several studies suggest that relationships between food deserts and health outcomes are inconsistent (An and Sturm, 2012; Dubowitz et al., 2015; Holsten, 2009; Lee, 2012), and therefore, more research in this area is warranted.

3.1.4. Mobility independence

Mobility independence is the ability to utilize various transportation modes to access commodities, neighborhood facilities, and participate in meaningful social, cultural, and physical activities without assistance or supervision (Rantanen, 2013). Quality of life (QOL) is impacted by six factors, one of which is the level of independence (World Health Organization, 1997). Therefore, poor mobility independence may influence poor QOL.

The elderly and children are population groups that may be dependent on capable individuals for transportation assistance due to declining/developing motor skills and awareness. A systematic review of qualitative studies in the United Kingdom highlighted the importance of mobility independence for older populations aged over 60 years in rural areas (Graham et al., 2018). Graham et al. (2018) highlighted that the ability to travel independently enabled elderly people to be self-reliant and socially connected. Furthermore, mobility independence promotes healthy aging through physical activity and engagement in community activities which sustain cognitive ability (Rantanen, 2013). Mobility independence may also positively influence mental well-being and self-esteem (Mindell and Karlsen, 2012). To maintain adequate levels of mobility independence for the elderly, accessible, safe, reliable, and affordable alternative and independent modes of transportation need to be provided in place of driving, if and when those populations need to rely on other modes (Shrestha et al., 2017). Children's rates of independent active transportation were reported to be higher in areas where parents perceived more land use diversity, higher residential density, shorter distances to school, road safety, and available walking/cycling infrastructure (De Meester et al., 2014). The built environment, transportation infrastructure, and mode choice all influence mobility independence (Marzi et al., 2018).

3.1.5. Contamination

Oils, gasoline, heavy metals, particulate matter (Asian Development Bank, 2015), lead, and polycyclic aromatic hydrocarbons (PAHs) are chemicals and pollutants that can be found on roadway surfaces due to motor vehicle traffic (Burant et al., 2018; Gaffield et al., 2003; Khan and Strand, 2018; Schwarz et al., 2016). They result from road surface, brake, and tire wear (Adamiec et al., 2016). These chemicals and pollutants can contaminate water sources, soils, and air, which pose significant threats to humans and the environment (Adamiec et al., 2016). These contaminating substances can cause liver failure, renal dysfunction and kidney failure (Mohod and Dhote, 2013), arthritis, abdominal pain, depression, fatigue, headache, memory loss, hypertension, low blood pressure, nausea, premature birth, low birth weight, rashes, sleeplessness, and ulcers (Centers for Disease Control and Prevention, 2018; Jaishankar et al., 2014).

In urban areas, roads and parking lots which do not allow rainfall absorption are sprawling and increase the volume and velocity of polluted runoff (Environmental Protection Agency, 2017b). Pollution from runoff threatens water quality and may cause illness due to water and food source contamination (Kibblewhite, 2018). For example, high concentrations of PAHs (carcinogens produced by incomplete combustion in motor vehicle engines) have been found in agricultural fields near highways where road traffic is heavy (Kibblewhite, 2018). Motor vehicle traffic can increase lead concentrations in soils that are hundreds of meters from the roadway; however, this is dependent on the history and frequency of motor vehicle traffic in the area (Pouyat et al., 2008; Schwarz et al., 2016). In China, for example, traffic emissions were one of the main sources of lead pollution in soil between 1990 and 2017 (Zhang et al., 2019). Humans may be exposed to the contaminated soil by inhalation, ingestion, skin contact, and lead-enriched crop ingestion which poses a risk to human health and food security (Zhang et al., 2019). Minimizing vehicle trips, and the associated infrastructure, by supporting alternative modes of transportation could reduce the overall presence of these harmful substances. Similarly, the provision of green spaces and the development of biodegradable and environmentally conservative vehicle and road surface materials could mitigate the effects of roadway contamination (Asphalt Pavement Association of Oregon, 2013; Federal Highway Administration, 2016). Leaded fuels are no longer permitted in many countries, but the phasing out of leaded fuels played out over different periods and the risk of exposure may still be present where leaded fuels were permitted more recently. In fact, lead is non-biodegradable and does not decay, therefore presenting a long-term health risk despite widespread bans of leaded fuels in the 1990s (Xintaras, 1992). As of 2017, Algeria was the only country still allowing the use of leaded fuel for motor vehicles (Johnston, 2017).

3.1.6. Social exclusion

In this context, social exclusion refers to the culmination of transportation-related inhibitions and/or deprivations – affordability, accessibility, availability, appropriateness, geographical location, time, and fear – that limit the opportunity to participate in community activities and be socially engaged. Social exclusion is a consequence of accessibility inadequacies and contributes to social isolation and loneliness, that are each associated with negative health outcomes (Julien et al., 2015); a systematic review found these result in a 29% and 26% increased likelihood in mortality, respectively, almost as high as the 32% increased mortality in adults who live alone (Holt-Lunstad et al., 2015). Transportation-related social exclusion affects certain groups more than others. Most notably, these include low-income groups, the disabled, elderly, adolescents, women, and minorities (Mackett and Thoreau, 2015).

One deterrent to public transportation use and a contributing factor to social exclusion is fear of crime. Crime poses a threat to the physical safety of passengers and leads to decreased ridership impacting access to jobs, education, health services, and leisure activities, especially for low-income individuals (Pablo Madriaza et al., 2016). The Federation Internationale de l'Automobile (FIA) report on women's safety using public transportation noted that perceived fear of crime on public transit has been a barrier for some women in their job participation (Allen and Vanderschuren, 2016). Furthermore, crime on marshrutkas (public minibuses) has negatively affected women's transportation experiences in Bishkek, the capital of Kyrgyzstan; which leads to greater mobility restriction and risk for social exclusion (Turdalieva and Edling, 2018). Fear of sexual harassment is an additional limitation on women's utility of public transportation (Asian Development Bank, 2015). Fear pervades women's participation in active transportation, as fear of crime and harassment while walking is a strong deterrent in cities around the world (Crabtree and Nsubuga, 2012). Still, people who are prevented from accessing public transportation or participating in active transportation due to fear of crime suffer the consequences of social exclusion.

A study found that elderly Japanese individuals, especially women, were at higher risk (9–34%) of premature mortality when socially excluded (Saito et al., 2012). Negative health outcomes resulting from these inhibitions and/or deprivations include poor mental health, cardiovascular disease (Leigh-Hunt et al., 2017), and stress (Cohen et al., 2014), each of which diminishes QOL, life chances, and choices (Church et al., 2000; Kenyon et al., 2002).

