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Consideration of Automated Vehicle Benefits and Research Needs for Rural America

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Consideration of Automated Vehicle Benefits and Research Needs for Rural America

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A Research Report from the National Center for Sustainable Transportation

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16. Abstract

Safety, mobility, accessibility challenges, and dependence on personal vehicles have long plagued rural transportation systems. Benefits in these areas are widely touted by autonomous vehicle (AV) advocates. Seven mechanisms for AV-induced increases in vehicle miles traveled (VMT) are reviewed here, and five of these mechanisms are expected to have a disproportionately larger impact on rural VMT. There is an almost uniform expectation that AV-related VMT increases must be managed through car-sharing and ride-sharing systems. The landscape of origins and destinations and the total population of rural areas preclude reasonable sharing, and there is a risk of unintended consequences from pro-sharing policies that will limit rural AV adoption or increase unit costs leading to a failure to attain safety and mobility benefits. Designing policies for optimal AV deployment in rural areas requires modeling. This paper outlines five methods that have been used to study VMT changes: travel demand equalization; travel demand elasticity; travel demand models; and stated and revealed preference surveys. The first three suffer from a lack of rural-specific data. Revealed preference surveys are very expensive but may be worthwhile given the scope of the potential benefits to a large portion of the country and nearly 20% of its residents. Alternatively, the more cost-effective, albeit biased, stated preference survey might fill the rural AV data gap. Rural data are essential to inform policy design because rural areas will experience different AV benefits and impacts than are seen in urban areas.

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Consideration of Automated Vehicle Benefits and Research Needs for Rural America

A National Center for Sustainable Transportation Research Report

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EXECUTIVE SUMMARY

Fully autonomous vehicles (AVs) hold the potential to significantly improve traffic safety, mobility and accessibility, and energy efficiency -- longstanding challenges for rural transportation planning. AVs may also significantly increase vehicle miles traveled (VMT) and the negative environmental outcomes associated with those miles. With close to 1/5th of the population in the United States living in rural areas and 1/3rd of VMT incurred there, improving our understanding of the benefits and impacts of AVs in rural areas is essential, especially for state and regional policymakers looking to balance mobility and climate change goals.

Unfortunately, travel behavior data are very limited for rural areas, and there is considerable uncertainty about how AVs will alter rural travel behavior. The magnitude and even direction of VMT changes depend on the extent to which AVs are individually owned, operated from a shared fleet (car-sharing), or used to provide shared rides (ride-sharing). While there is a frequent assumption that policymakers should work to promote shared mobility as a means of mitigating VMT growth, shared mobility is more challenging in rural areas where origins and destinations are widely distributed and the population density is low. As a result, uncertainty about the level of benefits provided or environmental impact incurred by AVs is even larger in small communities and rural areas than in more urban areas.

This project sought to develop a research agenda to support equitable policymaking for AVs that considers the unique benefits and challenges of automation and sharing in rural regions of the United States. To do so, we conduct conceptual assessments of the benefits inherent to AVs (regardless of ownership model) as well as of the benefits and challenges of AV sharing in rural areas. We present a set of mechanisms through which automation is likely to impact VMT and then summarize how effectively existing methodologies for VMT estimation could be used to assess the impact of each of these mechanisms in rural environments.

Our conceptual consideration of the benefits inherent to AV demonstrates that safety and mobility benefits are likely much more important in rural areas than urban areas. This stems from the comparatively long distance between origins and destinations and the dominance of the personal vehicle. Access to destinations and alternative transportation modes are lower in rural areas, and walking and bicycling are often infeasible for non-discretionary purposeful travel. Rural areas also experience higher rates of fatal traffic crashes and have a higher proportion of older residents and residents with disabilities. While efficiency gains may be smaller in rural areas, the overall impact on the safety and mobility of rural residents could be substantial.

In addition to those benefits that are achieved by automation alone, multiple studies have suggested that shared AVs (SAVs) can facilitate car-sharing and ride-sharing. These sharing systems can dramatically reduce the expected costs of AV use relative to a private ownership

model while also supporting improved energy efficiency by increasing vehicle occupancy and enabling individuals to "right-size" their vehicles for specific trips. Ultimately, the conceptual benefits of low-cost, shared rides would be valuable in rural environments, but the likelihood and feasibility of such a system are more challenging and the efficiency benefits likely significantly lower than in urban environments. It is unlikely that shared AV systems will play a large role in rural travel in the near future.

Consequently, research is needed to consider how trips and VMT will change in rural areas to ensure planners understand the costs, emissions, and potential congestion impacts of rural AVs so that urban-based AV policies are not applied uncritically to rural areas. To illustrate the research required to quantify rural VMT changes, we present a set of mechanisms through which automation can impact VMT and summarize how effectively existing VMT estimation methodologies could be used to estimate the impact of each of these mechanisms in rural areas. Mechanisms for VMT change include new or longer vehicle trips resulting from the:

1. elimination of physical, regulatory, and cost barriers to vehicle travel
2. elimination of driver burden
3. lower value of time and marginal cost of travel
4. unoccupied errands
5. unoccupied vehicle repositioning
6. unoccupied vehicle parking
7. changes in vehicle occupancy and trip chaining

Ideally, planners would have access to techniques and data to estimate VMT change for all of these mechanisms in rural areas. Research teams have considered the magnitude of VMT changes using at least five methods: 1) travel demand equalization, 2) travel demand elasticity, 3) stated preference surveys, 4) revealed preference surveys, and 5) modification of travel demand models. These methods vary in terms of the VMT change mechanisms they capture as well as in their utility in rural regions. In the immediate future, a better understanding of rural VMT changes could be achieved in a cost-effective manner by conducting demand equalization and demand elasticity analyses specifically for rural regions. Unfortunately, some data shortcomings exist around the scale of the elasticities, and these methods are not well-suited for capturing unoccupied vehicle trips. A revealed preference study could be undertaken in rural study areas or with rural residents spread across multiple rural regions. This would provide significant value, but funding such a study could be challenging. Including a larger number of rural household observations in national and state-wide travel surveys would aid in AV modeling and would also benefit other demand modeling needs. Ultimately, with complications to all these approaches for quantifying the expected impact of AVs in rural areas, the only tool left—albeit imperfect—is a stated preference survey of rural residents.

This project documents how AV benefits and impacts will differ in rural areas. Since designing policy and pricing systems that meet both urban and rural needs will difficult, different policies will be needed for rural areas. Attention to the topic of AV use in rural areas is needed to establish nationwide automated vehicle systems on a reasonable time scale and provide the commonly touted safety and mobility benefits to all populations.

