# Impacts of Autonomous Vehicles on Public Health: A Conceptual Model and Policy Recommendations

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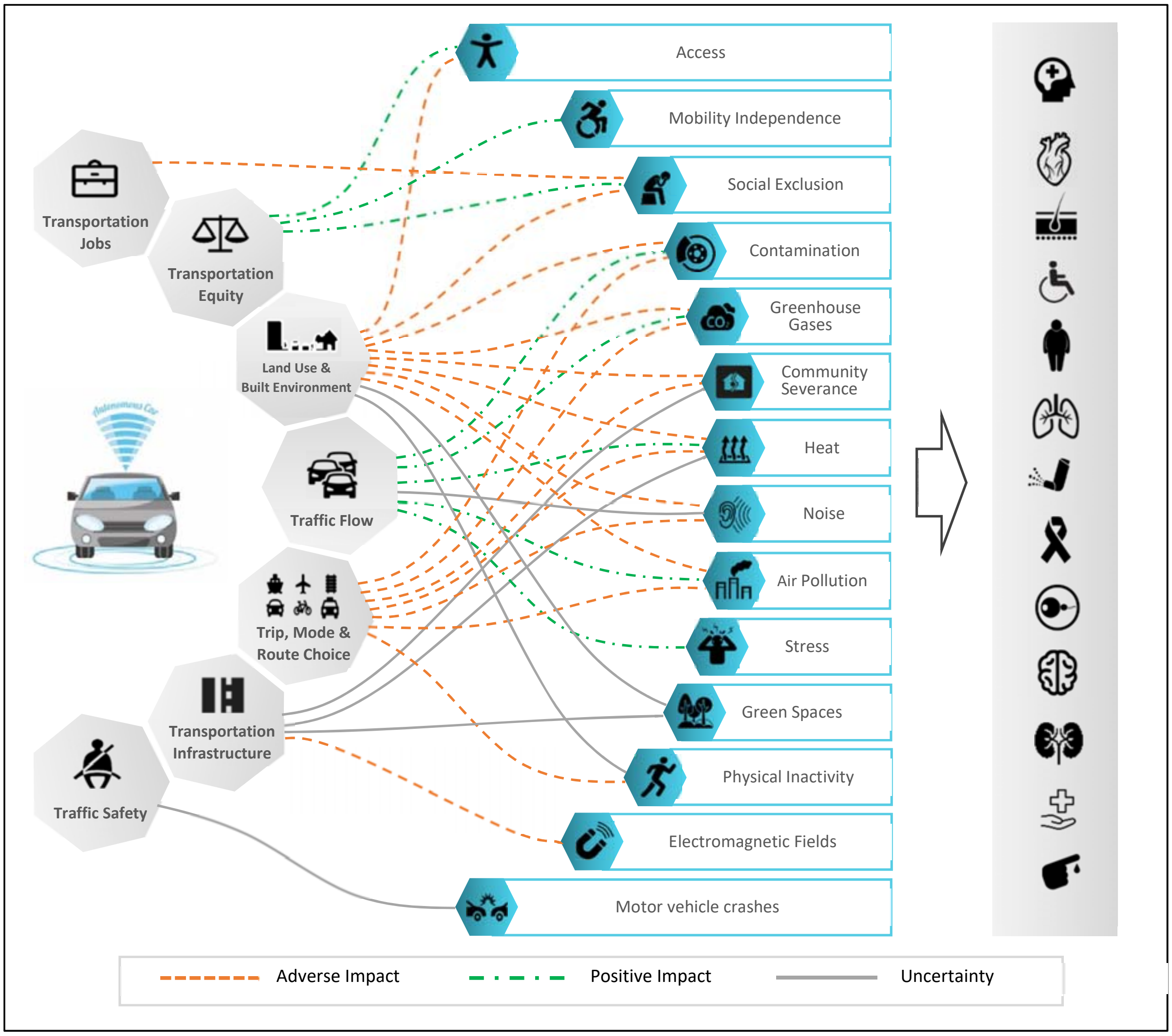
## ABSTRACT

Supporting policies are required to govern the negative consequences of Autonomous Vehicle (AV) implementation and to maximize their benefits. The first step towards formulating policies is to identify the potential impacts of AVs. While the impacts of AVs on the economy, environment, and society are well explored, the discussion around their beneficial and adverse impacts on public health is still in its infancy. Based on evidence from previous systematic reviews about AVs' impacts, we developed a conceptual model in this study to systematically identify the potential health impacts of AVs in cities. The proposed model, first, summarizes the potential changes in transportation after AV implementation into seven points of impact: (1) transportation infrastructure, (2) land use and the built environment, (3) traffic flow, (4) transportation mode choice, (5) transportation equity, (6) jobs related to transportation, and (7) traffic safety. Second, transportation-related risk factors that affect health are outlined. Third, information from the first two steps is consolidated, and the potential pathways between AVs and public health are formulated. Based on the proposed model, we found that AVs can impact public health through 32 pathways, of which 17 can adversely impact health, eight can positively impact health, and seven are uncertain. The health impacts of AVs are contingent upon supporting policies. Equipping AVs with electric motors, regulating urban area development, implementing traffic demand management strategies, controlling AV ownership, and imposing ride-sharing policies are some strategies that can reinforce the positive impacts of AVs on public health.

**Keywords:** Autonomous vehicle; Public health; Unintended impact; Supporting policy; Pathways to health, Transportation, Urban area

## GRAPHICAL ABSTRACT



## 1. Introduction

There is a growing field of information on how transportation—and the systems, technologies, activities, land use, and infrastructure behind it—dramatically impact public health in cities (Khreis et al., 2016). A significant number of preventable deaths and a large burden of disease are attributable to transportation. According to the World Health Organization (WHO), in 2016, 1.4 million deaths were due to motor vehicle crashes globally (WHO, 2018c). In 2016, 4.2 million deaths were attributable to ambient air pollution (WHO, 2018b), where traffic-related air pollution was responsible for one-fifth of deaths in the United Kingdom, United States, and Germany (Lelieveld et al., 2015). Transportation noise is also is a major contributor to the burden of premature mortality and morbidity in cities (Tainio, 2015, Mueller et al., 2017, Sohrabi and Khreis, 2020). Contaminants from traffic (Burant et al., 2018), traffic-related stress (Wei, 2015), lack of active travel and physical inactivity (Reiner et al., 2013), and greenhouse gases (Woodcock et al., 2009) are a few of the other detrimental exposures of transportation that lead to worse health, as manifested in premature mortality and increased morbidity across a wide spectrum of diseases.

The introduction of Autonomous Vehicles (AVs) can profoundly transform transportation systems (Fagnant and Kockelman, 2015) and, therefore, impact public health. Nevertheless, alongside the promises of AVs, several negative consequences are expected after their implementation, for example, increasing travel demand and encouraging modal shifts from public transit and active transportation to AVs (Pakusch et al., 2018). Supporting policies are required to govern the negative consequences of AVs' implementation, and to maximize their benefits. The first step towards policy formulation is to identify problems that require attention, decide which issues deserve the most attention, and define the nature of the problem (Howlett et al., 2009). Despite the numerous attempts to identify the consequences of AVs' implementation, a systematic review on the impacts of AVs with a focus on its policy implications by Milakis et al. (2017a) indicated that the discussion around the public health impacts of AVs is still in its infancy. The role of understanding the impacts of AVs on public health in backcasting and formulating policies for better governance was later emphasized by Lit et al. (2018). Also, from a policy implementation standpoint, the importance of public awareness of the potential health benefits of AVs was discussed by Pettigew (2017), where such awareness can facilitate the acceptance of AV regulations and enhance vehicle adoption. However, a lack of awareness of the potential health benefits of AVs was shown in a survey conducted by Pettigrew et al. (2018c), who found that there were neutral levels of receptiveness and very low perceptions of the salience of AV health benefits among respondents.