3.1.7. Noise

In this context, noise is defined as motorized vehicle sounds at levels that are detrimental to health. The World Health Organization (WHO) recently updated their noise level guidelines through a series of systematic reviews which recommend noise levels from road traffic stay below 53 dB (dBs) in the European region (World Health Organization, 2018d). The United States Federal Highway Administration in the United States has standards for traffic noise that range from 67 to 72 dB, depending on surrounding land uses (Federal Highway Administration, 2010). Noise level is dependent on transportation-related factors like road networks, junctions, traffic flow and speed, acoustics, and meteorological conditions. Like motor vehicle crashes, noise pollution is more pervasive and extreme in developing countries (Schmidt, 2005).

Noise level is often a product of the prominent transportation mode in an area, but transportation mode choice is usually influenced by the built environment and existing transportation infrastructure (Hong et al., 2014; Zhao, 2014). Encouraging mixed-use, dense, and connected developments are all factors that can lead to increased active transportation, which could reduce noise pollution from transportation (Nieuwenhuijsen, 2016; U.S. Department of Transportation, 2015). It is worth noting the possibility that increasing population density is accompanied by the risk of exposing more individuals to noise and air pollution and possibly other environmental stressors, if no mitigation policies are put in place (Marshall et al., 2005; Vardoulakis et al., 2003; Yuan et al., 2019). Other feasible traffic noise reduction strategies include physical barriers (Federal Highway Administration, 2017), low-noise tires and road surfaces (European Commission, 2017), and vegetation near roadways (Jang et al., 2015; Peng et al., 2014).

Another option to reduce road traffic noise is the deployment of electric vehicles (Maffei and Masullo, 2014). When comparing an EV to an internal combustion engine vehicle (ICEV), there is less overall noise due to the absence of engine noise. However, as speed increases, the noise levels of the two vehicle types become increasingly similar due to tire-on-road sounds. A 15 dB difference between EVs and ICEVs was measured while idling, but no noise level difference was measured at speeds over 50 km/h (Maffei and Masullo, 2014). While EVs may not be the cure for busy highway traffic noise, the implementation of EVs may potentially provide relief for busy residential roads in neighborhoods with lower traffic speeds. Still, redesigning roads and urban cores to promote alternative modes of transportation may be a more sustainable approach to reduce noise and bring along various other health benefits through, for example, the increase in physical activity. There are also concerns about the safety of blind or visually impaired pedestrians with EV deployment (Parizet et al., 2014). Further, EVs still require extensive road infrastructure, limiting land for green spaces while increasing heat (Maria et al., 2013); play a role in motor vehicle crashes; contribute to air pollution (Soret et al., 2014; Timmers and Achten, 2016); and do not address the many adverse health effects of physical inactivity.

Noise contributes to health issues such as mortality from cardiovascular diseases (including stroke, heart attack, and ischemic heart disease) (Héritier et al., 2017, 2018; Van Kempen et al., 2018), diabetes, hypertension, obesity (Van Kempen et al., 2018), sleep disturbance (Basner and McGuire, 2018), annoyance (Guski et al., 2017), cognitive impairment (Clark and Paunovic, 2018a), reproductive complications (including low birth weight and preterm birth) (Nieuwenhuijsen et al., 2017; Ristovska et al., 2014), stress (Basner et al., 2014), and mental health problems (Clark and Paunovic, 2018b). Furthermore, transportation noise level and annoyance have been found to exacerbate asthma symptoms in adults, indicating that the respiratory system may be affected by noise (Eze et al., 2018). The burden of disease attributable to noise is comparable to that from second-hand smoke (Hänninen et al., 2014). Traffic noise in Barcelona, for example, is responsible for 18,000 disability-adjusted life years (DALYs), the largest of all transportation-related burden of diseases (Mueller et al., 2017a). In Western Europe, over 1 million DALYs are lost annually due to road traffic noise (World Health Organization, 2011). In Houston, Texas, an estimated 302 premature deaths (adults 30–75 years) were attributable to transportation-related (road and aviation) noise, compared with 330 premature fatalities from motor vehicle crashes (Sohrabi and Khreis, 2020).

3.1.8. *Heat*

Urban heat islands (UHIs) are urban spaces with greater surface and air temperatures compared with surrounding areas (Coseo and Larsen, 2014). UHIs are becoming more common in cities as the built environment and transportation infrastructure, composed of heat-absorbing concretes and asphalts, continue to expand and replace trees, vegetation, open and green spaces (Khreis et al., 2017a; Nieuwenhuijsen, 2016) which can cool temperatures (Doick et al., 2014; Petralli et al., 2014). Differences between urban and rural temperatures are observed around the world: 8 °C in Barcelona, Spain (Mueller et al., 2017b), 6 °C in Adelaide, Australia (Soltani and Sharifi, 2017), and 4 °C in Las Vegas, United States (Kenward et al., 2014). An observational study of temperature-related mortality in 13 countries concluded that moderate deviations from the average ambient temperature can explain the majority of temperature-related mortality (Gasparrini et al., 2015). The impact of moderate and extreme heat on temperature-related mortality was most pronounced in Thailand where the share of temperature-related mortality attributable to warmer temperatures was 22.6%, 14.8% in Italy, 16.2% in Spain, 18.1% in Taiwan, and 19.8% in Brazil (Gasparrini et al., 2015).

There have been numerous occasions in which heat waves have proved fatal. Two examples are the 2003 Paris heat wave which resulted in 15,000 premature deaths (Fouillet et al., 2006), and the 2006 California heat wave which resulted in 600 premature deaths and caused 16,000 emergency room visits (Knowlton et al., 2009; Ostro et al., 2009). The frequency of heatwaves will increase throughout the 21st century (Lemonsu et al., 2014); for every 1 °C increase in heat wave intensity, there is a 4.5% increase in mortality risk (Anderson and Bell, 2011). Cities like New York, Los Angeles, and Tokyo have recently employed urban cooling programs while several European cities have mapped UHI-prone areas to identify at-risk populations in extreme heat events and provide access to "cool" places during heat waves (Shickman, 2017).

