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The impacts of vehicle automation on transport-disadvantaged people

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ABSTRACT

As an emerging technology, vehicle automation will have profound impacts on various aspects of society. Although recent studies have examined the impacts of the proliferation of vehicles with high/full-level automation, few have emphasized the implications for social equity. To better understand how autonomous vehicles (AVs) may influence equity, this study explores the potential influence of AVs on eight groups of transportation-disadvantaged people. Specifically, we synthesize prominent travel behaviors of the identified groups and explore possible impacts of AVs on these groups. We found that AVs tend to bring more benefits than harm to some people but may have mixed effects on others. Based on the findings, we provide policy recommendations for future policy decision-making, which will likely to play an essential role in maximizing AVs' benefits and mitigating their challenges.

Introduction

The rapid development of the technologies that enable automated vehicles (AVs) has drawn increased attention in the last several years. As more manufacturers begin to test AV prototypes and sell vehicles with certain automation features (Boesch et al., 2016), it is reasonable to believe that vehicles with higher levels of automation will be on the road in the foreseeable future, disrupting various aspects of our society along the way (Clements and Kockelman, 2017; Fagnant and Kockelman, 2015). Understanding the potential impacts of AVs is essential to maximizing their benefits and minimizing their challenges to society.

Similar to ripple effects, AV impacts spread sequentially onto various aspects of the society (Milakis et al., 2017; Milakis et al., 2015). First-order impacts are mostly on the traffic and travel costs. For example, AVs can reduce the disutility of travel time and decrease parking costs by self-parking in cheaper areas independently (Anderson et al., 2014; Aria, 2016). The first-order impacts further result in second-order impacts that affect travel behaviors and the transportation system. AVs may reduce the demand for public transit and non-motorized transportation and increase vehicle miles traveled (VMT) (Bahamonde-Birke et al., 2018; Kröger et al., 2019). AVs may also result in fewer lanes, narrower lanes, smaller medians, and fewer street signs and signals (Chapin et al., 2016; Chen et al., 2016a). Finally, the first- and second-order impacts have profound influences on equity, economy, and the environment. AVs have the potential to boost the economy and reduce greenhouse gas emissions (Fagnant and Kockelman, 2015; Greenblatt and Saxena, 2015). They can also enhance the mobility of conventionally disadvantaged people (Alessandrini et al., 2015; Harper et al., 2016; Litman, 2017).

AV impacts are likely to vary among individuals with differing socio-economic and demographic characteristics. However, despite some initial attempts (Cohen et al., 2017), this divergence remains under-discussed in the literature (Douma et al., 2017), rendering policy-makers and the society less prepared for potential inequity issues caused by AVs. Consequently, while some people enjoy the benefits of AVs, others may be worse off due to their disadvantages. For example, people who are unable to drive non-automated vehicles because of disabilities will be able to "drive" AVs, but low-income people may not be able to afford costly AVs. Moreover, during the transitional period, those who have adopted AVs may villainize those who have not for obstructing safety and technology deployment (Levinson, 2015).

As a disruptive technology, vehicle automation has the potential to help create a more sustainable transportation system, but it may also further widen the disparities between population groups. Ultimately, the impacts of AVs, particularly on disadvantaged groups, will depend on the design and implementation of AV-related policies. This paper aims to address two main questions: 1. What population groups are likely to be impacted by AV's, and how? 2. What should policymakers prepare for mitigating the negative impacts of AVs?

As a discussion article, this paper offers insights into potential equity issues related to the development of AVs and the implications for future policymaking. We discuss how AVs might affect transportation equity

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based on the literature and our informed knowledge. Specifically, we first identify transportation-disadvantaged groups. Then, we review the literature and synthesize prominent travel characteristics of each of the groups. Based on these travel behaviors and AV features, we discuss AVs' impacts on the disadvantaged groups, including potential benefits and challenges. These impacts become the foundation for our deliberation of policy recommendations.

Background

Before exploring the prospective impacts of AVs, we set the stage for further discussion from four perspectives. First, we introduce the levels of vehicle automation and limit our discussion within the higher automated levels. Second, we synthesize different forms of operating and ownership models that potentially lead to different behaviors. Third, we present AVs' potential impacts on transit and non-motorized transportation systems, which have profound effects on frequent users of these systems, particularly those in the disadvantaged groups. Finally, we identify groups of transportation-disadvantaged population that may be greatly impacted by AVs.