In this study, we identify the health implications of fully automated vehicles in urban areas (also referred to as self-driving cars, driverless vehicles, and level 5 vehicles, according to the Society of Automotive Engineers (SAE) (SAE, 2016)). AVs' impacts on public health were investigated through the potential changes in transportation as well as the technologies, activities, land use, and infrastructure behind it. The contributions of this paper are threefold. First, we provide a holistic and narrative overview of the available reviews about the impact of AVs on public health and explore the gaps in the literature. Second, we address some of the gaps identified in the literature by proposing a framework in the form of a conceptual model to clarify and systematically identify the potential beneficial and adverse impacts of AVs on public health. Third, we discuss the required supporting policies to control the negative consequences of AVs' implementation in cities, drawing on the proposed conceptual model. This paper contributes to the previous attempts to identify AVs' impacts on public health (Crayton and Meier, 2017, Dean et al., 2019, Rojas-Rueda et al., 2020, Singleton et al., 2020) through one or more of the avenues listed above. The results of this study could be used for making more informed decisions about AVs' supporting policies, increasing the public awareness of the health impacts of AVs, and incentivizing the health sectors to intervene and contribute to the discussions around policymaking and investments in AVs. The results can also promote the dialogue about the contribution of AVs to the sustainable development of cities (Chehri and Mouftah, 2019, Yigitcanlar et al., 2019). We expect that this study benefits future research by clarifying and providing a framework for researchers to consider and study the health impacts of AVs' implementation in a more holistic manner.

## 2. Literature review

Thus far, a number of studies have addressed the impacts of AVs on transportation and mobility, including the impacts on traffic flow efficiency, travel behavior, and traffic safety (reviewed by (Bagloee et al., 2016, Sousa et al., 2017, Martínez-Díaz and Soriguera, 2018, Montanaro et al., 2018)). However, the impacts of AVs are not limited to transportation and mobility; they can also affect the economy, society, land use, environment, and public health. Literature discussions concerning the economic and societal impacts of AVs have emphasized the concomitant changes in the job market and potential improvements in transportation equity (reviewed by (Fagnant and Kockelman, 2015, Milakis et al., 2017a)). With regard to the potential impacts on land use, the literature has focused on the possible changes in an urban area after their implementation, such as urban sprawl (reviewed by (Sousa et al., 2017, Duarte and Ratti, 2018, Soteropoulos et al., 2018)). Similar to the three previous topics, the environmental impacts of AVs have also been evaluated and have typically focused on the contribution of AVs to vehicle energy efficiency through smoother driving (reviewed by (Milakis et al., 2017a, Taiebat et al., 2018)). The discussion about AVs' impacts on public health is relatively new, with less attention in the literature. A systematic review of AVs' impacts by Milakis et al. (2017) showed that there are a limited number of studies addressing this topic, and no review studies existed at the time of that review.

The literature about the health impacts of AVs was limited until recently when four review studies were published on this topic (Crayton and Meier, 2017, Dean et al., 2019, Rojas-Rueda et al., 2020, Singleton et al., 2020). Dean et al. (2019) identified and systematically reviewed the potential impacts of AVs on public health under five themes: road safety, natural environment, built environment, social equity, and lifestyle. Another attempt to identify the impacts of AVs on public health can be found in Crayton and Meier (2017), who produced a research agenda highlighting areas of potential health effects of AVs, including roadway safety, environment, aging populations, non-communicable disease, land use, and labor markets. Recently, Rojas-Rueda et al. (2020) reviewed AVs' impacts on public health, investigating the direct effects of AVs on vehicle users and the indirect effects of AVs on the broader community. The direct health impacts of AVs were identified through changes in traffic safety, physical activity, air pollution, noise, electromagnetic fields, substance abuse, work conditions, stress, and social interactions after AVs' implementation. The indirect effects are less commonly associated with AVs, but still have health implications through changes in traffic congestion, public transportation, land use, urban design, energy consumption, and accessibility. Singletone et al. (2020) looked at the health implications of AVs through a transportation lens and proposed a conceptual model for identifying AVs' impacts on health and well-being. The authors explored AVs' impacts on health by investigating the effect of transportation on traffic injury and deaths, air pollution, physical activity, and noise. Travel satisfaction, access to activities, and spill-over effect of travel satisfaction on life satisfaction were considered as potential impacts on well-being. In the following, we synthesized the health implications of AVs through the change in transportation by exploring the existing review studies.

AVs have the potential to promote public health in several directions. Fleetwood (2017) introduced AVs as one of the most critical advancements in improving public health in the

21st century, highlighting the contribution of AVs to preventing road causalities. AVs have the potential to promote public health by reducing crashes through eliminating drivers' errors (Kelley, 2017), leading to safer driving behavior via technologies (Subit et al., 2017), or enforcing driving regulations and identifying violations more efficiently by autonomous police vehicles (e.g., speeding and sudden lane changing) (Al Suwaidi et al., 2018). A study on United States crashes in 2012 showed that a 90% market penetration of AVs could save $27 billion in healthcare costs by reducing roadway crashes (Luttrell et al., 2015). Freedman et al. (2018) compared projected vehicle costs and safety benefits of private and taxi AVs in the form of saved quality-adjusted life-years based on microsimulations. The authors demonstrated the cost-effectiveness of AVs compared to regular cars. Providing the option of social inclusion and access to healthy food and medical care for people with different physical abilities were addressed in a few studies as key pathways between AVs and better health (Brooks et al., 2018, Pettigrew et al., 2018a, Pettigrew et al., 2018c). The role of AVs in mobility independence, a factor that influences individuals' health and well-being, was discussed and examined for people with intellectual disabilities (Bennett et al., 2019b). AVs also have the potential to prolong the independent living of elderly people and consequently improve their health and well-being (McLoughlin et al., 2018, Singleton et al., 2020). Moreover, the potential of AVs in reducing congestion was associated with health benefits, considering the psychological consequences attributable to stress from driving (Pettigrew et al., 2018c, Rojas-Rueda et al., 2020). Therefore, traveling with AVs could be more satisfactory, which will result in higher life satisfaction that leads to improvements in well-being (Singleton et al., 2020). In addition, AVs may contribute to public health by mitigating congestion and emission reduction, which leads to lower diseases associated with air pollution (Hardy and Liu, 2017, Crayton and Meier, 2017), non-exhaust emissions (Rojas-Rueda et al., 2020) and noise (Rojas-Rueda et al., 2020).

On the other hand, the induced transportation demand after AVs' implementation could be associated with adverse public health outcomes by increasing air pollution, and congestion through possible increases in vehicle-miles-traveled (VMT) (Lim and Taeihagh, 2018). AVs have the potential to encourage door-to-door transport and eliminate short cycling and walking trips, which will negatively impact the health of travelers by reducing their physical activity (Watkins, 2017, Spence et al., 2020). The modal shift from public transit and active transportation to private cars can decrease the rate of physical activity, which can lead to numerous health issues (Crayton and Meier, 2017, van Schalkwyk and Mindell, 2018). Also, Crayton and Meier (2017) addressed the health impacts of AVs by investigating the potential changes in urban areas, where AVs' implementation may result in denser urban areas or urban sprawl, with opposite health impacts. For instance, urban sprawl leads to an increase in automobile use and negative health impacts (Crayton and Meier, 2017).

