Shaping Autonomous Vehicle Deployment to Meet Climate and Energy Goals: A Policy Toolkit for Cities

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December 2019

An ACEEE White Paper

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Contents

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Acknowledgments

This white paper was made possible through the generous support of the Heising-Simons Foundation. Support does not imply affiliation or endorsement. We gratefully acknowledge the paper's reviewers, including Andrew Duvall of the National Renewable Energy Laboratory (NREL), Carlos Pardo of Numo, Joshua Sperling of NREL, Sam Spofforth of Clean Fuels Ohio, and Christopher Ziemann of the City of Alexandria, Virginia. We also thank Naomi Baum, Neal Elliott, Steve Nadel, and Lauren Ross of ACEEE for providing internal feedback, as well as ACEEE interns Connor Hoffman and Ben Jennings for their contributions to this paper. Last, we thank Karin Matchett for developmental editing; Kristin Cleveland and Fred Grossberg for managing the editorial process; Elise Marton, Sean O'Brien, and Roxanna Usher for copy editing; and Wendy Koch and Kate Doughty for their help in launching this paper into the world.

Abstract

Even as the extensive deployment of fully autonomous vehicles (AVs) is still many years away, cities hoping to ensure that these vehicles contribute to—rather than detract from—the achievement of their transportation-related climate and energy goals need to lay the groundwork for their arrival now. Cities are well positioned to lead on policies to reduce transportation emissions and energy consumption. Autonomous vehicles may be more fuel efficient due to connectivity and automation features, and potentially due to their greater likelihood of electrification, but their impacts on energy use and the environment will be determined largely by how many miles they travel and the modes of transportation they displace.

This toolkit outlines the outcomes that cities should strive for when incorporating AVs into their transportation systems and describes major challenges that may arise as AV deployment proceeds. It also discusses the broad transportation policies available to cities today that will help shape AV deployment to achieve beneficial outcomes in tandem with cities' transportation energy and climate goals.

Introduction

While extensive deployment of fully autonomous vehicles (AVs) is still many years away, it is important that planning for their arrival begin now, given their sweeping positive and negative implications for travel. While AV development is being driven largely by the desire for improved highway safety, expanded mobility, and greater convenience, these vehicles can change how people choose to travel and how transportation systems are designed and function. They can also affect levels of congestion, the total number of miles driven, and levels of pollutants from vehicle emissions. Cities hoping to ensure that these vehicles will contribute to—and not detract from—their transportation and climate objectives need to lay the groundwork for their arrival now.

Vehicles account for a large share of urban greenhouse gas emissions, so reducing vehicle emissions must be central to cities' sustainable transportation goals. Achieving major reductions will require both clean, efficient vehicles and less driving. In this regard, AVs potentially offer some benefits. Yet none of these benefits are guaranteed; the emissions impacts of AVs in urban environments will depend on how these vehicles are integrated into the broader transportation system. Policies are required to ensure they materialize.

Cities are well positioned to lead on policies to reduce transportation emissions and energy consumption. Leadership on shifting the way we use vehicles and travel to improve economic, equity, and environmental outcomes falls largely to states and cities because these jurisdictions have the greatest oversight over policies that impact travel behavior. Some cities are seizing the opportunity to reduce fossil fuel consumption in transportation and decouple economic growth from environmental damage, while also harnessing enhanced mobility choices and opportunities. In light of the United States' withdrawal from the United Nations Framework Convention on Climate Change's Paris Agreement, initiatives such as We Are Still In, Climate Mayors, and the Global Covenant of Mayors for Climate and Energy have emerged, spurring cities to develop detailed plans to mitigate climate change and build resiliency under shifting conditions. Reducing energy consumption is central to those plans.

Autonomous vehicles could offer fuel efficiency advantages through connectivity and automation features, and perhaps also due to a greater likelihood of electrification. However their overall impacts on energy use and the environment will be determined largely by a broader set of factors, including future vehicle ownership models, how many miles AVs travel, and the modes of transportation they displace. This toolkit gives an overview of the outcomes that city decision makers should be striving for when planning for the deployment of AVs and the elements of policy planning required to prepare for them. Many of those elements coincide with strategies cities are already developing to achieve their sustainable transportation goals more broadly, including efficiency, reliability, affordability, equity, and safety. This toolkit discusses some leading cities' actions to put those planning elements in place—providing examples that other cities throughout the country can emulate and adapt for their own circumstances.

STATUS OF AV DEVELOPMENT AND DEPLOYMENT

Automation technologies like automatic emergency braking, adaptive cruise control, lane-keep assist, traffic jam assist, automated route guidance, traffic sign recognition, and automatic high beams are already finding their way into vehicles currently on American roads. While these technologies serve largely to improve safety and help drivers navigate congested roads, some can also improve vehicle fuel efficiency. For example, adaptive cruise control helps drivers save fuel by moderating acceleration and deceleration (ACEEE 2019). Connectivity and automation together can enable advanced eco-driving and route optimization.