Our discussion focuses on AVs of full automation, with certain extensions to high automation. The Society of Automotive Engineers International classifies vehicle automation into six levels from full human operation to full automation. Vehicles of the first four levels (Level 0 to 3) require drivers to remain alert and ready to take over at a moment's notice, while the automated driving systems of the highest two levels (Level 4 and 5) can perform all driving tasks with no driver participation under any conditions. In this study, we will consider AVs of high automation and full automation because they do not require a driver's license to operate a vehicle and they enable travelers to engage in other activities onboard. These features represent significant advance in vehicle technologies, which fundamentally alter the way people travel and benefit those who are too young, old, or disabled to drive. These changes are truly disruptive to the transportation system, bringing about the ripple effects to society. Moreover, because many companies are testing prototypes of fully automated vehicles, we believe that Level 4 and Level 5 AVs are the direction of future development. Compared with vehicles with lower-level automation, they can fully realize the benefits of vehicle automation.

As AVs approach these higher levels of automation, we observe five ownership/operating models: full ownership, fractional ownership, carpooling, car-sharing, and ride-hailing (Table 1). Currently, full ownership dominates the market share, while other ownership/operating models are present but not prevalent. The penetration of AVs will likely alter shares of these models, making the shared ownership and operating models more common.

Many studies have sought to understand the influences of highly or fully automated vehicles on the transportation system (Fagnant and Kockelman, 2015; Kröger et al., 2019; Zhang et al., 2015a). First, vehicles with higher levels of automation may fundamentally change the transit system (Abe, 2019; Wu et al., 2020). For instance, automation is likely to be implemented first on fleet vehicles such as bus services and trains. The technology eliminates the need for drivers, saving labor costs and freeing up resources for service improvement. AVs enable more efficient demand-responsive transit and micro transit services than current fleet. Transit agencies can also address the "first-mile and last-mile" problem by deploying AVs to feed trunk lines. These automated feeder services improve accessibility to transit by increasing service frequencies, service hours, and service areas at lower operating costs. Second, the implementation of AVs may make streets friendlier to pedestrians and bicyclists. They can provide a safer environment for non-motorized modes of transport. AVs eliminate careless and reckless driving of human drivers. They respond to the behaviors of bicyclists and pedestrians in more reliable ways such as slower speeds and wider braking distances (Millard-Ball, 2018). Moreover, AVs require less space, so cities can reduce lane width to 8 – 9 feet (Snyder, 2018). Narrow lanes are safer for bicyclists and pedestrians to cross than wide ones. Additional road space can be repurposed as bike lanes, sidewalks, or buffers between motorized and non-motorized traffic.

Despite the benefits, it is possible that AV penetration undermines transit and non-motorized transportation. As AV technology makes automobiles more accessible and easier to operate, people may become more auto-dependent. AVs require smaller operating and parking spaces (Nourinejad et al., 2018). When congestion and parking space shortages are eased by AVs, driving costs decrease, which could then unleash latent driving demand, likely at the expense of lower-cost modes like transit and non-motorized transportation. In addition, because connected AVs require fewer traffic signals/signs to operate (Chapin et al., 2016; Chen et al., 2016b), there may be more uncontrolled intersections, which are less accessible for and more dangerous to pedestrians and bicyclists. Moreover, as more people begin to operate AVs, transportation investments may become more skewed towards automobiles, further marginalizing transit and non-motorized transportation infrastructures.

To assess the differential impacts of AVs, it is necessary to identify transport-disadvantaged people. Several factors contribute to transport disadvantages including low income, lack of driving privileges, cultural and language barriers, mobility impairments, caregiving roles, and geographic isolation (Humboldt County, 2006; Litman, 2017). Based on these criteria, we identified eight groups of people that are more sensitive to changes brought by AVs (Table 2):

Table 1
Vehicle Ownership and Operating Models.

Ownership/ Operating Model	Definitions	Vehicle Owned by users?	Sources
Full ownership	An individual or household is the sole owner of a vehicle.	Yes	
Fractional ownership	Several individuals or households jointly own a vehicle and share the cost.	Yes	Takalloo et al. (2021)
Carpooling	Informal arrangements within or across households to share rides	Yes	Kelly (2007)
Car-sharing	A car rental model that allows individuals to pay for use of a vehicle for a certain period	No	Shaheen et al. (2018)
Ride-hailing	A ride-booking service that allows one or more individual(s) on the same trip to reserve rides.	No	Feng et al. (2020)

Table 2
Population Groups.

