Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

ANNUAL REVIEWS

Annual Review of Public Health

Autonomous Vehicles and Public Health

David Rojas-Rueda,[1,2] Mark J. Nieuwenhuijsen,[2,3,4,5] Haneen Khreis,[2,3,4,6] and Howard Frumkin[7]

[1]Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, Colorado 80523, USA; email: david.rojas@colostate.edu

[2]ISGlobal, Centre for Research in Environmental Epidemiology (CREAL), Barcelona 08003, Spain; email: mark.nieuwenhuijsen@isglobal.org

[3]Universitat Pompeu Fabra (UPF), Barcelona 08003, Spain

[4]CIBER Epidemiología y Salud Pública (CIBERESP), Madrid 28029, Spain

[5]Municipal Institute of Medical Research (IMIM), Hospital del Mar, Barcelona 08003, Spain

[6]Center for Advancing Research in Transportation Emissions, Energy, and Health (CARTEEH), Texas A&M Transportation Institute (TTI), Texas 77843, USA; email: H-Khreis@tti.tamu.edu

[7]Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, Washington 98195, USA; email: frumkin@uw.edu

ANNUAL REVIEWS CONNECT
www.annualreviews.org
• Download figures
• Navigate cited references
• Keyword search
• Explore related articles
• Share via email or social media

Annu. Rev. Public Health 2020. 41:329–45

First published as a Review in Advance on January 31, 2020

The *Annual Review of Public Health* is online at publhealth.annualreviews.org

https://doi.org/10.1146/annurev-publhealth-040119-094035

Copyright © 2020 by Annual Reviews. This work is licensed under a Creative Commons Attribution 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See credit lines of images or other third-party material in this article for license information.

OPEN ACCESS (cc) BY

Keywords

autonomous vehicles, self-driving cars, public health, environmental health, transportation, built environment

Abstract

Autonomous vehicles (AVs) have the potential to shape urban life and significantly modify travel behaviors. "Autonomous technology" means technology that can drive a vehicle without active physical control or monitoring by a human operator. The first AV fleets are already in service in US cities. AVs offer a variety of automation, vehicle ownership, and vehicle use options. AVs could increase some health risks (such as air pollution, noise, and sedentarism); however, if proper regulated, AVs will likely reduce morbidity and mortality from motor vehicle crashes and may help reshape cities to promote healthy urban environments. Healthy models of AV use include fully electric vehicles in a system of ridesharing and ridesplitting. Public health will benefit if proper policies and regulatory frameworks are implemented before the complete introduction of AVs into the market.

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

1. INTRODUCTION

Globally, more people are living in urban than in rural areas, with 55% of the world's population residing in urban areas in 2018 (77). The urban environment shapes populations through multiple health pathways, such as physical activity, air pollution, green spaces, social capital, access to health services, and transport, among others (60, 89). Urban transportation policies, in particular, have been suggested as a principal pathway through which urban environments can either impair or promote health (23, 60). This field is dynamic and rapidly evolving; recent advances in technology have led to transportation innovations such as multimodal integration via online applications, on-demand digitally enabled transportation, electrification of motorized transportation, and connected autonomous vehicles (AVs) (26).

AVs are considered a major disruptive technology in the transportation sector, with the potential to produce significant changes in travel behaviors and the built environment (42). "Autonomous technology" refers to technology that has the capability to drive a vehicle without active physical control or monitoring by a human operator (74). There are six levels of vehicle autonomy, as defined by the Society of Automotive Engineers (SAE): Levels 0–2 are those where the human driver needs to monitor the driving environment, and levels 3–5 are those where an automated driving system monitors the driving environment (also referred to in the US federal policy guidance as highly automated vehicles) (69, 92). A fully autonomous vehicle is a vehicle that has a full-time automated driving system that undertakes all aspects of driving that would otherwise be undertaken by a human, under all roadway and environmental conditions (64). This article focuses on the role of higher levels of AVs in public health.

In 2018, Waymo, the Google subsidiary developing AVs, introduced the first shared AV fleet to the market (Waymo-One) (**https://waymo.com/**). More than 1,400 self-driving cars, trucks, and other vehicles are currently being tested by more than 80 companies across 36 US states and the District of Columbia (25). Recent estimates suggest that by 2020, 5% of car sales will be AVs, representing 2% of the vehicle fleet and 4% of the miles traveled in the United States (42). The same estimates predict that by 2030, AVs will cover 40% of the car market sales, representing 20% of the vehicle fleet and 30% of the miles traveled in the United States (42).

The potential impacts of AVs on public health could vary depending on the level of automation, type of use and ownership, and type of engine (internal combustion, hybrid, electric, etc.). In terms of automation, this review refers mostly to those AVs with full automation (where an automated driving system performs all aspects of the dynamic driving task under all roadway and environmental conditions). Various patterns of AV ownership and use have been suggested; for instance, private AVs imply private vehicle ownership and private use, and shared autonomous vehicles (SAVs) imply shared uses, with or without vehicle ownership. Variants include carsharing, personal vehicle sharing, ridesharing, and on-demand services (**Figure 1**). Carsharing is a model of shared transportation in which several people use the same vehicle at a different time without car ownership. Carsharing may be station based, where the car is picked up and returned to the same location, and free floating, where the car is picked up at one location and left near the user's destination. Personal vehicle sharing is a system in which car owners convert their personal vehicles into shared cars and rent them to others on a short-term basis; this arrangement could be between peers (peer-to-peer) or through shared vehicle ownership (fractional ownership). Ridesharing pools multiple travelers with similar or overlapping paths (origins/destinations) and departure times in the same vehicle (carpooling or vanpooling). On-demand services refer to vehicle sharing with door-to-door services and are classified as ridesourcing or ridesplitting. Ridesourcing is a door-to-door service that uses private vehicles for paid on-demand rides (such as Uber or Lyft). Ridesplitting is a variant of the ridesourcing model, in which passengers with similar or overlapping routes split a fare and ride in a ridesourcing vehicle (such as an Uber pool).

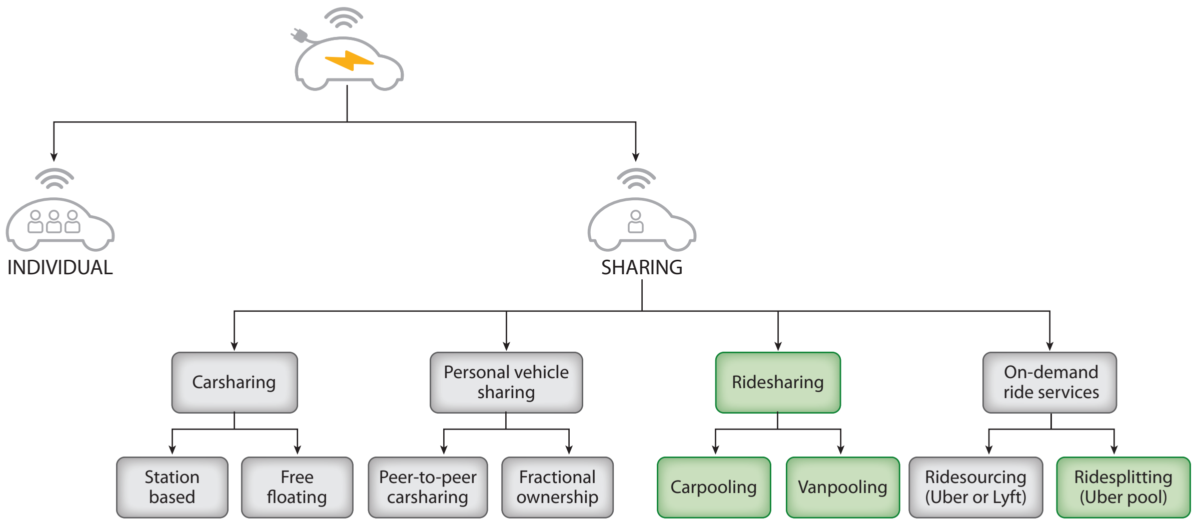

Figure 1

Autonomous vehicles by type of use and ownership (*green* indicates options with greatest expected health benefits and fewest health risks).