This paper focuses on vehicles with a higher level of automation, specifically the fully automatic vehicles classified by the Society of Automotive Engineers as "level 5," meaning "capable of performing all driving functions under all conditions" (NHTSA 2019). Automation levels lie on a continuum, technologically speaking, but it is only when the vehicle can function without a driver that behavioral issues such as travel patterns, mode choice, and vehicle ownership models are engaged. These are the issues that most call for the attention of city planners and others working toward sustainable urban transportation systems. It should be noted that the transportation service provided by an AV is already available wherever ride-hailing services are in place; the principal reason that AVs could further alter urban travel behavior is that not requiring a driver will substantially reduce the cost of these services. Fully autonomous vehicles are not yet in general use, but multiple private interests are investing heavily in their development.

Autonomous vehicles need not be connected vehicles; in fact, their marketability in the near to medium term may depend on their ability to function safely in an environment in which neither adjacent vehicles nor transportation infrastructure can be relied on to communicate information digitally. Nonetheless, AVs in the longer term are very likely to be connected to take advantage of the additional benefits of those technologies; therefore AVs are assumed to be connected in the remainder of this paper.

The auto manufacturers, tech companies, and ride-hailing companies investing in the design and deployment of AVs acknowledge the high degree of uncertainty regarding AVs' implications for personal vehicle ownership and usage patterns and even the features valued in vehicles. For example, a shift toward fleets or shared ownership of vehicles could lead to a resurgence of demand for highly efficient smaller cars with sophisticated connectivity features, especially in urban areas. Companies differ in their commitment to such shifts, however. For example, Via and Uber advocate urban transportation systems in which ride-sharing vehicles are autonomous and electric and serve all urban residents (Dooley 2019). Auto manufacturers, on the other hand, are still invested in the idea of personal vehicle ownership—in the short term at least.

Several cities are already serving as living labs for AVs, testing the vehicles' readiness for urban environments. These include Pittsburgh in partnership with Uber, and Washington, DC, working with Ford (Chafkin 2016; Chen 2019). These pilots are testing only the functionality of the technology, however, and will not address the impacts of large numbers of AVs on the transportation system. Integration is the job of planners, residents, business owners, and other stakeholders concerned with their city's goals for its transportation system.

Cities' collaboration with and support from the federal government and private corporations have been central to much of the planning for AVs to date. In 2015 the US

Department of Transportation (US DOT) launched the Smart City Challenge, asking midsize American cities to describe their vision for a smart transportation system using data, applications, and technology to move people and goods more quickly and efficiently. The competition spurred multiple cities to create detailed plans for technology-enabled transportation systems utilizing vehicle-to-vehicle and vehicle-to-infrastructure communication and universal data-sharing platforms and protocols (DOT 2017). Of the 78 submissions, 44 proposed pilot projects to test the use of automated, shared-use vehicles to move people (DOT 2017).

The US DOT also recently released *Automated Vehicles 3.0: Preparing for the Future of Transportation* to help guide autonomous vehicle integration into the American transportation system, with a priority on safety (DOT 2018a). The US Department of Energy's Energy Efficient Mobility Systems (EEMS) Program supports extensive research on the potential energy-related impacts of new mobility options, including AVs.

How AVs Can Help or Hinder Urban Sustainable Transportation Goals

While the development of AVs is currently driven primarily by the universal desire to reduce the frequency and severity of vehicle crashes, these vehicles will affect travel in other, fundamental ways as well. The range of potential impacts on energy use is wide, and some research has attempted to characterize those impacts. Figure 1 shows the conclusions of one study of the ways AVs can impact energy use, both positively and negatively.