Introduction

The adoption of driverless, fully autonomous vehicles (AVs) holds the potential to significantly improve traffic safety, mobility and accessibility, and energy efficiency (*1*, *2*). These three policy areas have been a decades-long challenge for rural transportation planning. Recent research studies, mostly focused on urban areas, also indicate that AVs may significantly increase vehicle miles traveled (VMT) and the negative environmental outcomes associated with those miles (*3*, *4*). With close to 1/5th of the U.S. population living in rural areas and 1/3rd of VMT incurred there, improving our understanding of the benefits and impacts of AVs in rural areas is essential, especially for state and regional policymakers looking to balance mobility and climate change goals. However, travel behavior data are more limited for rural areas, and there is uncertainty about how AVs will alter rural travel behavior, which is amplified by the variety of potential ownership and usage systems (individual ownership, car-sharing, ride-sharing) that could come to predominate in different regions. Crucially, the magnitude, and even direction, of VMT change depends on the extent to which AVs are individually owned, operated from a shared fleet (car-sharing), or used to provide shared rides (ride-sharing) (*5*–*9*). Additionally, there is a frequent assumption that policymakers should work to promote shared mobility, a rural challenge when origins and destinations are widely distributed and the population is low, as a means of mitigating VMT growth. Nowhere is uncertainty about the level of benefits provided or environmental impact incurred larger than in small communities and rural areas. However, research to date on the mobility and net environmental impact of AV adoption has focused on national assessments (*1*, *3*, *10*) and larger urban areas (*8*, *11*, *12*).

Because changes in travel behavior brought about by automation are very likely to differ in urban and rural environments, this report aims to bring greater focus to the potential contrast in benefits and impacts of AVs in rural environments relative to urban environments. First, we identify the benefits of automation from the literature and assess their salience in rural environments. Next, we review the additional benefits and challenges associated with shared AV constructs and their applicability in rural contexts. Distinguishing between benefits that are inherent to automation and therefore achievable with private AV ownership (such as improved mobility for non-drivers) from those that are specific to car-sharing (such as the ability to right-size the vehicle used for a particular trip) or ride-sharing (such as increased vehicle occupancy) is crucial in the rural context since the feasibility of sharing logistics is likely lower. While using AVs to provide lower-cost transit service in rural regions may hold promise, here we focus on the impacts of privately owned AVs or shared AVs in a “mobility as a service” model rather than in the context of traditional transit service. Finally, to illustrate the needed research agenda to quantify rural VMT changes, we first present a set of mechanisms through which automation is likely to impact VMT and then summarize how effectively existing methodologies for VMT estimation could be used to estimate the impact of each of these mechanisms in rural environments. We conclude with a discussion of policy implications of the differential impacts of AVs in rural areas as well as the research needs to support a better assessment of rural AV impacts. Unlike in urban areas, where the planning focus is on ensuring shared use of vehicles, the pursuit of the mobility benefits for rural areas may require relaxation of policies and pricing intended to discourage private ownership and promotion of shared concurrent rides.

Benefits of Automation and Salience in Rural Environments

Here we consider the importance and magnitude of improved a) safety, b) mobility and accessibility, and c) traffic operations and energy efficiency—three commonly cited benefits attributed to automation—for rural areas in the continental United States. We focus only on the benefits that are inherent to vehicle automation and thus can be achieved with any shared or private ownership and use schemes. Additional benefits that are achievable through AV vehicle- and ride-sharing systems are discussed in the subsequent section. The capacity for AVs to help achieve these three system benefits in rural regions will be an important factor in the desirability of rural AV adoption and should inform state policymakers. Policies aimed at curbing certain types of AV use in urban areas should not preclude rural areas from using AVs to achieve solutions to long-standing challenges.

It is worth emphasizing that there is no single type of "rural environment," but rather a range of environments encompassing different levels of population and development densities with differing landscapes, infrastructure and transportation challenges (*13*, *14*). Broadly speaking, however, rural areas have more dispersed origins and destinations as well as lower transit availability. As a result, rural travel is often characterized by higher rates of automobile usage and lower rates of transit, walking, and biking (*15*–*18*). Rural travelers often make fewer, and longer, daily trips than their urban counterparts (*15*, *19*) and often have reduced access to healthcare services, grocery stores, and other essential destinations (*20*, *21*). Many rural regions also have sociodemographic characteristics that can limit the transportation flexibility of rural residents, including populations that tend to be older and poorer with higher rates of disability than the population at large (*13*, *22*, *23*). This constellation of rural characteristics informs our discussion of potential AV benefits in rural areas, though the specific impacts will vary between rural regions.

Additionally, vehicle automation is not a binary process, and the benefits achieved through automation depend on the extent of automation of the driving process. The Society of Automotive Engineers (SAE) has developed a taxonomy with five levels of vehicle automation that has also been adopted by the National Highway Transportation Safety Administration (NHTSA) (*24*, *25*). The first two levels of automation require continuous driver engagement while providing "driver support." Automation levels 3 and 4 enable the vehicle to function independently but only under specific circumstances. Only with level 5 automation is an AV capable of functioning independently in all circumstances, rendering a driver unnecessary regardless of conditions or location. While all levels of automation bring benefits, level 5 automation is expected to result in the largest changes in travel behavior and is the sole focus of this research report.

Safety

Motor vehicle crashes are responsible for more than 100 fatalities daily in the U.S., with a total economic impact estimated in excess of $750 billion annually (*26*); thus, it is unsurprising that improved safety is one of the most widely cited benefits of automation (*25*). Driver error, including the effects of fatigue, distraction, and impairment, has been estimated to contribute to upwards of 90% of vehicle crashes (*27*, *28*). Because full AVs do not require any driver interaction, crashes caused by human factors could theoretically be eliminated. While several studies note challenges to safe AV deployment, including the need for multiple, expensive sensor systems to ensure pedestrian detection (*29*), software failures, loss of driving skill while transitioning from partial to full automation, and cybersecurity concerns (*30*), the theoretical potential for safety improvements is substantial and especially important in rural areas. Rural crash fatality rates (fatalities/VMT) have been estimated at twice urban rates—2.9 versus 1.3 per 100 million miles—and the injury fatality rate (fatal crashes/crashes with injury) to be nearly three times higher in rural areas—26.7 versus 8.8 per 1000 crashes with injuries (*31*). A wide variety of factors including speed and risk-taking behavior (*31*) have been identified as potentially contributing to the high rural fatality rates. Factors also include the nature of rural roads with undivided opposing direction traffic streams that make head-on collisions more likely. Driver behavior concerns include more frequent inebriation and an older population that experiences a higher crash involvement rate than middle-aged drivers. These factors are all addressable through automation. Additionally, the likelihood of surviving a crash was significantly lower in rural areas, reflecting the longer response time for emergency personnel, making crash avoidance especially important (*31*). Overall, the potential safety benefits of AVs are extremely important in rural environments and would accrue whether ownership and use were private or shared.