Research gaps exist in explaining the extent of transportation's impact on UHIs. However, some existing research provides useful insight into transportation factors that can influence UHI intensity. A handful of built environment characteristics, such as impervious surfaces, building height, road orientation, and green spaces, can modify the effects of UHIs (Coseo and Larsen, 2014). Coseo and Larsen (2014) measured the difference in the daytime and nighttime UHI temperatures in neighborhoods in Chicago, United States. They found that the percentage of impervious surface and tree canopy in an urban block explains 68% of the variance in air temperature at night and up to 91% of the variance in air temperature at night during an extreme heat event.

A reduction in VMT, vehicles on the road, and heat-absorbing concretes and asphalts, accompanied by green space provision, may contribute to decreased UHI occurrence. Additionally, car-sharing reduces the number of private vehicles on the road and the heat-absorbing materials required for parking (Paradatheth, 2015), while EVs emit 20% of the heat that ICEVs produce (Li et al., 2015).

Increasing ambient temperatures have been associated with higher rates of mortality (Gasparrini et al., 2015), hospital admissions (Hondula and Barnett, 2014), cardiovascular disease (including arrhythmia and stroke), diabetes, hypertension, respiratory disease (including chronic obstructive pulmonary disease (COPD) and asthma (Bunker et al., 2016), motor vehicle crashes (Basagaña et al., 2015), heat stress (Lemonsu et al., 2015), and premature birth (Schifano et al., 2016).

3.1.9. Road travel injuries

Most road travel injuries are caused by a collision involving a motor vehicle and are referred to as motor vehicle crashes which may result in death, injury, or disability. People most affected by motor vehicle crashes are vulnerable road users like pedestrians, cyclists, and motorcyclists who account for over 50% of all traffic deaths worldwide (World Health Organization, 2018a). The total number of motor vehicle crash fatalities in the United States has declined the last two years after reaching a decade-high of 34,748 in 2016. While over 70% of fatalities were vehicle occupants, pedestrians and cyclists accounted for 20% of motor vehicle crash fatalities (National Highway Traffic Safety Agency, 2017). Motor vehicle crashes in low- and middle-income countries account for 93% of global roadway fatalities, despite accounting for only half of the world's registered vehicles (World Health Organization, 2018a).

It is also important to note that pedestrians and cyclists may experience premature mortality or injury from falls where no motor vehicle was involved. In fact, four to nine times as many pedestrians are injured from a fall while walking for travel as from collision with a vehicle (Methorst et al., 2017). Mindell et al. (2012) investigated road safety by travel mode: there were more male cyclist deaths from falls than there were from traffic crashes in older groups aged 50 to 59 and 70+ in England (Mindell et al., 2012). Further, for injuries resulting in hospital admission, the risk from falls was very similar for cycling and walking (Mindell et al., 2012).

Land use and the built environment, transportation infrastructure, mode choice, and vehicle technology all influence road travel injuries. Most notably, the more sprawled the development, the greater the dependence is on personal automobiles (Litman, 2013). This inherently increases the risk of road travel injuries as more cars occupy the road. While the rate of crashes for vulnerable road users is high, there is evidence to support that increased volume of active transportation users can improve safety. This is not easily done, however, as the existing road infrastructure in many major cities is built to accommodate motor vehicles first, rendering pedestrian and cycling infrastructure insufficient to support increased active transportation (Nieuwenhuijsen et al., 2016). In car-dominated societies, developing active transportation infrastructure may encourage individuals to shift from motorized to active transportation and improve active transportation safety due to what is known as the "safety in numbers" effect (Elvik and Bjørnskau, 2017). This documents that a greater number of active transportation users is strongly associated with fewer road travel crashes. However, the extent to which this is causal or due to confounding factors that increase the safety of pedestrians and cyclists is unclear (Mindell, 2019). As such, motivating individuals to partake in active modes of transportation may not only improve their individual health (see physical activity pathway) but may also increase the safety of their peers who choose active transportation.

The risk exposure induced by motor vehicle use could be reduced in part by the continued innovation of connected and AVs since 90% of roadway crashes are due to human driver failure (Kockelman et al., 2016). In 2018, over 2800 people were killed and 400,000 were injured by distracted drivers in the United States (National Highway Traffic Safety Agency, 2020). In Europe, 10–30% of all motor vehicle crashes were due to distracted road users (European Commission et al., 2015). The integration of AVs is, however, not an overall positive, as AVs and human drivers must learn to share the road (Bhavsar et al., 2017). Google's AVs have been in several crashes, each occurring because human drivers were unprepared for the AV to stop for pedestrians and road obstructions or adhere to certain roadway rules (Millard-Ball, 2018). Tesla's AVs have also been involved in fatal crashes due to driver overconfidence in the vehicles' autopilot capabilities (The Guardian, 2018). Even though AVs are expected to reduce road dangers that result from human error, there are concerns about AV sensing technologies that fail to identify active transportation users (Sandt and Owens, 2017). Spaces where AVs and non-vehicle users share the road present the risk that an AV may prioritize the safety of its passengers above all else, endangering other road users and potentially discouraging physical activity through active transportation. This presents an ethical dilemma for AV developers known as the "trolley problem" (Bonnefon et al., 2016). While the trolley problem is not specific to AVs, how developers address the trolley problem has potential health ramifications for active transportation users like reduced physical activity or increased motor vehicle crashes.

Road travel crashes are ranked as the eighth leading cause of death in the world and the leading cause of death amongst people aged 5–29 (World Health Organization, 2018a). Annually, road travel crashes are responsible for 1.35 million deaths and up to 50 million injuries globally (World Health Organization, 2018a). Europe has the lowest fatality rate, at 49 fatalities per 1 million inhabitants, half the United States' fatality rate and less than a third of the global mean (European Commission, 2019).

3.1.10. Air pollution

Air pollution results from the emission and dispersion of toxic substances in the air. Ninety percent (90%) of the urban European population is exposed to air pollution levels exceeding the WHO standards (European Environmental Agency, 2017). Conservative estimates from the World Bank in 2014 attributed 184,000 annual deaths worldwide to TRAP (Bhalla, 2014), although a different study attributed 137,000 deaths just in China in 2013 to traffic-related particulate matter with a diameter of less than 2.5 μm ($PM_{2.5}$) (Global Burden of Disease Working Group, 2016). More recently, ozone (O_3) and $PM_{2.5}$ were estimated to be responsible for 385,000 global deaths in 2015 (Anenberg et al., 2019). Further, deaths attributable to transportation tailpipe emissions increased by 6.6%, and total $PM_{2.5}$ and O_3 mortality increased by 9.4% between 2010 and 2015 globally (Anenberg et al., 2019). Vehicle emissions are estimated to be responsible for almost 20% of all ambient $PM_{2.5}$ and O_3-related mortality in Germany, the United States, and the United Kingdom (Lelieveld et al., 2015).