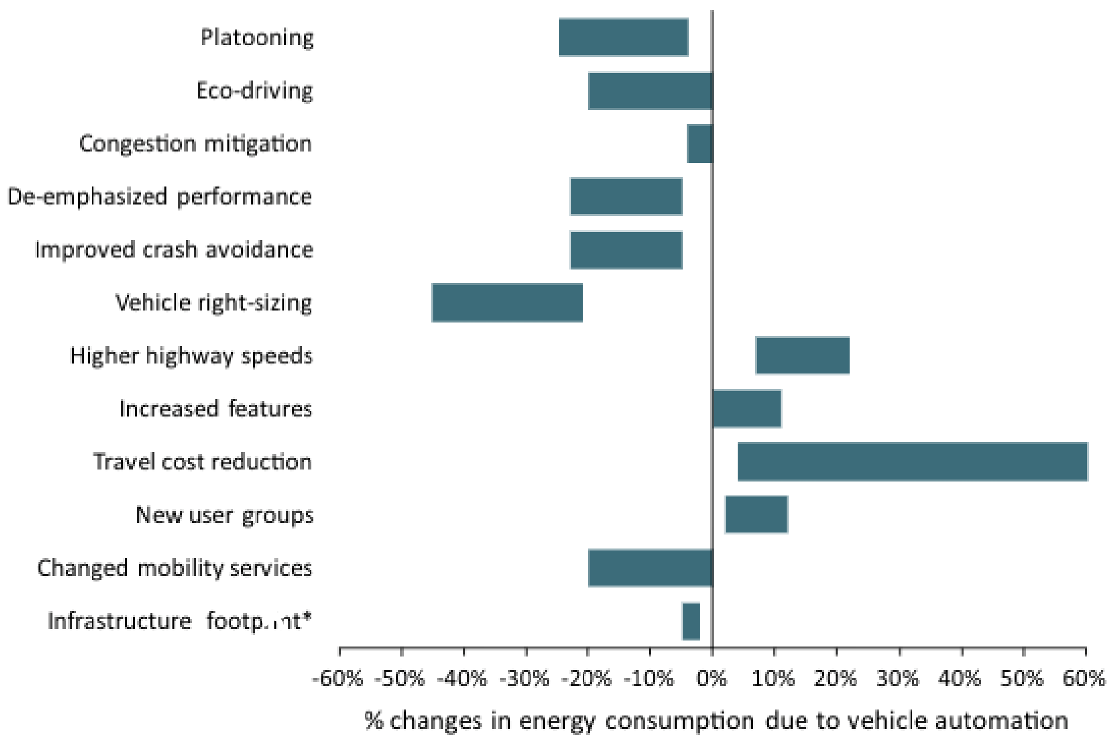

Figure 1. Potential changes in energy consumption due to vehicle automation. *Source:* Wadud, MacKenzie, and Leiby 2016.

While most of the impacts shown in figure 1 are relevant to urban transportation systems, their relative sizes may differ substantially between highway and local travel. Moreover, cities seeking to integrate AVs into their sustainable transportation plans typically will have additional priorities besides reducing energy consumption, such as equity, economic development, and multimodality. From that perspective, AVs have the potential to bring cities multiple benefits. They can:

Reduce personal vehicle ownership and use. Shared fleets of AVs that are available on a dynamic basis have the potential to reduce personal vehicle ownership in cities, effectively curbing daily, long, single-occupant trips. Shared AVs could also serve as first- and last-mile connectors and service gap fillers by connecting to public transit, giving residents reasonable alternatives to traveling by personal vehicles.

Expand transit service coverage. AVs could be used in transit fleets to expand coverage and increase the flexibility of cities' transit systems by providing on-demand, flexible-route services in appropriately sized vehicles outside high-density corridors that are well served by rail and bus (Bloomberg 2017). They can be a low-cost way for cities to provide mobility for young, aging, and disabled populations.

Connect under-resourced communities. Affordable autonomous ride-hailing could provide underserved communities with connections to transit facilities, allowing residents to access jobs and services more easily. Likewise, these services could provide employers with access to a larger number of potential employees.

Reclaim high-value land from inefficient uses. The average American city devotes on the order of 50–60% of its downtown space to car-related services and infrastructure; Los Angeles County dedicates 14% of its total land mass to parking facilities alone (Fraser et al. 2016). Displacement of a large number of privately owned, underutilized vehicles by a smaller number of shared-ride vehicles in constant use could release valuable land from roadways and parking for additional bicycle and pedestrian infrastructure, more affordable housing and additional commercial and office space around key transit nodes, and generally denser development where desired.

Improve fuel efficiency. AVs will likely inherit efficiency capabilities from various automation and connectivity technologies, including speed harmonization, eco-approach and -departure at traffic-signaled intersections, and eco-routing. To the extent that AVs are fleet vehicles rather than personal vehicles, they are likely to be right-sized for ride-hailing and hence typically small. Also, the economics of vehicle ownership may mean that AV fleet operators are relatively early adopters of electric vehicles.

Reduce drivers' time spent circling for parking. The average American driver spends 17 hours looking for parking every year (Cookson and Pishue 2017). One INRIX study has pegged the annual financial cost of searching for parking at $73 billion in the United States, £23 billion ($27 billion using the exchange rate at the time of this writing) in the United Kingdom, and €40 billion ($52 billion) in Germany; these figures account for not only the cost of fuel and fossil fuel emissions, but also the cost of people's time. In the United States, looking for parking consumes 1.7 billion gallons of fuel per year (Cookson and Pishue 2017). As more passengers are dropped off and pickup up by shared AVs, the resulting decline in searching for parking could mean a 4% reduction in vehicle fuel use in the United States, which translates to roughly 10 gallons of gas per person per year (Brown, Gonder, and Repac 2014).

Despite these benefits, however, it is important to recognize that AVs also have the potential to add to existing transportation and economic challenges in urban environments. The number of miles driven by AVs will depend on vehicle ownership models (ride-hailing fleets or personal vehicles), their occupancy, their integration with other modes of transportation, and the respective costs of various mobility options. AVs can:

Undermine transit ridership. AVs will give people flexibility and more control over their schedules by offering door-to-door service on demand, likely at lower cost, which could make them more attractive than transit to busy residents. Ride-hailing has already been shown to detract from transit ridership in some locations. Absent policies to avoid this outcome, such as road pricing and greater investment in transit infrastructure and service expansion, the diversion of trips from transit to ride-hailing is likely only to increase with the cost reductions anticipated with the deployment of AVs in ride-hailing fleets.