As a result of overviewing the previous review studies, we identified three major gaps in the literature with regard to the impact of AVs on public health. First, previous studies are mainly speculative and comprised commentary articles that draw conclusions upon the author(s) opinion and perspective as opposed to quantitative or qualitative objective studies (Dean et al., 2019, Singleton et al., 2020). Second, the nature and extent of AVs' impacts carry considerable uncertainty, mainly because of uncertainties in travel demand, travel patterns, and modal shift (Milakis et al., 2017a, Crayton and Meier, 2017, Singleton et al., 2020). Third, there is an inconsistency between the identified health implications of AVs in previous review studies. While a more comprehensive investigation can be found in the recent reviews by Singleton et al. (2020) and Rojas-Rueda et al. (2020), the identified impacts still vary between these two studies. This inconsistency can be a result of the lack of a framework to systematically identify and study AVs' health impacts.

## 3. Conceptual model

We augmented prior attempts to identify the potential impacts of AVs on public health by proposing a conceptual model. To this end, we followed a framework to systematically explore the potential impacts of AVs through changes in transportation. Given that several studies have systematically reviewed AVs' impacts on transportation and the technologies, activities, land use, and infrastructure behind it (Sousa et al., 2017, Milakis et al., 2017b, Montanaro et al., 2018, Duarte and Ratti, 2018, Soteropoulos et al., 2018, Taiebat et al., 2018, Dean et al., 2019) we conducted an overview of the existing review studies to synthesize AVs' implications and develop the conceptual model.

The proposed framework is described in three steps. First, the impacts of AVs on transportation are summarized into seven points of impact, highlighting the possible changes in transportation after the implementation of AVs. Second, the transportation-related exposures and risk factors that can affect public health are outlined. Third, the potential impacts of AVs on public health are identified, consolidating the knowledge gained in the two previous steps.

### *3.1. Step 1: Potential impacts of AVs on transportation*

Fully automated AVs embody the technology of driving a vehicle without any input or monitoring by a human operator. The review efforts on synthesizing AVs' implications (Hoogendoorn et al., 2014, Milakis et al., 2017a, Soteropoulos et al., 2018, Faisal et al., 2019) showed the potential changes in traveling behavior, driving behavior, and infrastructure and the built environment after AVs' implementation. It is expected that traveling behavior will change after the implementation of AVs, given the changes in travel time (Fagnant and Kockelman, 2015), value of time (Steck et al., 2018), comfort (Elbanhawi et al., 2015), fares (both for freight and passengers), and vehicle ownership (Fagnant and Kockelman, 2018), as well as emerging traveling choices for users with different abilities and unlicensed travelers (Fagnant and Kockelman, 2015). This would influence the travelers' choice of trip, mode, and route (Soteropoulos et al., 2018). One of the most significant advantages of automated driving is eliminating human error (Haboucha et al., 2017) and changing driving behavior, which leads to safer trips as well as to more efficient roadway operations in terms of roadway throughput (Talebpour and Mahmassani, 2016). Implementing an efficient automated driving technology requires equipping transportation infrastructure with control devices, smart signs, and advanced road markings. Also, traveling behavior, driving behavior, and transportation infrastructure are not mutually exclusive. More roadway throughput can be translated into a higher level of roadway capacity, consequently reducing the need for additional infrastructure. Also, changes in travel costs may make living in a suburban area more favorable than denser and more connected urban areas (Zakharenko, 2016), which in the long-run can affect the built environment. Considering the self-driving operations of AVs, analyzing the changes in transportation after AVs' implementation, and exploring the interaction effects of these changes, we categorized the potential outcomes of fully automated AVs into seven points of impact: traffic safety, traffic flow, trip/mode/route choice, land use and the built environment, transportation equity, transportation infrastructure, and transportation-related jobs. In subsequent sections, we describe each point of impact, supporting the discussion around it with evidence identified from previous studies and the authors' knowledge as gained from the media, discussions with experts, and unpublished materials as well as the authors' opinions. Summarizing the implications of AVs through these seven points of impact enables the proposed model to capture the impacts of AVs on transportation comprehensively.

#### *3.1.1. Traffic safety*

In optimistic views, AVs are expected to prevent 94% of traffic crashes by eliminating driver's error (National Highway Traffic Safety Administration, 2018); however, AVs' operation introduces new safety issues (Kockelman et al., 2016, Litman, 2017, Yang et al., 2017b). Before AVs find their way onto highways, they will need to be tested thoroughly (Kalra and Paddock, 2016). System operation failure is one probable risk of AV operation (Koopman and Wagner, 2016). Specifically, malfunctioning sensors in detecting objects (pedestrians, bikes and cyclists, vehicles, obstacles, etc.), misinterpretation of data, and poorly executed responses can jeopardize the reliability of AVs and cause serious safety consequences in an automated environment (Bila et al., 2017). Cybersecurity is another potential concern, where hacking and misuse of vehicles can result in catastrophic crashes (Lee, 2017, Taeihagh and Lim, 2018). Another possible safety issue of AVs can be the riskier behavior of users because of their overreliance on AVs—for example, neglecting the use of seatbelts due to an increased false sense of safety (Collingwood, 2017). Also, the ethical dilemma associated with AV reactions during unavoidable crashes received the attention of researchers (Goodall, 2014, Awad et al., 2018), which underlines the necessity of programming AVs for such scenarios.

#### *3.1.2. Traffic flow*

Eliminating human error, coupled with equipping the vehicles with real-time information obtained from the connected infrastructure and other vehicles, may result in substantial changes in driving behavior. We expect that AVs drive smoother and optimize the acceleration/deceleration by incorporating information about traffic flow and eliminating unnecessary maneuvers. In a fully automated system, the gap between vehicles can be remarkably reduced, which enables vehicle platooning (Hoogendoorn et al., 2014). AVs can sense the environment, which provides AVs with a large amount of information from traffic signals, other vehicles' maneuvering, deceleration/acceleration, etc. This allows AVs to choose the optimum course of action, which can result in significant fuel savings (Fagnant and Kockelman, 2015, Yang et al., 2017a), lower levels of detrimental emissions (Igliński and Babiak, 2017), mitigation of traffic congestion and an increase in average speed (Hoogendoorn et al., 2014), and a reduction in intersection delay (Zohdy and Rakha, 2016). Furthermore, the capacity of the transportation infrastructure (e.g., roadways (Talebpour and Mahmassani, 2016) intersections, and exclusive transit lanes) can increase in an automated system.

*3.1.3. Trip, mode, and route choice*

By offering a safer, cheaper, and more comfortable traveling option for individuals with different abilities, AVs may induce additional transportation demand and encourage longer trips. AVs can also encourage shifting from public transit and active transportation (walking and cycling) to private cars (Fagnant and Kockelman, 2015). Fagnant and Kockelman (2015) estimated a 26% increase in VMT at a 90% market penetration of AVs in Austin, Texas, accounting for the possible changes in trip, mode, and route choices. Such increases in VMT can be translated into more air pollution and greenhouse gas emissions (Wang et al., 2018).

*3.1.4. Land use and the built environment*

Transportation and land use are tightly linked in urban areas (Rodrigue et al., 2016). Providing a more affordable and comfortable traveling option with AVs can increase the willingness to travel longer distances, which ultimately results in urban sprawl (i.e., migrating to areas with lower density and consequently spreading cities). There is evidence that urban sprawl increases total VMT (Childress et al., 2015), and negatively influences accessibility in an urban area (Milakis et al., 2017a). AVs' ability to operate with no passengers affects the need for parking facilities in terms of size and location (Zhang et al., 2015). In other words, parking facilities can be relocated to farther locations after AV implementation (Millard-Ball, 2019), which enables cities to densify urban areas but may increase VMT. Living in areas with higher density, greater connectivity, and mixed land use have been associated with higher rates of active transportation (Saelens et al., 2003).