The total number of VMT and the number of vehicles on the road have increased in countries around the world (Kumar et al., 2018), negating the benefits of emission-reducing technologies. Air pollution can discourage people from going outside, being active, and disproportionately harms communities of color and lower socioeconomic status within cities (Khreis et al., 2016); as they generally have both higher exposure and higher susceptibility.

The potential implementation of car-sharing networks, specifically once AV technology is widely available, may present adverse public health outcomes as shared cars could operate continuously, resulting in greater vehicle emissions (Cohen and Shirazi, 2017). Car-sharing does decrease the number of vehicles on the road, but there is a gap in research investigating the emissions trade-off between the current pattern of vehicle use and continually operating shared AVs. While support for EVs is growing due to the allure of low-emissions, it is also worth noting that EVs cause more pollution during production (Eckart, 2017) and boast higher non-exhaust pollution rates (due to EV weight and its effect on tire, brake, and road friction) than ICEVs (Timmers and Achten, 2016). Further, nearly 63% of electricity in the United States in 2019 was generated by burning fossil fuels (United States Energy Information Administration, 2019). As such, solar-powered and other forms of clean energy require greater investment and research, in conjunction with mitigation of non-exhaust pollution, for EVs to reduce TRAP. Progress on electrification of road transportation comes from Norway, where 96% of electricity is produced through hydroelectric processes and the market share of electric vehicles is approaching 50% (Figenbaum et al., 2015; Norwegian Electric Car Association, 2020), and potentially reducing traffic-related exhaust emissions (Olstrup et al., 2018). Measurements of ambient air pollution in three cities (Stockholm, Gothenburg, and Malmö) in 2015 were compared to ambient air pollution concentrations from 1990. The concentration of NO_X – an exhaust pollutant associated with ICEVs (Stockfelt et al., 2017) – has been decreasing in each of the three cities between 1990 and 2015 (Olstrup et al., 2018).

TRAP contributes to many adverse health outcomes including premature mortality (Beelen et al., 2014); respiratory disease, including lung cancer (Raaschou-Nielsen et al., 2013), COPD (Lindgren et al., 2009), pneumonia (Nhung et al., 2017), childhood asthma (Khreis et al., 2017b), and respiratory infections in children (MacIntyre et al., 2014); cardiovascular disease (Lu et al., 2015), including heart attack (Hoek et al., 2013), congestive heart failure (Shah et al., 2013), stroke (Stafoggia et al., 2014), and arrhythmia (Lee et al., 2014); neurodegenerative disease (Landrigan, 2017), including dementia (Power et al., 2016); mental health problems (Power et al., 2016), autism and child behavior problems; congenital anomalies (Vrijheid et al., 2011); reproductive issues, including reduced sperm quality (Lafuente et al., 2016), preterm birth (Sapkota et al., 2012), and low birth weight (Fleischer et al., 2014); deep vein thrombosis (Brook et al., 2010); bone conditions (Prada et al., 2017); diabetes (Eze et al., 2015); and obesity (Jerrett et al., 2014). Emissions from exhausts as well as from brake and tire abrasions can also re-suspend heavy metals and PM. Moving traffic can re-suspend road dust (Jancsek-Turóczi et al., 2013). Health outcomes that have been associated with road dust include carcinoma (including lung cancer), respiratory inflammation, asthma, COPD, cardiovascular disease, allergies, fungal infection, low birth weight, and premature mortality (Khan and Strand, 2018). Lead, platinum group elements, aluminum, zinc, and vanadium road dust particles seem to be most commonly associated with adverse health effects (Khan and Strand, 2018).

3.1.11. *Community severance*

Community severance refers to transportation infrastructure and/or motorized traffic (speed or volume of traffic) that divides places and people, interfering with the ability of individuals to access goods, services, and personal networks (Mindell et al., 2017). It can also limit social interaction and reduce mobility independence. There is limited research that focuses on measuring the continued effects of community severance, partly because there was no way of measuring community severance until recently. Identifying a causal relationship between community severance and health risks is difficult when studies are not conducted in the same area because community severance is a context-dependent issue (Anciaes et al., 2016a).

There are solutions to removing the burdens presented by obstructive infrastructure. The most straightforward of these is removing the infrastructure itself, which occurred in the case of the deconstruction of the Cheonggyecheon Expressway in Seoul, South Korea. The removal of this highway has resulted in faster travel times, reduced the local urban heat island effect, and returned urban land to green space, in addition to uprooting a divisive element of the built environment (Newman and Kenworthy, 2015). Other approaches may include burying or sinking transportation infrastructure, including pedestrian-friendly features such as cross walks, or redesigning roads so that traffic flow does not present an obstacle to active travelers (protected cycle lanes, reduced number of vehicle lanes, or inserting a median) (Mindell and Anciaes, 2020).

“Pedestrian delay” is a term used to describe the time spent waiting to cross roads due to traffic flow, crossing facilities, or road design that contributes to community severance (Anciaes et al., 2016b). To minimize liability for AV manufacturers in the event of a motor vehicle crash, developers are exploring the consequences of respecting pedestrian “right-of-way”, which could reduce pedestrian delay. However, this could cause slower vehicle traffic and increase travel times due to frequent stopping, resulting in greater vehicle emissions (Millard-Ball, 2018). The relationship that is established between AVs and active transportation users will not only have a dramatic effect on the severity of community severance, but also on issues such as social exclusion and access, and even air pollution exposure.

Community severance can increase as a result of road safety concerns and may restrict access to public transportation (James, 2005). Community severance is thus strongly associated with reduced social interactions (Boniface et al., 2015) and social exclusion (Cohen et al., 2014); reductions in physical activity; stress (Cohen et al., 2014); poor mental health; cardiovascular disease (Leigh-Hunt et al., 2017); increases in exposure to air pollution (Hart and Parkhurst, 2011); and overall reduced mobility independence and access, therefore increasing morbidity and premature mortality (Mindell et al., 2017).

3.1.12. *Electromagnetic fields*

An electromagnetic field (EMF) is composed of moving electrically charged particles. EMFs can be created by differences in voltage and can be present near electricity generation stations, electric grids, and other similar infrastructure used to accommodate transportation technologies and disrupters (autonomous, connected, electric, and shared vehicles) (World Health Organization, 2018e).