Mobility and Accessibility

AVs provide access to the convenience of personal vehicle travel to individuals who have physical or cognitive conditions that prevent or limit their ability to drive as well as to individuals who are too young to drive. Moreover, drivers who become passengers in AVs experience a lower travel burden because the time and attention previously devoted to driving can be dedicated to other activities. AVs may also have lower marginal operating costs that could lead to additional opportunities for travel due to per trip cost or time savings.

As noted in a range of studies and countries (*17*, *18*), rural environments are more car-dependent, placing a large burden on driving-restricted populations. Car dependency in rural areas relates mainly to the low-density land-use patterns for both origins and destinations. These development patterns lead to long distances that are hard to serve by walking and biking and also lower total demand that is difficult to serve with transit, ride-hailing, or ride-sharing.

Rural areas in the United States have the fewest transit and non-automotive options and also a higher proportion of older residents and residents with disabilities. Nationally, disability rates are highest in rural counties and lowest in large metropolitan centers (*22*). Similarly, the age distribution in rural counties skews older than in other parts of the country, with 17.5% of rural residents older than 65 years compared to 13.8% of urban residents. Rural counties are trending upward in age and also have higher rates of poverty than urban counties (*23*). Given the higher-than-average proportion of elderly residents and residents with disabilities, the capability of AVs to eliminate physical barriers to personal vehicle travel is especially important for rural mobility and access.

Though destination densities are lower in rural regions, the National Household Travel Survey (NHTS) from 2017 showed that the time travelers spend in personal vehicles on a typical day is essentially the same in rural areas (54 minutes) and the country as a whole (55 minutes), but rural daily mileage was higher (*32*). The combination of lower destination density and similar driving times suggests that rural residents' access to goods and services is at a longer distance than urban residents' access and that congestion may be less of a factor. This suggests that eliminating the burden of driving longer distances and the ability to send a vehicle on an unoccupied errand may be particularly important in rural areas. Overall, the potential mobility benefits of AVs would be substantial in rural areas.

Traffic Operations and Energy Efficiency

In addition to improving safety and mobility, automation can support significant improvements in both traffic operations and energy efficiency. AV parameters can be set to minimize fuel consumption by prioritizing "eco-driving" practices, and engines can be designed to maximize efficiency instead of power (*3*). In scenarios with low crash rates, with near-universal AV adoption, and especially with connected AVs (CAVs), vehicle size and weight could be reduced significantly without adversely impacting safety outcomes (*3*, *5*). Closer following distances, smoother traffic flows, and reduced crash rates resulting from CAVs could all contribute to increased lane capacity and reductions in the congestion experienced at high-volume locations and intersections. Counteracting these factors, safety improvements could enable increased highway speed limits, reducing energy and emissions savings. Collectively, these vehicle and system-level changes could reduce the cost and environmental impact of each mile traveled in both urban and rural areas. Fuel efficiency savings may be greater in an urban environment than on highways because of the greater impact of congestion and the acceleration and deceleration associated with traffic controls (*33*). Moreover, the contribution of AVs to reducing congestion may be less important for rural areas.

Benefits of Sharing and Salience in Rural Environments

In addition to those benefits that are attributable to vehicle technology and achieved by automation alone, AVs can facilitate car-sharing and ride-sharing, and these sharing systems provide additional mobility and efficiency benefits. For individual users, sharing models can dramatically reduce the costs of AV use relative to a private ownership model (*5*, *34*). From an efficiency perspective, many of the largest gains envisioned in a heavily automated transportation system are dependent on the implementation of car-sharing and/or ride-sharing. Wadud et al., for example, found that vehicle right-sizing, the practice of allocating vehicles from a shared fleet to match the vehicle size needed for a specific trip, provided the single greatest energy savings among 12 operational and behavioral factors they considered (*3*). Accelerated shifts towards low-carbon fuels and widespread acceptance of AV ride-sharing are also major drivers of energy efficiency (*5*, *35*). In order to be feasible, however, sharing systems require proximate riders with common travel choices/demands over time and space. This alignment is harder to achieve in rural than urban areas based on population alone. Table 1 details the mobility and efficiency benefits and challenges associated with sharing systems and their relevance in rural settings. Overall, the benefits of sharing tend to be lower and challenges more significant in rural than in urban settings.

Table 1. Benefits of Shared AV Systems

Feature/Characteristics of Shared Ownership (Fleet AVs)		Relevance in Rural Settings
Mobility Benefits	Sharing systems provide lower upfront and marginal costs, improving transportation affordability. These cost savings are highest with ride-sharing.	Transportation affordability may be especially valuable for the rural poor who have few transit options *if* the shared model is economically viable in rural areas.
	Sharing systems can provide transit-complementary "first mile/last mile" service.	Limited transit in rural areas means there is less potential for transit-complimentary.
Efficiency Benefits	Sharing systems create the capacity to "right-size" vehicles for specific trips.	Vehicle right-sizing is more effectively accomplished with a larger vehicle fleet and would be more challenging to implement with smaller, rural fleets.
	Ride-sharing systems (multiple riders simultaneously) can increase vehicle occupancy and reduce VMT.	It is likely harder to align rides in rural areas with a smaller user base, and users may be more reluctant to use shared rides with strangers in remote areas (personal safety concerns) or on longer trips.
	Professional management of shared fleets may result in better vehicle maintenance, while higher vehicle utilization would support faster fleet turnover resulting in more efficient and technologically up-to-date vehicles entering the fleet more quickly.	Profit margins are likely to be smaller in rural areas and, therefore, not support the same level of investment in maintenance or vehicle upgrades as seen in urban fleets.
	Sharing systems can reduce the number of vehicles needed for a given level of travel, resulting in lower life cycle impacts.	To achieve acceptable wait times, shared AV fleets would likely need a higher vehicle-to-user ratio in rural areas, resulting in a smaller total vehicle reduction than could be achieved in urban areas.

