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ABSTRACT
Supporting policies are required to govern the unintended consequences of Autonomous Vehicles (AVs) implementation and maximize their benefits. The first step towards formulating policies is identifying 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. This study provides a review of the literature on AVs and public health and develops a framework to clarify the potential impacts. The proposed model, first, summarizes the potential changes in transportation after AVs implementation into seven points of impacts: transportation infrastructure, land-use, and the built environment, traffic flow, transportation mode choice, transportation equity, jobs related to transportation, and traffic safety. Second, the transportation-related risk factors that affect public health are outlined. Third, we formulate the pathways between AVs and public health using the knowledge gained from two previous steps. The review of the literature shows that the discussion around AVs impacts on public health is gaining increasing research attention in recent years but still needs more attention. Using the proposed model, we found that AVs can be associated with public health through 32 pathways, where they can adversely impact health through 24 of those. The health impacts of AVs are contingent upon supporting policies. Equipping AVs with electric motors, regulating urban area development, implementing traffic demand management, controlling AVs ownership, and imposing ride-sharing policies are the strategies that can reinforce the positive impacts of AVs on public health.

Keywords: Autonomous vehicle; Public health; Unintended impact; Supporting policy; Pathways to health
INTRODUCTION

Alongside the promises of Autonomous Vehicles (AVs), several unintended (negative) consequences are expected after their implementation (Pakusch et al., 2018). Supporting policies are required to govern the negative consequences of AVs and maximize their benefits. The first step toward formulating policy 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). Hitherto, a number of studies have addressed the impacts of AVs on transportation and mobility including investigating 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. AVs also contribute to the economy, society, land-use, environment, and public health. The impacts of AVs implementation on the economy and society are discussed in the literature, emphasizing the changes in the job market and potential improvements in transportation equity (reviewed by (Fagnant and Kockelman, 2015, Milakis et al., 2017)). The potential impacts of AVs on land-use are also discussed in the literature focusing on the possible changes in an urban area after the implementation of AVs, such as urban sprawl (reviewed by (Sousa et al., 2017, Duarte and Ratti, 2018, Soteropoulos et al., 2018)). The environmental impacts of AVs have also been evaluated, which usually focused on AVs' contribution to the energy efficiency of vehicles through smoother driving (reviewed by (Milakis et al., 2017, Taebat et al., 2018)). Despite the numerous attempts to recognizing and framing the outcomes of AVs implementation, Milakis et al. (2017) pointed out that the discussion around the public health impacts of AVs is still in its infancy (no review study exists to the best of authors’ knowledge).

Despite the little literature on the impacts of AVs on public health, there is a growing field of information on how transportation, and the systems, technologies, activities, land-use, and infrastructure behind it, dramatically impacts health (Khreis et al., 2016). A significant number of deaths worldwide are attributable to transportation. 1.4 million road deaths were reported globally in 2016 (World Health Organization, 2018c) and 4.2 million deaths attributed to ambient air pollution in the same year (World Health Organization, 2018b). In particular, traffic-related air pollution is responsible for one-fifth of deaths in the UK, U.S., and Germany (Lelieveld et al., 2015). Traffic noise (World Health Organization, 2018a), contaminants from traffic (Burant et al., 2018), traffic-related stress (Wei, 2015), lack of active travel and physical activity (Reiner et al., 2013) and greenhouse gases (Woodcock et al., 2009) are a few other detrimental impacts of transportation which lead to worse health as manifested in increased morbidity and mortality. Given that AVs may radically transform transportation systems, and therefore, the associated exposures, the potential impacts of AVs on public health needs more attention. Understanding the role of AVs in public health is not only required for better governing AVs but also underlines the importance of engaging the health sector in legislative, regulatory and policy decision making for the deployment of AVs.

In this study, we identify the impacts of fully automated vehicles (level six according to the Society of Automotive Engineers definition (Society of Automotive Engineers, 2016)) on public health in an urban area. The contribution of this paper is threefold. First, we review the literature and summarize previous discussions around AVs' impacts on public health. Second, we address the detected gap in the literature by proposing a systematic framework in the form of a conceptual model to recognize the potential beneficial and adverse impacts of AVs on public health through changes in transportation, and transportation-related exposures, after AVs implementation. Third, we discuss the required supporting policies to control the negative
consequences of AVs implementation, drawing on the proposed conceptual model. The results of this study could be used for making more informed decisions about AVs supporting policies, increasing the public awareness of health impacts of AVs, and incentivizing the health sectors to intervene and contribute to policymaking and investments regarding AVs.

