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CHAPTER SEVEN

Potential health and well-being implications of autonomous vehicles

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Abstract

Transportation's effects on health and well-being are widely recognized. In the near future, autonomous vehicles (AVs) are expected to revolutionize transportation options and ways of travel. Consequently, the effect of AVs on population health and well-being is a crucial topic of interest for transportation policymaking, one that has received comparatively little attention. This chapter discusses (and anticipates) potential AV impacts on health and well-being. First, we summarize knowledge surrounding effects of transportation on physical health (traffic safety, air and noise pollution, and physical activity) and well-being (travel satisfaction, access to activities, etc.). We then discuss how AVs may affect traveler behaviors, focusing on mode shifts toward private, shared, and/or

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pooled AVs, and how these shifts may lead to an overall increase in automobile travel, even if not necessarily in person-travel. Finally, we interpret the previous two sections to deduce potential positive, negative, and uncertain health/well-being effects of AVs. We expect benefits from improved safety, well-being, and access to opportunities; disadvantages from reduced physical activity; and uncertain impacts around land use changes and emissions. We conclude by discussing policy implications and research paths forward.

Keywords: Autonomous vehicles, Health, Well-being, Travel behavior, Safety, Access, Physical activity, Pollution, Satisfaction

1. Introduction

The transportation sector is currently undergoing a rapid transformation, in large part due to new mobility options and services made possible by technological developments. The emergence of "micro-mobility" modes, transportation network companies, mobility-as-a-service, vehicle-to-vehicle/infrastructure communications, and other changes will likely disrupt how people get around, how communities plan for future transportation needs, and how policymakers deal with (positive and negative) impacts of a complex transportation system. Adding on to these, autonomous vehicles (AVs), or self-driving cars (and trucks), if and when they become widespread in the future, may generate huge shifts in mobility patterns and behaviors. Therefore, policymakers and scholars are already actively investigating the many policy implications of ubiquitous automated driving. Much research currently addresses the impacts of AVs on vehicle ownership and use, energy consumption, and location choices, yet the area of health and well-being has received comparatively less attention, according to a recent review (Milakis et al., 2017). A possible reason for this knowledge gap is the uncertainty regarding how AVs may affect travel behavior (Soteropoulos et al., 2019), including AV ownership and use models (private, shared, and/or pooled), which have important implications for health and well-being analyses. Nevertheless, research in the area of AVs and health is increasing, with recent publications by Richland et al. (2016), Crayton and Meier (2017), and Curl et al. (2018), and even two articles (Dean et al., 2019; Sohrabi et al., 2020) available since our work on this chapter commenced in mid-2019.

In this chapter, we discuss the potential implications of AVs for health (both physical and mental health) and well-being (happiness, satisfaction, and fulfillment). Given the relative lack of empirical evidence on this topic, we employ a deductive approach rather than a systematic review of the literature. First, we review the major pathways by which the transportation system affects multiple dimensions of health and well-being. Given the importance of travel choices in these pathways, we then summarize some of the most relevant ways in which AVs may change travel behaviors. Finally, we combine these insights to deduce potential positive, negative, and unknown effects of AVs on health/well-being, leading to a discussion of policy implications and a prospective research agenda (a similar deductive approach was also used by Curl et al. (2018) and Sohrabi et al. (2020)). Although we cannot offer definitive conclusions because the exact technology and future use of AVs is still unknown, we aim to initiate a broader conversation among planners and industry leaders about potential health and well-being impacts of AVs. This is a crucial conversation for the present time, because AV use is not yet ingrained in travelers' daily lives and policies can still play a major role in helping lead the automated driving transition toward healthier outcomes.

2. How transportation influences health and well-being

Transportation is linked to various health and well-being outcomes. In recent decades, this linkage has been increasingly recognized among academics and practitioners (De Vos, 2018b; Malekafzali, 2009; van Wee and Ettema, 2016), resulting in new interdisciplinary collaborations, journals (the *Journal of Transport & Health*), and conferences (e.g., the International Conference on Transport & Health). There are various ways to discuss the health and well-being impacts of transport, although it is beyond the scope of this chapter to discuss this in detail (see, e.g., Giles-Corti et al. (2016) for a conceptualization). In this section, we first discuss relationships between transportation and physical health, followed by an overview of intersections with well-being. Our aim is not to conduct a systematic review, but rather to provide an overview of existing (systematic) reviews or, in the absence of such studies, key policy and empirical papers. We conclude by summarizing these impacts in a conceptual framework.

2.1 Physical health

The four main pathways through which travel affects physical health are the following: (i) traffic safety, (ii) air pollution, (iii) physical activity, and (iv) noise. This selection of impacts is based on the current list of the health risks of transportation acknowledged by the World Health Organization (WHO, 2019a), although we excluded climate change in our discussion. These impacts correspond with the main risk exposures listed by Giles-Corti et al. (2016).

2.1.1 Traffic injuries and deaths

Poor traffic safety has long been recognized as a detriment to individual and public health. According to the WHO, road traffic crashes are one of the top 10 causes of death worldwide and the leading cause of death for children and young adults (WHO, 2018a). Several developed countries have successfully reduced the number of deaths and relative deaths by inhabitants and distances traveled (OECD, 2019). Nevertheless, the absolute number of deaths globally due to road traffic has continued to climb in recent years, reaching 1.35 million people in 2016; however, relative to the size of the world's population, it has stabilized. Between 2013 and 2016, there were no reductions in road traffic deaths in any low-income country (WHO, 2018a).