Sub-groups	Key Disadvantages
Low-income people	• *Low income*
Racial minorities	• *Discrimination* • Low income
Immigrants	• *Lack of driving privileges* • *Cultural and language barriers* • Low income • Discrimination
Women	• *Caregiving roles* • Low income • Discrimination
People with disabilities and Senior Population	• *Mobility impairments* • Geographic isolation
Rural residents	• *Geographic isolation*
Teenagers	• *Lack of driving privileges* • Low income • Geographic isolation

*Note: The characteristics unique to each population group are shown in *italics*.

- Low-income people
- Racial minorities
- Immigrants
- Women[1]
- People with disabilities
- Seniors
- Teenagers
- Rural residents.

AVs' impacts on population groups

This section illustrates the potential influences of AVs on specific population groups based on their current travel behaviors. In each individual subsection, we first review and summarize the prominent travel behavior of the corresponding population group, and then assess the prospective effects of AVs on this particular group.

Mixed impacts

Some population groups deal with relatively even amounts of challenges and benefits induced by AVs. Based on our knowledge of the literature, four population groups fall into this category: low-income people, racial minorities, immigrants, and women.

Low-income people

Low-income people are sensitive to travel costs. They tend to have lower mobility, make fewer trips, travel shorter distances (Pucher and Renne, 2003) and own fewer automobiles than high-income people (Renne and Bennett, 2014). Accordingly, they are less likely to drive and more likely to use transit, non-motorized modes, and taxi for their daily travel (Pucher and Renne, 2003; Renne and Bennett, 2014). However, automobiles are still critical for low-income people: households earning less than $20,000 per year use automobiles (including carpooling) for 70% of their trips (Renne and Bennett, 2014). Furthermore, low-income people are more likely to be employed in shift work, which requires them to travel at non-rush hours when transportation options are limited.

AVs have the potential to improve low-income people's mobility that is held back by their limited financial resources. Since highly automated vehicles will be able to travel without a human driver, AVs make fractional ownership and sharing more feasible than now. Fractional car ownership allows several households to purchase or lease a vehicle and to share insurance, gas, and maintenance costs (Midroit, 2018). This new ownership scheme eases the burden of single households to purchase and operate vehicles. Shared AVs make it more affordable for low-income people to access vehicles without having to make the purchase or pay for the maintenance. Moreover, by saving or even eliminating the costs of human drivers, AVs will make ride-hailing and taxi trips more affordable. Overall, the growing access to automobiles will improve the mobility of low-income people and their access to jobs and services.

However, AVs may bring challenges to low-income people because of their disadvantages. If owned, AVs are less affordable than conventional vehicles as the advanced technology and equipment of AVs are costly (Litman, 2017). These high costs would be a significant barrier for low-income people. Should this end up being the case, low-income people will probably not be able to absorb these costs, and therefore have to reduce their auto use. Furthermore, if AVs deteriorate the performance of transit and non-motorized transportation systems, these people will face even greater challenges to finding alternative modes than they do now.

Some scholars contend that AV ride-hailing will be widely available and become a viable alternative for zero-car households (Zhang et al., 2015b). However, AV ride-hailing services may not be equally available to all people. For example, most ride-hailing services require users to have a smartphone and an active bank account, but about 26% of U.S. households do not have smartphones (Statista, 2020), and approximately 30% of U.S. households are unbanked or underbanked (Brakewood and Kocur, 2013). The potential geographical imbalance of AV ride-hailing services may also marginalize low-income people. For example, in early stages of adoption, AV ride-hailing may be available only in densely populated and affluent neighborhoods. This disparity has already appeared in the geographical distribution of other shared modes, such as dockless electric scooters. In San Francisco, for example, the electric scooter company Scoot blocked drop-offs in two of the poorest neighborhoods (Baron, 2019). Similar geographical disparities of AVs may occur and exclude people living in low-income neighborhoods from access to AV services.

Racial minorities

The population of racial and ethnic minorities in the U.S. are growing rapidly and have an increasing impact on the transportation system (Colby and Ortman, 2017; Sun, 2007). Racial minorities have different socio-economic characteristics from white people. They tend to have lower employment rates, lower incomes, and live in larger households than white people (Contrino and McGuckin, 2009). These differences lead to different travel behaviors. Compared with white households, Asian households drive fewer miles and Hispanic and black households have a lower number of vehicles and are more likely to carpool (Contrino and McGuckin, 2009; NHTS, 2017). Racial minorities use alternative modes of transportation more frequently (Preston and McLafferty, 2016; Renne and Bennett, 2014). The historical discrimination against racial minorities also puts them in a disadvantaged position in ride-hailing. For example, Uber ride requests of passengers with African American sounding names are two times more likely to be canceled than those of other passengers in Boston (Ge et al., 2016). Black people often need to limit their travel to places that are safe from racism, so their mobility is constrained (Lee and Scott, 2017).