AV use and ownership could translate meaningfully into health impacts. AV use and ownership variations could increase health risks, by increasing overall vehicle miles traveled (VMTs) per person, increasing emissions, and promoting sedentarism, or yield health benefits, by reducing vehicle crashes and reducing the number of vehicles on the streets, freeing urban space for recreational use or vegetation.

2. POTENTIAL IMPACTS OF AVs ON PUBLIC HEALTH

We have developed a framework on autonomous vehicles and health determinants (**Figure 2**). In this framework, we summarize the main health determinants related to AVs, consider two different levels of impacts, direct and indirect, and highlight the expected changes in such determinants (increments or reductions). "Direct impacts" refer to those impacts affecting travelers who use AVs. "Indirect impacts" refer to those impacts that occur after widespread implementation of AVs and that affect the larger community. The following sections describe the health determinants presented in this framework and their interrelation with AVs.

2.1. Direct Impacts

AV direct impacts are those health determinants that affect travelers using AVs and are the most common impacts associated with AVs.

2.1.1. Traffic safety. The AV industry and authorities claim that improved traffic safety would be one of the significant beneficial impacts of AV use (30, 59). In 2017, 37,133 people were killed in motor vehicle crashes in the United States (including nearly 7,000 pedestrians and cyclists) (54, 78). Of all serious motor vehicle crashes, 94% involve driver-related factors, such as impaired driving, distraction, and speeding or illegal maneuvers (78). Globally, road traffic incidents are one of the leading causes of mortality, with 1.3 million people killed each year (86), and almost 90% of those road traffic deaths are concentrated in low- and middle-income countries (44), despite that

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

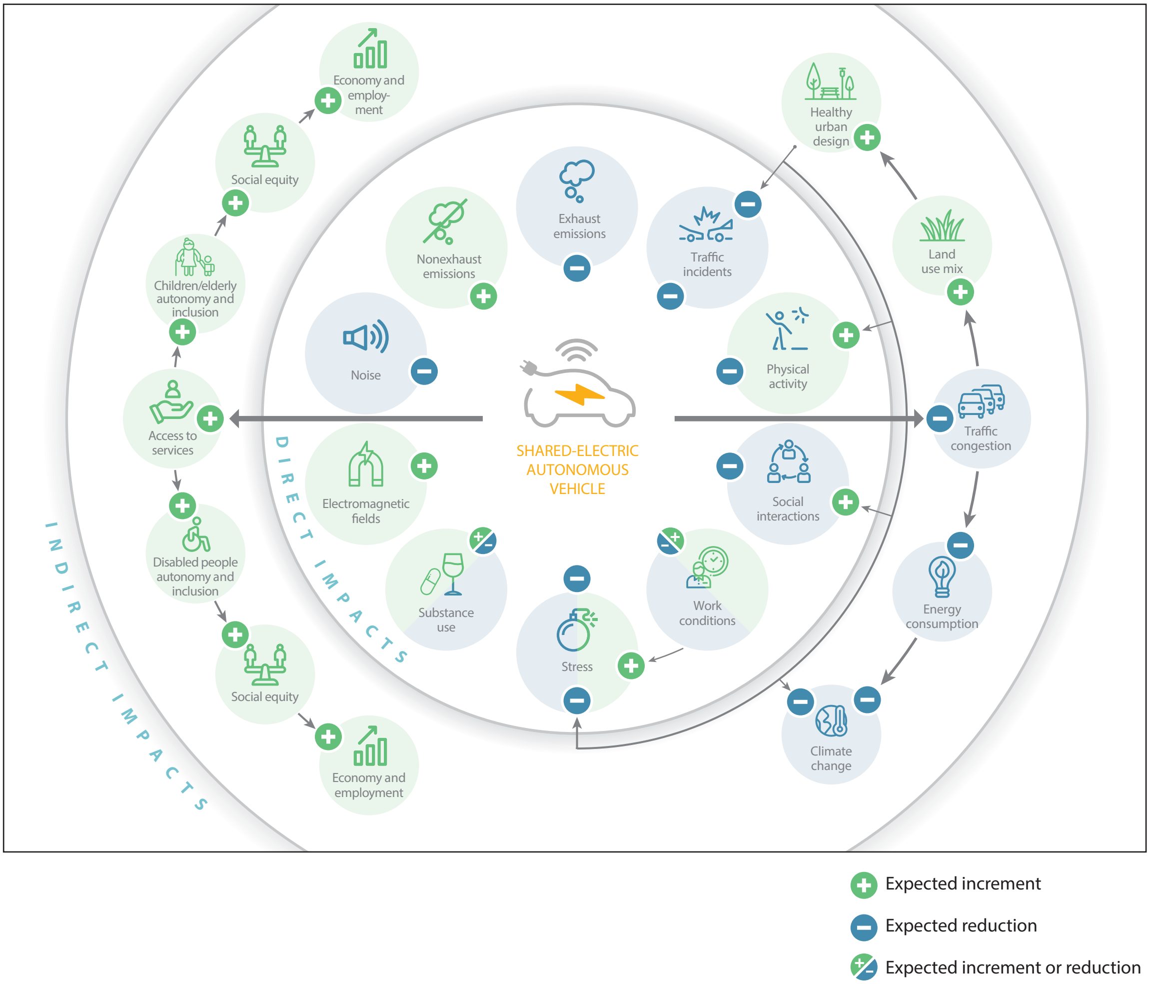

Figure 2

A framework of autonomous vehicles and health determinants.

these countries have 48% of the world's registered vehicles (86). A relevant health consideration on traffic safety is that the majority of traffic injuries and fatalities in the United States happened in individuals between ages 16 and 40 years old, where the number of years lived with disability or years of life lost are greater (12, 49).

Fully automated vehicles could lead to reductions in the number of driver-related crashes (44). Luttrell et al. (44) in 2015 modeled the expected impacts of AVs on motor vehicle crash injuries and fatalities. They estimated that if 90% of the automobiles in the United States became autonomous, an estimated 25,000 lives could be saved each year, with annual economic savings estimated at more than $200 billion in the United States (44). These impacts are highly dependent on the market penetration of AVs and are expected to be small initially but to grow as AVs are more widely adopted. The safety benefits of AVs are expected to emerge more rapidly in wealthy countries, which will adopt AVs sooner, than in low- and middle-income countries, where adoption will lag—a paradox given the higher risk in low- and middle-income settings. A barrier to the rapid

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

adoption of AVs is public reluctance due to high-profile news coverage of AV crashes in recent years (28).