Exacerbate congestion. Conventional ride-hailing services are already contributing to congestion in many cities across the United States. A recent study commissioned by Uber and Lyft showed that the two companies are having a measurable impact on traffic in six large core urban areas, making up between 7% and 13.5% of total vehicles miles traveled in those areas (Hawkins 2019b). The same study showed that one-third of the mileage that can be attributed to ride-hailing fleets occurs with no passengers in the vehicle (Hawkins 2019b). With the arrival of AVs, use of these services is likely to increase due to reduced fares, exacerbating the problem. Both in fleets and when privately owned, AVs could give rise to many more zero-occupancy trips in a city, increasing miles driven and the associated energy use.

Induce additional travel and increase sprawl. The convenience associated with AVs could lead to induced travel demand in the form of new vehicle trips and longer trips. A study from the University of California, Berkeley, conducted in 2017 attempted to anticipate some of the potential behavior-change impacts of self-driving vehicles by providing subjects with access to a chauffeur for one week. The experiment found a significant increase in vehicle miles traveled (VMT) and number of trips, particularly in the evening and for longer distances (Harb et al. 2017). Additionally, by allowing travelers to use commute time productively, AVs could also make longer commutes more acceptable and thus promote suburban sprawl (Litman 2019).

Eliminate jobs. Integrating AVs into urban transportation systems could lead to income inequalities. Job losses among low-income communities and communities of color are the primary concern. The arrival of AVs could potentially lead to truck drivers, ride-hailing service drivers, transit operators, and delivery service workers being replaced by lower-cost, automated solutions, disproportionately harming certain ethnic and income groups (Creger, Espino, and Sanchez 2019).

Many of the costs and benefits outlined above are elements that city policymakers would be thinking about, even without the arrival of AVs, as they work to achieve their broader transportation goals. AVs can either amplify the benefits or exacerbate the negative impacts, depending on how they are deployed.

Desired Outcomes

A sustainable urban transportation system will help to protect the climate and improve health, safety, and equity for residents. Certain key goals can help ensure that such a system is put in place. These goals include:

- Shared use of low-emissions vehicles
- A robust transportation system composed of multiple efficient modes
- The optimized use of public space

Reaching each of these goals will require multiple strategies, many directly relevant to how AVs are deployed, as discussed below.

Shared-Use Low-Emissions Vehicles

Encourage shared rides. To achieve the greenhouse gas (GHG) reductions needed from the transportation sector, the number of vehicle occupants per trip must increase. App-based ride-hailing services have skyrocketed in popularity since the introduction of Uber in the late 2000s. According to a Pew Research Center survey conducted in 2018, 36% of US adults said they had used a ride-hailing service such as Uber or Lyft, compared with just 15% in late 2015 (Pew Research Center 2018). However the growth in *shared* ride-hailing trips has proved to be much slower due to people's anxiety about sharing and their diminished control over scheduling (Greenwald and Kornhauser 2019). Providers and cities need to communicate benefits such as reduced cost and, eventually, less congestion to win customers over to shared rides.

Discourage personal ownership of AVs. Once AVs become a feasible mobility option for passenger movement, widespread personal ownership of AVs would reduce the likelihood of high vehicle occupancy and instead produce more miles driven, greater congestion, and increased travel time in urban areas. Personal AV ownership in suburban areas could increase the number of empty trips made by these vehicles and exacerbate urban sprawl by enabling solo commuters to use their travel time productively (Shared Mobility Principles 2019; Trommer et al. 2016). Fleets of shared-use AVs can lead to a much different outcome, filling gaps in transit service and providing communities with access to an additional efficient mobility option. Ride-hailing companies like taxi services, Uber, and Lyft provide models for fleet ownership of vehicles, and other models such as the Zipcar car-sharing service exist as well.

Encourage electric vehicle adoption. Most companies working toward manufacture or deployment of AVs are planning for those vehicles to be all-electric, bringing an inherent energy efficiency advantage over internal combustion engine vehicles. Indeed, if AVs are to become a long-term mobility solution and help cities achieve their energy use and emissions goals, they will need to be electric. Simultaneous actions to clean up the grid will also be necessary to take full advantage of the emissions reduction potential that electric AVs can provide.

Today, ride-hailing companies can help to accelerate the adoption of electric vehicles by incentivizing their drivers to buy or lease them. In high-mileage uses, electric vehicles' lower operating costs in terms of both fueling and maintenance can offset their high up-front costs (ACEEE 2019). Likewise, autonomous electric vehicles will be more expensive to purchase but will reduce ride-hailing operating expenses and provide these companies with a distinct advantage over households to amortize the cost of an autonomous electric vehicle, especially given the high number of miles traveled annually by their vehicles. Ride-hailing companies' planning for the future of their fleets already includes a strong emphasis on electric vehicles. Lyft, for example, has announced aggressive goals for combining electrification and autonomy, aiming to provide at least 1 billion annual rides in electric AVs by 2025 (Coplon-Newfield 2017).