AVs can decrease the discrimination against racial minorities when used in ride-hailing. With no drivers involved, ride requests will not be canceled because of passengers' race. AVs can also eliminate human errors while operating vehicles and substantially decrease the number of crashes that currently disproportionally affect racial minorities (Barajas, 2018). AVs will reduce tailpipe emissions by using clean energy, easing congestion, and conducting eco-friendly driving techniques (Wadud et al., 2016). This benefits racial minorities, who tend to live in the areas with high exposure to travel-related air pollution (Houston, et al. 2004).

[1] We use this gender identity to refer to all people self-identified in gender roles that have been traditionally associated with women.

On the other hand, AVs may cause racial inequity issues due to existing biases. For example, because AV algorithms are primarily trained with images of white people, AVs recognize white pedestrians more accurately than pedestrians with darker skins (Wilson et al., 2019). Accordingly, pedestrians of racial minorities may experience greater risk of being hit by AVs. This bias also implies systematic racism in the development of AV technologies. Similar biases need to be fixed by proactive policies and regulations before the technologies are implemented.

The proliferation of AVs may disproportionally affect employment opportunities for racial minorities. Approximately 2.85% of employees work as drivers in the U.S., but the percentage of workers in driving occupations is higher in Hispanics (3.25%) and black people (4.23%) (Austin, 2017). For racial minorities other than Asians, driving occupations provide about $2,000 to $5,800 higher wages than non-driving jobs (Austin, 2017). If there is a rapid transition to AVs, professional drivers will be at a higher risk of displacement or even unemployment. This risk will disproportionally affect racial minorities, especially Hispanics and African Americans.

Immigrants

Immigrants accounted for 13.6% of the population in the U.S. in 2019 (Radford, 2019). How immigrants travel have a substantial impact on the transportation system. Immigrants take public transit and carpool more often than native-born Americans (Blumenberg, 2009). Recent immigrants are especially dependent on public transit (Blumenberg, 2009; Handy et al., 2009) as they are more likely to be financially disadvantaged and have a limited access to automobiles. Furthermore, their travel habits in home countries may persist, which usually means they are less inclined to drive and have a more favorable impression on transit (Kim, 2009). Carpooling is also popular among recent immigrants (Blumenberg, 2009; Kim, 2009). The limited access to automobiles is a key reason for carpooling (Blumenberg, 2009). Immigrants often live in larger households than native-born Americans, which makes it more convenient for them to share rides with family members. To retain ethnic ties and share social networks, recent immigrants are more likely to cluster in traditional ethnic neighborhoods known as “ethnic enclaves”. These ethnic communities create a suitable environment for people to carpool with neighbors for commuting (Charles and Kline, 2006). After living in the U.S. for several years, immigrants’ travel behaviors gradually assimilate to the automobile-oriented culture, and their use of public transit and carpooling starts to decline (Blumenberg and Smart, 2010; Liu and Painter, 2012). On the other hand, the rate of assimilation appears to slow down in the last few decades (Xu, 2018).

Because of immigrants’ frequent use of transit and carpooling, AVs influence immigrants’ travel behaviors by affecting these two modes. In the case where AVs improve transit, transit will be more accessible for transit-dependent immigrants. In the other scenario where AVs worsen transit services, reduced transit supply may be a major challenge for recent immigrants with limited access to automobiles. This potential reduction in transit services can be mitigated by the increase in AV carpooling. Automation technologies make carpooling more convenient and accessible to immigrants. Compared with transit, AV carpooling operates with more flexible schedules. It also avoids the hassle of coordinating routes and eliminates the cost of having human drivers (Ostrovsky and Schwarz, 2019). With the use of AVs, carpooling will be more commonly used by immigrants.

About half of the immigrants are not fluent in English (Radford and NOE-Bustamante, 2019). Some of them are not familiar with automobiles due to their previous travel behaviors. These two barriers may discourage some immigrants from using AVs and app-based AV ride-hailing services.