Table 2. Challenges for Shared AV Systems

Features/Characteristics of Shared Ownership (Fleet AVs)		Relevance in Rural Settings
Mobility Challenges	In order to achieve consumer acceptance of shared systems, the wait times required for an AV to arrive at a trip origin after request, usually made using a mobile device, must not be excessive.	Due to the long distance between destinations and the smaller user base in rural settings, achieving acceptable wait times is more difficult than in urban areas. Moreover, while internet access at home would allow for reliable requests for AVs, requests at other rural trips ends may be unreliable due to inadequate cellular coverage.
	Shared systems must be able to reliably assure vehicle access including for specialized vehicle types, e.g., wheelchair-accessible vehicles.	Assuring vehicle availability, especially of specific vehicle types, requires a higher vehicle-to-user ratio, which may be costly to provide for lower populations and user bases in rural areas.
Efficiency Challenges	Shared systems will require some level of unoccupied repositioning between users.	Unoccupied repositioning miles are easier to minimize in denser urban environments with a larger user base than in sparser environments with a smaller user base. Significant VMT for vehicle re-positioning can be expected.
	Shared vehicles will require regular cleaning and maintenance (especially in winter weather).	The dispersed nature of the fleet across larger rural landscapes will require longer travel time and wages, thus increasing costs.

Several studies express skepticism about the future of sharing, even for urban areas (*34*–*36*). Empirical evidence supporting behavioral acceptance of ride-sharing is limited (*35*). A cost-based analysis by Bosch et al. concluded that private vehicle ownership will persist, especially outside of dense urban areas, and that the shared vehicle approach may not be cost-effective due to fleet costs such as cleaning and maintenance (*34*). Survey research in Germany found that while current vehicle owners found car-sharing to be more appealing with AVs than conventional vehicles, close to 88% still expressed a preference for private vehicle ownership (*36*). Truong et al. point out that a move toward shared rides would be counter to long-term trends in vehicle occupancy, which have been decreasing over the past 10 years (*37*).

Ultimately, the conceptual benefits of low-cost, shared rides would be valuable in rural environments, but the likelihood and feasibility of such a system are more challenging and the efficiency benefits likely significantly lower than in urban environments. It is unlikely that shared AV systems will play a large role in rural travel in the near future. However, the inability to implement shared systems does not negate the key role AVs could play in bringing systems benefits to rural areas. It is worthwhile to specifically design rural-appropriate, AV system elements, even if they involve non-shared use. There is a research need to consider how trips and VMT will change in rural areas to ensure planners understand the costs, emissions, and potential congestion impacts of rural AVs.

Mechanisms of Trip and VMT Changes

Except under circumstances that include substantial ride-sharing, the benefits AVs provide are likely to come at the cost of increased VMT. Consequently, the net change in congestion, energy consumption, and greenhouse gas (GHG) emissions depends on the relative magnitude of changes in VMT, passenger load, and system operations. Generally, the potential technical efficiency impacts of AVs are relatively well understood, while behavioral impacts are more uncertain but potentially significantly larger than the efficiency gains (*6*). Papers examining the net environmental impact of vehicle automation find a large degree of uncertainty that largely hinges on the extent to which VMT changes (*3*, *4*). Across seven studies using a variety of methodologies, Taibet et al. document estimates of VMT change ranging from a 30% decrease to a 160% increase (*4*). For the reasons described above, one can assume that VMT will most certainly increase in rural regions.

Data supporting the level of changes in travel and trip-making in response to AVs are understandably limited and more robust for urban areas. Before evaluating the methods available to estimate VMT changes and their applicability to rural areas, we first identify a framework of seven mechanisms through which automation impacts VMT. Methods to estimate VMT change would ideally account for all these mechanisms. The mechanisms are not mutually exclusive nor completely exhaustive, but they will impact rural areas. Thereafter, we identify several VMT estimation methodologies with examples from existing literature and their expected effectiveness. The seven mechanisms we have identified for consideration in the rural context are as follows:

1. New vehicle trips resulting from the **elimination of physical, regulatory, and cost barriers** to vehicle travel: Driving restricted and non-driving populations facing physical and regulatory barriers to driving (such as vision problems that prevent driving at night or being too young to drive) will likely increase rates of vehicle trip-making as AVs enable these people to take independent vehicle trips (*1*, *3*, *6*). In shared AV and ride-hailing scenarios, where the per-mile costs might be significantly lower than with private vehicle ownership (*4*), non-drivers facing financial barriers to making vehicle trips could also see an increase in their vehicle trip rate. Some of these new vehicle trips may be the result of modal shifts, while others will satisfy previously unmet travel demand. Note that AV trips that replace comparable trips with the non-drivers as passengers would not be a new vehicle trip, and there is some potential for a reduction in vehicle trips by current drivers traveling to meet non-drivers to provide them with a ride. This mechanism will be large in rural areas.

2. New vehicle trips resulting from the **elimination of driver burden**: Without the need to devote attention to driving, current drivers will be able to engage in other activities while taking vehicle trips, potentially resulting in increased rates of vehicle trip-making (*3*–*6*). We distinguish here between the elimination of barriers to vehicle travel and the elimination of driver burden to emphasize the distinction between new trips that would previously have been impossible and those that would have been deemed too onerous to be worthwhile. The rate at which trip-making increases will likely differ between these two mechanisms, and the quality of life implications of the former are higher than the latter. As with new trips resulting from the elimination of barriers to vehicle travel, some portion of these new vehicle trips will be the result of mode shifts, and others will satisfy previously unmet travel demand. This factor may be quite large for long-distance non-routine trips for rural residents.
3. Changes in destination and mode choices resulting from the **lower value of time and marginal cost of travel**: Lower generalized travel costs, which include changes to the value of time people place on vehicle travel resulting from the elimination of driver burden, are likely to lead to changes in destinations and mode choices (traveling to a "better" grocery store that is farther away or using an AV in place of an airplane trip) that increase VMT (*3*–*6*). While this mechanism overlaps with the elimination of driver burden, we separate them here to emphasize that AVs could lead to differences in both trip rates (traveling to the grocery store more often) and trip lengths and that these mechanisms could each impact VMT significantly. In the longer term, changes in trip length are likely to result not only from destination and mode selection choices but also from changes in land-use patterns that enable people to live farther from work locations and other destinations. This mechanism is also expected to be relatively large for rural areas where access by proximity is currently much more limited than in urban areas.
4. New vehicle trips to perform **unoccupied errands**: AVs will have the capacity to obtain services or goods without a driver, which is likely to induce users to undertake errands that previously would have been skipped, combined, or postponed (*38*). Unoccupied errands may also compete with shippers or package delivery providers, leading to a large number of AVs serving last-mile delivery trips. As with trips generated by the elimination of barriers to vehicle travel, trips that replace previously driver-occupied trips would not be considered new. This mechanism may be significant in rural areas where immediate access to goods is limited by travel time constraints. The per unit distance cost of these trips may be high due to trip length and may counter this effect to some extent.
5. New vehicle trips for **unoccupied vehicle repositioning**: In order to meet the travel needs of multiple individuals with non-coincident trip ends, unoccupied AVs will need to reposition between passenger trips (*3*, *5*, *39*). These types of trips would occur most frequently in a shared AV scenario but could also occur when a private AV travels between trip ends required by different household members. While individual repositioning trips may be longer in rural areas, the overall impact of this mechanism may be relatively small due to the limited opportunities for vehicle sharing in rural settings and the higher cost of longer repositioning trips.