Improved road safety related to AV use may lead to a decline in organ donations (1). In 2018 in the United States, organ donations from motor vehicle crashes represented 13% of all donations (81). The implementation of AVs should, therefore, trigger efforts to promote and strengthen organ donation systems (36).

Finally, ethical issues involving the decisions made by AVs in the case of traffic incidents are a relevant factor to consider (47). An imminent crash may pose instantaneous decisions about who will die: a passenger or pedestrian, an older person or a child? The moral elements of such decisions must be programmed into the algorithms used by AVs. A recent multinational survey on moral decisions related to AV and road safety found that these moral decisions vary considerably by gender, social status, and nation and appear to reflect underlying societal-level preferences for egalitarianism (47).

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

2.1.2. Physical activity. Transport-related physical activity (walking, cycling, or walking to and from public transport) has been suggested as a strategy for increasing daily levels of physical activity (24, 65, 67). The benefits of active transportation have been quantified in several cities around the world and have shown both direct benefits for pedestrians and cyclists and broader indirect benefits through improved air quality and reduced traffic noise (51). The impact of AVs on travel behavior (and their corresponding impact on transport-related physical activity) is difficult to predict. But recent modeling studies suggest that AVs could increase VMTs by between 15% and 59% and reduce the use of public and active transportation (73). In these transportation models, private AVs also led to a more dispersed urban growth pattern (sprawl), which could increase trip distances, making walking and cycling less attractive (66). However, some studies also suggest that SAVs could decrease VMTs (in the range of 10–25%) if a large share of the travelers are willing to rideshare (73). SAVs, especially when utilized through ridesharing or ridesplitting, are likely to reduce transport-related physical activity less than private AVs, as this approach is more compatible with being complemented by walking, cycling, or using public transportation.

2.1.3. Air pollution emissions. Ninety-five percent of the world's population lives in areas exceeding the World Health Organization (WHO) guideline for healthy air (34). Air pollution is a global leading risk factor for mortality and morbidity (34). Motorized vehicles are a major source of air pollution in urban areas (3, 68). In 2015, estimates indicate that, globally, the attributable number of deaths related to road transport air pollution was ∼250,000 (4). Moreover, exposure to air pollution tends to be greater for people within automobiles than for those who are walking, cycling, or riding buses (22). Transport-related air pollution emissions can be classified as exhaust and nonexhaust emissions.

2.1.3.1. Exhaust emissions. The impact of AVs on air pollution exposure relates to three factors: whether AV use increases the overall amount of VMTs, the extent to which AVs pollute (gasoline and diesel engines pollute more than electric vehicles do), and the extent of integration between AVs and active and public transport. AV implementation could increase air pollution exposure if it increases overall VMTs (65), which is a possibility if AVs continue to rely on internal combustion engines (73) and/or if AV use patterns do not facilitate walking, cycling, and transit use. If AVs are not fully electric, future higher exposure periods to air pollution may affect AV travelers, and higher air pollution exhaust emissions would then affect the general public. AV regulations could account for these issues to reduce the negative externalities of motorized transport, not only in air pollution exposure but also through contributions to CO_2 and black carbon emissions associated with climate change.

2.1.3.2. Nonexhaust emissions. Air pollution from motor vehicles is not limited to exhaust emissions. Other sources include brake and tire wear, road surface wear, and resuspension of road dust. Together these may exceed tailpipe emissions, at least with regard to particulate matter (3). Moreover, brake and tire wear particles may have higher oxidative potential than other traffic-related sources, which could translate to worse health impacts (3). Electric vehicles also have been suggested to emit more nonexhaust emissions because they weigh more than nonelectric vehicles (76). If AV use increases VMTs, even with a shift to electric vehicles, nonexhaust emissions will be an issue for air quality. Potential strategies to reduce these emissions include source minimization by improving the wear properties of materials, reducing the wear potential of traffic (e.g., studded tires), and minimizing dust suspension to air by removing dust from road surfaces (road cleaning), immobilizing dust (binding dust to road surfaces), and adjusting traffic (less traffic, lower speeds, lighter weight vehicles) (3).

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

2.1.4. Noise. Another important aspect of AVs is the impact on road traffic noise. Road traffic noise has been associated with multiple health outcomes, including sleep disturbance, annoyance, cardiovascular disease, and hypertension (6, 10, 14, 32, 50, 61). In Europe, for instance, environmental noise causes an estimated 10,000 premature deaths per year (9, 88). AVs using internal combustion engines could continue to contribute to road traffic noise. As in the case of air pollution, if AV use results in increased VMTs, then noise exposure would increase commensurately (73). In contrast, electrification of the vehicle fleet would reduce noise exposure [although at speeds above 50 km per hour, electric and hybrid cars are not quieter than conventional cars (82)]. A Dutch study projected that a fully electric car fleet would reduce average urban noise levels by 3–4 dB and reduce annoyance effects by more than 30% (82). At low speeds, electric cars may also pose a safety risk, owing to the lack of noise, especially for pedestrians with visual impairments who rely on auditory cues (9, 15). In some countries such as the United States and Japan, regulators are considering requiring manufacturers of hybrid and electric cars to install an artificial warning sound (21). This intervention, if implemented for electric AVs, would lead to road safety improvements.

2.1.5. Electromagnetic fields. Electric and magnetic fields (EMFs) are invisible areas of energy (also called radiation) that are produced by electricity (53). Low- to mid-frequency EMFs are in the nonionizing radiation part of the electromagnetic spectrum and are not known to damage DNA or cells directly (53). Numerous epidemiologic studies have evaluated possible associations between exposure to nonionizing EMFs and the risk of cancer, without conclusive results (53). But a recent study of the US National Toxicology Program concluded that there is clear evidence that male rats exposed to high levels of radiofrequency, such as that used in 2G and 3G cell phones, developed heart tumors (56). AVs use multiple technologies that would entail exposure to a range of EMFs. Owing to the current lack of evidence on the health impacts of EMFs, it is difficult to draw conclusions or offer recommendations on this issue. Further research is needed to clarify the potential health implications of EMFs.

2.1.6. Substance abuse. Alcohol and cannabis are the most frequently detected drugs in US drivers (55). In 2013, 9.9 million people in the United States reported driving under the influence of illicit drugs (55, 58). Traffic laws prohibit driving under the influence of alcohol or drugs. Such policies, together with associated shifts in social norms, have increased public awareness and have discouraged abuse of these substances while driving (62). It is conceivable that widespread AV use would contribute to laxity in public attitudes toward alcohol and drugs. Australia's National Transport Commission, in a 2017 discussion paper, likened occupants of fully autonomous vehicles to taxi passengers and suggested that they may be exempted from legal restrictions on drunk- and drug-impaired driving (57). A clear definition of the capabilities and requirements of AV passengers will need to be aligned with future drink-driving and drug-impaired driving policies. Also, broader efforts to discourage alcohol and drug abuse should be maintained so that any relaxation of restrictions in the context of road travel does not undermine social norms against alcohol and drug abuse.