Women

Many studies shed light on gender gaps in travel behavior (Basarić et al., 2016; Best and Lanzendorf, 2005; Boarnet and Hsu, 2015; Mokhtarian et al., 2010). Women’s travel behavior has four distinct characteristics: trip chaining, auto dependence, carpooling, and opting for modes that enhance personal safety. Household duties are a major cause of trip chaining. Although trips made by women tend to be shorter in time and distance than those made by men, women make a larger number of trips because of their needs to make multiple shorter trips and to stop more often for household duties (McGuckin and Nakamoto, 2005). In general, people who are responsible for fulfilling various household obligations such as caregiving and housekeeping are more likely to conduct chained trips. A large portion of caregivers are females, who provide informal caregiving to children, spouses, older family members, and so on (National Alliance for Caregiving, 2009; Navaie-Waliser et al., 2002), and a significant assistance from informal caregivers is providing transportation. For instance, chauffeuring children for schools and/or daycares is more likely to fall on women’s shoulders (Scheiner and Holz-Rau, 2017). These chauffeuring trips cause women to change their commuting departure time to accommodate the schedule of schools and daycares (McGuckin and Nakamoto, 2005).

Women are more dependent on automobiles for their daily travel than men. Trip chaining makes women auto-dependent because it is more convenient to chain trips though automobiles than through transit. Women have worse impressions of public transit than men (Namgung and Akar, 2014). Their concern for personal safety and security leads them to drive more often instead of taking public transit or use non-motorized modes (Loukaitou-Sideris, 2014). Compared with men, women usually show more worries over crime and traffic issues when traveling (Goddard et al., 2006). A large percentage of women are afraid to go out or take transit after dark (Atkins, 1989). Traveling to/from transit stations and waiting at stations are perceived as more unsafe by women than people of other genders (Mahmoud and Currie, 2010). Therefore, women often drive or take taxis to avoid being victimized while walking or taking transit (Loukaitou-Sideris and Fink, 2009; Wekerle and Whitzman, 1995).

On the other hand, women’s dependence on automobiles makes them more willing to consider carpooling (Bianco and Lawson, 1996). Women are more likely to carpool than men, especially with friends and family members (Young, 1995). Employed women are two to four times more likely than men to conduct household-based carpool trips. Employed women with small children are about three times more inclined to carpool with household members than those without children (Ferguson, 1995). This preference goes so far that many women who have children, but would otherwise prefer alternative modes, choose to drive to fulfill a sentiment of “good mothering” (Dowling, 2000). However, women’s use of ride-hailing services is sometimes discouraged due to their child caregiving role. When traveling with children, many women consider the lack of child safety seats on ride-hailing vehicles a barrier for using these services (Owens et al., 2019).

AVs can have complex effects on women and others serving roles of caregiving and shopping. AVs liberate caregivers from driving responsibilities as these vehicles can chauffeur passengers independently. Even if they have to stay with passengers in the vehicle, caregivers do not need to operate the vehicle, freeing them to engage in other activities. AVs are more suitable for car-sharing and carpooling than conventional vehicles, benefiting women. However, when conducting chained shopping trips by ride-hailing, people will have to transfer their purchases from one vehicle to another, creating inconvenience.

AVs can improve the safety of riders when used in ride-hailing. Uber received almost 6,000 complaints of sexual harassment (from unwanted touching to raping) by their drivers in 2018 and 2019 (Bond, 2019). Without a driver, AVs eliminate this danger. However, when used in services such as UberPool and LyftShare where passengers share rides with strangers, AV shared rides could be more dangerous in the absence of human drivers. In these services, drivers can serve the role similar to a bus driver, who not only operates the vehicle, but also maintains the order onboard. When human drivers are absent, other measures, such as more careful matching of users and/or remote monitoring through camera, will be necessary to ensure riders are not more vulnerable to inappropriate behaviors from other passengers.

Similar to their concerns over personal security, women have more safety concerns over AVs than men (Charness et al., 2018; Hohenberger et al., 2016). According to the data of American Automobile Association (AAA), about 81% of women showed distrust in the safety of fully automated vehicles, whereas this share among men is 67% (AAA, 2016; Hayward, 2016). Women are more reluctant than men to let children ride unaccompanied in AVs (Hand and Lee, 2018). They are also vulnerable to injury in crashes because the safety system of AVs is designed around "average male" bodies (Muller, 2019), another evidence of systematic biases.

Beneficial impacts

Some people are likely to enjoy more benefits associated with AVs than challenges. Population groups in this category include people with disabilities, seniors, teenagers, and rural residents.