### *3.1.5. Transportation infrastructure*

AVs have the potential to remarkably change the existing transportation infrastructure. First, the existing infrastructure needs to be equipped with the devices required for efficient AV operation, including control devices, signs, and roadway markings, among others. Second, AVs can change the need for road network expansion, depending on some (uncertain) results after implementation. For instance, roadway capacity might be increased because of possible vehicle platooning, which will reduce the need for new roads (Litman, 2017, Milakis et al., 2017a). On the other hand, the induced travel demand after AVs' deployment may result in an increase in the need for new roadways. Third, uncertain changes in traveling behavior can affect parking demand and, consequently, the need for parking facilities (Zhang et al., 2015).

### *3.1.6. Transportation jobs*

There is a concern about losing driving jobs after the deployment of AVs (Pettigrew et al., 2018b). Not only will driving jobs in public transit, road freight transport, and on-demand transportation be diminished, but also some vehicle-related service jobs—e.g., insurance appraisers, postal service mail carriers, police and sheriff's patrol officers, automotive service technicians, and mechanics—may be reduced or completely eliminated (Groshen et al., 2019). However, based on the results of a study on the future of jobs (with an emphasis on the role of computerization), a transformation to technology-related jobs (with different skill requirements) is anticipated after the introduction of AVs (Frey and Osborne, 2017).

*3.1.7. Transportation equity*

Individuals who do not have adequate access to transportation may have social, academic, health, and career disadvantages in comparison to their peers who do. The potential of AVs to improve transportation equity has been discussed in the literature (Milakis et al., 2017a). Enabling the elderly, the non-licensed, and individuals with mental (Bennett et al., 2019b) and physical disabilities (Bennett et al., 2019a) to participate in activities and access jobs, education, healthy food, and health care services are positive impacts of AVs in the transportation equity context (Fagnant and Kockelman, 2015).

*3.2. Step 2: Transportation and public health*

Transportation in urban areas is growing and has a significant impact on public health. Several transportation-related exposures are considered as health risk factors. These risk factors have been identified in previous studies and discussed through the most recent framework proposed by Khreis et al. (2019). Khreis and colleagues identified 14 transportation-related risk factors with considerable adverse health outcomes (Khreis et al., 2019). These risk factors and associated health outcomes are summarized in Figure 1 and are briefly described here:

1. **Motor vehicle crashes** are known as one of the most significant health risks, ranked as the 8th leading cause of death in the world and the leading cause of death among those aged 15–29 years (WHO, 2018c). Annually, motor vehicle crashes are responsible for 1.4 million global deaths (WHO, 2018c). Bhalla et al. (2014) showed that in 2010, 78.2 million nonfatal injuries warranting medical care resulted from motor vehicle crashes.
2. Transportation-related **noise** is an emerging environmental issue in urban areas, affecting a large number of people (WHO, 2018a). The level of transportation-related noise depends on the distance to roads and intersections, vehicle characteristics,

traffic flow characteristics (volume and speed), and acoustic characteristics of the urban setting (WHO, 2018a). It has been shown that noise contributes to serious health issues, such as reproductive complications, type-2 diabetes, and cardiovascular diseases (WHO, 2018a). It also has been linked to impaired cognitive performance, disrupted sleep patterns, hearing impairment, tinnitus, and mental health issues (WHO, 2018a)

3. Conservative estimates from the World Bank in 2016 attributed 4.2 million annual global deaths to **air pollution** (WHO, 2018b). Traffic-related air pollution, in particular, is responsible for one-fifth of deaths in the United Kingdom, the United States, and Germany (Lelieveld et al., 2015). Traffic-related air pollution contributes to health issues, such as lung cancer (Raaschou-Nielsen et al., 2013); respiratory disease (Kurt et al., 2016), including chronic obstructive pulmonary disease (Bhalla et al., 2014); asthma (Kampa and Castanas, 2008, Khreis et al., 2017); and cardiovascular disease (Cesaroni et al., 2014), including stroke (Bhalla et al., 2014).
4. Exposure to **heat** affects human health negatively. Transportation infrastructure exacerbates the urban heat island effect with paved surfaces compared to surrounding areas (Coseo and Larsen, 2014). Previous studies associated increased ambient temperatures with higher rates of cardiorespiratory disease (Cheng et al., 2014), reduced lung function in children (Li et al., 2014), and diabetes (Feldman et al., 2014).
5. Relying on motor vehicle transportation encourages **physical inactivity.** Physical inactivity is a contemporary public health crisis due to its role in the obesity epidemic and its contribution to numerous diseases (Khreis et al., 2016). The list of diseases that have been associated with physical inactivity is extensive and includes cardiovascular disease (ischemic heart disease, stroke), dementia, Alzheimer’s

disease, Parkinson's disease, breast cancer, diabetes, and colon cancer (Kyu et al., 2016).

6. The production of **greenhouse gases** (GHG) within cities is known as a major contributor to global warming and associated climatic changes (Dulal and Akbar, 2013). Climate change can compound the public health outcomes related to other transportation-related exposures, such as urban heat, air pollution, and decreased physical activity.
7. Transportation-related **social exclusion** refers to the culmination of transportation-related inhibitions and deprivations that limit the opportunity to participate in community activities (Özkazanç and Sönmez, 2017). Social exclusion results in negative health outcomes and diminished quality of life, life opportunities, and choices (Church et al., 2000, Kenyon et al., 2002), which can contribute to mental (Julien et al., 2015) and physical health issues. Social exclusion can increase the risk of death through lower physical activity and limited access to health care (Holt-Lunstad et al., 2015).
8. **Electromagnetic fields** (EMF) are created by differences in voltage and can be present around electricity generation stations, electric grids, and other similar infrastructure used to accommodate transportation technologies and disrupters (Halgamuge et al., 2010). EMFs has been suggested to contribute to adverse health effects, although this evidence base is under-developed and inconsistent (Kostoff and Lau, 2013, National Cancer Institute, 2019). On the one hand, some studies have shown adverse effects (Zhang et al., 2016, Li et al., 2017), on the other hand, the necessity of future investigation to uncover the health impacts of EMFs is underscored in some studies (Kostoff and Lau, 2013, Grellier et al., 2014, Calvente et al., 2016). Some of the potential health effects cited in the literature include

miscarriage (Litman, 2017); hindered children's cognitive development (Calvente et al., 2016); immune, circulatory, neural, and endocrine system performance degradation (Kostoff and Lau, 2013); gene mutations (Kostoff and Lau, 2013); abnormal cell growth (Kostoff and Lau, 2013); potentially childhood leukemia (Grellier et al., 2014); and cancer (Zhang et al., 2016).