The distributions of traffic casualties and serious injuries, as well as the risk of serious injury or death from traffic, is unequally distributed and depends on location and travel mode. Controlling for the number of inhabitants, the risk is three times higher in developing countries compared to developed countries (27.5 vs 8.3 deaths per 100,000 population) (WHO, 2018a). In the EU, the majority of traffic fatalities occur on urban (38%) or rural roads (53%); few take place on motorways (9%) (Eurostat, 2017). Globally, pedestrian and cyclists constitute a quarter of all fatalities, motorized two-wheelers comprise another quarter, and car occupants 29% (WHO, 2018a). This distribution varies by location. Most deaths in Africa are of pedestrians and cyclists, whereas in south-east Asia, deaths occur primarily for motorized two-wheelers. In Europe and the US, car occupants constitute the highest number of deaths, but non-occupants are overrepresented among deaths and serious injuries (USDOT, 2019). Driver errors cause more than 90% of traffic collisions (USDOT, 2015).

2.1.2 Air pollution

In addition to contributing to climate change, the transportation sector is responsible for a large proportion of urban air pollution, including particulate matter, CO_2, and NO_x. In the EU, transportation contributes a quarter of direct greenhouse gas emissions and a fifth of CO_2 emissions (EEA, 2018a). Although many sectors have successfully reduced their emissions in recent decades, transportation emissions are stable in the UK and EU

(DfT, 2018; EEA, 2018b). Transportation is thus not only a major contributor, but its relative contribution is growing. Road travel is estimated to be responsible for up to 30% of particulate emissions in European cities and up to 50% in OECD countries, mostly due to diesel traffic, though the exact amount varies widely between locations (WHO, 2019b). Moreover, air travel (a heavily polluting mode) continues to grow.

The WHO estimates that 4.2 million annual deaths result from exposure to ambient (outdoor) air pollution, and 91% of the global population lives in areas exceeding WHO exposure guidance levels. Health consequences of ambient air pollution include lung cancer, acute lower respiratory tract infection, stroke, ischemic heart disease, and chronic obstructive pulmonary disease (WHO, 2018b).

Differences exist in exposure to air pollution and the inhaled dose by mode of travel. Most studies report that car commuters have the highest cumulative exposure levels (Cepeda et al., 2017). However, due to the active nature of walking and cycling and resulting higher respiratory rates, active commuters have higher inhalation doses than do commuters using motorized modes.

2.1.3 Physical activity

The lack of physical activity is a major cause of morbidity and mortality (Lee et al., 2012). The WHO (2010) recommends spending at least 150 min of moderate-intensity aerobic activity—or at least 75 min of vigorous-intensity aerobic activity (or an equivalent combination)—a week. Annually, two million deaths can be attributed to a lack of physical activity. A lack of physical activity is a leading risk factor for obesity and cardiovascular disease, type 2 diabetes, and some types of cancer. Independent of the level of physical activity, sedentary behavior (total sitting and TV-viewing time) is associated with greater risks for several major chronic diseases (Patterson et al., 2018).

Levels of engagement in physical activity differ by location and socioeconomic characteristics. Globally, 25% of adults are insufficiently active (WHO, 2018c). Women are more likely to be insufficiently active than men, and a higher gross domestic product is often associated with lower physical activity levels (WHO, 2018c).

The decrease in physical activity over time has coincided with an increase in motorization, including motorized transportation. Walking, cycling, and other forms of active travel provide a sufficient level of physical activity to improve health and well-being (Chief Medical Officers, 2011). For example, a cycling level corresponding to WHO recommendations results in a 10% reduction in the risk of all-cause mortality (Kelly et al., 2014). Walking and cycling levels sharply differ between locations, and the social and spatial context has a strong influence (Heinen et al., 2010).

2.1.4 Noise

Despite receiving less attention than the previous three topics, noise is increasingly acknowledged to have negative health impacts. Noise can affect the auditory system and result in hearing loss and tinnitus. Moreover, noise (especially following long-term exposure) has additional adverse health effects resulting from psychological and physiological distress, homeostasis disturbance, and increasing allostatic load (Basner et al., 2014, in WHO, 2018d). Exposure to noise can disturb sleep, cause cardiovascular and psychophysiological effects, reduce performance, and provoke annoyance responses and changes in social behavior (WHO, 2018d).

Road traffic is the largest contributor to noise pollution in urban areas and is the most important source of noise annoyance. Over 70 million Europeans are assumed to have a day–evening–night noise level greater than 55 dB as a result of road traffic noise (EEA, 2014, 2018c). In addition, noise from air transportation can be high in specific areas. Noise levels increase with higher traffic volumes and speeds, but urban design, road surfaces, and weather conditions influence noise levels as well.

2.2 Well-being

In recent decades, interest in linkages between travel and well-being has rapidly increased (De Vos et al., 2013; Mokhtarian, 2019). In this section, we consider three main effects of transportation on mental health and well-being: (i) travel satisfaction, (ii) access to activities, and (iii) spill-over effects on the activity at the destination.

2.2.1 Travel satisfaction

Travel satisfaction refers to the emotions people experience during trips and how they evaluate these trips (De Vos and Witlox, 2017). After the development of a reliable tool to measure travel satisfaction—the satisfaction with travel scale (Ettema et al., 2011)—multiple studies (from different geographical contexts) have analyzed determinants of travel satisfaction. The chosen travel mode has an important influence on how people perceive their trips: specifically, active travel mostly results in the highest levels of travel satisfaction, while public transit (bus in particular) is perceived least positively (De Vos et al., 2016; Singleton, 2019b; Ye and Titheridge, 2017). Most studies also find a negative effect of trip duration on travel satisfaction (Higgins et al., 2018; Morris and Guerra, 2015), since long trips might be a mental and physical burden. Positive (or negative) attitudes toward the chosen travel mode positively (or negatively) impact satisfaction with the trip made (De Vos, 2018a; St-Louis et al., 2014), while traveling alone has a negative effect on satisfaction levels (De Vos, 2019; Zhu and Fan, 2018). The effects of the built environment and travel distance on travel satisfaction remain unclear so far (De Vos et al., 2016; Ye and Titheridge, 2017). Finally, satisfaction can be influenced by the activities people undertake while traveling. For public transit users, productive activities and talking to other passengers are found to positively affect satisfaction levels, while entertaining and relaxing activities seem to negatively influence travel satisfaction (Ettema et al., 2012; Lyons et al., 2007); perhaps they are done to cope with a burdensome trip. Since experiencing positive emotions can improve people's life satisfaction (by stimulating original thinking, fostering skills, liking of self and others, etc. (Lyubomirsky et al., 2005)), travel satisfaction can directly influence well-being and mental health.