People with disabilities and Senior population

Many travel demands of people with disabilities are not currently met (Marston and Golledge, 2003), leading to a diminished quality of life. People with disabilities make fewer trips and have limited modal options than those without disabilities. A survey conducted by the Bureau of Transportation Statistics in 2018 shows that:

- about 70% of respondents with disabilities have reduced travel frequencies;
- except for medical trips, people with disabilities take fewer trips for all purposes (shopping, errands, recreation, work, etc.) than people without disabilities; and
- people with disabilities are less likely to drive and more likely to ride as passengers, walk, or use transit (Brumbaugh, 2018).

Although transit services are often regarded as the "best" mode for providing mobility and access to people with disabilities, they are not able to fully meet the needs of riders with disabilities (Brumbaugh, 2018). In particular, there is significant demand for more shelters and seating at transit stations. Transit users with disabilities also face different challenges depending on the type of disability, such as accessing stations (riders with physical disabilities) and reading maps and schedules (riders with cognitive disabilities). Some users are concerned about the capability of bus drivers to administer care in the case of a health crisis, which discourages them from taking transit. Paratransit has problems as well: many users think that the schedule of paratransit does not meet their needs, and that travel time and wait time are unpredictable. Overall, despite high user loyalty, many passengers of paratransit express dissatisfaction with multiple aspects of the service (Joewono and Kubota, 2007).

AVs may improve the mobility of people with disabilities. For those who are capable of riding alone, the automation technology enables them to "drive" independently. Increased mobility improves their access to job opportunities, medical appointments, and other services. For those who cannot ride alone, AVs liberate their caregivers from the driving responsibility and allow them to engage in other activities. For example, when used for ADA paratransit, AVs liberate drivers from the duty of operating vehicles and allow them to administer care to riders with disabilities. As attendants instead of drivers, ADA staff can help riders access and understand information onboard such as maps and schedules.

Similar to people with disabilities, seniors' mobility is also constrained by their health conditions (Nyaupane et al., 2008; Rantanen, 2013). According to the Disability Statistics Annual Report (2017), 35.2% of people age 65 and up have disabilities, which is significantly higher than the percentage in other age groups. Seniors are more prone to hearing, ambulatory, and independent living disabilities. The deteriorating health condition of seniors brings them similar challenges faced by people with disabilities. Some of them have to give up driving altogether. Seniors are also discouraged from aging in place in the areas where driving is a practical necessity due to land use patterns and lack of alternative transportation options (UCED, 2017). Seniors who are still able to drive are more vulnerable to crashes than younger adults because of their longer reaction times. Statistics have shown that seniors who are 75 or older are more likely to be involved in car crashes and have a higher death rate than others (CDC, 2019; O'sullivan, 2007).

AVs can improve the mobility of seniors in multiple ways. AVs reduce the probability of crashes, providing a safer travel environment for seniors. For seniors who face mobility constraints due to disabilities or decreased driving capability, AVs improve their mobility and provide a sense of mobility independence, allowing them to travel without relying on family, friends, or caretakers. However, many seniors do not trust AVs to be a reliable form of transportation and are reluctant to use this technology (Eby et al., 2018). To realize AVs' benefits, trust will need to be built by providing opportunities to educate seniors on how AVs work and offer them opportunities to experience this technology.

Teenagers

Teenagers' mobility is constrained by the lack of driver's licenses, limited access to vehicles with advanced safety features (Williams et al., 2006), and safety concerns of their parents (Cain, 2006). In most states, teenagers under the age of 16 do not qualify for a driver's license, so they depend on parents or peers for transportation. They are also frequent users of non-motorized transportation and transit. Once teenagers receive their licenses, they are more likely to be involved in crashes. The brains of 16-year-old teenagers are not fully developed, and they are more likely to be distracted or to engage in risky behaviors (Romer et al., 2014). Although teenagers (aged 15 to 19) represented 6.5% of the population, the costs associated with teenagers' car injuries accounted for 8% of the total costs in the U.S. in 2017 (CDC, 2019). Teenagers also comprised 8% passenger vehicle fatalities in 2018 (IIHS, 2019). Almost all the dominant causes of car crashes with teen drivers are related to human errors such as driving inexperience, speeding, nighttime driving, and driving under the influence (CDC, 2019).

AVs are capable of improving the mobility and travel safety of teenagers. For teenagers incapable of traveling alone, caregivers can use their travel time productively without being obliged to drive. The freedom to engage in other activities makes caregivers more willing to accompany teenagers, thus improving the mobility of teenagers. For teenagers capable of traveling alone, AVs can improve their mobility. Moreover, by counteracting human errors, AVs are more safe than conventional vehicles and increase their travel safety (Farmer et al., 2010). When used in carpooling or ride-hailing services, AVs can decrease the cost of travel and increase the mobility of some teenagers who currently cannot afford vehicles.