6. New vehicle trips for **unoccupied vehicle parking**: In order to avoid parking costs, AVs may drive to a remote location for parking or circle a destination instead of parking, thus incurring additional VMT (*6*, *12*). This mechanism is expected to be small in rural areas, as parking is not typically a challenge.
7. Changes in **vehicle occupancy and trip chaining**: Lower travel burden might decrease the incentive for trip chaining. Ride-sharing could increase vehicle occupancy (*5*), though this would mark a reversal of recent trends that have been towards lower vehicle occupancy. Longer trip lengths may limit this impact in rural areas.

Methods to Estimate VMT Changes

Ideally, planners and analysts would have access to techniques and data to estimate VMT change for all of the mechanisms above. To date, several research approaches have been explored to estimate VMT changes associated with automation. Here we consider how effective each of these existing methods is at capturing VMT changes related to each of the seven mechanisms. We consider the following five approaches:

1. Travel demand equalization
2. Travel demand elasticity
3. Stated preference surveys
4. Revealed preference surveys
5. Modification of travel demand models

Each of these methods is technically feasible to implement for studying VMT changes in rural environments. The drawbacks of each method specifically for rural environments relate either to limitations in resources and data availability or the level of model sophistication present in rural regions. Given the diversity of rural environments, the transferability of findings between rural regions may also present a challenge.

Travel Equalization

Travel demand equalization estimates increased vehicle travel for various driving-restricted individuals so that their vehicle trip patterns more closely align with that of a baseline group. Travel demand equalization studies utilize large-scale household travel surveys such as the NHTS in the United States and the Victorian Integrated Survey of Travel and Activity (VISTA) in Victoria, Australia, to determine a “natural” baseline demand for personal vehicle travel for different populations (age groups, genders) in the absence of physical or regulatory driving restrictions. Harper et al. use this approach to estimate the upper bound of additional VMT “demand wedges” for non-driving, elderly, and medically restricted populations using NHTS data from 2009 (*1*). The authors estimate the demand wedge for non-drivers over age 19 years by assuming that these individuals will generate the same vehicle miles driven as drivers within their age group and gender cohort. The vehicle miles driven for drivers from age 65-74 years are equalized with those of drivers age 19-64 years and for drivers age 75 years and older with those of drivers age 65 years. Finally, the vehicle miles driven of medically restricted travelers is equalized with the travel of drivers in the same age and gender cohort without medical conditions. Cumulatively, these wedges result in a 14% increase in overall VMT.

Wadud et al. also use the travel equalization approach with 2009 NHTS data to estimate VMT for new user groups (*3*). First, the authors set the share of drivers within each age group (16 years and above) equal to that of individuals age 35–55 years, the group with the largest share of drivers. Next, the authors estimate a "natural" decline in travel related to declining travel needs rather (as opposed to a decline caused by diminished driving ability) by fitting a linear trend line to the travel of individuals age 44–62 years and set the driving of individuals age 63 and above to the levels projected by this trend line. Using this approach, the authors find an increase in VMT of 2–10%. Truong et al. create age-based estimates of baseline travel need, measured in vehicle trips, using VISTA data from 2007–2010 (*37*). The author notes that licensure peaks for individuals age 30-65 years old and that within this cohort, trip-making increases nearly linearly from age 30 through 44 years before decreasing, also linearly between ages 44 and 67 years. The authors estimate the "natural" rate of trip-making for individuals between 12 and 29 years by extrapolating the trip-making rate of those aged 30 to 44. The unrestricted trip rates of individuals over 66 years are extrapolated from the trend observed in individuals age 44–67 years. This method produces a 5.3% increase in daily personal vehicle trips, assuming that vehicle occupancy rates remain unchanged.

While the travel equalization approach does have some shortcomings, notably that it is not suitable for understanding other mechanisms of VMT change, the approach provides a useful heuristic method for considering the increases in mobility for driving-restricted populations. Though it has not yet been applied specifically to rural regions, it is technically feasible to do so if surveys have a large enough rural sample. This might be the case for state or national surveys, but often some of the most comprehensive household travel surveys are conducted by metropolitan areas, and the number of rural households is very limited.

Demand Elasticity

Travel demand elasticity studies use estimates of fuel and time cost elasticity to project growth in travel demand resulting from decreased operating costs and decreased travel time costs associated with automation. Wadud et al. (3) use estimates of the generalized travel cost elasticities from the existing literature. The authors note two limitations to this approach—first that the generalized cost elasticity estimates, which account for the cost of travel time as well as the cost of fuel, are much less common than simple fuel price elasticities, and second that they were developed from a relatively narrow range of empirical cost data and thus their validity over the wider range of cost reductions posited for AVs may be limited. Acknowledging these limitations, the authors find a wide range of possible VMT impacts resulting from uncertainty about changes in mobility service and how users will value travel time in an AV, ranging from a 4% increase for low levels of automation to a 60% increase for full AVs. Taiebet et al. (*4*) aim to improve on the work of (*3*) by estimating VMT elasticities for fuel and time costs using data from the 2017 NHTS. The authors observe that their central estimate of combined fuel and time cost elasticity (-0.39) is significantly lower than the prior estimates of generalized travel cost elasticity, which range from -1.0 to -2.3. They note that fuel cost elasticity diminishes at higher incomes, while time cost elasticity increases. The elasticities that the authors calculate are then used as inputs for a microeconomic VMT choice model. Overall results show a 2–47% increase in travel demand that potentially outstrips the efficiency gains achieved by connected AVs. Given the data limitations overall, it is difficult to imagine that rural-specific elasticities are viable.