2.2.2 Access to activities

Transportation also affects well-being by providing access to activities at different locations (accessibility additionally influences physical health through access to health care, healthy food, and recreational opportunities). Elements such as life satisfaction, personal growth, and realization of the best in oneself are significantly influenced by the participation in (and performance of) out-of-home activities enabled by travel (Ettema et al., 2010; Morris, 2015). Even the potential to travel (motility)—having access to transportation options (e.g., living close to public transport, owning a car) and the knowledge and skills to use them (Kaufmann et al., 2004)—can generate feelings of freedom, competence, and belonging.

Not being able to reach rewarding out-of-home activities due to limited travel options can consequently affect quality of life in a negative way (Delbosc and Currie, 2011; Lucas, 2012). Especially low-income groups and individuals with limitations on physical or cognitive functioning (e.g., older adults) might suffer from transportation disadvantage and social isolation. Travel might also restrict the execution of certain rewarding activities, as time spent traveling cannot be used for other activities (disregarding activities during travel). For instance, Stutzer and Frey (2008) found that long commute trips resulted in low levels of subjective well-being, partly due to limited time for family activities. On the other hand, examining relationships between commute duration and life satisfaction is complicated (Clark et al., 2019; Morris and Zhou, 2018), since long commutes are often linked to (financially) rewarding jobs, owning a house, and being married, which positively impact life satisfaction.

2.2.3 Spill-over effects on the activity at the destination

Not only does transportation provide access to out-of-home activities, but the performance of (and satisfaction with) that activity can be influenced by perceptions of the preceding travel episode. In fact, travel satisfaction might mainly influence life satisfaction indirectly (De Vos, 2019), i.e., through satisfaction with destination activities. Morris and Zhou (2018) associated longer commute durations with lower positive emotions at work. Friman et al. (2017) found that satisfaction with the trip to work influenced the mood directly after the commute trip but not later in the day. Studies focusing on children found active travel to be associated with a positive mood after arriving at school or during the first school lesson (Stark et al., 2018; Westman et al., 2017). In addition to satisfaction with the destination activity, travel may also affect the performance of that activity. Stress experienced during the commute can negatively affect job performance (Legrain et al., 2015); while Loong et al. (2017) found that cyclists felt most energized at work, drivers were least energized. On the other hand, travel time can also be used to mentally prepare for the activity ahead, potentially improving the performance of that activity (Jain and Lyons, 2008).

2.3 Conceptual framework

So far, we have discussed health and well-being impacts as a consequence of transportation. However, in order to fully understand the impacts of changes in transportation supply—such as the introduction of AVs—it is crucial to recognize that such changes first influence individuals' travel choices (which are also partly affected by the acceptance levels of AVs; see, e.g., Becker and Axhausen (2017) for a review on acceptance of AVs), which subsequently affect health and well-being. Handy (2014) explains how choices of travel amount, travel mode, and other dimensions (e.g., time-of-day, driving speed and style, physical and mental condition) impact individual and population health. Fig. 1 translates her discussion into a conceptual diagram and supplements it with well-being impacts. It also relates to other conceptualizations of health–transportation relationships (e.g., van Wee and Ettema, 2016).

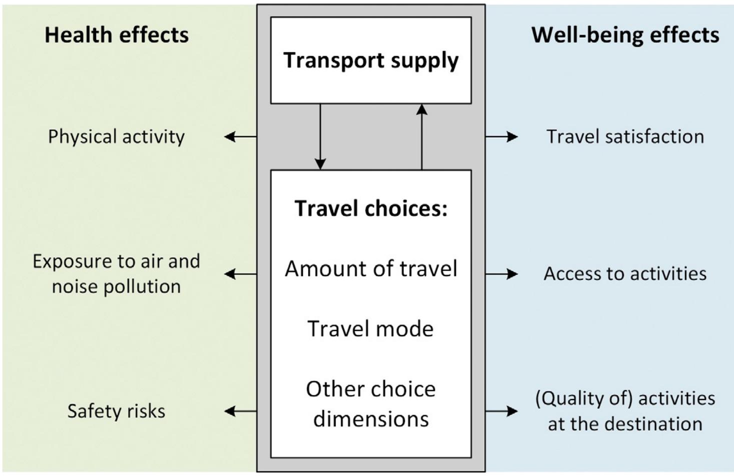

Fig. 1 Conceptual framework of individual health and well-being impacts of travel choices.

Fig. 1 demonstrates not only how the characteristics of the transportation supply (e.g., AVs) directly impact health and well-being, but also how supply interacts with demand—the various dimensions of travel choices. Therefore, these two should be examined jointly when studying AV effects on health and well-being. Although we focus on individual effects in the following sections, the population effects of AVs can be thought of as the sum of individual impacts and any higher-order influences due to aggregation (e.g., access to activities leads to land use changes, which again influences the access to activities).

3. Expected effects of autonomous vehicles on travel behavior

The major anticipated benefits of AVs are that they would make "driving" safer and reduce negative emotions (e.g., stress) often linked with navigating a car through traffic. By reducing the burdens of driving and navigating, AVs could allow travelers to use travel time for other purposes: working, reading, entertainment, or rest (Pfleging et al., 2016; Singleton, 2019a). According to Fig. 1, this change in transportation supply would influence travel choices, which would further affect individual and population health and well-being. In particular, the amount of individual travel together with travel mode choice (including the various proposed forms of AV-sharing) influences vehicle-distances traveled, which carries health and well-being impacts. These two travel behavior dimensions are discussed in the following sections.