It cannot be assumed that AVs will be electric, however. Full electrification poses challenges for AVs in fleet use, including loss in revenue service time due to charging and the range reduction associated with the increased power needs of highly automated and connected vehicles. Some companies pursuing AVs anticipate using vehicles with internal combustion engines, at least initially (ACEEE 2019).

Ensure equitable access to AVs. Transportation equity is crucial to job access and economic development in underserved communities. Equitable access to mobility options is also necessary to minimize the energy and environmental impacts of the transportation system. In the United States, the average household spends almost 20% of its total income on transportation. For low-income households, the average burden can be as high as 30% (Hickey et al. 2012). As cities have grown outward and jobs have moved away from urban cores, many low-income and minority communities find themselves inadequately served by affordable and efficient transportation options, a problem that is compounded by declining public transit ridership and, therefore, service provision.

Shared rides in AVs combined with other affordable new mobility options could fill transportation service gaps for under-resourced communities. It will be important to ensure the availability of these options by setting requirements for siting and distribution of AVs in disadvantaged communities. Updating local zoning codes to favor more compact, walkable neighborhoods will also have a significant role to play in ensuring equitable access to various transportation options and in preventing a reliance on single-occupancy rides.

Energy Implications

Preliminary modeling indicates that there is opportunity for 12% reductions in VMT, emissions, and transportation costs through a transition to conventional ride-sharing from single-occupancy driving (DOE 2013). Other studies demonstrate that in urban areas the vehicle population could be reduced by 25% (Lavieri and Bhat 2019). An additional study has shown that the needs currently met through 32 million vehicle trips taken each day in New Jersey could be serviced with 43% fewer VMT and a 50% smaller fleet through ride-sharing and transit investment, functionally eliminating peak-hour road congestion (Brownell and Kornhauser 2014). AVs have the potential to achieve these gains by making ride-sharing cheaper and more convenient. Policies that increase ride-sharing, therefore, will help to bring about a future in which fewer vehicles serve a greater number of people at significantly lower energy costs to consumers, with benefits to the livability of cities, connectivity of rural areas, maintenance burdens of road infrastructure, and environmental sustainability.

Robust System of Multiple Efficient Modes

Grow public transportation ridership and investment in public transit service and infrastructure. The quality of public transit in the United States varies greatly from city to city, reflecting differences in coverage, reliability, frequency, and cost. All systems have service gaps that low-cost, shared-ride AV services could help to fill, including first-mile and last-mile connections to transit nodes. The emergence of AVs could also push transit services to evolve in order to compete better with other mobility choices. On the other hand, it is possible that personal AVs could outcompete transit by giving people more flexibility and control over their schedules and by providing door-to-door service (Trommer et al. 2016). The experience of ride-hailing services to date provides a preview of possible effects: one study found that users of ride-hailing services in major US cities reduced the net usage of public transportation by 6% on average; bus ridership was most strongly affected (Clewlow and Mishra 2017).

Absent policies to avoid this outcome, the diversion of trips from transit to ride-hailing is likely only to increase with the cost reductions anticipated from the deployment of AVs in ride-hailing fleets (ACEEE 2019). Proper pricing of transportation infrastructure will be essential but not sufficient to prevent such diversion. Preserving transit in an era of new, convenient, and affordable transportation options will require major improvements and investment in transit facilities and service, particularly in denser urban areas, where public transportation serves as the backbone of passenger mobility and is the most efficient way to move people over wide distances.

Deploy autonomous transit vehicles where appropriate. Transit agencies themselves will be able to deploy AVs effectively in the future. With no need for additional drivers to operate new routes, AVs should be a relatively low-cost option for transit agencies to provide on-demand, flexible-route services outside of high-density corridors that are already well served by rail and bus (ACEEE 2019). Numerous cities in the United States and globally are experimenting with autonomous shuttles as a way to connect neighborhoods to larger transit nodes. Singapore, Orlando, and Providence are all investigating the ways that autonomous shuttles can be incorporated into public transit systems on an on-demand basis by focusing on neighborhoods that are served infrequently by buses and trains.

Increase use of other first- and last-mile solutions for passenger mobility. While AVs can fill connectivity gaps in the broader transportation system, they cannot be the only first- and last-mile option if cities are aiming to simultaneously reduce their energy consumption and GHG emissions. Cities should invest in other, more energy-efficient solutions, such as docked and undocked bike-sharing services, bicycle or pedestrian infrastructure more broadly, and scooter-sharing programs. Not only will the addition of such programs provide urban residents with a broader suite of low-emissions transportation options, but it will also extend the reach of public transit and reduce the need for vehicles, autonomous or otherwise, for trips.