Elasticity studies are useful for understanding the impacts of eliminating driver burden and lowering marginal costs of travel but are estimated over a limited range of cost data and are not effective for capturing other VMT mechanisms. In order to be useful for estimating rural VMT changes, elasticities would have to be calculated using rural data, as elasticity studies in other contexts have found that elasticity is markedly higher for urban than rural VMT (*40*).

Stated Preference Surveys

Stated preference methods use survey data collected by asking individuals about their interest in AVs and how their behavior might change if they owned or had access to an AV. Researchers at the United States Department of Energy National Renewable Energy Lab (NREL) surveyed over 1,000 adults in the continental United States seeking to understand the likely adopters of AVs and how VMT would change with AV adoption (*41*). Their analysis was limited to a subset of respondents (approximately 85%) who reported that they had heard of AV technology. Younger and urban respondents expressed the greatest interest in AVs, while older and rural respondents expressed the least interest. Current VMT was highest among rural respondents and lowest among urban respondents. Asked about anticipated changes in their future travel due to AVs, a plurality of respondents expected no change in the length of their commute or distance that they traveled for errands and recreation. Between 36% and 48% of respondents thought they would travel somewhat or much farther for these purposes, and between 70 and 75% of respondents thought they would travel somewhat or much farther on long-distance trips.

Korlova et al. used a state choice survey of 511 people in Germany to evaluate the differential value that respondents place on travel time in AVs versus conventional vehicles (*42*). Respondents were presented with a series of mode choice options, with associated travel time and cost attributes that included the use of a private AV, an individual ride in a shared AV, and a ride with other passengers in a shared AV. This study supported the hypothesis that travel by AVs would be perceived as less burdensome than travel by conventional vehicles and that private ownership was more attractive than shared AVs. No distinction was made for rural versus urban residents.

Stated preference methods could be used to inform the assessment of any of the VMT change mechanisms identified above; however, as noted by several of the researchers working with this method, the accuracy of stated preference is likely limited when considering unfamiliar and disruptive technologies (*36*, *41*). Collecting stated preference data is relatively cost-effective and, given the high cost of other dedicated data collection methods, might have to be the method of choice for collecting rural preferences. There is the potential that some correction factors for stated preference bias could be adopted from urban areas and transferred for use in rural studies.

Revealed Preference Surveys

Revealed preference studies use empirical data to measure how individuals use AVs. Given that AVs remain in the early pilot stage, opportunities to collect revealed preference data are limited. In an innovative effort to overcome the limitations of state preference research for AVs, Harb et al. attempted to replicate the experience of owning an AV by providing study participants with a free chauffeur service for 60 hours over a one-week period (*38*). A pilot study included 13 households with privately owned vehicles classified as millennials, families, or retirees. Comparing vehicle travel during the week with chauffeured travel to the weeks immediately preceding and following it, the authors observed a substantial increase in VMT, driven by an increase in trip-making, trip lengths, and zero-occupancy VMT. Overall, the study found a 58% average increase in vehicle trips and an 83% average increase in VMT when provided with a chauffeur compared to the baseline weeks. Study participants listing improved productivity/enjoyment of travel time, the ability to complete errands without being in the car, and convenience as reasons for increased travel during the chauffeured week. Participants also indicated that they were more likely to participate in leisure activities, travel after dark/when tired, and travel for longer distances when they did not have to drive themselves. Retirees saw the largest percentage increase in terms of VMT, long trips, and evening trips, and they highlighted safety as a primary reason for their changed behavior, perhaps supporting the travel equalization approach used by (*1*, *3*). All of these factors cited by participants are important and apply directly to rural areas. While there are clear limitations to this approach, notably the short duration of the chauffeur service and its novelty during that period, the study provides initial empirical evidence of how AVs might be utilized and demonstrates travel behavior trends that are consistent with those that have been hypothesized by the AV research community.

Ultimately, while expensive to collect, revealed preference data will be able to provide insight into all of the VMT change mechanisms described above and could be applied in rural regions. Given the percent of VMT that occurs in rural areas and the substantial rural benefits of AVs, investment in this type of research may be worthwhile.

Travel Demand Models

Modifications to travel demand models, especially agent and activity-based models, have been used to study a variety of VMT change mechanisms, especially vehicle repositioning. The spatial nature of disaggregate travel demand forecasting models makes them useful for estimating the VMT associated with different scenarios. Unfortunately, these models are often reliant on data to inform trip generation rates and trip length distributions that are not necessarily sensitive to the specific factors that may relate to AV ownership or use. Moreover, most rural regions are not covered by travel demand models in any detail or are covered by aggregate traditional four-step models that are of more limited utility for AV research.

Discussion and Conclusion

A conceptual consideration of the benefits of automation in rural environments demonstrates that safety and mobility benefits are likely much more important in rural areas than urban areas. This stems from the comparatively long distance between origins and destinations and the dominance of the personal vehicle. Access to destinations and alternative transportation modes are lower and walking and bicycling often infeasible. Rural areas experience higher rates of fatal crashes and have a higher proportion of older residents and residents with disabilities. While efficiency gains may be smaller in rural areas, the overall impact on the safety and mobility of rural residents could be substantial, and there is a good argument that policies and pricing schemes should not create disincentives or barriers for AV adoption in rural areas. Proposals for additional fees on privately owned AVs or non-shared trips in AVs risk precluding important safety and mobility benefits in rural areas. Policymakers should not assume that shared mobility will dominate the rural environment and should be careful when crafting policies that limit VMT growth not to unduly penalize rural regions. Increased VMT in rural areas may mean improved well-being.

A more comprehensive understanding of the VMT impacts of private versus shared AV ownership in rural areas is required. Unfortunately, this is not easy to attain due to a paucity of rural travel data and more limited models for these regions. Agent-based models are not generally available to rural planners, and four-step models have only limited utility often applied with large zone sizes at the state-wide level. In the immediate future, a better understanding of rural VMT changes could be achieved in a cost-effective manner by conducting demand equalization and demand elasticity analyses specifically for rural regions. Unfortunately, some data shortcomings exist around the scale of the elasticities, and these methods are not well-suited to capturing unoccupied vehicle trips, which contributed significantly to the VMT growth in the one revealed preference study. A more costly way to obtain a better forecast of rural AV use would be to undertake a revealed preference study in a rural region or with rural residents spread across multiple rural regions. This would be of great value, but funding such a study could be challenging. Without dedicated rural research projects, planners might pursue a larger number of rural household observations in national and state-wide travel surveys as an option. Other small sub-populations are often oversampled in surveys (transit riders for example). More representative rural observations would also benefit other demand modeling needs in addition to planning for AVs. Potentially, new big data OD efforts such as the upcoming NextGen NHTS will have more thorough coverage of rural areas. Ultimately, with complications to all these approaches for quantifying the expected impact of AVs in rural areas, the only tool left—albeit imperfect—is the stated preference survey of rural residents.