9. Dividing spaces and people by transportation infrastructure and motorized traffic results in **community severance,** which interferes with the ability of individuals to access goods, services, and personal networks (Mindell et al., 2017). Community severance can discourage and decrease active transportation (Emond and Handy, 2012); limit social interactions (Hart and Parkhurst, 2011); lead to isolation, depression, and stress (Cohen et al., 2014); and reduce access to healthy food and healthcare services (Reiner et al., 2013).
10. Transportation grants **access** to health facilities and services, healthy food, and social activities (Litman, 2013). Participating in social activities prevents social exclusion and associated health consequences.
11. **Stress** can be associated with traffic, congestion, parking, or the fear of getting involved in a crash (Gee and Takeuchi, 2004). Commuters experience a higher level of stress during traffic congestion (Stutzer and Frey, 2008). While the private car is the most stressful mode of transportation, in contrast, active and public transportation users experience a lower level of stress (Legrain et al., 2015). The major health consequences of stress are mental problems (Schnurr and Green, 2004), cardiovascular diseases (Kivimäki and Steptoe, 2018), and type-2 diabetes mellitus (Hackett and Steptoe, 2017).
12. Engine oil, grease, pesticides, gasoline, pavement wear, tire wear, brake pad wear are motor vehicle-related **contaminants** that can be found on roadway surfaces (Hwang

et al., 2019). These contaminants are linked to a wide range of adverse health effects, including arthritis, depression, fatigue, headache, hypertension, memory loss, premature birth, reduced birth weight, kidney failure, rashes, respiratory problems, sleeplessness, and ulcers (Jaishankar et al., 2014).

13. **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). Individuals with mobility independence will benefit from the positive health consequences of the two abovementioned pathways: access and social inclusion.
14. The expansion of the transportation network in cities may result in replacing **green spaces** with transportation-related infrastructure (Nieuwenhuijsen, 2016). Exposure to green spaces can increase physical activity and social contacts (Hartig et al., 2014), reduce stress (De Vries et al., 2013), and reduce ambient pollutants such as noise, air pollution, and heat (Gascon et al., 2016). Green spaces have been associated with a number of beneficial health effects, including reduced cardiovascular disease (Tamosiunas et al., 2014), better mental health (Gascon et al., 2015), reduced birth defects (Dzhambov et al., 2014), and a lower number of premature mortalities (Gascon et al., 2016).

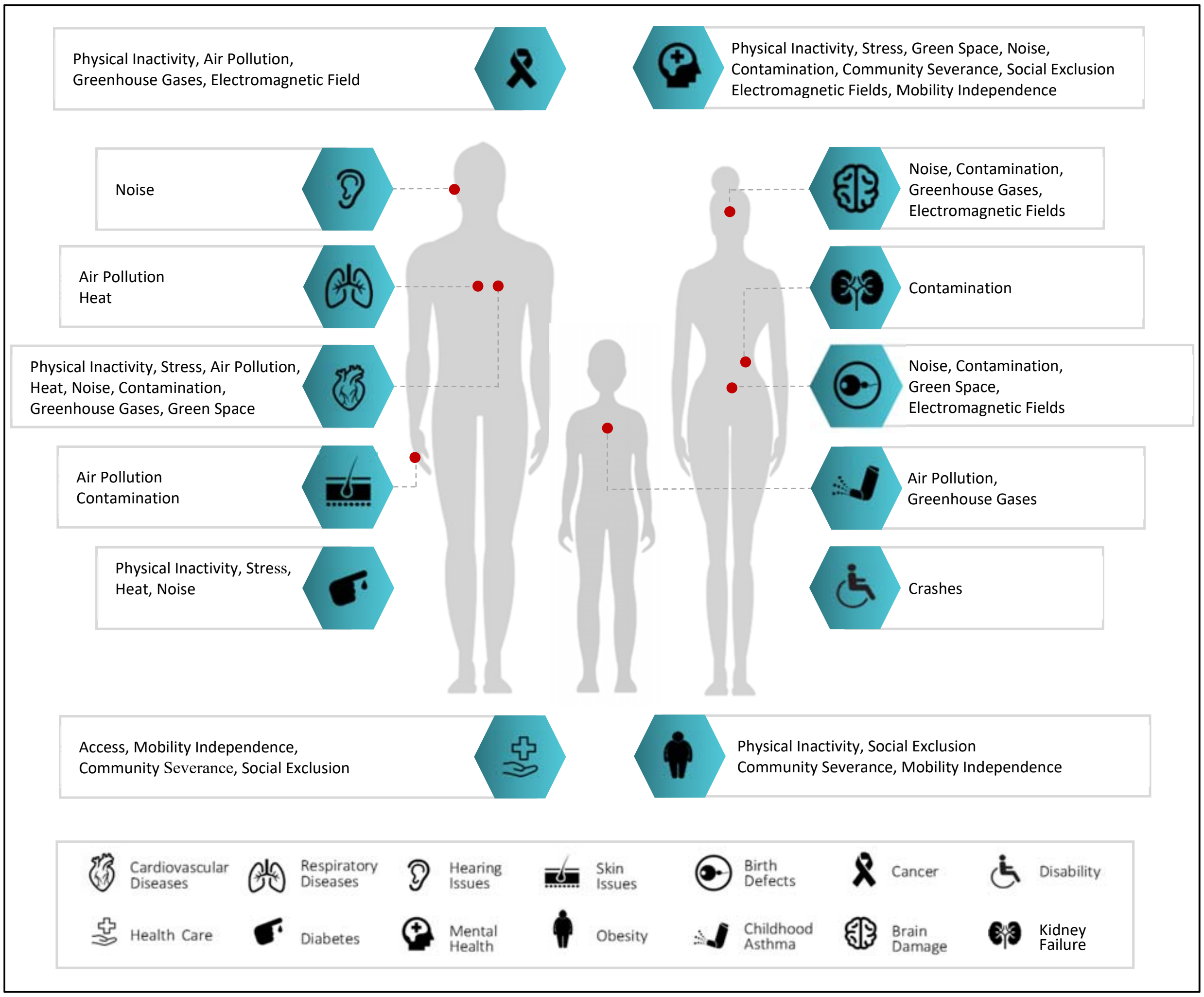



**Figure 1. Mapping health issues attributable to transportation**

### *3.3. Step 3: The health impacts of AVs*

Based on the findings from Steps 1 and 2, we formulated the linkages between AVs and public health. To this end, the potential impacts were identified by linking the seven transportation points of impact to the above-established transportation-related health risk factors. The pathways between AVs' implementation and public health can further be translated into health outcomes.

The identified pathways are illustrated in Figure 2 and are briefly described next. The pathways are categorized into three groups, adverse, positive, and uncertain impacts, based on the direction of the effects. The potential contribution of AVs to job losses is associated with social exclusion and, consequently, mental diseases and increases in premature mortality. The potential constructive role of AVs in increasing equity in transportation is linked to higher levels of accessibility to healthy food and health care, mobility independence, and social inclusion. Urban sprawl and its consequences after AVs' deployment can restrict accessibility and social inclusion and increase community severance. An increase in VMT is expected after urban sprawl, which may lead to a higher level of traffic-related noise, heat, GHG, air pollution, and contamination. While urban sprawl hinders active transportation, the possible reduction in the demand for parking facilities may free up spaces in dense urban areas and enhance urban designs that are active transportation-friendly. Changes in land use will affect the amount and distribution of green spaces in urban areas, but the nature of this effect remains unclear. Smoother traffic flow can reduce harmful exposures such as heat, GHG, air pollution, and contamination. While traffic noise may be reduced by less acceleration/deceleration of AVs, the expected rise in flow speeds can increase overall noise emissions (WHO, 2018a). The stress attributable to driving and traffic congestion can also be mitigated in an automated system. The potential of AVs in encouraging public transit and active transportation users to switch to private cars will increase the total VMT in the system, which will result in higher levels of noise, heat, GHG, air pollution, and contamination. Also, the modal shift from active transportation to motorized vehicle transportation can reduce physical activity. In addition, increases in the number of cars on the roads may exacerbate community severance. Depending on the nature and magnitude of changes in transportation demand and modal shift after the implementation of AVs, the demand for transportation infrastructure will change. Transportation infrastructure is known as a source of urban heat, it contributes to community severance, and it occupies the green spaces in an urban area. In addition, the required equipment for AVs is a source of EMFs, which in case EMFs affect human health, the impact is more likely to be negative than positive. Finally, the potential of AVs to improve traffic safety may significantly contribute to public health by reducing morbidity and mortality from motor vehicle crashes. However, the possibilities of system operation failure, malfunctioning error, cybersecurity, safety overconfidence of passengers, and vehicle performance during unavoidable crashes need to be addressed to maximize the safety benefits of AVs. More details on the identified pathways between AVs and health are reported in Table 1.