**LITERATURE REVIEW**

The AVs impacts on public health are discussed in the literature, stressing on its role in backcasting and before formulating potential policies for better governing AV (Li et al., 2018). Milakis et al. (2017) reviewed the potential effect of AVs that are relevant to policy and society, including impacts of AVs on public health, and unveiled the lack of research on this matter. From the policy implementation perspective, public awareness of the potential health benefits of AVs can facilitate the acceptance of AVs regulation and also enhance vehicle adoption (Pettigrew, 2017). However, the lack of awareness of the potential health benefits of AVs is shown in a survey conducted by Pettigrew et al. (2018c). An attempt to identify the uncertainties in AVs impacts on public health by Crayton and Meier (2017) resulted in a research agenda highlighting areas of the potential effects of AVs, including roadway safety, environment, aging populations, non-communicable disease, land-use, and labor markets. Further below, we synthesize the Crayton and Meier’s results with other existing evidence from previous studies on the health consequences of AVs implementation. We summarize the benefits and elaborate on the detrimental impacts as discussed in the literature.

Fleetwood (2017) introduced AVs as one of the most critical advancements in improving public health in the 21st century, by highlighting AVs contribution to preventing road causalities. AVs have the potential to promote public health by reducing crashes through eliminating drivers’ error (Kelley, 2017), leading to safer driving behavior via technologies (Subit et al., 2017), or enforcing driving violation (e.g., speeding and sudden lane changing) efficiently using autonomous police vehicle (Al Suwaidi et al., 2018). A study of U.S. crashes in 2012 shows that $27 billion in healthcare costs attributable to roadway crashes may be saved with a 90% market penetration of AVs (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 (from microsimulations). The authors showed the cost-effectiveness of AVs compared to regular cars. Bennett et al. (2019) discussed the role of AVs in mobility independence for people with intellectual disabilities as a factor that influences individuals’ health and wellbeing. Providing the option of social inclusion and access to healthy food and medical care for people with different physical abilities was addressed in a few studies as one pathway between AVs and better health (Brooks et al., 2018, Pettigrew et al., 2018a, Pettigrew et al., 2018c). In addition, AVs have the potential to prolong independent living of elderly people and consequently improve their health and well-being (McLoughlin et al., 2018). The potential of AVs in reducing congestion was discussed as a contributor to health by mitigating psychological consequences attributable to stress (Pettigrew et al., 2018c). AVs may also contribute to public health is by mitigating congestion and improving the energy efficiency of traveling which leads to less air pollution and associated diseases (Hardy and Liu, 2017, Crayton and Meier, 2017).

On the other hand, the induced transportation demand after AVs implementation adversely impacts public health by increasing air pollution and congestion (Lim and Taeihagh, 2018). AVs has the potential to encourage door-to-door transport by eliminating short cycling and walking trips, which will negatively impact traveler health by reducing physical activity (Watkins, 2017). The modal shift from public transit and active transportation to private cars
may lead to a decrease in physical activity which can be translated to numerous health issues (Crayton and Meier, 2017, van Schalkwyk and Mindell, 2018). The uncertainty in public health consequences of the possible changes in cities after AVs implementation is discussed by Crayon and Meier (2017).

Despite the discussed importance of identifying AVs' role on public health for both policy-making purposes and public awareness, a few studies have focused on this matter. The reviewed studies are mainly commentary articles and are concluded based on the author(s) opinion. Although a number of potential public health consequences are associated with AVs implementation in the literature, many other potential impacts are missing because of a lack of a systematic framework for identifying the impacts. The uncertainty in the consequences of AVs' implementations is usually not considered in the literature, and even if analyzed (in a few studies), the method of analysis is not discussed. In this study, we addressed the mentioned gaps in the literature by proposing a systematic framework for identifying the AVs impacts on public health and the potential uncertainty in the consequences. The proposed model and the discussion around it are supported by evidence from previous studies.

MODEL

We augment prior attempts to identify the potential impacts of AVs on public health by proposing a conceptual model. The model is described in this section in three steps. First, the impacts of AVs on transportation is summarized into seven points of impacts, highlighting the possible changes in transportation after AVs implementation. Then, the transportation-related risk factors that can affect public health are outlined. Third, the potential impact of AVs on public health is identified using the knowledge gained in the two previous steps.