This report demonstrates that the benefits and impacts of AVs will be different for rural areas and the attainment of policy and pricing systems that meet both urban and rural needs will be tricky to achieve. Attention to the topic of AV use in rural areas is needed, and research gaps should be filled if automated vehicle systems are going to be established nationally on a reasonable time scale. All too often, rural America lags behind in crucial services (e.g., high-speed internet) and is not considered a critical transportation focus. AVs may be more important for solving the challenging public and private transportation challenges of rural America. and the first step is recognizing that the behavioral and operational differences will be significant. Rural areas are not just “little low-density cities” where a scaled-down version of a shared AV pooled ride App system can be deployed after the fact. Some deliberate research and distinct advanced policy are needed to ensure optimal outcomes.

References

1. Harper, C. D., C. T. Hendrickson, S. Mangones, and C. Samaras. Estimating Potential Increases in Travel with Autonomous Vehicles for the Non-Driving, Elderly and People with Travel-Restrictive Medical Conditions. *Transportation Research Part C: Emerging Technologies*, Vol. 72, 2016, pp. 1–9. https://doi.org/10.1016/j.trc.2016.09.003.
2. Meyer, J., H. Becker, P. M. Bösch, and K. W. Axhausen. Autonomous Vehicles: The next Jump in Accessibilities? *Research in Transportation Economics*, Vol. 62, 2017, pp. 80–91. https://doi.org/10.1016/j.retrec.2017.03.005.
3. Wadud, Z., D. MacKenzie, and P. Leiby. Help or Hindrance? The Travel, Energy and Carbon Impacts of Highly Automated Vehicles. *Transportation Research Part A: Policy and Practice*, Vol. 86, 2016, pp. 1–18. https://doi.org/10.1016/j.tra.2015.12.001.
4. Taiebat, M., S. Stolper, and M. Xu. Forecasting the Impact of Connected and Automated Vehicles on Energy Use: A Microeconomic Study of Induced Travel and Energy Rebound. *Applied Energy*, Vol. 247, 2019, pp. 297–308. https://doi.org/10.1016/j.apenergy.2019.03.174.
5. Taiebat, M., A. L. Brown, H. R. Safford, S. Qu, and M. Xu. A Review on Energy, Environmental, and Sustainability Implications of Connected and Automated Vehicles. *Environmental Science & Technology*, Vol. 52, No. 20, 2018, pp. 11449–11465. https://doi.org/10.1021/acs.est.8b00127.
6. Miller, S. A., and B. R. Heard. The Environmental Impact of Autonomous Vehicles Depends on Adoption Patterns. *Environmental Science & Technology*, Vol. 50, No. 12, 2016, pp. 6119–6121. https://doi.org/10.1021/acs.est.6b02490.
7. Gurumurthy, K. M., K. M. Kockelman, and M. D. Simoni. Benefits and Costs of Ride-Sharing in Shared Automated Vehicles across Austin, Texas: Opportunities for Congestion Pricing. *Transportation Research Record*, Vol. 2673, No. 6, 2019, pp. 548–556. https://doi.org/10.1177/0361198119850785.
8. Fagnant, D. J., and K. M. Kockelman. Dynamic Ride-Sharing and Fleet Sizing for a System of Shared Autonomous Vehicles in Austin, Texas. *Transportation*, Vol. 45, No. 1, 2018, pp. 143–158.
9. Ross, C., and S. Guhathakurta. Autonomous Vehicles and Energy Impacts: A Scenario Analysis. *Energy Procedia*, Vol. 143, 2017, pp. 47–52. https://doi.org/10.1016/j.egypro.2017.12.646.
10. Kröger, L., T. Kuhnimhof, and S. Trommer. Does Context Matter? A Comparative Study Modelling Autonomous Vehicle Impact on Travel Behaviour for Germany and the USA. *Transportation Research Part A: Policy and Practice*, Vol. 122, 2019, pp. 146–161. https://doi.org/10.1016/j.tra.2018.03.033.
11. Fagnant, D. J., K. M. Kockelman, and P. Bansal. Operations of Shared Autonomous Vehicle Fleet for Austin, Texas, Market. *Transportation Research Record*, Vol. 2563, No. 1, 2016, pp. 98–106. https://doi.org/10.3141/2536-12.
12. Harper, C. D., C. T. Hendrickson, and C. Samaras. Exploring the Economic, Environmental, and Travel Implications of Changes in Parking Choices Due to Driverless Vehicles: An

Agent-Based Simulation Approach. *Journal of Urban Planning and Development*, Vol. 144, No. 4, 2018, p. 04018043.

13. Kidder, B. *The Challenges of Rural Transportation*. Western Rural Development Center, 2006, p. 19.
14. Morton, B., Y. Song, J. Huh, A. Hartell, J. Huegy, M. Ingram, E. Murray, and C. Wang. *Impacts of Land Use on Travel Behavior in Small Communities and Rural Areas*. Publication NCHRP 25-36. National Cooperative Highway Research Program, 2014.
15. Pucher, J., and J. L. Renne. Rural Mobility and Mode Choice: Evidence from the 2001 National Household Travel Survey. *Transportation*, Vol. 32, No. 2, 2005, pp. 165–186. https://doi.org/10.1007/s11116-004-5508-3.
16. Millward, H., and J. Spinney. Time Use, Travel Behavior, and the Rural–Urban Continuum: Results from the Halifax STAR Project. *Journal of transport geography*, Vol. 19, No. 1, 2011, pp. 51–58. https://doi.org/10.1016/j.jtrangeo.2009.12.005.
17. Hanson, T. R., and E. D. Hildebrand. Can Rural Older Drivers Meet Their Needs without a Car? Stated Adaptation Responses from a GPS Travel Diary Survey. *Transportation*, Vol. 38, No. 6, 2011, pp. 975–992. https://doi.org/10.1007/s11116-011-9323-3.
18. Ahern, A., and J. Hine. Rural Transport – Valuing the Mobility of Older People. *Gender and transport: Transaction costs, competing claims and transport policy gaps*, Vol. 34, No. 1, 2012, pp. 27–34. https://doi.org/10.1016/j.retrec.2011.12.004.
19. Holz-Rau, C., J. Scheiner, and K. Sicks. Travel Distances in Daily Travel and Long-Distance Travel: What Role Is Played by Urban Form? *Environment and Planning A: Economy and Space*, Vol. 46, No. 2, 2014, pp. 488–507. https://doi.org/10.1068/a4640.
20. Sharkey, J. R. Measuring Potential Access to Food Stores and Food-Service Places in Rural Areas in the U.S. *Measurement of the Food and Physical Activity Environments*, Vol. 36, No. 4, Supplement, 2009, pp. S151–S155. https://doi.org/10.1016/j.amepre.2009.01.004.
21. Caldwell, J. T., C. L. Ford, S. P. Wallace, M. C. Wang, and L. M. Takahashi. Intersection of Living in a Rural Versus Urban Area and Race/Ethnicity in Explaining Access to Health Care in the United States. *American Journal of Public Health*, Vol. 106, No. 8, 2016, pp. 1463–1469. https://doi.org/10.2105/AJPH.2016.303212.
22. Zhao, G., C. A. Okoro, J. Hsia, W. S. Garvin, and M. Town. Prevalence of Disability and Disability Types by Urban–Rural County Classification—U.S., 2016. *American Journal of Preventive Medicine*, Vol. 57, No. 6, 2019, pp. 749–756. https://doi.org/10.1016/j.amepre.2019.07.022.
23. Bureau, U. C. The Older Population in Rural America: 2012-2016. *The United States Census Bureau*. https://www.census.gov/library/publications/2019/acs/acs-41.html. Accessed Jul. 30, 2020.
24. SAE International. *J3016_201806: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. 2018.
25. NHTSA. *Preparing for the Future of Transportation: Automated Vehicle 3.0*. U.S. Department of Transportation, 2018, p. 80.