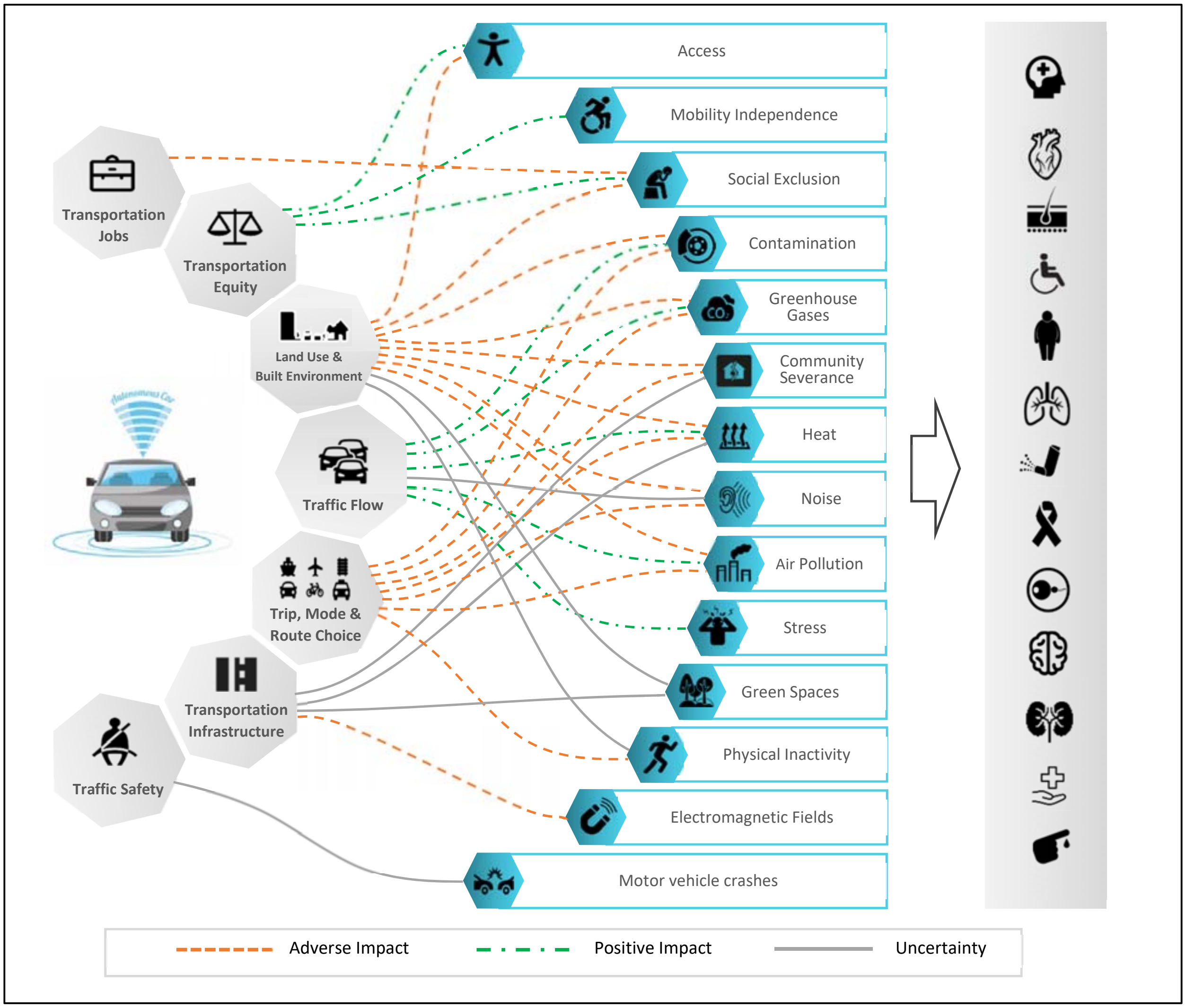



**Figure 2. The proposed conceptual model for assessing the AVs' health implications**

**Table 1. Summarizing the potential AVs impacts on public health**

| Transportation point of impact | AVs implementation impact | Uncertainty | Transportation-related health risk factors | Major health issues | Manner of impacts | Pathway number |
|---|---|---|---|---|---|---|
| **Transportation job** | Losing transportation-related job | | Social exclusion | Mental health, health care access, obesity | Adverse | 1 |
| **Transportation equity** | Providing access to social, academic, health, and jobs for elderly, non-licensed, and individuals with mental, physical and visual disabilities | | Access | Health care accessibility | Positive | 2 |
| | | | Mobility independence | Mental health, health care access, obesity | Positive | 3 |
| | | | Social inclusion | Mental health | positive | 4 |
| **Land use and built environment** | Encouraging urban sprawl and longer distance between origin and destinations | | Access | Health care accessibility | Adverse | 5 |
| | | | Community severance | Mental health, health care accessibility, obesity | Adverse | 6 |
| | | | Social exclusion | Mental health, health care access, obesity | Adverse | 7 |
| | Increasing Vehicle Miles Traveled (VMT) | | Contamination | Cardiovascular diseases, cognitive impairment, mental health, kidney failure, birth defects | Adverse | 8 |
| | | | Greenhouse gases | Cardiovascular diseases, lung cancer, asthma | Adverse | 9 |
| | | | Heat | Cardiorespiratory diseases, children respiratory diseases, diabetes | Adverse | 10 |
| | | | Noise | Cardiovascular diseases, birth defects, type-2 diabetes, cognitive impairment, mental health, hearing issues | Adverse | 11 |
| | | | Air pollution | Cardiovascular diseases, respiratory diseases, lung cancer, skin cancer, asthma | Adverse | 12 |
| | Transforming to denser and active-transportation-friendly urban design because of the changes in parking facility demand | The amount of private AVs ownership and consequently the parking demand | Green spaces | Cardiovascular disease, mental health, and birth defects | Uncertainty | 13 |
| | | | Physical inactivity | Cardiovascular diseases, mental health, breast cancer, colon cancer, obesity | Uncertainty | 14 |
| **Traffic flow** | Smoother and efficient driving with the aim of sensors and consequently increasing traffic flow and speed, and reducing traffic congestion and delay | Increasing noise emission associated with traffic speed and uncertainty in the level of the electric vehicles' market penetrations | Contamination | Cardiovascular diseases, cognitive impairment, mental health, kidney failure, birth defects | Positive | 15 |
| | | | Greenhouse gases | Cardiovascular diseases, lung cancer, asthma | Positive | 16 |
| | | | Heat | Cardiorespiratory diseases, children respiratory diseases, diabetes | Positive | 17 |
| | | | Noise | Cardiovascular diseases, birth defects, type-2 diabetes, cognitive impairment, mental health, hearing issues | Uncertainty | 18 |
| | | | Air pollution | Cardiovascular diseases, respiratory diseases, lung cancer, skin cancer, asthma | Positive | 19 |
| | | | Stress | Mental health, type-2 diabetes, cardiovascular diseases | Positive | 20 |
| **Trip, mode and route choice** | Encouraging a shift from public transit and active transportation to private cars which can increase the total VMT in the system | | Community severance | Mental health, health care accessibility, obesity | Adverse | 21 |
| | | | Contamination | Cardiovascular diseases, cognitive impairment, mental health, kidney failure, birth defects | Adverse | 22 |
| | | | Greenhouse gases | Cardiovascular diseases, lung cancer, asthma | Adverse | 23 |
| | | | Heat | Cardiorespiratory diseases, children respiratory diseases, diabetes | Adverse | 24 |
| | | | Noise | Cardiovascular diseases, birth defects, type-2 diabetes, cognitive impairment, mental health, hearing issues | Adverse | 25 |
| | | | Air pollution | Cardiovascular diseases, respiratory diseases, lung cancer, skin cancer, asthma | Adverse | 26 |
| | | | Physical inactivity | Cardiovascular diseases, mental health, breast cancer, colon cancer, obesity | Adverse | 27 |
| **Transportation infrastructure** | Producing EMF by AVs infrastructure | | Electromagnetic field | Cognitive impairment, birth defects, leukemia | Adverse* | 28 |
| | Increasing parking and roadway needs as a result of changes in transportation demand and modal shift | Increases in roadway capacity as a result of platooning and shifting to shared AVs which reduce the need for transportation infrastructure | Community severance | Mental health, health care accessibility, obesity | Uncertainty | 29 |
| | | | Heat | Cardiorespiratory diseases, children respiratory diseases, diabetes | Uncertainty | 30 |
| | | | Green spaces | Cardiovascular disease, mental health, and birth defects | Uncertainty | 31 |
| **Traffic safety** | Promoting traffic safety by eliminating drivers' error | System operation failure, malfunctioning error, cybersecurity, and safety over-feeling of passengers and vehicle performance during unavoidable crashes | Motor vehicle crashes | Disability/Fatality | Uncertainty | 32 |