2.1.7. Work conditions. A growing body of evidence suggests that long working hours adversely affect the health and well-being of workers, increasing their risk of hypertension, cardiovascular disease, fatigue, stress, depression, musculoskeletal disorders, chronic infections, diabetes, general health complaints, and all-cause mortality (72). Because 15% of daily trips in the United States are taken for commuting (11), changes in travel patterns have an impact on work. Fully AVs will not require passenger attention to driving tasks, which could result in the dedication of commute time to work-related activities (as now occurs with some bus and train commuters). No studies have considered the impact of AVs on work schedules and activities. But we have considered two main scenarios: (*a*) Commuting time in AVs extends unpaid and unofficial working times, resulting in long working hours, and (*b*) commuting time in AVs comes to be considered official work time. Considerations of work regulations related to commuting by AVs will be needed to avoid excessive working hours and associated negative health impacts.

2.1.8. Stress. The experience of driving has been suggested to be potentially detrimental to health (5). A recent review provided evidence to suggest that driving for long hours elicits a stress response over an extended period of time (5). Stress, in turn, has adverse impacts on the immune, cardiovascular, and nervous systems, among others (45). Evidence indicates that automation is likely to decrease mental workload and stress, thereby producing a more positive set of emotional responses (18). The use of AVs could reduce the stress of driving, yielding health benefits.

2.1.9. Social interactions. AVs could have either positive or negative impacts on social interactions. On the positive side, AVs could facilitate increased access to venues for social interactions and social support that help promote good mental health (73), and shared AVs could offer opportunities for social interactions among passengers during rides. On the negative side, AVs could increase commuting time (if commuting by AV is seen as more painless than driving, and people, therefore, choose to live farther from work), and longer commute times are associated with reduced community involvement, reduced time with friends and family, and reduced levels of social capital (8, 13, 46).

2.2. Indirect Impacts

AV indirect impacts are those impacts that occur after widespread implementation of AVs and that affect the larger community. These impacts could be less commonly associated with AVs but could have important health implications.

2.2.1. Traffic congestion. Vehicles that are highly but not fully automated would probably not behave significantly differently from normal vehicles with respect to their contribution to congestion. For fully automated AVs (driverless vehicles), some factors seem likely to operate both to increase and to decrease congestion (48). A study of a theoretical grid-based urban area indicated that one shared-ownership AV could replace 11 conventional vehicles (27). The International Transport Forum estimated that the travel needs of the city of Lisbon could be met without the use of private cars in the urban core area and hence without congestion if fleets of SAVs replaced all car

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

and bus trips in the city of Lisbon, in addition to existing rail and subway services (37). Reduction in traffic congestion related to SAVs could have beneficial impacts on travel time, reducing travel sitting time, air pollution, and noise.

2.2.2. Impact on public transportation. Public transportation has been associated with a lower risk of traffic incidents, compared with other modes of transportation (41, 66, 67). Public transportation has also been suggested as a promoter of physical activity, owing to the inclusion of walking trips to and from public transport stations (63, 66, 70, 90). Furthermore, if public transportation substituted car trips, the shift could lead to a reduction in air pollution emissions, specifically if the public transportation fleet relies on electricity (e.g., light transit rail), hybrid energy, or natural gas (buses) (7, 33, 67).

While AV implementation could lead to various impacts on public transportation use, not all impacts are positive. If public transportation were to be fully supplanted by private AV alternatives such as ridesharing offering door-to-door services, this change may lead to physical activity reductions and socioeconomic inequities, removing affordable transportation options for low-income citizens (35). A possible path to mitigate this scenario is the integration of AVs in the public transport system. Recent projects in the European Union have successfully tested autonomous transit in 7 European cities, carrying more than 60,000 passengers and sharing the infrastructure with other road users (2). Other types of public transit, such as bus rapid transit (BRT) using autonomous platooning with precision docking, will produce a BRT-type service that can offer the same capacity and service as rail transit with significantly less cost (43).

Transit planners must find ways to characterize autonomous vehicles accurately and include them in the spectrum of mode choices available to travelers when confronted with alternative choices. Possible disruptive impacts on public transportation should be considered an equity issue owing to the impacts on the transit-dependent population. Finally, another possible consequence of AV integration with public transportation would be the disappearance of driving jobs, which in European Union countries account for 4.8 million employees (38). However, some research predicts that the replacement of professional drivers by technology will be gradual, with software initially taking over some elements of driving but with people still being required for tasks such as close maneuvering (38).

2.2.3. Land use and healthy urban design. SAV fleets could have positive impacts on urban land use. Urban parking space may be reduced as much as 90% if AVs are implemented in ridesharing mode (73). Moreover, AVs could also permit the relocation of public space from automobile infrastructure to other activities, such as green and blue spaces that support physical activity and social interaction (52, 83). However, modeling results on parking space related to AVs are very sensitive to model assumptions, which are still very uncertain (e.g., the perception of time in AVs or operational costs) (73).

AVs will also increase accessibility to multiple destinations, which could be more relevant for populations living in suburbs and rural regions. Increasing access to destinations by reducing the opportunity cost of travel time, increasing road capacity, and reducing travel time could result in increased urban sprawl (19, 39, 40, 73). One modeling study of private AVs in Melbourne, Australia, with a scenario for the year 2046, projected a 4% reduction in the population living in inner parts of the city and a 3% increase in the population living in the far outer suburbs (75). In the same study, a scenario considering ridesharing SAVs in Melbourne reported a 4% increase in population in inner parts of the city, while far outer suburbs experienced a 3% reduction in the population (75). Another modeling study, in Atlanta, concluded that SAV use would not induce residential sprawl into exurban areas but would accelerate urban deindustrialization (91).

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

2.2.4. Clean energy, energy consumption, and climate change.

Climate change is a leading threat to human health in the present era (84). Climate change impacts health through multiple pathways, from food access and quality to air pollution to extreme weather (29, 87). The combustion of fossil fuels as energy sources releases greenhouse gases, a principal contributor to climate change. The transportation sector is an important contributor, representing about 14% of greenhouse gas emissions globally and twice that amount in the United States (80). In 2017, on-road vehicles in the United States, including light-duty passenger cars and trucks, buses, and commercial and freight trucks, consumed 11.6 million barrels per day (b/d) oil equivalent, which accounted for 80% of all transportation energy use and 31% of all delivered end-use energy in the United States (79).

The impact of AVs on climate change will depend on several factors: the impact on VMTs (with more VMTs, *ceteris paribus*, requiring more energy), the energy usage per vehicle, and the source of energy used. If AV use increases overall VMTs, then the overall transportation energy demand would increase. An increase in traveler population could increase empty miles driven, as well as travel demand, and may shift travel from other modes to AVs (79). On the other hand, AV use could reduce energy consumption through reductions in parking hunting, ridesharing, eco-driving, congestion mitigation, collision avoidance, and vehicle/power resizing (79).