Rural residents

Compared with urban dwellers, rural residents face multiple mobility barriers and risk resulting from geographic isolation. Because of limited transit supply, rural residents rely on automobiles for daily travel. Zero-vehicle rural households are often more bicycle-reliant than their urban counterparts (Pucher and Renne, 2005). Furthermore, the low density in rural areas leads to fewer but longer trips. For example, as grocery stores begin to centralize in larger cities and towns, many rural areas have become so-called "food deserts" that lack access to affordable and fresh groceries (Wrigley, 2002). Accordingly, rural residents have to travel farther to get groceries (Bitto et al., 2003). Moreover, because rural households often need more automobiles per household member to meet their travel demand, the same amount of income needs to spread across multiple vehicle purchases, adding financial burdens to rural residents. Finally, crashes in rural areas are more severe than those in urban areas. In 2016, about 48% of fatal crashes in the U.S. happened in rural areas, but only 19% of the population lived in rural areas and only

30% of vehicle miles were traveled in rural areas (NHTSA, 2019).

AVs can moderate the negative effects of geographic isolation and increase travel safety and mobility of rural residents. About 95% of crashes are associated with human errors (Brown, 2017). With automation technologies, AVs can greatly reduce crash risk and help create a safer driving environment in rural areas. AV grocery delivery can increase rural residents' access to fresh and affordable groceries. AVs can also provide new ownership and operation models, including carpooling, car-sharing, and fractional ownership. Because AVs can move independently to another trip origin after dropping someone off, instead of waiting in a parking lot, they can make car-sharing more feasible both within and across households. Fractional ownership is also a potential option that allows several adjacent households to share the same AV, which can be "summoned" when needed. Fractional ownership reduces the need to buy multiple vehicles and lowers rural residents' driving costs.

Policy recommendations

AVs can promote sustainable transportation, but they may also widen the disparities among population groups. The overall impacts of AVs, particularly on certain disadvantaged groups, depend on the design of policies. As discussed in Section 3, the current auto-oriented transportation system imposes challenges on transportation-disadvantaged people because they are more likely to rely on transit and non-motorized transportation for their daily activities. Without adequate policy interventions, they may suffer negative impacts from AVs, especially those in the mixed-impact group including low-income people, racial minorities, immigrants, and women. How policymakers promote benefits and minimize challenges through pro-active planning is key to achieving an equitable transportation system. In this section, we offer the following sets of policy recommendations to exploit the benefits of AVs while mitigating or eliminating their negative outcomes.

Transit: Transit is critical to transport-disadvantaged people. Because of their ease of use and possible increased convenience, AVs may reduce transit ridership and cause transit services to scale down and be marginalized. We recommend that policymakers focus on three directions. First, as the market penetration of AVs increases, and particularly when they are electrified and revenues from motor fuel taxes decrease, it is essential to secure reliable funding sources for transit and ensure adequate services for the transit-dependent population. Second, transit agencies could use the automation technology to provide innovative forms of services such as automated feeder buses, micro transit, and demand-responsive transit, offering viable alternatives to people who did not ride transit before due to the lack of access to the service (e.g., residents living in suburban and rural areas (Shaheen et al., 2020)). Third, to alleviate the potential unemployment caused by AVs, policymakers should engage labor leaders and vocational educators to develop new opportunities for transit operators in the AV. For example, "pilots" will likely be needed to ensure safe vehicle operation in new service areas and around construction and other dynamic environments and attendants may also help maintain safety and offer personal care services to passengers onboard.

Non-motorized Infrastructures: If AVs are deployed in the ways that stimulate auto-oriented infrastructure, non-motorized modes will likely become less convenient and more dangerous. This will adversely affect people who walk and/or bike frequently and people who travel with mobility aids. To support non-motorized transportation in the era of AVs, policymakers need to reinforce the role of non-motorized travel in the transportation system through comprehensive plans and zoning regulations. Specifically, urban planners could promote programs like "complete streets" that are accessible to all users. For example, road spaces could be repurposed to include more sidewalks, dedicated lanes, tunnels, and skyways for pedestrians and cyclists. Local governments could ensure an adequate number of traffic lights for pedestrian and cyclist crossing, or they could implement pedestrian/cyclist-triggered signals.