*** Contingent upon future evidence on EMFs' health impacts.**

## 4. Discussion

### *4.1. Key findings*

A conceptual model was proposed to identify the health impacts of AVs' implementation systematically. The model linked AVs to public health through 32 pathways (as shown in Figure 2), of which 17 can adversely impact health, eight can positively impact health, and seven are uncertain. The adverse and uncertain health consequences were related to the anticipated changes in transportation demand, modal shift and city sprawl, increases in VMT, transportation jobs losses, EMF produced by AVs' and their infrastructure, and safety issues related to AVs' operation. Supporting policies are needed to prevent negative health consequences, or to at least alleviate them, and to facilitate the positive impacts.

### *4.2. Policy recommendations*

In this section, we highlight the policy interventions to mitigate the negative health impacts related to the deployment of AVs and maximize their benefits. The first issue that may cause AVs to impact public health adversely is the possibility of urban sprawl after AVs' implementation. In this regard, imposing traffic demand management policies (e.g., road pricing) and creating urban development boundaries were suggested to control urban sprawl (Habibi and Asadi, 2011, Fertner et al., 2016). Second, controlling for modal shift, induced transportation demand, and parking demand are potential strategies that can prevent increases in VMT and consequently help to mitigate the negative consequences of AVs' deployment. Thus, encouraging the switch from privately owned AVs to shared AVs was proposed as an effective solution to reduce the expected growth in VMT (Fagnant and Kockelman, 2014, Greenblatt and Shaheen, 2015, Krueger et al., 2016), and parking needs (Zhang et al., 2015). Traffic demand management strategies (e.g., road pricing, dedicated lanes for high-occupancy vehicles, parking pricing, VMT tax) are other alternatives that can control the transportation modal shift from public transit and active transportation to private cars. Third, replacing combustion motors with electric engines that produce less harmful vehicle emissions (Buekers et al., 2014) and contaminants, such as engine oil, can also reduce the negative impacts of AVs on public health. AVs with electric engines will be more efficient than conventional electric vehicles in terms of driving range and recharging—two major limitations of electric vehicles (Chen and Kockelman, 2016)—given the driverless operation capabilities. Fourth, losing a number of transportation-related jobs after the transition from regular cars to automated cars is inevitable. However, a smoother transition to automated driving can mitigate the social and health impacts of job losses, as it enables workers displaced by automated driving technology to develop new skills and find new jobs eventually (Center for Global Policy Solutions, 2017). Fifth, although AVs can improve traffic safety dramatically, emerging safety issues attributable to AV operation need to be fully considered. Thus, further research and design are required to significantly reduce, if not eliminate, system operation failure, malfunctioning errors, and cybersecurity issues of the vehicle. Protocols and laws are required to pre-program AVs for taking optimal courses of action during unavoidable crashes. A summary of the recommended policies and their health implications is reported in Table 2.

**Table 2. Implications of recommended AVs' supporting policies**

| Policy | Goal | Implications | Pathway to Health |
|---|---|---|---|
| **Traffic demand management** | Control modal shift from public transit and active transportation to private cars, and control urban sprawl | Reducing VMT | Contamination. greenhouse gases, heat, noise, air pollution, crashes, and community severance |
| | | Encouraging public transit and active transportation | Physical inactivity |
| | Control transportation infrastructure expansion and parking demand | Increasing urban green spaces and reducing the urban heat island effect and community severance | Green spaces, community severance, and heat |
| **Incentivize shared AVs** | Control private AVs ownership and traffic | Reducing VMT | Contamination. greenhouse gases, heat, noise, air pollution, crashes, and community severance |
| | Control transportation infrastructure expansion and parking demand | Increasing urban green spaces and reducing the urban heat island effect and community severance | Green spaces, community severance, and heat |
| **Create urban development boundaries** | Control urban sprawl | Reducing VMT | Contamination. greenhouse gases, heat, noise, air pollution, crashes, and community severance |
| | Densify cities | Encouraging public transit and active transportation, improving access and social inclusion and reducing community severance | Physical inactivity, access, community severance, and social exclusion |
| **A smoother transition to autonomous vehicles** | Alleviate transportation jobs losses | Develop new skills and find new jobs for displaced workers | Social exclusion |
| **Support research on AVs' safety** | Test AVs' safety | Promote AVs safety and address emerging safety concerns | Crashes |
| **Incentivize electric vehicles deployment** | Replacing combustion motors with electric engines | Reduce transportation-related emissions | Noise, air pollution, heat, greenhouse gases, and contamination |