EMFs are an issue of current concern in approaches for charging EVs. One limitation of EVs is the mileage per battery charge, which is substantially less than fuel-efficient ICEVs (Gao et al., 2015). Charging stations for battery-powered vehicles are becoming common in many cities and more convenient modes of charging, like wireless power transfer (WPT), are being researched to address concerns regarding mileage (Bi et al., 2016). “Dynamic charging” is a method of WPT that is conducted when a charging station creates an EMF which transfers power to an EV battery during operation (Bi et al., 2016). Because the vehicle would be able to recharge during operation, the vehicle could travel farther. Additionally, the size of the battery could be reduced, mitigating some of the weight-related non-exhaust air pollution problems posed by EVs (Bi et al., 2016). However, there is concern about how the EMF from WPT will affect humans, electronic and implanted medical devices, and the environment (Gao et al., 2015). Several studies have suggested that charging stations built in accordance with the International Commission on Non-Ionizing Radiation Protection standards should ensure human safety (Bi et al., 2016; Ding et al., 2014b; Watanabe and Ishida, 2016; Wen and Huang, 2017). However, other studies have noted precautions about proximity to WPT stations that are in use (Christ et al., 2013; Gao et al., 2015), as well as the potential risks of EMF produced by dynamic charging in open traffic environments (Bi et al., 2016). Further research is needed to understand the health implications of wireless charging stations and the resulting EMFs, even when the magnetic or electric fields do not exceed practiced standards.

Transportation-related EMF exposure may contribute to reproductive complications (Li et al., 2017); potential hindered cognitive and/or behavioral development in children (Calvente et al., 2016); stimulation of central and peripheral nervous tissues; and retinal phosphene occurrence (Bi et al., 2016) as suggested in several studies. Further, a systematic review of EMF health effects found both adverse and beneficial effects concerning genes, cell growth, and the performance of the neural, circulatory, immune, and endocrine systems depending on the intensity, frequency, and duration of EMF exposure (Kostoff and Lau, 2013). On the contrary, one observational study of pacemaker surgery patients concluded that EMFs produced by EVs do not affect cardiac implantable electronic devices, indicating that driving and charging EVs is likely safe for people with these devices (Lennerz et al., 2020). Another observational study investigated the effect of static magnetic fields from EVs on neuropsychological cognitive functions and determined that the effects were not considerable (He et al., 2019). More research is warranted in this emerging area to address heterogeneity of findings to inform more concrete conclusions on the health effects of EMFs from the transportation sector.

3.1.13. Stress

Stress, the body's response to any demand, was labeled the "Health Epidemic of the 21st Century" and was estimated to cost Americans \$300 billion annually (Fink, 2017). Stress is associated with travel. Travel duration is a frequent stressor for users of motorized modes. For car users, stress might result from congestion, searching for parking, interaction with other drivers, and safety (Ding et al., 2014a). Traffic noise (Das et al., 2015) and the lack of green space availability (Khreis et al., 2016) are also a result of transportation decisions that impact the stress levels of individuals (Zijlema et al., 2018). Public transportation users may be stressed by waiting times, overcrowding, costs, and uncertainty over routes and timetables. Of the five most congested cities in the world, four are in South America – Bogota, Rio de Janeiro, Mexico City, and Sao Paulo, in descending order - while Istanbul is the fifth (INRIX, 2020). Among these cities, the average motor vehicle commuter will spend 169 h in traffic congestion annually (INRIX, 2020). In the United States, the average commuter spends 99 h in traffic congestion every year, at a notional cost (time that could be spent more productively) of \$1400 per commuter (INRIX, 2020).

Mode choice plays an important role in determining levels of stress related to commuting, with driving being the most stressful mode (Legrain et al., 2015). Legrain et al. (2015) concluded that active and public transportation users have lower levels of stress, increasing the health benefits of ensuring accessibility and modal diversity in cities. Avila-Palencia et al. (2017) found an inverse relationship between stress levels and commuting via bicycle, even after adjusting for individual and environmental confounders and using different thresholds of perceived stress. Cycling to work at least four days a week resulted in a lower risk of being stressed relative to people who cycled less or not at all (Avila-Palencia et al., 2017).

Time spent in traffic also reduces the opportunity for engaging in health-promoting activities. The consolidation of schools and the construction of new schools often results in a longer commute for most students (Voulgaris et al., 2017). Students who traveled to school using active transportation were physically active for over an hour more each day than their peers who traveled to school via motorized transportation. Furthermore, students who had to commute more than 30 min to school engaged in physical activity for 75 min per day less than their peers. Each minute spent commuting was also associated with 1.3 fewer minutes of sleep (Voulgaris et al., 2017). The health effects of physical inactivity have already been noted while sleep deprivation among teens can result in an increased risk of acute illness (Orzech et al., 2014), obesity and unhealthy diets (Chaput and Dutil, 2016), and motor vehicle crashes related to drowsy driving (Higgins et al., 2017). Generally, stress can result in anxiety, depression, mental health-related QOL, substance use, unhealthy diet, sleeplessness, weight gain (Goyal et al., 2014), obesity, high cholesterol, heart disease, hypertension, and stroke (Khoury et al., 2015).

3.1.14. Greenhouse gas emissions

Greenhouse gases (GHGs) are gases including carbon dioxide (CO_2), methane, nitrous oxide, and fluorinated gases which trap heat in the atmosphere (Environmental Protection Agency, 2016). In 2016, global GHG emissions totaled 49.3 gigatons (GT), 72% of which were from CO_2 (Olivier et al., 2017). In the United States, 81% of GHG emissions are CO_2 (Environmental Protection Agency, 2016), 30% of which are produced by motor vehicles (United States Energy Information Administration, 2017). The transportation sector is the largest contributor to GHG in the United States (Kay et al., 2014), while it accounts for 23% of total energy-related CO_2 emissions globally (Intergovernmental Panel on Climate Change, 2015). The transportation sector is also one of the fastest-growing sources of global emissions, despite advances in vehicle efficiency (Intergovernmental Panel on Climate Change, 2015). In contrast with most other major sources of global emissions, fossil fuels remain the dominant final energy source in transport, with oil accounting for over 90% of the final energy demand (International Energy Agency, 2016).