Energy Implications

Energy savings resulting from the creation of a multimodal transportation system arise from a reduced reliance on personal vehicles as a primary mode of mobility. Ridership on the most efficient mass transport option could rise with the improvement of public transit service and the provision of cost and time information to commuters at what is effectively the point of purchase for transportation services. Multimodal payment and planning apps help to reduce wait times, increase predictability, and coordinate connections between different mobility options. Energy savings also result from the use of muscle-powered mobility such as walking or biking, from micro-mobility services in the form of electric bikes or scooters, and from shared ride-hailing—all of which may be employed as first/last-mile connections to mass transit for longer trips. Policies that encourage the use of efficient modes of travel can reinforce socio-behavioral shifts toward a shared AV mobility future.

Smart, Optimized Use of Public Space

Promote deployment of smart infrastructure. One of the biggest developments in urban transportation systems is the emergence of tech-enabled services and infrastructure. "Smart" cities seek to plan transportation systems more holistically and take advantage of new technologies and data to increase system efficiency (Chen, Ardila-Gomez, and Frame 2017). Many vehicles on the road today have a limited ability to communicate with other vehicles and infrastructure. Taking full advantage of AVs' potential to increase transportation system efficiency and safety will require comprehensive smart infrastructure that allows connected and automated vehicles to communicate with other vehicles as well as streets, traffic lights, and road signs.

Reduce the amount of urban space devoted to private automobiles. Since the mid-20th century, American cities have actively promoted the personal automobile. Post–World War II zoning practices have traditionally segregated industrial and residential uses of land, and some land-use plans further differentiate among commercial, institutional, and recreational purposes. In combination with auto-focused transportation investment, this has worked against the creation of compact communities well served by public transportation and has encouraged instead a proliferation of land uses dedicated to personal vehicles, including parking lots and high-speed urban roadways (Ribeiro et al. 2019). As shared use of AVs becomes widespread, cities will have opportunities to reclaim some of these spaces from the automobile, for example by reducing or eliminating parking-space requirements imposed on developers and expanding bike and pedestrian infrastructure. Doing so will require adequate resident and stakeholder input to planning processes for public spaces (APA 2019).

Manage curb space for multiple uses. As efficient transportation options become more attractive and reliable and there is less demand for personal vehicle ownership and on-street parking, cities will be able to put valuable curb space to better use. AVs used in any capacity will have little need for long-term parking but frequent need for curb access, so advanced curb management is important preparation for the arrival of AVs. A number of cities have embarked on curb space pilots. For example, Washington, DC, has introduced a yearlong flex-space pilot program that reserves four blocks in a busy neighborhood for ride-hailing pick-up and drop-off zones during peak hours. Likewise, San Francisco and Fort Lauderdale have pilot programs that vary what curbs can be used for at various times of the day: Uber and Lyft cars, Fed Ex and UPS trucks, personal vehicles, bike-share drop-off, and more (Marshall 2017).

Energy Implications

Energy savings from more efficient land use arise from the reallocation of urban space from off-street parking to a variety of components of denser communities. Developers no longer facing the onerous burden of constructing off-street parking can allocate that space to mixed-use development in which amenities like grocery stores, child-care services, and transit connections can be incorporated into the community rather than constructed at a distance, where land is less costly. Residents of mixed-use communities are closer to these amenities, and their transportation needs are reduced, increasing the share of trips that low-emission modes like walking, biking, and micro-mobility can accommodate. Additionally, as construction becomes denser, there are energy savings opportunities for residential and commercial buildings within those communities. A building sharing a wall with another enclosed structure, rather than being adjacent to a parking lot or garage, loses less heat to the environment in winter and gains less heat in summer, decreasing the energy use of air-conditioning and heating systems. In addition, the reallocation of some parking facilities to green space makes use of evaporative cooling to reduce the urban heat island effect, diminishing air-conditioning loads and making muscle-powered mobility more attractive in summer temperatures (Güneralp et al. 2017).

Policies to Achieve Desired Outcomes

Cities have a suite of policies available to them as they prepare their transportation systems for the arrival of AVs. Key steps to ensure that AVs help rather than hinder cities' achievement of sustainable transportation goals largely coincide with steps cities should be taking anyway. The bottom line is that the prospect of AVs on urban streets should serve largely as an impetus to accelerate the transformation from car-centered to people-centered urban mobility systems.

Yet in addition to opportunities, the arrival of AVs does bring specific challenges. In some instances, AVs have the potential to aggravate an existing problem such as the diversion of transit trips to less fuel-efficient modes. That is because AVs can provide the convenience of today's ride-hailing services but at lower cost due to the absence of a driver.[1] Thus, while not all the policies described below are AV specific—some pertain to existing problems that AVs will exacerbate—they will all be important to ensuring that the introduction of AVs reduce GHG emissions from urban transportation. The phenomenon of induced travel, trends in ride-hailing, and basic economic principles serve as warning signs for the negative impacts that AVs could potentially have on urban transportation, including supplanting more efficient forms of personal mobility and public transport as well as worsening congestion. Smart policymaking will be crucial to ensure that the net energy and environmental impacts of these vehicles are positive.