Step 1: Potential impacts of AVs on transportation

Fully automated vehicles are the technology of driving a vehicle without any input or monitoring by a human operator (also known as a self-driving car), which is possible through the capability of sensing the environment. From the authors’ perspective, AVs' impacts on the existing transportation system can be discussed through changes in traveling behavior, driving behavior, and infrastructure and built environment. The changes in traveling behavior after AVs implementation are anticipated because of changes in travel time, the value of time, comfort, fares (both for freight and passengers), vehicle ownership and emerging new traveling choices for users with different abilities and unlicensed travelers. This would influence the trip, mode and route choices. One of the most significant advantages of automated driving is eliminating human error and improving driving behavior, which leads to safer trips as well as more efficient traffic flow. Implementing AVs’ technology requires equipping transportation infrastructures with control devices, smart signs and advanced road marking to be wirelessly connected to the AV (vehicle to infrastructure connection). The above mentioned three major concepts of transportation systems (traveling behavior, driving behavior, transportation infrastructure) are in interaction. For instance, more efficient traffic flow can be translated to more roadway capacity and consequently, reducing the need for infrastructure. Also, changing in travel cost makes living in a suburban area more favorable than denser urban areas, which in the long run can affect the built environment. The impact of AVs on transportation is illustrated in Figure 3. Considering the AVs capability of operating without any human driver and by investigating the possible changes in the transportation system and their interaction, we categorize the potential outcomes of AVs implementation into seven groups comprising: traffic safety, traffic flow, mode choice,
land-use and built environment, transportation equity, transportation infrastructure, and transportation-related jobs. These categories are elaborated based on the evidence identified from previous studies, the knowledge gained from media, experts’ opinions and unpublished discussions, as well as the authors’ opinion.

![Figure 3. Illustration of AVs impacts on transportation](image)

**Traffic safety**

In optimistic views, eliminating human error through an automated system is expected to reduce roadway crashes by 94% (National Highway Traffic Safety Administration, 2018). Although traffic crashes with driver responsibility are anticipated to be prevented after implementing AVs, other safety issues may emerge (Kockelman et al., 2016, Litman, 2017, Yang et al., 2017b). Before AVs find their way on roads, the vehicle needs to be tested thoroughly. Since system operation failure is one probable risk that AVs operation may encounter (Koopman and Wagner, 2016), malfunctioning sensors, cameras, and computers can jeopardize the reliability of AVs and cause serious safety consequences in an automated environment (Bila et al., 2017). Cybersecurity is another potential concern of AVs operation 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 neglecting using seatbelt due to the increased safety feeling of passengers riding AVs (Collingwood, 2017). Also, the uncertainty in AVs reaction during unavoidable crashes received the attention of researchers (Goodall, 2014, Awad et al., 2018), which underlines the necessity of programming AVs for such unforeseeable scenarios.

**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 cars drive smoother by optimizing the acceleration/deceleration in traffic flow and eliminating unnecessary maneuvers. In a fully automated system, the gap between vehicles can be remarkably reduced, which contributes to
vehicle platooning. AVs can communicate with infrastructure and other vehicles (e.g.,
intersection signals) which let vehicle (via its computer) choose the optimum course of action
while driving. This can result in significant fuel savings (Fagnant and Kockelman, 2015, Yang et
al., 2017a) along with lower level of detrimental emissions (Igliński and Babiak, 2017), a
reduction in traffic congestion and increasing in the flow speed (Hoogendoorn et al., 2014), and
decreasing the intersections’ delay (Zohdy and Rakha, 2016). Furthermore, the capacity of the
transportation infrastructure, including roadways (Talebpour and Mahmassani, 2016),
intersections, and exclusive transit lanes could increase in a fully automated system.

Trip, mode and route choice

More comfortable, safer and cheaper traveling along independence in transportation for
individuals with different abilities may induce additional transportation demand and encourages
longer trips after the implementation of AVs. AVs make cars a more favorable mode of
transportation that may lead to a shift from public transit and active transportation (walking and
cycling) to the private car. Therefore, more cars are expected to travel on roads. Fagnant and
Kockelman (2015) estimated a 26% increase of vehicle miles traveled (VMT) at a 90% market
penetration rate of automated vehicles in Austin, Texas, by encountering the possible changes in
the trip, mode and route choice after AVs implementations. The increase in VMT can be
translated into more air pollution and greenhouse gases emission (Wang et al., 2018).