While CO_2 and other GHGs are not directly threatening to human health, the consequences of a 2 °C increase in global mean temperature from levels recorded pre-global industrialization would result in harmful effects for human populations and the ecosystems that sustain them (Watts et al., 2018). Global warming can exacerbate the adverse health effects related to UHIs, air pollution, and physical activity. Additionally, extreme flooding, storms and drought cycles (which can each damage transportation infrastructure), and increased rates of infectious disease transmission induced by climate change (Patz et al., 2014) can result in displacement, adverse mental and physical health, altered vector-pathogen relations, worsened air pollution, physical injury, and premature mortality (Patz et al., 2014; Watts et al., 2015). The second-hand effects of these changes can harm crop yields, livestock, and fisheries obstructing many from receiving proper nutrition and degrading health. Mitigating GHG emissions will not only result in improved air quality, but it may lead to co-benefits related to other pathways including increased physical activity and social contact (Gao et al., 2018), which are associated with their own health benefits (Mindell et al., 2011).

The Intergovernmental Panel on Climate Change has determined that by 2050, GHG emissions should be 50–85% of what they were in 1990 to avoid irreparable environmental damage (Kay et al., 2014). Cities are the largest producers of GHGs globally (80%) due to energy consumption and increasing urbanization patterns (Dulal and Akbar, 2013). In urban transportation, the largest emissions reduction impact will come from limiting private vehicle usage, something that can be done by increasing employment and residential density, shortening the distances between trip origins and destinations, and encouraging alternative transportation modes to private vehicles. Gouldson et al. (2018) discuss the impacts of GHG reduction policies within cities. By taking a public health approach to land use planning, encouraging a modal shift away from private vehicles, and improving public transportation and passenger car efficiency and freight policies, an estimated 2.8 GT of GHG could be removed in cities worldwide by 2050 (Gouldson et al., 2018).

Efforts to reduce GHG emissions by supporting active transportation have been modeled by several studies. Maizlish et al. (2013) project that increasing median active transportation levels across the San Francisco Bay Area population by 18 min per day would reduce GHG emissions regionally by 14% and reduce the burden of disease from cardiovascular disease and diabetes by 14%. If this change was implemented in conjunction with the wide-spread implementation of low-carbon emission vehicles, the result would be a 33.5% reduction in GHG (Maizlish et al., 2013). Similarly, Woodcock et al. (2009) modeled the effects of reduced motorization, the use of low carbon emission vehicles, and increased active transportation on GHG emissions and health outcomes in London and Delhi. In Delhi, heart disease and cerebrovascular disease were reduced by an estimated range of 11–25% each, diabetes by 6–17%, and road traffic injuries by 27%, resulting in a reduction of 1000 motor vehicle related deaths and 25,000 DALYs. In London, heart disease was reduced by 10–19%, cerebrovascular disease by 10–18%, breast cancer by 12–13%, dementia by 7–8%, and depression by 4–6%, resulting in the reduction of 1000 motor vehicle related deaths and 15,000 DALYs (Woodcock et al., 2009). Both studies suggest that the bundling of policy measures – instead of implementing them in isolation – can be more effective in reducing GHGs and produce significant public health co-benefits by reducing both the burden of disease and mortality.

3.1.15. *Equity and modifiers*

Two additional factors influence the abovementioned transportation-related exposures and their resulting health outcomes as well as health outcome severity. The first is inequity, which refers to the unfair and inappropriate distribution of exposures related to transportation planning (Litman, 2019). Inequity factors can modify the exposure to each of the 14 pathways at the population level due to the placement of, proximity, and access to transportation facilities, services, infrastructure, and activities. The second factor is intrinsic and extrinsic individual characteristics, such as sex, age, race/ethnicity, genetics, etc., which influence the susceptibility of individuals to transportation-related exposures and subsequently the severity of health outcomes experienced by each individual. These factors include malnutrition (Walson and Berkley, 2018); and the lack of antioxidant intakes (Barthelemy et al., 2020), exposure to stress (Salleh, 2008), and exposure to violence (Wright and Steinbach, 2001). These factors can modify and often amplify the adverse health effects of transportation-related exposures.

In the context of equity, one important factor to consider is where populations live in reference to major transportation infrastructure. Worldwide, rural healthcare access is becoming an issue for patients, partly due to transportation inequities as transportation infrastructure and services often do not extend to rural communities (Scheil-Adlung, 2015). Even when transportation services or infrastructure are available, the financial cost of utilizing them may pose another barrier to receiving healthcare (Scheil-Adlung, 2015). TRAP exposure and its associated adverse health effects tend to be higher and more concentrated in lower socioeconomic locales and ethnic minority communities. A wealth of studies, old and new, show that adverse exposure levels are often socially patterned with more socioeconomically deprived or ethnically diverse communities being disproportionately exposed. Inequalities in air pollution exposure in the United States were related to income and race-ethnicity between 2000 and 2010 (Clark et al., 2017). Notably, these disparities were larger by race-ethnicity than income (Clark et al., 2017). In the United States, exposure to $PM_{2.5}$ is disproportionate between ethnic groups when compared with their contribution to $PM_{2.5}$ concentrations. Specifically, African Americans and Hispanics are exposed to more $PM_{2.5}$ than they are responsible for producing, while non-Hispanic whites are exposed to less $PM_{2.5}$ than they produce (Tessum et al., 2019). This disparity occurs partly due to social, economic, and environmental factors that have resulted in minority neighborhoods living closer to high traffic volume roads, increasing their exposures to air pollution and other transportation-related exposures and adverse health effects (McAndrews and Marcus, 2014; Rowangould, 2013). Finally, a national-level study in the United States found that students attending “high risk” (of exposure to ambient neurotoxicants) public schools were significantly more likely to be eligible for free/reduced price meals and to be Hispanic, Black, or Asian/Pacific Islander than White or another race (Grineski and Collins, 2018). This higher exposure is exacerbated by the greater susceptibility of poorer groups, including the very young and old, to the adverse impacts of a given exposure, due to a higher likelihood of pre-existing cardio-respiratory disease. Further, exposures are not limited to air pollution alone; they extend to other pathways such as noise, heat, green space and access to physical activity opportunities (Khreis et al., 2016; Mueller et al., 2018).