3.1 Amount of individual travel

Literature suggests that the introduction of AVs will prompt people to travel longer distances for their daily activities (choosing further destinations and/or traveling more frequently); supporting results have been obtained from activity-based modeling studies (Auld et al., 2017; Childress et al., 2015). However, it is worth noting that these studies assume that improved travel experiences—commonly formalized as reduced values of travel time—will make people accept longer in-vehicle travel times. Although this may occur in aggregate, two individual-level considerations warrant discussion. First, new activities performed during travel could interact with other daily activities and lead to a variety of total travel time developments, including a possibility of reduced daily travel time (Mokhtarian, 2018; Pudāne et al., 2018).[a] Second, increased travel time means less time for other activities, possibly altering travelers' daily activity schedules. Changing daily routines to accommodate more travel is not easy or desired by all (Zmud et al., 2016). Alternatively, increased travel for holidays seems a more likely consequence of AVs, since that does not require systematic changes in daily activity schedules (LaMondia et al., 2016).

The other proposed source of increasing individual travel amounts comes from longer-term changes to home and/or work locations, resulting (as before) from the reductions in travel disutility. This would lead to an unwelcome effect of urban sprawl (Heinrichs, 2016; Zakharenko, 2016). However, the implications of accepting longer commute durations (and possible counter-arguments for doing so) should also be considered carefully, e.g., in the context of travelers' daily activity schedules. Furthermore, if value of time is used as the main predictor of travel behavior changes, then it should preferably be obtained from stated choice studies using a trip-making or residential location (as opposed to mode choice) context. Adopting the latter, Krueger et al. (2019) did not observe significant changes in the value of travel time.

[a] An example in Pudāne et al. (2018) shows how a traveler, who is able to rest in an AV, may eliminate a detour to home after work and go straight to an evening activity, thereby reducing the total travel time. Such activity rearrangement is fully rational and in line with microeconomic theory, given a certain activity wish list. Although such instances may occur less often than activity rearrangements that result in more travel, the possibility of less individual travel cannot be excluded *a priori*.

3.2 Travel mode choice

That AVs could lead to a higher mode share for (private) cars is just as widely expected as the potentially increasing travel distances (e.g., Soteropoulos et al., 2019). To reduce the negative effects of such modal shifts, shared and pooled AVs are often suggested as more sustainable future modes. Therefore, the question of shared AV acceptance and success has been among the top priorities in AV-research in the last few years (Haboucha et al., 2017; Krueger et al., 2016; Lavieri and Bhat, 2019; Nazari et al., 2018; Stoiber et al., 2019). Although most studies find increased acceptance of car-sharing as compared to the low present levels (Conway et al., 2018), the travelers most interested in shared AV systems are current public transit, car-sharing, or active mode users, not private car users (Haboucha et al., 2017; Krueger et al., 2016; Nazari et al., 2018). Relatedly, shared/pooled-AV acceptance is high in places where travelers are accustomed to attractive public transit options (Stoiber et al., 2019). Finally, even among current non-automated modes, car-sharing has been shown to be a weak substitute to private car travel and tends to replace public transit and bicycle modes instead (Carrone et al., 2019; Gehrke et al., 2018).

These empirical studies support an intuitive idea that travelers prefer the mode most similar to their current choice: the travel option that is the best substitute for their current ways of travel (van Wee et al., 2019). We represent this concept in Fig. 2, which shows characteristics of current and future AV modes and expected modal shifts. Even though this comparison does not include all relevant travel characteristics and is qualitative—the exact values and relative importance of attributes could magnify or reduce the impact of various characteristics—it provides a framework to discuss potential modal shifts in an AV future. Overall, we expect modal shifts toward private, shared, and pooled AV modes. However, changes in distances traveled are determined not only by the relative preferences for new AV modes, but also by the shifts away from current modes.

Although, at first glance, shared or pooled AVs could seem to be a close substitute to private cars, Fig. 2 shows that, with respect to many attributes, they resemble—and hence could substitute—current car-sharing, taxis, and, most importantly, public transit.[b] Furthermore, it can be argued that the

[b] There may be exceptions to this correspondence, as shown by the thin arrows in Fig. 2. For example, public transit passengers who currently like the ability to be productive while traveling may be attracted to the activity facilitation made possible by shared or even private AVs. In the opposite direction, current car drivers who choose to own because they value or require door-to-door service and departure time flexibility may find some value in shared or even pooled AVs, if the lower costs and multitaskability outweigh the loss of privacy and personalization.