Land-use and built environment

Transportation and land-use are in a close relationship in urban areas (Rodrigue et al.,
2016). Providing a more affordable and comfortable traveling option with AVs can increase
willingness to travel longer distances, which ultimately can cause city sprawling (migrating to
the area with lower density and consequently spreading cities). Sprawl will result in increases in
total VMT (Childress et al., 2015) and influences accessibility (Milakis et al., 2017) in the urban
area. AVs also need different parking facilities in term of size and location (Zhang et al., 2015).
The changes in parking demand and AVs ability to operate with no passenger provides the
opportunity of relocating parking facilities from dense urban areas to farther areas (Millard-
Ball, 2019). Also, the anticipated changes in land-uses enable urban planners to design more
active-transportation-friendly urban environment.

Transportation infrastructure

AVs can change the existing transportation infrastructure remarkably. First, the existing
infrastructure needs to be equipped with the devices required for AVs operation, including
control devices, signs, roadway marking, pavement, etc. Second, AVs can change the
requirement of road networks expansion depending on the uncertainties in implementations. For
instance, increasing roadway capacity from the possibility of vehicle platooning will reduce the
needs of new roads (Litman, 2017, Milakis et al., 2017). On the other hand, changes in traveling
behavior and land-use may result in growing the needs of roadways. Third, changes in traveling
behavior can affect the parking demand and consequently, the need for parking facilities (Zhang
et al., 2015).

Transportation jobs

There is a concern relating to job losses in driving occupations after the deployment of
AVs (Pettigrew et al., 2018b). Not only driving jobs in public transit, road freight transport, and
on-demand transportation diminish 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 eliminated (Groshen et al., 2019). However, new jobs will be created after the AVs’ implementation. Based on the results of a study on the future of jobs, emphasizing the role of computerization, a transformation to technology-related jobs (with a different skill requirement) is anticipated after the introduction of AVs (Frey and Osborne, 2017).

*Transportation equity*

Individuals who do not have easy access to transportation may have social, academic, health, and career disadvantage in comparison to their peers. AVs have the potential to grant equity in transportation (Milakis et al., 2017) by enabling the elderly, non-licensed, and individuals with mental, physical and visual disabilities to participate in activities, access jobs, education, and healthy food, and maintain their access to health care (Fagnant and Kockelman, 2015).

**Step 2: Transportation and public health**

Transportation in urban areas is growing and has significant impacts on public health. Several transportation-related health risk factors have been identified in previous studies and linked to health outcomes (have been discussed extensively in (Khreis et al., 2019)). A summary of the health impacts attributable to transportation-related risk factors (borrowed from are (Khreis et al., 2019)) is depicted in Figure 4. The 14 risk factors are briefly described as follows:

1. **Motor vehicle crashes** are one the most significant health risk factors, ranked as the 8th leading cause of death in the world and the leading cause of death amongst those aged 15-29 (World Health Organization, 2018c).
2. **Traffic noise** is one of the environmental issues, particularly in urban areas, affecting a large number of people. Noise level is dependent on factors such as road networks, intersections, traffic flow and speed, acoustics, and meteorological conditions (World Health Organization, 2018a).
3. Conservative estimates from the World Bank in 2016 attributed 4.2 million annual deaths worldwide to **air pollution** (World Health Organization, 2018b), where traffic-related air pollution can be responsible for one-fifth of deaths in the UK, U.S., and Germany (Lelieveld et al., 2015).
4. Exposure to **heat** may affect human health. Transportation infrastructures contribute to the urban heat island effect with bigger surface and air temperatures compared to surrounding rural areas (Coseo and Larsen, 2014).
5. The production of **greenhouse gases** (GHG) within cities has been a significant contributor to global warming and the associated climatic changes (Dulal and Akbar, 2013).
6. Relying on motor vehicle transportation leads to increase in physical inactivity which is considered as a public health crisis due to its role in the obesity epidemic and contribution to numerous diseases (Khreis et al., 2016).
7. **Social exclusion** refers to the culmination of transportation-related inhibitions and deprivations that limit the opportunity to participate in community activities.
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.

9) Dividing space and people by transportation infrastructure and motorized traffic (characterized by traffic flow rate and speed) refer to community severance which interferes with the ability of individuals to access goods, services, and personal networks (Mindell et al., 2017).

10) Transportation grants access for individuals to health facilities and services, healthy food, and enable them to participate in activities (Litman, 2013).

11) **Stress** can be associated with traffic, congestion, or fear of getting involved in a crash. Commuters experience a higher level of stress during traffic congestion (Stutzer and Frey, 2008) and driving private car is the most stressful mode of transportation, while active and public transportation users experience a lower level of stress (Legrain et al., 2015).