[1] Today's ride-hailing companies may operate at considerable loss, however, and it is not clear how market-rate AV ride-hailing would compare with current ride-hailing rates.

REQUIREMENTS FOR VEHICLE PURCHASE AND USE

AVs represent a major departure from vehicles with human operators, and the need for new rules governing their features and use is widely accepted. Development of AV rules has thus far focused primarily on safety and security issues, but rules to promote positive emissions outcomes from AVs should also be considered.

One approach to ensuring that AVs reduce emissions is to place direct requirements or limitations on their fuel type, ownership, or use. For example, the Shared Mobility Principles for Livable Cities specify that AVs "in dense urban areas should be operated only in shared fleets" (Shared Mobility Principles 2019). Others have suggested a requirement that all AVs be fully electric, to offset possible emissions increases due to high VMT, or that ownership of AVs for personal use be limited.

As is the case for many policies discussed here, ride-hailing fleets will provide the proving grounds for these rules. California has adopted targets for ride-hailing companies to reduce GHG emissions per passenger mile to push these companies to prioritize shared rather than single-passenger trips and to promote the use of low-emissions vehicles in their fleets. Additional goals of California's program include promoting carpooling, active transport (biking and walking), and transit usage and maximizing the equity of access to transportation services (CARB 2019). While cities may not have the authority to set GHG standards similar to California's, they can advance the same general objectives and complement existing state policies through the use of incentives and fees.

Chicago Downtown Zone Surcharge

In October 2019, Chicago's newly elected mayor, Lori Lightfoot, proposed a downtown surcharge, in addition to a heftier per-ride tax, for solo Uber and Lyft trips. The proposed program aims to address the congestion impacts caused by ride-hailing vehicles in the central business district, and also to generate revenue for mass transit upgrades (Spielman 2019).

Chicago currently imposes a flat charge of 72 cents for rides booked through Uber and Lyft, but according to critics, this does not address city goals of improving the equity of the urban transportation system or reducing GHG emissions and congestion. The new plan calls for a "downtown zone surcharge" of $1.75 per solo ride-hail trip and a 60-cent surcharge for shared ride-hail trips downtown. The city's ground transportation tax will also be changed. Single Uber and Lyft trips will see an 88% increase in this tax to $1.13, and shared trips will undergo a 12% reduction to 53 cents (Spielman 2019).

As city planners think about ways to transition to a comprehensive congestion pricing scheme, these changes will in the meantime help to encourage transit ridership and shared rides.

MODIFIED PARKING REQUIREMENTS AND PRICING

AVs are expected to reduce parking demand in several ways. AVs could drop off their occupants and return home or find a space some distance away where parking demand is low.[2] Shared-use AVs might additionally reduce parking needs by remaining in service throughout the day. Less need for parking would allow cities to repurpose valuable space in their busiest districts for more dynamic uses including walking and biking, deliveries, recreation, and new development.

Many cities are already seeking opportunities to reduce space devoted to the automobile by revising the parking-space requirements imposed on developers to cut parking oversupply in favor of creating compact, walkable neighborhoods. Ride-hailing services are providing new impetus to do so, both by highlighting the need for curb space and by lowering demand for parking in high-traffic areas. Hence cities today can advance the concept of shared versus individual vehicle ownership models prior to AVs' arrival by strategically repurposing parking infrastructure or avoiding its creation in the first place.

Elimination of Minimum Parking Requirements

Minimum parking requirements are antiquated vestiges of city centers that embraced the personal automobile revolution of the 20th century, often to the detriment of the city's transit infrastructure and livability. These requirements were designed to ensure that new construction projects provided adequate off-street parking to service their residential and commercial occupants. Today these policies impose an unnecessary cost burden on developers where alternatives to personal car ownership are readily available and often more in keeping with city sustainability goals. Policies need to be updated to reflect current trends and needs, accompanied by increased mixed-use development and expansion of transit, among other mobility services, to both provide alternatives to personal vehicles and reduce the distance between residents and urban amenities. Accurate data on the number of existing parking spaces in a given city could also help cities better identify future parking needs.

Inflated parking supply helps to induce demand for that resource, incentivizing city residents to purchase and keep personal cars despite living in areas with easy access to transit or other mobility services. Minimum parking requirements lock developers into including parking facilities in new construction, the cost of which is passed on to tenants in the form of higher rent. Tenants without vehicles effectively subsidize the cost of car ownership for their neighbors. Elimination of minimum parking requirements or the application of parking maximums forces car-owning tenants to shoulder the higher costs of parking a personal car by limiting the number of spaces available for it (Shoup 2016).

MEXICO CITY

Mexico City is the largest city in North America to eliminate traditional minimum parking requirements, going so far as to replace those minimums with off-street parking maximums. Additionally, the city imposes fees on buildings constructed with parking beyond 50% of the established maximum, thus incentivizing developers to keep off-street parking capacity

[2] Such behaviors raise the possibility of increased VMT and emissions due to more driving without passengers; the policies discussed are needed to discourage this outcome.

low. Developers are required to abide by another minimum parking requirement, however—for bicycles (ITDP 2017).