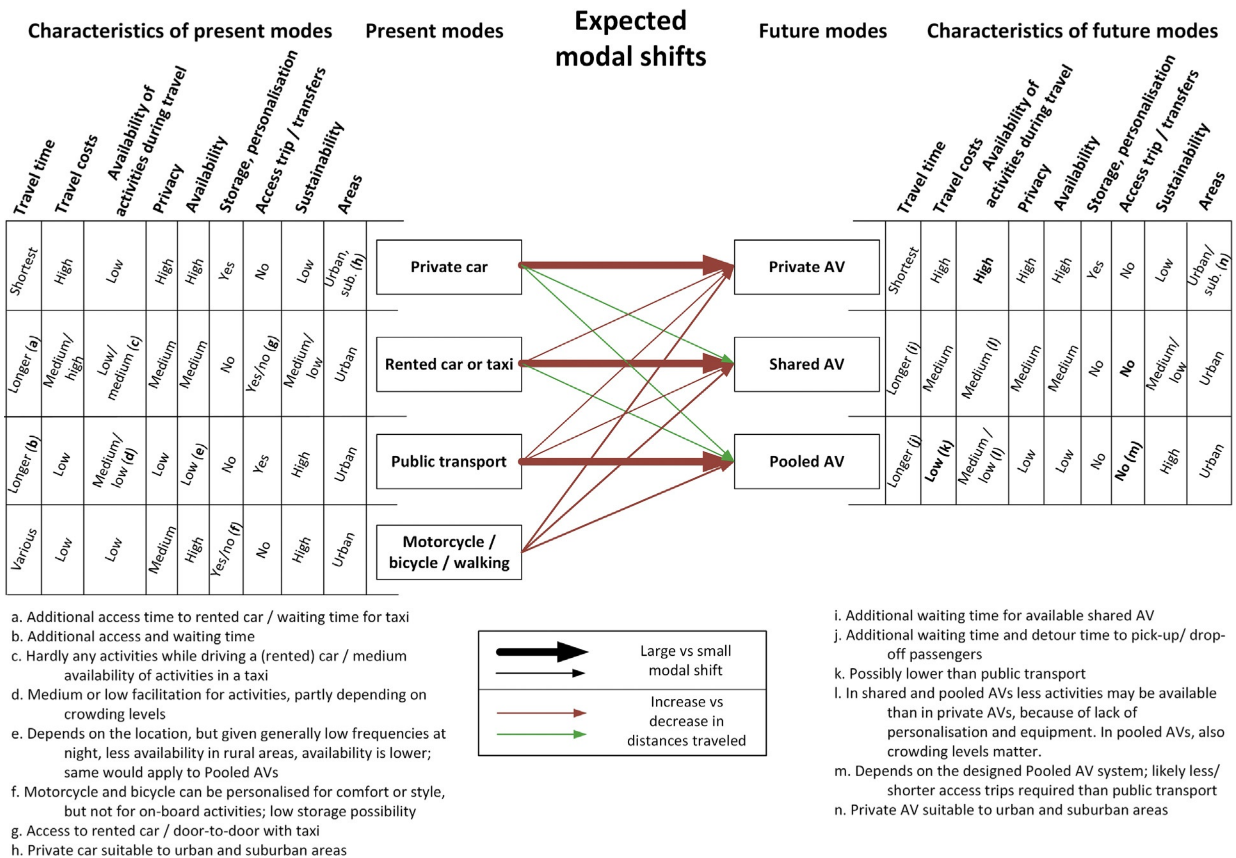

Fig. 2 Comparison of present and future transportation modes and expected modal shifts.

new AV modes improve upon their current mode "counterparts" (highlighted bold on the right side of Fig. 2). For today's private car users, private AVs offer much greater possibility to engage in new non-driving activities during travel. Shared AVs would provide present rental car and car-sharing users a comparable level of multitasking facilities, plus reduced access times and improved door-to-door and one-way services (Krueger et al., 2016). For public transit riders, pooled AVs would likely pick-up and drop-off closer to the destination and might even be cheaper than public transit thanks to the savings of driver costs (Bösch et al., 2018), especially outside of dense urban areas.[c] These benefits will likely motivate the users of the current modes to shift to the most similar automated modes. Results of Pakusch et al. (2018) empirically support these trends, although they also argue that the current modes will most likely remain popular in the near future.

The preceding discussion on the shifts from current modes to their AV "counterparts" is crucial, because we expect that this shift would result in increased vehicle use and distances traveled (the thick red arrows in Fig. 2), due to three potential reasons. First, if travelers experience the new mode as superior to the present mode, they (in aggregate) might use it more—for longer and/or more frequent travel (however, see Section 3.1 for points of caution). Ferdman (2020) even warns that corporations, who may own the future shared or pooled AV fleets, will have an interest in prolonging trips to maximize exposure to in-vehicle advertising. Second, the nature of shared/pooled AVs is such that greater vehicle-distances will be traveled to satisfy the same number of person-trips, compared to the most similar non-automated mode. Shared AVs would travel further distances to provide door-to-door travel, instead of requiring drivers to pick-up and drop-off vehicles at designated locations. The same is true for pooled AVs, which would (additionally) generate greater travel distances than public transit because they have a lower capacity/occupancy. Third, all automated modes might involve empty travel: to access the next customer for a shared AV or to share a private vehicle among household members; to perform pick-up or drop-off tasks independently (reducing some trip chaining behavior); or to access cheaper parking.

[c] Some have noted that AVs might even attract a portion of active mode users (cyclists and pedestrians) because of the much greater convenience to use AVs for short trips (e.g., it would not be necessary to look for a parking spot); however, Fig. 2 hypothesizes that this shift would not be great due to dissimilarity of active modes and AVs in other aspects.

To summarize, this section has argued that AVs may change travel choices in a way that would lead to more automobile travel, even if not necessarily to more person-travel. In particular, this increase could be most strongly determined by modal shifts away from current modes to their more attractive (but also more travel-distance-intensive) AV counterparts.

4. Potential effects of autonomous vehicles on health and well-being

We now turn our attention to outlining potential effects that AVs could have on health and well-being. It should be noted that these impacts are speculative, deduced in part from our discussions in earlier sections—about the more general health/well-being impacts of the current transportation system and how/why AVs might affect traveler behaviors within that system. Rather than conducting a systematic review ourselves, we also rely in part upon summaries of the literature identified in a recent scoping review (Dean et al., 2019). Recent work by Richland et al. (2016), Crayton and Meier (2017), Curl et al. (2018), and Sohrabi et al. (2020) is also particularly informative.

We organize this section around the central transportation—health/well-being linkages we identified earlier: safety, travel satisfaction, access to activities, physical activity, air pollution and noise. Within each topic, we discuss the variety of possible benefits and adverse effects of AVs that we and others have considered. Despite the potential varied effects, based on our exploration we suggest that AVs are likely to have overall positive impacts on some health and well-being aspects (safety, travel satisfaction, access to activities) and overall negative impacts on others (physical activity), while effects are more uncertain for other topics (urban built environments, air and noise pollution).

4.1 Overall positive effects

4.1.1 Improved safety

The most consistently cited health benefit of AVs is the reduction of injuries and deaths from traffic collisions (Dean et al., 2019; Pettigrew et al., 2018). AVs will be (ostensibly) safer than current vehicles because they will be driven by computers rather than people, thus removing the human element—the cause of the majority of traffic crashes (USDOT, 2015). The computer vision systems of fully-automated vehicles are expected to improve collision avoidance, lane keeping, and other driving tasks, while connected vehicles/infrastructure will allow for sharing vehicle trajectories and improving safety in high-crash-risk situations (e.g., queues, intersections) (Milakis et al., 2017). Crashes could be reduced by 40% or more (Fagnant and Kockelman, 2015).