The source of energy for AVs is a critical factor. In 2017, 99% of the energy used by light-duty passenger cars and trucks came from gasoline and diesel (79). The AVs currently being tested are gasoline dependent, with some hybrid vehicles in the mix. In the future, AVs are expected to be fully electric (30, 85). AVs could be an opportunity to promote the sale of more energy-efficient or clean-energy vehicles through a faster payback of the more expensive purchase price (79). Shared-use mobility providers offer the greatest potential for a faster payback (79). AVs could also promote the use of alternative fuels through refueling without the rider and by reducing the anxiety related to plug-in electric vehicles by ensuring that consumers always have a sufficiently charged electric vehicle available (79). In general, AVs offer an opportunity to promote the transition from fossil fuels to renewable sources of energy if the AVs are implemented as fully electric vehicles together with a supply chain based on renewable energy sources. In addition to electric AVs based on renewable energy sources, shared-electric AVs represent the optimal strategy to increasing energy efficiency, reducing consumption, especially when integrated into healthy urban and transport environments, and supporting active and public transport.

2.2.5. Access to services, autonomy and inclusion, social equity, employment, and economy.

For some population groups, driving is not a feasible option. Barriers to driving include the cost of full-time car ownership, the cost of learning to drive, difficulties with licensing, or factors related to health, disability, or age (20). For those affected communities, the difficulty in accessing transportation contributes to socioeconomic disadvantage (20). Some equity priorities in transportation are related to transportation costs, access to destinations, services (such as health services), and employment (16). A recent study modeled the equity impact of AVs in terms of job accessibility in Washington, DC (17). The study found that in all the scenarios modeled, AVs increased job accessibility, especially in more disadvantaged populations and in scenarios using ridesharing SAVs (17). Two main recommendations to support social equity for AVs are (*a*) to engage and include disadvantaged communities in transportation planning, especially regarding SAVs; and (*b*) to reduce barriers to using SAVs, including financial, technological, language, and cultural barriers. In addition to these recommendations, a 2018 report related to the impact of AV on US workers found that the introduction of autonomous cars and trucks could directly eliminate 1.3–2.3 million workers' jobs over the next 30 years; this issue also needs to be considered in terms of workers' health (31).

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

3. RECOMMENDATIONS

At a high level, the optimal strategies for advancing public health through AVs appear to be shifting from internal combustion to electric vehicles, ensuring support from a renewable energy supply system, and favoring SAVs over individually owned vehicles. Policy and research recommendations for policy makers, health practitioners, and researchers are summarized in **Table 1**, with reference to specific health determinants and outcomes as discussed above. AV policies and regulations should be analyzed, debated, and implemented in advance of the full introduction of AVs to the market. A "health in all policies" approach will help minimize the health risks related to AVs and maximize their possible benefits (71). Public health practitioners should lead intersectoral groups to introduce health vision into the AV projections. Substantial research gaps exist around AVs. More funding opportunities should be available to focus on understanding the implication of AVs on travel behavior, traffic safety, land use, urban built environments, and transportation-related costs. From the public health perspective, more understanding of the ethics related to AVs and road safety, health equity, and environmental and urban health is required to understand the health implications of AV technologies. In general, there are many uncertainties about the direction of the impacts related to AVs. The range of impacts depends on the type of model that the industry and governments promote. Substantial health gains are expected for approaches that utilize fully electric AVs in a shared system with a ridesharing or ridesplitting format.

Table 1 Autonomous vehicle (AV) recommendations for policy makers, health practitioners, and researchers

	Health determinant										
Recommendations	Road safety	Physical activity	Clean energy, energy consumption, and climate change	Air pollution	Noise	Electromagnetic fields	Substance abuse	Work conditions	Social interaction	Land use	Social equity, autonomy, inclusion, employment, and economy
Favor shared AVs over private AVs	✓	✓	✓	✓	✓				✓	✓	✓
Favor rideshare and ridesplitting	✓	✓	✓	✓	✓				✓	✓	✓
Integrate shared-electric AVs in the public transport system	✓	✓	✓	✓	✓				✓	✓	✓
Integrate shared-electric AVs to promote (not to compete with) active transportation	✓	✓	✓	✓	✓				✓	✓	✓
Prioritize shared-electric AVs on those vulnerable and disadvantaged communities (in all geographical areas), who will benefit more from traffic safety interventions	✓									✓	✓
Consider market penetrance of AVs when designing and estimating the road safety impacts	✓										✓

(*Continued*)

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

Table 1 ***(Continued)***

Recommendations	Health determinant										
	Road safety	Physical activity	Clean energy, energy consumption, and climate change	Air pollution	Noise	Electromagnetic fields	Substance abuse	Work conditions	Social interaction	Land use	Social equity, autonomy, inclusion, employment, and economy
Promote research that provides a comprehensive vision of moral and ethical issues related to AVs and road safety	✓										✓
Promote and strengthen organ donation national systems	✓										
Promote research on travel behavior related to AVs and modal share		✓							✓	✓	✓
Prioritize the implementation of fully electric AVs			✓	✓	✓						✓
Prioritize the energy supply (in urban and rural areas) based on renewable energy sources			✓	✓	✓					✓	✓
Improve AVs' wear properties of materials and reduce the wear potential of traffic sources				✓	✓						✓
Reduce road dust suspension by removing/immobilizing dust from road surfaces (road cleaning)				✓	✓						✓
Bind dust to the road surface and adjust traffic (less traffic, lower speed, less heavy AVs)				✓	✓						✓
Engage with and include disadvantaged communities in transportation planning, especially regarding shared-electric AVs				✓	✓				✓	✓	✓
Reduce barriers to using shared-electric AVs, including financial, technological, language, and cultural barriers				✓	✓				✓		✓
Support research on exposure levels of electromagnetic fields in AVs						✓					
Support research on health implications of electromagnetic fields in general and in particular those related to AVs						✓					
Define the AV passenger/driver regulations on alcohol and drug consumption							✓				
Support drinking- and drug-oriented policies to reduce substance abuse							✓				
Clearly define and regulate work-related activities during commuting in AVs to avoid overtime or long working hours								✓			

4. CONCLUSIONS

Autonomous vehicles are an innovative transport intervention that will impact public health. Main health impacts (risks and/or benefits) rely on the AV implementation model related to the type of use, ownership, engine, fuel, and integration with other modes of transportation. Aside from the expected benefits associated with traffic safety, AVs could offer major opportunities for public health when AVs are implemented as fully electric (depending on renewable sources), in a ridesharing format, and integrated with public and active transportation modes. All these characteristics could promote physical activity, improve the urban environment (air quality and noise), and provide more public space to support a healthy urban design. On the other hand, major risks can be present when AVs are implemented for individual use, depend on fossil fuels, lead to more miles traveled, exacerbate traffic congestion, and increase occupancy of public spaces; all of these factors result in more sedentarism, degradation of the urban environment (air quality and noise), and reductions in the amount of public space available for social interaction and physical activity. Prioritizing research to increase understanding related to AV market penetration, travel behavior, safety, land use, and built environments will lead to improved current health frameworks and help implement future health impact assessments on AVs. At this stage, general recommendations can be generated to support policies and regulations prioritizing electric AVs in a format of ridesharing or ridesplitting. The implementation of AVs should aim to support public and active transportation, prioritizing more disadvantaged communities and contributing to the evolution of urban and transport planning toward a healthier urban environment.