26. Center for Disease Control. Cost Data and Prevention Policies | Motor Vehicle Safety | CDC Injury Center. https://www.cdc.gov/motorvehiclesafety/costs/index.html. Accessed Jul. 31, 2020.
27. Dingus, T. A., F. Guo, S. Lee, J. F. Antin, M. Perez, M. Buchanan-King, and J. Hankey. Driver Crash Risk Factors and Prevalence Evaluation Using Naturalistic Driving Data. *Proceedings of the National Academy of Sciences*, Vol. 113, No. 10, 2016, pp. 2636–2641. https://doi.org/10.1073/pnas.1513271113.
28. NHTSA. *Critical Reasons for Crashes Investigated in the National Motor Vehicle Crash Causation Survey*. Publication DOT HS 812 115. U.S. Department of Transportation, 2015.
29. Combs, T. S., L. S. Sandt, M. P. Clamann, and N. C. McDonald. Automated Vehicles and Pedestrian Safety: Exploring the Promise and Limits of Pedestrian Detection. *American Journal of Preventive Medicine*, Vol. 56, No. 1, 2019, pp. 1–7. https://doi.org/10.1016/j.amepre.2018.06.024.
30. Noy, I. Y., D. Shinar, and W. J. Horrey. Automated Driving: Safety Blind Spots. *Safety Science*, Vol. 102, 2018, pp. 68–78. https://doi.org/10.1016/j.ssci.2017.07.018.
31. Zwerling, C., C. Peek-Asa, P. S. Whitten, S.-W. Choi, N. L. Sprince, and M. P. Jones. Fatal Motor Vehicle Crashes in Rural and Urban Areas: Decomposing Rates into Contributing Factors. *Injury Prevention*, Vol. 11, No. 1, 2005, pp. 24–28. https://doi.org/10.1136/ip.2004.005959.
32. McGuckin, N., and A. Fucci. *Summary of Travel Trends 2017 National Household Travel Survey*. Publication FHWA-PL-18-019. Federal Highway Administration, 2018.
33. Chen, Y., J. Gonder, S. Young, and E. Wood. Quantifying Autonomous Vehicles National Fuel Consumption Impacts: A Data-Rich Approach. *Transportation Research Part A: Policy and Practice*, Vol. 122, 2019, pp. 134–145. https://doi.org/10.1016/j.tra.2017.10.012.
34. Bösch, P. M., F. Becker, H. Becker, and K. W. Axhausen. Cost-Based Analysis of Autonomous Mobility Services. *Transport Policy*, Vol. 64, 2018, pp. 76–91. https://doi.org/10.1016/j.tranpol.2017.09.005.
35. Stoiber, T., I. Schubert, R. Hoerler, and P. Burger. Will Consumers Prefer Shared and Pooled-Use Autonomous Vehicles? A Stated Choice Experiment with Swiss Households. *Transportation Research Part D: Transport and Environment*, Vol. 71, 2019, pp. 265–282. https://doi.org/10.1016/j.trd.2018.12.019.
36. Pakusch, C., G. Stevens, A. Boden, and P. Bossauer. Unintended Effects of Autonomous Driving: A Study on Mobility Preferences in the Future. *Sustainability*, Vol. 10, No. 7, 2018, p. 2404. https://doi.org/10.3390/su10072404.
37. Truong, L. T., C. De Gruyter, G. Currie, and A. Delbosc. Estimating the Trip Generation Impacts of Autonomous Vehicles on Car Travel in Victoria, Australia. *Transportation*, Vol. 44, No. 6, 2017, pp. 1279–1292. https://doi.org/10.1007/s11116-017-9802-2.
38. Harb, M., Y. Xiao, G. Circella, P. L. Mokhtarian, and J. L. Walker. Projecting Travelers into a World of Self-Driving Vehicles: Estimating Travel Behavior Implications via a Naturalistic Experiment. *Transportation*, Vol. 45, No. 6, 2018, pp. 1671–1685. https://doi.org/10.1007/s11116-018-9937-9.

39. Zhang, C., L. Jennings, L. Aultman-Hall, and D. Benoit. Towards More Robust Spatial Sampling Strategies for Non-Motorized Traffic. Washington DC, 2010.
40. Rentziou, A., K. Gkritza, and R. R. Souleyrette. VMT, Energy Consumption, and GHG Emissions Forecasting for Passenger Transportation. *Transportation Research Part A: Policy and Practice*, Vol. 46, No. 3, 2012, pp. 487–500. https://doi.org/10.1016/j.tra.2011.11.009.
41. Fleming, K., and M. Singer. *Energy Implications of Current Travel and the Adoption of Automated Vehicles*. 2019.
42. Kolarova, V., F. Steck, R. Cyganski, and S. Trommer. Estimation of the Value of Time for Automated Driving Using Revealed and Stated Preference Methods. *Assessing wider impacts of transportation policies*, Vol. 31, 2018, pp. 35–46. https://doi.org/10.1016/j.trpro.2018.09.044.

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