Nevertheless, such safety benefits may be modest until AV penetration rates are high and AVs can operate without any human intervention; also, aggregate safety gains could be reduced if AVs lead to more car travel. Safety could actually decrease for AVs in which humans are required to monitor and take over driving under certain conditions (Strand et al., 2014). Recent fatalities involving such vehicles highlight these and other questions regarding the safety performance of AVs in challenging (low light, poor weather) conditions and in complex or unique traffic situations. Cyberattacks may also be a threat (Petit and Shladover, 2014). Finally, there are ethical and legal issues remaining to be resolved over how AVs should act in situations where a collision is unavoidable (Bonnefon et al., 2016): does the computer prioritize protecting the vehicle occupants over non-occupants (including vulnerable road users)? The way in which this issue is resolved could exacerbate existing inequalities in safety between motorized and non-motorized users. Nevertheless, we expect overall positive health benefits from improved safety.

4.1.2 Improved travel satisfaction and spill-over effects

AVs will likely improve travel experiences of "driving" that affect mental health and well-being. By removing the need to operate a vehicle when traveling alone, AVs may reduce many of the stresses associated with navigating urban traffic and congestion (Crayton and Meier, 2017; Curl et al., 2018; Dean et al., 2019; Richland et al., 2016), thus improving mental well-being and physical health. By providing opportunities to do other, more productive/rewarding things while traveling by car, AVs may also improve enjoyment and happiness with travel (and satisfaction with the destination activity). Although these well-being effects may be substantial, they should not be overestimated (Singleton, 2019a).

There could also be some negative impacts to well-being as a result of AVs. Some studies find that the increased possibility to use travel time productively creates psychological pressure to do so and may actually decrease travel satisfaction and well-being (Pudāne et al., 2019; Shaw et al., 2019). Furthermore, sharing and especially pooling AVs reduces one of its core benefits: the improved travel experience and the multitasking possibility during travel. This is also reflected in stated choice studies that find the value of travel time to be lower for shared (exclusive use) AVs than pooled AVs (e.g., Krueger et al., 2016). Finally, some people enjoy the act of driving and gain status from owning a specific vehicle; these intrinsic experiences related to driving might be diminished when (especially shared) AVs dominate (Curl et al., 2018).

4.1.3 Greater access to activities

We and others expect that AVs will likely improve access to activity opportunities, for a couple of reasons. First, distant activities—which may have been too time-consuming to reach with conventional cars—might become accessible if people do not "lose" time and can perform certain activities (e.g., working, studying, etc.) during AV travel (Meyer et al., 2017). More generally, formerly outside-the-trip activities can be brought into the trip, thereby freeing time for new or expanded out-of-trip activities (Mokhtarian, 2018; Pudāne et al., 2018). Even if travelers do not (frequently) make use of the enhanced accessibility, there is an "option-value" from having greater activity opportunities (Laird et al., 2009).

Second, AVs can increase accessibility for people with mobility limitations (Curl et al., 2018; Dean et al., 2019; Pettigrew, 2017; Richland et al., 2016). A large minority of the population cannot (easily) transport themselves to/from daily activities: young children, older adults, and people with certain physical and intellectual disabilities (Bennett et al., 2019; Pettigrew et al., 2018). By eliminating the need to rely on others for travel, AVs will likely improve access to health care, grocery stores, jobs, education, etc., for these people. These user groups are expected to be among the main drivers of increased AV travel demand (Harper et al., 2016). Improved mobility may also help people living in rural areas to access hospitals and other services. Additionally, by facilitating independent mobility and access to opportunities, including social activities and connections with family and friends, AVs may indirectly reduce social isolation, increase social inclusion/connectivity, and improve mental health and quality of life (Curl et al., 2018; Pettigrew, 2017; Richland et al., 2016).

At the same time, AVs have the potential to widen existing disparities in transportation access, depending on how they are implemented and managed and how much they cost to use. Private AV ownership models may exacerbate inequalities by increasing financial barriers to accessing driver-less mobility, especially for low-income and aging populations (Curl et al., 2018; Dean et al., 2019; Pettigrew et al., 2019). Historically-disadvantaged communities (including low income, people of color, and immigrant communities) already face financial, technological, and social barriers to accessing electric and shared mobility, issues unlikely to be addressed simply through the addition of AVs (Cohen and Shirazi, 2017). Finally, there are concerns that increasing suburban sprawl and mode shifts toward AVs may reduce funding and political support for public transportation, thus exacerbating access for transit-dependent populations (Cohen and Shirazi, 2017; Fleetwood, 2017).

4.2 Overall negative effects

4.2.1 Reduced transport-related physical activity

Due to some of the positive well-being effects anticipated (see above) and other improvements to the existing suite of transportation options (see Fig. 2), we and others expect AVs to reduce transport-related physical activity by taking some mode share away from walking, bicycling, public transit, and other forms of active transportation (Crayton and Meier, 2017; Curl et al., 2018; Milakis et al., 2017; Sohrabi et al., 2020; Soteropoulos et al., 2019). Such modal shifts away from these active modes pose a high health risk, because—as Handy (2014) notes—trips with active modes are more beneficial if they replace sedentary passive travel in a car (as opposed to being newly-generated leisure trips). Similarly, replacement of active mode trips with less active AV travel is likely more harmful for the individual (per distance traveled) than current car trips becoming longer or more frequent in AVs. Less physically-active transportation and more sitting (in AVs) is likely to increase risks of obesity and non-communicable diseases (Crayton and Meier, 2017).