SUMMARY POINTS

1. AVs could result in health risks and/or benefits.
2. Proper policies and regulations prioritizing electric AVs in a format of ridesharing or ridesplitting would optimize benefits for health.
3. AVs should be designed to support public and active transportation.
4. AVs should be prioritized in disadvantageous communities.
5. AVs should contribute to an urban planning revolution with a vision for healthy urban environments.
6. AV policies and regulatory frameworks should be implemented before the complete introduction of AVs into the market.

FUTURE ISSUES

1. Future research should provide a comprehensive vision of moral and ethical issues related to AVs and road safety.
2. Research is needed on travel behavior related to AVs and modal share.
3. Future research should investigate barriers to using shared-electric AVs, including financial, technological, language, and cultural barriers.
4. Research on exposure and health impacts of electromagnetic fields in AVs is needed.
5. Health impact assessment of AVs is critical.

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

LITERATURE CITED

1. Adams I, Hobson A. 2016. Self-driving cars will make organ shortages even worse. *Slate*, Dec. 30. **https://slate.com/technology/2016/12/self-driving-cars-will-exacerbate-organ-shortages.html**
2. Ainsalu J, Arffman V, Bellone M, Ellner M, Haapamäki T, et al. 2018. State of the art of automated buses. *Sustainability* 10(9):3118
3. Amato F, Cassee FR, Denier van der Gon HAC, Gehrig R, Gustafsson M, et al. 2014. Urban air quality: the challenge of traffic non-exhaust emissions. *J. Hazard. Mater.* 275:31–36
4. Anenberg S, Miller J, Henze D, Minjares R. 2019. *A global snapshot of the air pollution-related health impacts of transportation sector emissions in 2010 and 2015*. Rep., Int. Counc. Clean Transp. (ICCT), Washington, DC. **https://theicct.org/sites/default/files/publications/Global_health_impacts_transport_emissions_2010-2015_20190226.pdf**
5. Antoun M, Edwards KM, Sweeting J, Ding D. 2017. The acute physiological stress response to driving: a systematic review. *PLOS ONE* 12(10):e0185517
6. Basner M, McGuire S. 2018. WHO Environmental Noise Guidelines for the European Region: a systematic review on environmental noise and effects on sleep. *Int. J. Environ. Res. Public Health* 15(3):E519
7. Bel G, Holst M. 2018. Evaluation of the impact of bus rapid transit on air pollution. *Transport Policy* 63:209–20
8. Besser LM, Marcus M, Frumkin H. 2008. Commute time and social capital in the U.S. *Am. J. Prev. Med.* 34(3):207–11
9. Brown AL. 2015. Effects of road traffic noise on health: from burden of disease to effectiveness of interventions. *Procedia Environ. Sci.* 30:3–9
10. Brown AL, Van Kamp I. 2017. WHO Environmental Noise Guidelines for the European Region: a systematic review of transport noise interventions and their impacts on health. *Int. J. Environ. Res. Public Health* 14:E873
11. BTS (Bur. Transp. Stat.). 2017. National household travel survey daily travel quick facts. *Bureau of Transportation Statistics*. **https://www.bts.gov/statistical-products/surveys/national-household-travel-survey-daily-travel-quick-facts**
12. Chang D. 2008. *Comparison of crash fatalities by sex and age group*. Res. Note DOT HS 810 853, Natl. Cent. Stat. Anal. Washington, DC. **https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/810853**
13. Christian TJ. 2012. Automobile commuting duration and the quantity of time spent with spouse, children, and friends. *Prev. Med.* 55(3):215–18
14. Clark C, Paunovic K. 2018. WHO Environmental Noise Guidelines for the European Region: a systematic review on environmental noise and quality of life, wellbeing and mental health. *Int. J. Environ. Res. Public Health* 15(11):E2400
15. Clendinning EA. 2018. Driving future sounds: imagination, identity and safety in electric vehicle noise design. *Sound Stud.* 4(1):61–76
16. Cohen S, Shirazi S, Curtis T. 2017. *Can we advance social equity with shared, autonomous and electric vehicles?* Policy Brief, Inst. Transp. Stud., Univ. Calif., Davis. **http://www.transformca.org/sites/default/files/3R.Equity.Indesign.Final_.pdf**
17. Cohn J, Ezike R, Martin J, Donkor K, Ridgway M, Balding M. 2019. Examining the equity impacts of autonomous vehicles: a travel demand model approach. *Transp. Res. Rec. J. Transp. Res. Board*, 2673:23–35
18. Cottrell ND, Barton BK. 2013. The role of automation in reducing stress and negative affect while driving. *Theor. Issues Ergon. Sci.* 14(1):53–68
19. Creger H, Espino J, Sanchez AS. 2019. *Autonomous vehicle heaven or hell? Creating a transportation revolution that benefits all*. Rep., Greenlining Inst., Oakland. **http://greenlining.org/wp-content/uploads/2019/01/R4_AutonomousVehiclesReportSingle_2019_2.pdf**