12) Oils, gasoline, heavy metals, flame retardants, particulate matter, and hydrocarbons are contaminations that can be found on roadway surfaces due to motor vehicle traffic (Gaffield et al., 2003) which have adverse impacts on human health.

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).

14) **Green space** is a land that is partially or entirely covered with grass, trees, shrubs, or other vegetation that is accessible to the public. Green spaces have been associated with a number of beneficial health effects.
Step 3: AVs health impacts

Based on the findings documented in steps 1 and 2, we associated AVs' implementation in an urban area with public health. The impacts of AVs on public health were identified by linking the changes in the seven transportation points of impacts to the above-established transportation-related health risk factors. The pathway between AVs implementation and public health can be ultimately translated into health outcomes.

Identified pathways are illustrated in Figure 5. AVs potential contribution to job losses is associated with social exclusion and consequently, mental diseases and potential increases in premature mortality. The potential constructive role of AVs in increasing equity in transportation is linked to a higher level of accessibility to healthy food and health care, mobility independence, and social inclusion. City sprawling and its consequences after AVs' implementation can restrict accessibility and social inclusion, and increase community severance. Increases in traffic-related noise, heat, GHG, air pollution and contamination are attributable to a rise in VMT after city sprawling. While sprawl hinders active transportation, the possible reduction in parking facilities enhances urban designs that can encourage active transportation. Changes in land-use will affect the amount and distribution of green spaces in urban area. Smoother traffic flow will reduce...
harmful traffic exposures, such as heat, GHG, air pollution, and contamination. While the traffic noise can be reduced by less acceleration/deceleration, the expected higher flow speed will increase the traffic noise level (World Health Organization, 2018a). Also, stress attributable to driving and traffic congestions can be eliminated (or at least mitigated) in an automated transportation system. The potential of AVs in encouraging a shift from public transit and active transportation to private cars can increase total VMT in the system, which can be translated to higher traffic noise, heat, GHG, air pollution and contamination. Shifting from active transportation to cars can reduce the amount of physical activity. Increases in traffic flow may also result in more community severance. Given the magnitude changes in transportation demand and modal shift after AVs implementation, more or fewer infrastructures are required. Transportation infrastructure is associated with urban heat and community severance as well as green spaces. Required AVs equipment is a source of electromagnetic fields with adverse health impacts. Finally, AVs impact on promoting traffic safety may significantly contribute to public health by reducing morbidity and mortality from roadway crashes. However, the system operation failure, malfunctioning error, cybersecurity, safety over-feeling of passengers, and vehicle performance during unavoidable crashes need to be addressed to maximize the safety benefits of AVs. The identified pathways between AVs and health are reported in detail in Table A1.
Figure 5. The proposed conceptual model for assessing the impact of AVs’ implementation on public health

DISCUSSION

Key findings

The proposed model sheds light on the potential impacts of AVs on public health. AVs’ implementation was linked to public health through 32 pathways, as is shown in Figure 5, where AVs can adversely impact health through 24 pathways. The adverse consequences were derived from anticipated changes in transportation demand and modal shift, increases in VMT, transportation jobs losses, the produced electromagnetic fields in the required infrastructure, and safety issues related to AVs operation. Supporting policies are needed to prevent negative consequences or at least alleviate them. We highlighted the key issues that need to be addressed to mitigate the negative health impacts related to the deployment of AVs and maximize their benefit.
Policy recommendation

The first issue that may cause AVs to impact public health adversely is the possibility of urban sprawling after AVs implementation. To control sprawling of an urban area, imposing traffic demand management policies (e.g., road pricing) and creating urban boundaries are suggested (Habibi and Asadi, 2011, Fertner et al., 2016). Second, controlling for modal shift, induced transportation demand, parking demand and expected increase in VMT was introduced as countermeasures that can lessen the unintended consequences of AVs' implementation. Encouraging switching from privately owned AVs to shared AVs is an effective solution to reduce the expected growth in VMT (Fagnant and Kockelman, 2014, Greenblatt and Shaheen, 2015, Krueger et al., 2016) as well as private car ownership (Fagnant and Kockelman, 2018). Classic traffic demand management strategies (e.g., road pricing, dedicated lanes for high-occupancy vehicles, parking pricing, VMT tax) are other alternatives that can regulate the transportation modal shift and persuade drivers to abandon private vehicles. Third, replacing combustion motors with electric engines can reduce harmful vehicle emissions, such as air pollutants and noise (Buekers et al., 2014). However, it has been suggested that Electric Vehicles (EVs) emit more non-exhaust emissions (Timmers and Achten, 2016). Potential strategies to reduce these emissions include reducing EVs weight, improved tires design and regenerative brakes (Timmers and Achten, 2016). AVs with electric engines will be more efficient comparing to conventional EVs in term of driving range and recharging (major limitation of EVs according to (Chen and Kockelman, 2016)). Fourth, although losing transportation jobs after the transition from regular cars to automated cars is inevitable, a smoother transition can mitigate the social and health impacts of job losses. Fifth, AVs required infrastructure and equipment should be controlled to avoid health issues. Standard settings need to be developed to regulate the AVs infrastructure based on a reference threshold exposure level that provides health protection (World Health Organization, 2006). Sixth, although autonomous vehicle can improve traffic safety dramatically, emerging safety issues attributable to AVs 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 managing cybersecurity of the vehicle. Protocols and laws are required to pre-program AVs for optimal reacting during unavoidable crashes.