Although the exact impacts are difficult to predict, AVs may offer some pathways to increase overall physical activity. Being productive in AVs may free up time for other physically-active non-travel activities, or compensating behavior may increase leisure-time physical activity, and it is possible (though not highly likely) that AVs could be equipped with exercise machines (Crayton and Meier, 2017; Curl et al., 2018). Road capacity might increase with connected AVs, and some suggest that this (plus a reduction in demand for on-street parking) might open up road space for non-motorized infrastructure (Milakis et al., 2017; Soteropoulos et al., 2019). Yet, these opportunities seem unlikely to outweigh negatives from mode shifts. Overall, we expect physical activity obtained through personal transportation to decrease.

4.3 Uncertain effects

4.3.1 Changes to urban built environments

Two main perspectives have been articulated regarding how AVs might change built environments. The "hopeful view" for health (Richland et al., 2016) is that AVs will lead to denser urban developments and reallocation of road space (Crayton and Meier, 2017; Curl et al., 2018; Dean et al., 2019; Milakis et al., 2017). In dense urban areas, land is valuable and in high demand. According to Fraedrich et al. (2019), widespread AV adoption is expected to reduce the need for parking in dense urban centers as AVs, after dropping off passengers, can drive themselves to a remote (cheaper) location to wait for their next trip (shared and pooled AVs might furthermore reduce the total number of vehicles, thus also reducing parking demands). As previously mentioned, road space may be reallocated toward transit and/or walk/bicycle infrastructure. Altogether, this may open up land for more development as well as public space, which has the opportunity to make for more attractive, walkable urban environments, thus facilitating greater physical activity. Also, people interested in using AVs might be inclined to move to cities if AVs are introduced there first.

The pessimistic view is that AVs will increase urban sprawl and lead to more land dedicated to transportation and parking (Crayton and Meier, 2017; Curl et al., 2018; Richland et al., 2016). This view presumes that the reduced disutility of travel would lead to a willingness to live further from work and therefore increased levels of urban sprawl and automobile dependence (Mokhtarian, 2018; Soteropoulos et al., 2019). However, this link is complex (see Section 3), and a recent study shows that travel disutility is not reduced in the context of residential location (Krueger et al., 2019). Nevertheless, even if AVs do not lead to increased person-travel (and thereby urban sprawl), the increases in vehicle travel (see Section 3.2) could further strain crowded and congested urban street networks, forcing more traffic onto local streets and making them less conducive for walking and cycling. At the same time, other parts of urban/suburban locations (especially those in close proximity to urban centers) may experience an influx of parked or circling (empty) AVs (Ostermeijer et al., 2019). Land area dedicated to cars would increase, thus deteriorating walkable environments, discouraging physical activity, and further exacerbating geospatial inequities in healthy travel behaviors. Because these land use and built environment changes are likely to occur over a long period of time, we are uncertain about whether they will be positive or negative, overall.

4.3.2 Air pollution and noise

Overall impacts of AVs on air pollution and noise are similarly uncertain (Crayton and Meier, 2017; Dean et al., 2019; Sohrabi et al., 2020). There are likely to be benefits since many experts expect AVs to be battery-electric powered (Pettigrew, 2017). Even without electrification, more smooth driving operations, improved navigation, and fewer cold starts (especially for shared/pooled AVs) could lower tailpipe emissions of air pollutants such as NO_x, CO, and CO_2 (Milakis et al., 2017). In the long run, heavy safety equipment may not be as necessary, thus reducing vehicle weights and emissions (Richland et al., 2016). Reduced vehicle emissions would yield public health benefits in population centers, but the overall emission (including GhG) impacts of increased electric energy demand depend upon the portfolio of energy generation methods in different regions. Areas with less renewable and more polluting electric energy sources would see less health benefits.

On the other hand, the impact of more trips and longer vehicle-distances traveled by AVs could work against some of these emissions reductions (Richland et al., 2016; Wang et al., 2018). While electric vehicle engines operate more quietly, the majority of road noise comes from tire/pavement interactions (Rochat and Reiter, 2016) that would be only modestly decreased (if at all) and potentially counteracted by increased traffic volumes and faster speeds (Sohrabi et al., 2020). The impacts of AVs on air pollution will likely depend greatly upon changes in travel demand as well as the degree to which AVs are also EVs (Crayton and Meier, 2017).

4.3.3 Other

These discussions do not include other secondary and tertiary impacts of AVs on people's lives that may have implications for health, well-being, and equity, but that may act outside of the transportation system or in transport-adjacent ways. Positively, affordable shared/pooled AVs could help economically disadvantaged households free themselves from the burden of auto ownership and spend more money on health care and healthy food. AVs could also reshape the last mile of shipping and shopping, allowing people (especially those with mobility limitations) cheaper, quicker, and easier ordering and delivery of groceries, prescriptions, and other consumer goods. Negatively, improved traffic safety may reduce organ transplant availability (Pettigrew, 2017). Replacing drivers with computers could eliminate hundreds of thousands of transportation industry jobs (Crayton and Meier, 2017; Fagnant and Kockelman, 2015; Sohrabi et al., 2020), and increased independent mobility for seniors could reduce employment in home care (Pettigrew et al., 2019). Nevertheless, Clements and Kockelman (2017) offer a comprehensive analysis of AV effects on different industries, including also job and efficiency gains in different sectors. They conclude that AVs will bring a net gain for the economy. Overall, consideration of the multitude of potential impacts of AVs on health and well-being, some of which may not be apparent today, requires an evolving systems approach.

5. Conclusions

In this chapter, we have aimed to fill a gap in the literature discussing potential health and well-being implications of AVs. Given the scarcity of empirical work on this topic, our perspectives are based on merging understanding of current transportation–health relationships with discussion on potential travel behavior changes in an AV-era. As our discussion of the positive, negative, and uncertain effects of AVs on health and well-being makes clear, there appear to be likely benefits (improved safety, satisfaction, and access) as well as disadvantages (reduced physical activity), but much about these and other impacts remains unknown. It is our hope that this chapter: (1) increases awareness of the importance of considering health/well-being impacts of AVs; (2) encourages policymakers to consider how best to facilitate health benefits and mitigate disadvantages of AVs; and (3) inspires researchers to study these relationships and impacts in more detail. Toward these latter two aims, we close this chapter by discussing potential policy implications and research programs.