20. CSPC (Cent. Study Pres. Congr.). 2017. *The autonomous vehicle revolution: fostering innovation with smart regulation*. Rep., CSPC, Washington, DC
21. Dalrymple G. 2013. *Minimum sound requirements for hybrid and electric vehicles*. Draft Environ. Assess. Docket NHTSA-2011-0100, US Dep. Transp. Natl. Highw. Traffic Saf. Adm., Washington, DC. **https://www.nhtsa.gov/staticfiles/rulemaking/pdf/Quiet_Cars_Draft_EA.pdf**
22. de Nazelle A, Bode O, Orjuela JP. 2017. Comparison of air pollution exposures in active versus passive travel modes in European cities: a quantitative review. *Environ. Int.* 99:151–60
23. de Nazelle A, Nieuwenhuijsen MJ, Antó JM, Brauer M, Briggs D, et al. 2011. Improving health through policies that promote active travel: a review of evidence to support integrated health impact assessment. *Environ. Int.* 37(4):766–77
24. Dons E, Götschi T, Nieuwenhuijsen M, de Nazelle A, Anaya E, et al. 2015. Physical Activity through Sustainable Transport Approaches (PASTA): protocol for a multi-centre, longitudinal study. *BMC Public Health* 15(1):1126
25. Etherington D. 2019. Over 1,400 self-driving vehicles are now in testing by 80+ companies across the US. *Techcrunch*, June 11. **https://techcrunch.com/2019/06/11/over-1400-self-driving-vehicles-are-now-in-testing-by-80-companies-across-the-u-s/**
26. Exec. Off. Pres, Pres. Counc. Advis. Sci. Technol. 2016. *Technology and the future of cities*. Rep. Pres., Exec. Off. Pres., Washington, DC. **https://www.whitehouse.gov/sites/whitehouse.gov/files/images/Blog/PCAST%20Cities%20Report%20_%20FINAL.pdf**
27. Fagnant DJ, Kockelman KM. 2014. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transp. Res. Part C Emerg. Technol.* 40:1–13
28. Favarò FM, Nader N, Eurich SO, Tripp M, Varadaraju N. 2017. Examining accident reports involving autonomous vehicles in California. *PLOS ONE* 12:e0184952
29. Frumkin H, Haines A. 2019. Global environmental change and noncommunicable disease risks. *Annu. Rev. Public Health* 40:261–82
30. Gen. Motors. 2018. *2018 self-driving safety report*. Rep., Gen. Motors, Detroit, MI. **https://www.gm.com/content/dam/company/docs/us/en/gmcom/gmsafetyreport.pdf**
31. Groshen EL, Helper S, Macduffie JP, Carson C. 2018. *Preparing U.S. workers and employers for an autonomous vehicle future*. Rep., Secur. Am. Futur. Energy, Washington, DC. **https://avworkforce.secureenergy.org/wp-content/uploads/2018/06/Groshen-et-al-Report-June-2018-1.pdf**
32. Guski R, Schreckenberg D, Schuemer R. 2017. WHO Environmental Noise Guidelines for the European Region: a systematic review on environmental noise and annoyance. *Int. J. Environ. Res. Public Health* 14(12):E1539
33. Gwilliam K, Kojima M, Johnson T. 2004. *Reducing air pollution from urban transport*. Rep., World Bank, Washington, DC. **http://documents.worldbank.org/curated/en/989711468328204490/pdf/304250PAPER0Reducing0air0pollution.pdf**
34. Health Effects Inst. 2018. *State of Global Air/2018. A special report on global exposure to air pollution and its disease burden*. Rep., Health Effects Inst., Boston. **https://www.stateofglobalair.org/sites/default/files/soga-2018-report.pdf**
35. Henaghan J, ed. 2018. *Preparing communities for autonomous vehicles*. Rep., Am. Plan. Assoc., Chicago. **https://planning-org-uploaded-media.s3.amazonaws.com/document/Autonomous-Vehicles-Symposium-Report.pdf**
36. Inst. Med. Natl. Acad. 2006. *Organ Donation: Opportunities for Action*. Washington, DC: Natl. Acad. Press
37. Int. Transp. Forum. 2016. *Shared mobility innovation for liveable cities*. Rep., Int. Transp. Forum, Paris. **https://www.itf-oecd.org/sites/default/files/docs/shared-mobility-liveable-cities.pdf**
38. KPMG Int. 2019. *2019 autonomous vehicles readiness index: assessing countries' preparedness for autonomous vehicles*. Rep. 136024-G, KPMG Int. Amstelveen, Neth., **https://assets.kpmg/content/dam/kpmg/xx/pdf/2019/02/2019-autonomous-vehicles-readiness-index.pdf**
39. Lang NS, Rüßmann M, Chua J, Doubara X. 2017. *Making autonomous vehicles a reality: lessons from Boston and beyond*. Rep., Boston Consult. Group (BCG), Boston. **http://image-src.bcg.com/Images/BCG-Making-Autonomous-Vehicles-a-Reality-Oct-2017_tcm9-173687.pdf**

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

40. Levin P. 2018. Why self-driving cars will cause sprawl (according to an Italian Physicist). *Medium*, March 14. **https://medium.com/99-mph/introducing-the-marchetti-a-unit-of-measure-for-transit-379aa51170a4**
41. Litman T. 2016. *The hidden traffic safety solution: public transportation*. Rep., Am. Public Transp. Assoc., Washington, DC. **https://www.apta.com/wp-content/uploads/Resources/resources/reportsandpublications/Documents/APTA-Hidden-Traffic-Safety-Solution-Public-Transportation.pdf**
42. Litman T. 2019. *Autonomous vehicle implementation predictions: implications for transport planning*. Rep., Vic. Transp. Policy Inst., Vic., BC. **https://www.vtpi.org/avip.pdf**
43. Lutin JM. 2018. Not if, but when: autonomous driving and the future of transit. *J. Public Transp.* 21(1):92–103
44. Luttrell K, Weaver M, Harris M. 2015. The effect of autonomous vehicles on trauma and health care. *J. Trauma Acute Care Surg.* 79(4):678–82
45. Mariotti A. 2015. The effects of chronic stress on health: new insights into the molecular mechanisms of brain-body communication. *Futur. Sci. OA* 1(3):FS023
46. Mattisson K, Håkansson C, Jakobsson K. 2015. Relationships between commuting and social capital among men and women in southern Sweden. *Environ. Behav.* 47(7):734–53
47. Maxmen A. 2018. Self-driving car dilemmas reveal that moral choices are not universal. *Nature* 562:469–70
48. Metz D. 2018. Developing policy for urban autonomous vehicles: impact on congestion. *Urban Sci.* 2(2):33
49. Mokdad AH, Ballestros K, Echko M, Glenn S, Olsen HE, et al. 2018. The state of US health, 1990–2016: burden of diseases, injuries, and risk factors among US states. *JAMA* 319(14):1444–72
50. Mueller N, Rojas-Rueda D, Basagaña X, Cirach M, Cole-Hunter T, et al. 2017. Urban and transport planning related exposures and mortality: a health impact assessment for cities. *Environ. Health Perspect.* 125(1):89–96
51. Mueller N, Rojas-Rueda D, Cole-Hunter T, de Nazelle A, Dons E, et al. 2015. Health impact assessment of active transportation: a systematic review. *Prev. Med.* 76:103–14
52. Mueller N, Rojas-Rueda D, Khreis H, Cirach M, Milà C, et al. 2018. Socioeconomic inequalities in urban and transport planning related exposures and mortality: a health impact assessment study for Bradford, UK. *Environ. Int.* 121:931–41
53. Natl. Cancer Inst. 2019. *Electromagnetic fields and cancer*. Fact Sheet, Natl. Cancer Inst., Bethesda, MD. **https://www.cancer.gov/about-cancer/causes-prevention/risk/radiation/electromagnetic-fields-fact-sheet**
54. Natl. Cent. Stat. Anal. 2018. *2017 fatal motor vehicle crashes: overview*. Res. Note DOT HS 812 603, Natl. Highw. Traffic Saf. Adm. (NHTSA), Washington, DC. **https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812603**
55. Natl. Saf. Counc. 2017. *Cannabis (marijuana) and driving*. Res. Document., Natl. Saf. Counc., Itasca, IL. **https://www.nsc.org/Portals/0/Documents/NSCDocuments_Advocacy/Divisions/ADID/Position-on-Cannabis-and-Driving.pdf**
56. Natl. Toxicol. Progr. 2018. *The toxicology and carcinogenesis studies in Hsd:Sprague Dawley SD rats exposed to whole-body radio frequency radiation at a frequency (900 mhz) and modulations (GSM and CDMA) used by cell phones*. NTP Tech. Rep. 595, Natl. Toxicol. Progr. (NTP), Research Triangle Park, NC. **https://ntp.niehs.nih.gov/ntp/htdocs/lt_rpts/tr595_508.pdf?utm_source=direct&utm_medium=prod&utm_campaign=ntpgolinks&utm_term=tr595**
57. Natl. Transp. Comm. 2018. *Changing driving laws to support automated vehicles*. Policy Pap., Natl. Transp. Comm., Melbourne. **https://www.ntc.gov.au/sites/default/files/assets/files/NTC%20Policy%20Paper%20-%20Changing%20driving%20laws%20to%20support%20automated%20vehicles.pdf**
58. NHTSA (Natl. Highw. Traffic Saf. Adm.). 2019. Drug-impaired driving. *NHTSA*. **https://www.nhtsa.gov/risky-driving/drug-impaired-driving**