The health impact of inequities and intrinsic and extrinsic factors has been spotlighted by the Coronavirus (COVID-19) pandemic (Millett et al., 2020). The number of COVID-19 cases are 2.5–3x greater among Native Americans, Hispanic, and Black or African

American individuals in America compared to White, non-Hispanic individuals (Centers for Disease Control and Prevention, 2020b). Hospitalization rates are roughly 5x greater among these racial minority groups compared to White, non-Hispanic Americans and the risk of mortality for Black or African American individuals is double that of White, non-Hispanic Americans (Centers for Disease Control and Prevention, 2020b). The most common preexisting conditions among hospitalized COVID-19 patients are cardiovascular disease, diabetes, and chronic lung disease, morbidities that have been linked to transportation throughout this paper (Eze et al., 2015; Héritier et al., 2018; Raaschou-Nielsen et al., 2013). Hospitalization and mortality rates are 6x higher for individuals with these preexisting conditions (Stokes et al., 2020). Furthermore, lack of private vehicle ownership is a statistically significant indicator of increased likelihood of COVID-19 diagnosis and mortality in the United States (Karaye and Horney, 2020; Khazanchi et al., 2020). Public transportation ridership is higher among low-income and racial minority groups which increases risk of exposure for already disadvantaged communities (Chen et al., 2020). Additionally, reductions in public transportation service due to COVID-19 has limited health care access for transit-dependent populations (Chen et al., 2020).

4. Discussion

A conceptual model explaining the relationship between transportation and public health is significant to understanding how the transportation and public health fields are intertwined and in devising appropriate strategies to protect and promote public health. The aggregation of the existing literature has established the health burden imposed on populations by transportation systems, infrastructure, facilities, and activities. Several of the pathways connecting transportation and public health are well-recognized and researched in the literature, including physical activity, road travel injuries, air pollution, and GHGs, and, to a lesser extent green spaces, blue spaces, and aesthetics, access, noise, and heat. However, other pathways are new or understudied and require further research to better understand their impact on public health, and also the extent by which they are influenced by transportation planning and policy. These include mobility independence, contamination, social exclusion, community severance, EMFs, and stress.

The collective health impacts of the 14 pathways has not been quantified yet in any setting. However, quantifications of the health impacts of the separate pathways indicate that the adverse impacts may qualify as a health epidemic. The health burden associated with transportation affects populations globally and disproportionality affects socioeconomically deprived and ethnic minority communities, who are already more susceptible to their exposures, due to a host of extrinsic and intrinsic effect modifiers. Based on the aggregation of conservative estimates for each pathway as they are documented in the literature, over 4.5 million premature deaths occur each year globally from TRAP, motor vehicle crashes, and physical inactivity; a non-trivial proportion which could be reduced through healthier transportation practices including active and public transportation. The burden of disease attributable to environmental noise (most of which can be traced to transportation-related sources in urban areas) has become better recognized as the volume of relevant research increases. For example, in Western Europe alone, over 1 million DALYs are lost annually due to road traffic noise (World Health Organization, 2011). Further quantifying the health burden attributable to transportation, across as many pathways as possible, will help professionals in transportation and urban planning, public health, and policy to better grasp the magnitude of the health impacts and propose necessary policy recommendations and amendments. However, we are yet to better understand and account for the interactions and overlaps between the different pathways and their impacts.

The conceptual model of this paper presents three unique pathways not previously included in the transportation and health conceptual models or frameworks reviewed by the authors. These pathways are contamination, mobility independence, and electromagnetic fields. While there is scarce quantitative evaluation of the health effects of transportation-related electromagnetic fields, the inclusion of this pathway is meant to prompt a health-conscious dialogue as emergent and disruptive technologies – such as WPT stations – present potential reconfiguration of existing transportation systems and a new urban source for human exposure to electromagnetic fields. Contamination associated with transportation pertains to toxins which humans are exposed to, other than airborne pollutants. Numerous adverse health effects are associated with the exposure to non-airborne pollutants and this warrants a broadened discussion of the pollution associated with motor vehicle traffic than currently available in the literature. Mobility independence is a crucial element of mobility for vulnerable populations such as the elderly and children. Summarizing the health impacts of mobility independence (or lack thereof) may provide the evidence base to justify developing more inclusive and equitable transportation systems. The health effects of mobility independence remain understudied in the literature but are an important area to expand, especially given the potential effects of mobility independence on cognitive function, which is of increasing relevance in rapidly aging global populations with increasing rates of neurodegenerative diseases (Patterson, 2018; World Health Organization, 2012).

The other frameworks or models we reviewed also do not *explicitly* illustrate the role of equity and intrinsic and extrinsic effect modifiers in influencing the exposures and the severity of transportation-related health impacts. We have explicitly added these factors in our conceptual model to communicate that equity is relevant at all stages of the conceptual model; be it, for example, the unequal distribution or placement of transportation infrastructure, the unequal exposure to air pollution, noise or green space and aesthetics and therefore the unequal health impacts depending on those upstream planning and policy decisions and their associated exposures. Similarly, different populations will react differently even to the same exposures depending on extrinsic or intrinsic factors that increase or decrease susceptibility known as effect modifiers. These factors are important to consider and account for when studying the health impacts of transportation but also importantly when devising mitigation strategies and allocating scarce resources. Unfortunately, within the transportation and urban planning fields there is a history of racist practices that can explain some of the inequities that contribute to the disproportionate occurrence of adverse transportation-related exposure for different demographic groups (Fuller and Brugge, 2020; Whittemore, 2017). Practices that integrate meaningful levels of citizen participation and redefine the role of the professional in community-engagement exercises can improve participation and mitigate the occurrence of inequitable outcomes (Blue et al., 2019; Lyles and Swearingen White, 2019). Highlighting equity and effect modifiers as two important elements in this framework is also meant to raise awareness of these issues and formalize them in the conceptual model and future assessments.

Policy action is required to rectify the existing flaws of transportation and prevent the exacerbation of current health burdens through future transportation development and urban growth. Efforts to reduce car-dependency and unlock the potential health benefits mentioned in this paper, however, have been inconsistent and underwhelming. The conceptual model and literature referenced in this paper establish the validity of substantial transportation system changes to benefit public health outcomes at individual, population, and global levels. Global crisis also lies ahead with climate change. As the impacts of climate change continue, meeting with the timeline proposed by the Intergovernmental Panel on Climate Change (reducing GHG emissions to 50–85% of pre-industrial levels by the year 2050) requires meaningful changes to transportation systems and urban development patterns that must be pursued immediately and with greater purpose than past initiatives.

The following recommendations may improve the utility of current and future research to better inform practitioners and decision-makers.

4.1. Research needs

Although the evidence base has been expanded and strengthened in recent years, further research is needed to strengthen some preliminary claims made by existing studies that provide conflicting and inconclusive results. We identified several research needs and gaps after reviewing the weaknesses in each key factor and pathway's description and these are outlined in Table 1. This list is not exhaustive.