5.1 Policy implications

Policy measures should try to limit the possible negative effects of AVs on health and well-being, such as reduced physically-active travel and increased vehicle-distances traveled and urban sprawl. Spatial planning policies creating compact and mixed-use neighborhoods and restricting new suburban neighborhoods located far away from city centers (i.e., urban sprawl) therefore remain important. Improved infrastructure for cyclists and pedestrians (e.g., separated bike lanes, broad sidewalks with safe crossings) could mitigate the active travel-reducing effect of AVs, especially if road space can be reallocated from automobile parking and travel lanes. Care should be taken to avoid further legal restrictions on how, where, and when pedestrians can access and cross streets, as conflicts with automatically-yielding vehicles may become a point of contention.

The types of AVs people use may have an impact on the severity of health impacts (Dean et al., 2019; Fitt et al., 2018). Private AVs could have more negative effects, such as additional and longer car trips (especially for holiday purposes) but also equity issues due to the large up-front costs. However, shared and pooled AVs may also be associated with increased distances traveled due to their lower capacity (compared to public transport), door-to-door service policy, and empty trips. Therefore, we would recommend that policymakers seeking to prioritize health and well-being should focus on provisions for active travel rather than placing high hopes on shared AVs.

Attention should also be paid to facilitating a more widespread and equitable distribution of the health and well-being benefits of AVs in the areas of safety, travel satisfaction, and access to activities. Zoning and other urban development policies should ensure that disadvantaged communities do not end up on the receiving end of large AV parking and circulation zones. Pricing or other policies could discourage AVs in places where they might compete with more healthy modes (like public transportation, walking, and bicycling in dense urban areas) and encourage AVs in more exurban and rural areas where they might improve access the most. The safety of non-occupants and vulnerable road users should be considered when developing collision avoidance and decision algorithms, as there are ethical issues involved in forced choice situations in which a collision is unavoidable (Bonnefon et al., 2016; Fleetwood, 2017; Goodall, 2017). Financial incentives and subsidies, as well as programs to develop technological skills, may be warranted to help people in poverty, older adults, or rural residents to use AVs to access healthy opportunities and experience improved independent mobility and well-being. Other policy and planning strategies for AVs (not necessarily focused on health/well-being) are described in Zmud et al. (2017).

5.2 Research agenda

The difficulty with analyzing the effects of AVs on health and well-being is that AVs are currently very niche. As a result, it is hard to measure how people will change their travel behavior and how this will affect health and well-being. Ideally, one would measure individual and/or population health outcomes or risk factors before and after the introduction of AVs, compared to a control group. While difficult to conduct, such experimental or quasi-experimental designs may start to be possible as AV technology advances and AV testbeds expand. In the meantime, various other research approaches are possible.

Stated choice experiments are a common way to study options or attributes that are rare or non-existent. Among stated choice approaches, most attention has been devoted to willingness-to-pay for AVs and choice of privately-owned vs shared/pooled AVs (Gkartzonikas and Gkritza, 2019). However, other choices—e.g., activity generation and scheduling, location choices—are also outcomes of interest. To estimate some of these effects, more stated choice experiments should be directed toward destination choice (including residential location choice, as in Krueger et al., 2019) and trip-making choice in the AV-era. Changes to daily activity schedules should also be considered (Pudāne et al., 2019).

This relates to a widely-known limitation of all stated choice studies: respondents' answers might differ from their real reaction to AVs in the future, partly because their knowledge of different types of AVs may be limited and partly because the options provided by the researchers may condition their answers. An alternative approach is to simulate AV trips in the real-world. A privately-owned self-driving vehicle could be mimicked by providing respondents a free chauffeur service for a certain period of time (see, for instance, Harb et al., 2018). Of course, the high expense associated with these types of experiments makes it difficult to obtain large sample sizes, negatively affecting representativeness. Another promising approach is to research travel behavior in locations where chauffeur-driven cars are commonplace (Wadud and Huda, 2019). As analog for shared/pooled AVs, the impacts of ride-hailing services on travel behaviors and mode shifts could be studied (e.g., Alemi et al., 2018; Clewlow and Mishra, 2017). In all cases, the presence of a human driver likely affects user trust of the service and, possibly, the availability of some activities during travel, therefore challenging the transferability of knowledge to a driver-less situation.

A different way to simulate AVs and their health/well-being effects is to develop scenarios and model the impacts. Recent tools—e.g., the Integrated Transport and Health Impact Modeling Tool, based in epidemiological evidence—can model the health impacts (due to traffic injuries, air pollution, and physical activity) of various transportation scenarios. These health impact modeling tools could conceivably be used to examine the impacts of various AV adoption or policy scenarios (Pourrahmani et al., 2020). This information would be particularly useful to gain a better understanding of the relative magnitude of the tradeoffs between the positive effects of improved safety and the negative effects of reduced physical activity. Recent studies have found that the physical activity benefits of scenarios or interventions with even modest increases in active travel far outweigh the elevated safety risks and pollution exposure (Mueller et al., 2015); although, those studies did not consider AV scenarios.

No matter what method is used, there are key research questions that could illuminate potential health and well-being impacts as AVs become more widely used. The degree to which people are willing to use (and pay for) the experiential and productivity benefits of AVs is a critical travel behavioral factor—affecting mode choices, travel amounts, and location choices—and should be further investigated. Similarly important is the value travelers assign to the privacy and personal attributes of private AVs over shared/pooled AVs, given their differing societal impacts. Across all areas, research should also pay more attention to equity considerations and the distribution of the benefits and costs of AVs.

Overall, the existing state of the knowledge suggests that the effects of AVs on health and well-being are still uncertain and require continued attention. Great benefits are expected from this innovation—such as improvements in traffic safety—but the ripples from AV introduction will likely spread beyond the most obvious gains and have more varied (and potentially negative) impacts on health and well-being. We hope that this chapter has shed light on these future possibilities and opened gateways for further research and discussion.

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