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

59. NHTSA (Natl. Highw. Traffic Saf. Adm.). 2019. *Highly automated or "self-driving" vehicles*. Rep., NHTSA, Washington, DC. **https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/14269-overview_of_automated_vehicle_technology_042319_v1b.pdf**
60. Nieuwenhuijsen MJ. 2016. Urban and transport planning, environmental exposures and health-new concepts, methods and tools to improve health in cities. *Environ. Health.* 15(Suppl. 1):38
61. Nieuwenhuijsen MJ, Gascon M, Martinez D, Ponjoan A, Blanch J, et al. 2018. Air pollution, noise, blue space, and green space and premature mortality in Barcelona: a mega cohort. *Int. J. Environ. Res. Public Health* 15(11):E2405
62. Off. Surg. Gen. 2016. *Facing addiction in America: the Surgeon General's report on alcohol, drugs, and health*. Rep., US Dep. Health Hum. Serv., Washington, DC. **https://addiction.surgeongeneral.gov/sites/default/files/surgeon-generals-report.pdf**
63. Rissel C, Curac N, Greenaway M, Bauman A. 2012. Physical activity associated with public transport use—a review and modelling of potential benefits. *Int. J. Environ. Res. Public Health* 9(7):2454–78
64. Rojas-Rueda D. 2017. Autonomous vehicles and mental health. *J. Urban Des. Ment. Health* 3(2):1
65. Rojas-Rueda D, de Nazelle A, Tainio M, Nieuwenhuijsen MJ, et al. 2011. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. *BMJ* 343:d4521
66. Rojas-Rueda D, de Nazelle A, Teixidó O, Nieuwenhuijsen MJ. 2013. Health impact assessment of increasing public transport and cycling use in Barcelona: a morbidity and burden of disease approach. Appendix. *Prev. Med.* 57(5):573–79
67. Rojas-Rueda D, de Nazelle A, Teixidó O, Nieuwenhuijsen MJ. 2012. Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: a health impact assessment study. *Environ. Int.* 49:100–9
68. Rojas-Rueda D, Turner MC. 2016. Commentary: diesel, cars, and public health. *Epidemiology* 27(2):159–62
69. SAE Int. 2018. *Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*. Tech. Pap. J3016_201806, SAE Int., Warrendale, PA. **https://www.sae.org/standards/content/j3016_201806/**
70. Saelens BE, Moudon AV, Kang B, Hurvitz PM, Zhou C. 2014. Relation between higher physical activity and public transit use. *Am. J. Public Health* 104(5):854–59
71. Shankardass K, Muntaner C, Kokkinen L, Shahidi FV, Freiler A, et al. 2018. The implementation of Health in All Policies initiatives: a systems framework for government action. *Health Res. Policy Syst.* 16(1):26
72. Song J-T, Lee G, Kwon J, Park J-W, Choi H, Lim S. 2014. The association between long working hours and self-rated health. *Ann. Occup. Environ. Med.* 26(1):2
73. Soteropoulos A, Berger M, Ciari F. 2019. Impacts of automated vehicles on travel behaviour and land use: an international review of modelling studies. *Transp. Rev.* 39:29–49
74. State Calif. 2019. Key autonomous vehicle definitions. *State of California Department of Motor Vehicles*. **https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/definitions**
75. Thakur P, Kinghorn R, Grace R. 2016. Urban form and function in the autonomous era. In *Australasian Transport Research Forum 2016 Proceedings, Melbourne, Australia, November 16–18, 2016*. **https://pdfs.semanticscholar.org/1331/7a7e63709dffcf3bc921d224ccf7053e8778.pdf**
76. Timmers VRJH, Achten PAJ. 2016. Non-exhaust PM emissions from electric vehicles. *Atmos. Environ.* 134:10–17
77. UN Dep. Econ. Soc. Aff. 2018. *World urbanization prospects: the 2018 revision*. Rep. ST/ESA/SER.A/420, UN, New York. **https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf**
78. US Dep. Transp. 2018. *Automated vehicles 3.0. Preparing for the future of transportation*. Rep., US Dep. Transp., Washington, DC. **https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf**
79. US Energy Inf. Adm. 2018. *Autonomous vehicles: uncertainties and energy implications*. Rep., US Dep. Energy, Washington, DC. **https://www.eia.gov/outlooks/aeo/pdf/AV.pdf**

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.

80. US EPA (Environ. Prot. Agency). 2019. Global greenhouse gas emissions data. *Greenhouse Gas Emissions*. **https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data**
81. US Organ Procure. Transplant. Netw. 2019. Deceased donors recovered in the U.S. by circumstance of death. *National Data*. **https://optn.transplant.hrsa.gov/data/view-data-reports/national-data/**
82. Verheijen E, Jabben J. 2010. *Effect of electric cars on traffic noise and safety*. RIVM Lett. Rep. 680300009/2010, Natl. Inst. Public Health Environ. (RIVM), Bilthoven, Neth.
83. Vert C, Nieuwenhuijsen M, Gascon M, Grellier J, Fleming LE, et al. 2019. Health benefits of physical activity related to an urban riverside regeneration. *Int. J. Environ. Res. Public Health* 16(3):462
84. Wang H, Horton R. 2015. Tackling climate change: the greatest opportunity for global health. *Lancet* 386:1798–99
85. Waymo. 2018. *On the road to fully self-driving*. Saf. Rep., WAYMO, Mountain View, CA. **https://waymo.com/safety/**
86. WHO (World Health Organ.). 2018. *Global status report on road safety 2018*. Rep., WHO, Geneva. **https://www.who.int/violence_injury_prevention/road_safety_status/2018/en/**
87. WHO (World Health Organ.). 2018. *Health and climate change*. COP24 Spec. Rep., WHO, Geneva. **https://www.who.int/globalchange/publications/COP24-report-health-climate-change/en/**
88. WHO (World Health Organ.) Eur. Cent. Environ. Health. 2011. *Burden of disease from environmental noise: quantification of healthy life years lost in Europe*. Rep., WHO Reg. Off. Eur., Bonn, Ger. **http://www.euro.who.int/__data/assets/pdf_file/0008/136466/e94888.pdf**
89. WHO (World Health Organ.) Reg. Off. Eur. 2012. *Addressing the social determinants of health: the urban dimension and the role of local government*. Rep., WHO Reg. Off. Eur., Copenhagen. **http://www.euro.who.int/en/publications/abstracts/addressing-the-social-determinants-of-health-the-urban-dimension-and-the-role-of-local-government**
90. Xiao C, Goryakin Y, Cecchini M. 2019. Physical activity levels and new public transit: a systematic review and meta-analysis. *Am. J. Prev. Med.* 56(3):464–73
91. Zhang W. 2017. *The interaction between land use and transportation in the era of shared autonomous vehicles: a simulation model*. PhD Diss., Sch. City Reg. Plann., Ga. Inst. Technol., Atlanta. **https://smartech.gatech.edu/handle/1853/58665**
92. Zmud J, Goodin G, Moran M, Kalra N, Thorn E. 2017. *Strategies to Advance Automated and Connected Vehicles*. Washington, DC: Natl. Acad. Press

Annu. Rev. Public Health 2020.41:329-345. Downloaded from www.annualreviews.org
Access provided by University of Washington on 04/15/20. See copyright for approved use.