*4.3. Limitations*

This study has some limitations. First, we focused on urban areas, as the majority of the world's population will be living in cities by 2050 (United Nations, 2018). Therefore, the potential health impacts of AVs in rural areas were not considered in this study. Beyond the potential to improve public health through changes in community severance, transportation equity, and traffic safety in a rural area, AVs can contribute to resolving one of the major public health crises in rural areas by facilitating access to health care (Douthit et al., 2015). Second, we chose to investigate the health impacts of fully automated vehicles, as opposed to lower levels of automation, as full automation is expected to have the most profound impacts on transportation and public health. The proposed framework in this study is expected to cover the health impacts of the lower levels of automation. However, other potential impacts, such as driver behavior during disengagement in level 3 and 4 AVs (SAE, 2016) and the associated safety consequences, need to be investigated (Favarò et al., 2018). Third, AV impacts on health were investigated through changes in transportation, but these impacts are not limited to those occurring through such changes alone. For example, vehicles can be equipped with in-vehicle health care devices (Yang and Coughlin, 2014, Grifantini, 2018) and offer medical care services. Another example is the possible change in the extent of roadway construction, with certain construction vehicle emissions and work zone safety risks occurring after AV implementation. Fourth, this study did not consider the second-order impacts of AVs on health, including facilitating the spread of communicable diseases in shared AVs (Rojas-Rueda et al., 2020), increasing substance abuse in driverless cars (Rojas-Rueda et al., 2020), a potential decrease in donated organs after reduction crashes (Rojas-Rueda et al., 2020), or spill-over effects of travel satisfaction on well-being (Singleton et al., 2020). Fifth, the short-term and temporary impacts of AVs, such as the induced stress while riding driverless cars in the short-run (Morris et al., 2017), were not discussed. Sixth, this study focused on the potential impacts of AVs on public health, with the assumption of equal accessibility and availability of vehicles to the public. Such a scenario is unlikely, and there is a high level of uncertainty in AV adoption and its potential uneven and mixed impacts across urban areas and socioeconomic classes. Seventh, the impacts of AVs with different levels of penetration rates were not considered in this study. Although the magnitude of impacts will not be similar for different levels of penetration, we expect that its direction does not change. Eight, the relationship between exposure to EMF fields and adverse human health effects remains uncertain, although research suggests the presence of negative effects. However, definitive conclusions cannot be drawn, and much research remains to be done before more concrete statements about the health effects of EMF can be made. Ninth, similar to the majority of the previous studies, the findings of this study are mainly based on speculations, approximations, and experts' opinions about AVs' implementation rather than on rigorous quantifications. Tenth, the recommended policies regarding shared AVs and electric AVs are based on the literature. Future research is required to examine their effectiveness in the context of public health. Particularly, future studies are required to consider the role of shared AVs in communicable disease and well-to-wheel emissions of electric vehicles. Finally, given that conducting a systematic review was out of the scope of this study, the proposed framework was developed based on the overview of the existing review studies. Future studies are encouraged to conduct a systematic review of these effects as more studies become available.

### *4.4. Research recommendations*

Future research should be conducted to address some of the limitations of this study. AVs' health implications are not limited to the urban areas, and future research is required to investigate AVs' impacts on rural areas. Also, while we looked at AVs' health impacts through the changes in transportation, we did not consider the second-order impacts of AVs' on public health—including the spread of communicable diseases, substance abuse in driverless cars, and limiting organ donors. Future research can investigate the broader health implications of AVs. The extent of AVs' impacts needs to be studied for different levels of automation.

The proposed framework in this study highlighted the sources of uncertainties in AVs' health impacts. Future research needs to study these uncertainties to gain a more accurate insight into AVs' impacts on public health. Since the nature and extent of AVs' impacts largely depend on the intent to use this new technology, the discussion around AVs' health impacts can benefit from accurate estimations of AVs' adaptation rates (Haboucha et al., 2017, Zmud and Sener, 2017). AVs have the potential to change the travel pattern in the urban environment and either increase or decrease the travel demand. These changes need to be further investigated for more reliable estimations of AVs' impacts (Soteropoulos et al., 2018). AVs' system operation failure and malfunctioning and AVs' cybersecurity need to be well examined before any decision regarding AVs' implementation (Lee, 2017, Taeihagh and Lim, 2018). In addition, AVs' introduce new safety and legal challenges, such as ethical decision making of AVs during unavoidable crashes (Goodall, 2014) and the potential reckless behavior of AVs' passengers to adjust their level of risk (risk homeostasis hypothesis), that should be studied in future research. In terms of AVs' related policies, more research is needed to investigate the uncertainties in the health implications of shared AVs and electric vehicles. Also, further research on the social and health implications of transportation job losses after AVs' implementations, the supporting policies to alleviate the negative health impacts, and the efficiency and practicality of smoother transition to automated driving would be beneficial. Future research is required to examine the EMF impacts on public health and AVs' health implications through the exposure to EMF. Policies will be needed to regulate the exposure to EMFs, in case of reaching a consensus that EMFs' induce negative human health effects.

Future studies can benefit from quantitative analyses of AVs' impacts on public health, in addition to monetizing these health impacts to increase their policy utility and studying the distribution of these impacts to better steer the spending of limited mitigation resources. Quantifying the health impacts of AVs is a complicated and interdisciplinary problem that requires efforts from experts in various fields, namely, automotive engineering, transportation engineering, urban and environmental policy and engineering, social science, environmental science and public health. This interdisciplinary effort, in turn, will contribute to cost-benefit analyses of AVs' implementations and would be a requisite of policy planning and evaluation. AVs' health impacts can be quantified in two-steps. First, the changes in transportation after AVs' implementations on transportation needs to be investigated based on the seven points of impacts, introduced in this study. The nature and extent of AVs' impacts can be captured by evaluating several possible scenarios for AVs' implementation. Second, the changes in transportation can be translated into health outcomes through the 32 identified pathways using health impact assessment tools (Waheed et al., 2018, Cole et al., 2019).

We suggested a list of future research to augment the discussion about AVs' health implications. The suggestions for future research are summarized in three areas, identifying impacts, quantifying impacts, and supporting policy evaluations, in Table 3.

**Table 3. Future research suggestions**

| Area | Research Topic |
|---|---|
| **Identifying AVs' impacts** | Investigating the impacts of AVs on public health in rural areas |
| | Identifying AVs' impacts during the early deployment period and for different levels of automation |
| | Exploring AVs' adoption barriers and how they affect AV implementation |
| | Identifying safety issues of AVs |
| | Identifying AVs' second-order health impacts |
| **Quantifying AVs' health implications** | Quantifying AVs' impact on public health through the 32 pathways |
| | Estimating AVs' intent to use and changes in VMT, modal split, land use and the built environment, and infrastructure and the associated health impacts |
| | Cost-benefit analysis of AVs' implementations and supporting policies |
| | Quantifying how AVs affect the frequency and severity of crashes |
| | Examining the impacts of EMF on public health and AVs' health implications through EMF emissions |
| | Analyzing AVs' impacts on transportation equity and the potential health inequalities of AVs implementation |
| | Estimating the number of job losses after AVs' implementation |
| | Examining risk homeostasis for AV users |
| **Policy evaluation** | Investigating the implications of shared AV and the associated health consequences |
| | Investigating the health implications of electric vehicles and AVs' with electric engines |
| | Introducing and evaluating potential policies to alleviate the adverse health impacts of AVs' implementation |

## 5. Summary and Conclusions

Despite the promises of AVs, this technology has negative consequences. In order to make a successful transition from conventional vehicles to AVs, supporting policies are required to govern the implementation of AVs, maximize their benefits, and mitigate their negative impacts. The focus of this study was to explore the potential impacts of AVs on public health, and we proposed a conceptual model capable of identifying these impacts systematically. We found that AVs can contribute to public health through 32 pathways—17 of which can adversely impact health, eight can positively impact health, while the impact on health is uncertain through seven pathways. The negative consequences are derived from increasing transportation demand and modal shift, increases in VMT, transportation job losses, EMF from supporting infrastructure, and safety issues related to AV operation. Controlling urban sprawl, imposing policies to control transportation demand and modal shifts, introducing policies to encourage ride-sharing, incentivizing shifting to electric vehicles with clean electricity generation, and a smoother transition to the automated system are solutions that can prevent or alleviate adverse health impacts. The applications of identifying the public health impacts of AVs are not limited to designing supporting policies—it also extends to informing the public and health sectors about the benefits and potential harms of this technology and steering research to fill current knowledge gaps.

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**Conflict of Interest**

The authors report that they have no conflicts of interest.

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