While the conceptual model is meant to be a tool to identify and evaluate the health impacts of transportation in urban areas, there is potential for substantial health benefits if the overlap and interaction between pathways is better understood. Stronger interdisciplinary collaboration may further elucidate these overlaps and interactions and could help devise integrated strategies and solutions which address multiple issues, rather than focusing on isolated pathways. This narrow focus has proven harmful as policy makers could induce "unintended consequences" by solutions targeted at isolated pathways (see for example critical discussion of negative consequences of Europe's shift towards the diesel powertrain for GHG emissions objectives) (Cames and Helmers, 2013). Not only should practitioners and policy makers be encouraged to build coalitions with peers from adjacent fields, but researchers can use the conceptual model to explore the specific overlaps between the 14 pathways that can inform practice and policy. Doing so will advance mitigation of transportation issues beyond the 'one exposure-one outcome-one solution' approach. Doing so will also enable more meaningful, and perhaps accurate, quantifications as we can control for the different pathways when we estimate their health impacts and therefore avoid for example double counting of benefits and harms.

4.2. Practice and policy needs

The way we frame transportation and public health in this paper emphasizes why collaboration between experts in various fields is necessary. Transportation has a huge, yet preventable, impact on many adverse health outcomes, and interdisciplinary approaches in practice and policy are needed to promote healthy transportation practices (Khreis et al., 2016). However, the transportation and health fields have traditionally been separated with limited collaboration opportunities in education, training, and workforce development (Sanchez and Khreis, 2020). The many health outcomes associated with each pathway are by-products of previous iterations of innovation that were inconsiderate of public health and driven by various markets. Several of the reviewed pathways are

Table 1
Research recommendations.

Pathway	Research Needs
Autonomous Vehicles	To understand the impacts that shared AVs will have on total transportation-related emissions, air pollution exposures, health impacts and equity.
Community Severance	To quantify the impacts of community severance as related to transportation.
Social Exclusion	To clarify the physical health impacts of social exclusion/inclusion as related to transportation.
Electromagnetic Fields	To investigate the contribution of transportation technologies and disruptors to electromagnetic fields and the health effects induced by transportation-related electromagnetic fields.
Air Pollution	To explore further whether the risk of higher air pollution exposures outweigh physical activity benefits in near-road environments, and in different contexts with different air pollution concentrations and mixtures.
Green Space and Aesthetics Heat Mobility Independence Electromagnetic fields	To better understand the relationship with transportation and health effects.
Key Transportation Factors	Recommendation
Disruptive or Emergent Technology	To focus on the impacts that shared AVs and electric vehicles will have on total transportation-related emissions, especially non-exhaust and stationary emissions (e.g. electricity generation) from electric vehicles. Health effects from non-exhaust emissions from brake, tire and road wear and road dust resuspension are also under-researched.
Built Environment	To evaluate the impact of urban growth management strategies on shifts to health-promoting transportation modes (active and public transportation) in different contexts.
Transportation Mode Choice	To conduct longitudinal studies quantifying the health effects of transportation mode shifts, and more studies evaluating the benefits and risks trade-off of active transportation in near-road environments, where air pollution and noise exposures, and risk of road travel injuries, can be higher.

experiencing paradigm shifts due to emergent technologies that are expected to improve the function and efficiency of transportation, but whose health impacts are as yet to be determined. With paradigm shifts as significant as motor vehicle automation and electrification, an interdisciplinary perspective limits the capacity for detrimental transportation-induced health outcomes and further exacerbations of health and social inequity.

There are a growing number of interdisciplinary opportunities in the transportation and health fields, although there remains untapped potential for further collaboration. Since the value of interdisciplinary knowledge and skills is increasing as they are necessary to solve complex problems, it is necessary to promote interdisciplinary opportunities in education, training, and the workforce across practice and policy. Policymakers must recognize the interconnected relationship between transportation and health as their decisions impact more than just the built environment, infrastructure, transportation mode, and emerging technologies and disruptors.

5. Conclusion

Five new pathways connecting transportation and health were added as an update to our previous conceptual model reported in Khreis et al. (2017a), resulting in this latest conceptual model containing 14 pathways. Three of those five new pathways have not been explicitly included in any of the other more recent conceptual models reviewed prior to the writing of this paper (Frank et al., 2019; Nieuwenhuijsen, 2020). Four intertwined factors that influence transportation were defined, namely, land use and the built environment, transportation infrastructure, transportation mode, and emerging transportation technologies and disruptors. These factors have all been identified as eliciting specific public health outcomes. Contamination, social exclusion, noise, heat, road travel injuries, air pollution, community severance, EMFs, stress and GHGs are pathways that may increase population morbidity and mortality rates while green and blue spaces and aesthetics, physical activity, access, and transportation independence are pathways that can improve public health across multiple outcomes. Additionally, inequity and intrinsic and extrinsic characteristics modify the exposure and severity of health effects and outcomes experienced at the individual and population levels, respectively, and these factors were formalized in our conceptual model.

We emphasize the interdisciplinary nature of the pathways so that urban and transportation planning, public health, and policy professionals can promote holistic solutions that enhance the beneficial health impacts of transportation and mitigate the detrimental ones. Our framing of transportation as a composite of land use and the built environment, infrastructure, mode choice, and emergent technologies is meant to be inclusive of multiple professional fields to prompt interdisciplinary collaboration when addressing transportation issues.

The key result of this paper is a conceptual model that can guide future research and practice to identify and evaluate the health outcomes of transportation decisions. Although the evidence base has been expanded and strengthened in recent years, we also identified where research that further explores health outcomes associated with specific pathways and the contribution of transportation to these pathways is needed. This paper also synthesizes multiple studies which quantify the health impacts of transportation. We believe these impacts should inform policy decision-making. The significant overlap and interaction between the 14 pathways (green and blue spaces and aesthetics, air pollution, and heat, for example) highlight the necessity of systemic reform to urban transportation and public health, rather than a “one exposure-one outcome-one intervention” approach.

Declaration of competing interest

No conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2021.101070.

Authors’ contribution statement

This work represents a strategic initiative under the Center for Advancing Research in Transportation Emissions, Energy, and Health (CARTEEH) directed by JZ. HK conceived and led the development of the conceptual model. HK and AG designed and drafted this paper and conducted all literature reviews. KS assisted with the literature review. JSM proposed the addition of contamination and mobility independence as relevant pathways to the conceptual model. All authors read, provided feedback and input, and approved the final manuscript and the conceptual model.

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