Limitations

This study contains some limitations. First, we focused on AVs impacts on health in urban areas because of the bolder role of transportation in health in an urban area and the fact that the majority of the global population are expected to live in urban areas by 2050 (68% from United Nations (United Nations, 2018)). The potential role of AVs in rural areas, such as providing access to health care, need to be addressed in future studies. Second, AVs impacts on health are investigated through changes in transportation; nonetheless, AVs’ health impacts are not limited to those occurring through changes in transportation. For instance, vehicles can be equipped with in-vehicle health care devices (Yang and Coughlin, 2014, Grifantini, 2018) and offer medical care services, issues which we did not discuss in the current study. Another example is the possible change in the volume of roadway constructions (depending on increase/decrease of roadway demand) after AVs implementations with certain health impacts considering the construction vehicles emissions and work zone safety issues. Third, this study does not consider 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). Fourth, 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. A higher level of uncertainty is expected when accounting for disparities in AVs adoption and its uneven distribution across the urban area. Fifth, AVs impacts for different levels of the AVs penetration rate are not considered in this study. Although the magnitude of impacts will not be consistent for different levels of AVs penetration rate, we expect that its direction does not change. In other words, this study has the potential to reflect the impacts of AVs on public health for different AVs penetration rates.

Research recommendations
Further studies are suggested to address the limitations of this study—namely, to investigate the impacts of AVs on public health in rural areas, the short term impacts of AVs, the AVs adoption obstacles and how it affects AVs implementation and the extent of health impacts for different levels of market penetration. Also, quantifying the impacts of AVs on health will contribute to cost-benefit analyses required to support decision-making regarding AVs policies and investments. The proposed framework in this study can be utilized for further health impact assessment of AVs.

SUMMARY AND CONCLUSIONS
Despite the promises of AVs, this technology has unintended consequences. For a successful transition from conventional vehicles to AVs, supporting policies are required to govern the implementation of AVs to maximize their benefits and mitigate their negative impacts. The focus of this study was to discuss the potential impacts of AVs on public health. In addition to reviewing previous studies on this topic, we proposed a conceptual model to identify the potential impacts of AVs on public health systematically. We found that AVs can contribute to public health through 32 pathways; 24 of them are associated with adverse health impacts. The adverse consequences are derived from changes in transportation demand and modal shift, increases in VMT, transportation jobs losses, the produced electromagnetic fields from AVs required infrastructure and safety issues related to AVs operation. Regulating urban sprawl, imposing policies to control transportation demand and modal shift, introducing policies to encourage shared-riding, supporting vehicles with electric engines, smoother transition to the automated system for mitigating job transformation adverse impacts, and reducing and regulating electromagnetic fields from AVs infrastructures are solutions that can prevent or alleviate adverse public health impacts. The applications of identifying AVs impact on public health is not only limited to designing supporting policies but also informing the public and health sectors about the benefits and harms of this technology. Awareness of the public of the potential impacts of AVs would affect vehicle adoption and the transition to automated driving. Public health impacts of AVs can encourage health sectors to intervene and contribute to investments and policymaking.

AUTHOR CONTRIBUTIONS
The authors confirm contribution to the paper as follows: study conception and design: Soheil Sohrabi. data collection: Soheil Sohrabi and Haneen Khreis. analysis and interpretation of results: Soheil Sohrabi, Haneen Khreis, and Dominique Lord; draft manuscript preparation: Soheil Sohrabi. All authors reviewed the results and approved the final version of the manuscript.
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