Furthermore, AVs could equip vehicle-to-others (V2O) technologies, which enable communications between AVs and pedestrians/cyclists nearby. Besides V2O, AVs could also equip sensory devices such as radars, infrared or LiDAR distance measurement devices, vehicle-to-infrastructure (V2I), and vehicle-to-vehicle (V2V) equipment technology. These wireless communications among vehicles as well as between vehicles and the surrounding environment will allow AVs to react more quickly than human operators, creating a safer environment for those inside and outside of the vehicle. For these sensory devices to produce the best possible outcome, most vehicles need to be equipped with these technologies, especially V2V (NHTSA, 2018). Therefore, we recommend certain levels of mandate to ensure the availability of sensory technologies on AVs to achieve a base level of safety.

Shared mobility: Promoting the use of AVs in a sharing scheme can encourage auto-dependent people to adopt a more efficient way of using automobiles. Policymakers could promote shared AV ownership. Related policies may include vehicle sales tax exemptions/deductions. To increase the practicability of ownership sharing, state governments could regulate financial and legal issues associated with fractional ownership, such as insurance and titling. Besides shared ownership, certain policies could be introduced to support the shared use of AVs by transportation disadvantaged people (Shaheen et al., 2017). Non-profit car-sharing could include a focus on providing low-income people with access to AVs. Car-sharing companies need to provide alternative ways of reservation such as kiosks, interfaces, phone calls, and in-person services for the population without access to smartphones and bank accounts and multilingual services. Moreover, local governments could consider mandating the provision of AV sharing services in certain areas such as low-income neighborhoods. To prevent assaults, harassment, and other inappropriate or prejudiced behaviors, ride-hailing providers could consider installing sensors and cameras in the vehicle for real-time monitoring of the situation. The mobile apps of these services could also embed a "safe word" set by the user and will direct the route to the closest police station when being used. Instead of using the fastest route, the automation system could suggest the safest routes under some circumstances. Besides, ride-hailing providers could consider introducing gender-specific services, allowing individuals to select more comfortable ways to use the service (Siripanich, 2019).

Inclusion: We recommend policymakers to consider three aspects of inclusion. First, they should ensure procedural equity. During the transitional period of AV deployment, people who cannot afford AVs may be marginalized and excluded from the discussion and participation processes. Policymakers should ensure the representation of major population groups in policymaking processes. Moreover, the development of AV technology should be inclusive and free of systematic biases. Because pedestrian detection technologies on AVs were developed using a disproportionate number of images of white males, racial minorities and women are underrepresented in the development of this technology, which makes AVs less sensitive to non-white and non-male populations. Policymakers could regulate AV manufacturers to train the technology with sufficient images of racial minorities and women, ensuring that AVs accurately recognize people of varying physical characteristics. Finally, to make AVs trustworthy to the general public, especially women and seniors who tend to consider AV unsafe or unreliable, piloting programs of AVs could be inclusive as well to give the public opportunities to experience AVs and start to build trust at an early stage.

Conclusion

Although AVs are still developing, scholars and practitioners anticipate that their future penetration will have profound impacts on society. Some studies have discussed AVs' potential effects on the transportation system, the environment, and the economy (Alessandrini et al., 2015; Clements and Kockelman, 2017; Fagnant and Kockelman, 2015). Nevertheless, AVs' influence on social equity remains inadequately discussed. Our paper helps fill this research gap by exploring AVs' potential impacts on transportation-disadvantaged populations. It shows that AVs can have both positive and negative influences on these people. Therefore, policies and regulations are necessary to achieving positive influences and to mitigating negative effects. Based on the findings, we recommend policy innovation that help achieve an equitable transportation system in the AV era.

The method used in this study has a few limitations. First, the discussion of AV benefits and challenges was based on prominent travel behaviors of the current population. Because the market penetration of AVs takes time, people's travel behaviors may change gradually over time. Potential changes in future travel behaviors may lead to different impacts of AVs. Moreover, AVs are developing with uncertainties in technologies and regulations. The impacts we presented in this study are potential outcomes informing policymaking. Furthermore, because of our focus on general policy orientations, this paper falls short of discussions on specific and actionable policy recommendations. We suggest future research to emphasize practical and specified policies that help solve the issues raised in this paper. Despite these limitations, by highlighting potential issues early in the development and deployment of AV technologies, this paper contributes to the understanding of AVs' influence on equity and can help policymakers accommodate and inspire more in-depth research.

CRediT authorship contribution statement

Xinyi Wu: Formal analysis, Investigation, Writing – original draft, Writing - review & editing. **Jason Cao:** Methodology, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Frank Douma:** Conceptualization, Resources, Writing - review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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