Intelligent Pricing of Curb Space

Autonomous vehicles are likely to add to the multiple demands for the curb, which include freight deliveries and ride-hailing drop-offs as well as parking, a challenge that could be met most efficiently with a well-designed pricing scheme for all users. Currently, municipal parking costs both on and off the street are often heavily subsidized and therefore fail to reflect the true price of that parking in terms of land allocation and the environmental degradation resulting from a dependence on personal vehicles for transportation.

Cities should invest in retrofitting existing parking infrastructure with sensors and metering devices capable of tracking demand for curbside parking and appropriately pricing that parking. Curb space should be priced dynamically to reflect changing demand over the course of the day, which will encourage optimal use. This system can be integrated with a smartphone-enabled application developed by the municipality that gives users information on curbside availability and price projections based on historical data.

Intelligent pricing of the curb has the additional benefit of incentivizing freight operators to modify their delivery schedules to operate during off-peak hours and consolidate deliveries in order to minimize their curb time, thus freeing up space on the curb and the roads themselves during peak hours. The pricing mechanism could be modified over time to reflect changing curbside needs; as personal vehicle ownership and long-term parking give way to shared AVs, rates could be increased to leave additional space on the curb for higher-value uses.

This model would require substantial adjustments in norms and behaviors of vehicle users and investments by municipalities. Cities might wish to begin the transition by implementing a set schedule on which prices fluctuate within a defined and limited range. This incremental change would permit users to anticipate costs with greater facility and allow them to get accustomed to the idea of variable pricing itself. Cities must continue observing parking behavior and collect data that will enable incremental schedule adjustments to achieve the desired outcome, while also being fair to ride-hailing and freight companies by ensuring that they are able to conduct their business efficiently.

WASHINGTON, DC

In 2008 two pilot studies of intelligent parking strategies were conducted in the Columbia Heights and Ballpark districts of Washington, DC. The pilots' results were promising, and since then the city has been expanding the testing of demand-based parking schedules to other neighborhoods, the most recent addition being the Penn Quarter and Chinatown performance parking zone in 2016. This program has several notable features:

- Parking prices were varied dynamically for each block by time of day, by day of the week, and for special events.
- Mobile applications ParkDC and VoicePark were developed to provide real-time information on parking availability in the zone and to allow app-based payments for parking.

- Loading and freight zones were priced as well, which reduced their illegal occupancy by non-freight vehicles.
- The pilots used empirical data to set prices based on historical use, with pricing adjustments every three months. City leaders' long-term vision for intelligent pricing programs is for real-time dynamic pricing (DDOT 2014).

These intelligent parking strategies were effective. In the Penn Quarter and Chinatown program, the percentage of high-demand block-faces at ideal occupancy increased from 62% to 72%. In underutilized block-faces there was a 12% increase in occupancy and a 14-minute increase in length of stay. Time spent circulating decreased by 15% over all periods, and automobile congestion in the zone fell by 5% (Allen 2019).

COLLECTION AND SHARING OF TRANSPORTATION DATA

Tech-enabled mobility generates voluminous transportation data that could be of great use to city transportation planning and the provision of services. The National Association of City Transportation Officials has referred to data as "the new concrete of transportation infrastructure," with the capacity to improve the efficiency, cost, and inclusiveness of transportation systems (NACTO 2019). Analysis of such data provides cities with a unique window into the travel habits and decision making of travelers. This in turn helps identify existing service and infrastructure gaps and can inform future city-led transportation infrastructure and service development and climate planning. Real-time data are essential to the provision of services and capabilities that respond dynamically to users and conditions.

With the arrival of AVs into urban spaces, strategic use of transportation data will be essential to achieving cities' goals for the deployment of these vehicles. If AVs are to carry multiple occupants, complement and enhance transit, operate with greater fuel efficiency, and affordably serve previously underserved communities, they will need a high degree of connectivity together with data input from other vehicles, other modes, infrastructure, and travelers.

Taking best advantage of the detailed transportation data that exist today will require concrete guidelines for facilitating cooperation between cities and private entities. The responsibility for structuring data-sharing processes and expediting interoperability among mobility providers lies squarely on the shoulders of local governments for the time being (Rouse et al. 2018). Open data specifications that enable the free communication of real-time data among various city programs, mobility providers, app developers, and other stakeholders are integral to the deployment and success of AVs and other tech-enabled mobility platforms (NACTO 2019). At the same time, it is equally important that provisions be made within open data specifications to protect and anonymize sensitive user data. Ensuring the protection of individuals' personally identifiable information (PII) and securing data that will help support the creation of sustainable transportation systems are of the utmost importance, meaning that agreements between the private and public sectors regarding open data specifications should be considered requisite to any mobility provider's entrance into city markets (NACTO 2019).

Aggregated data collected through open data specifications will help planners determine where AVs can be added to achieve broader transportation and energy goals. First, these data will help to identify service and infrastructure gaps, a comprehensive understanding of which will greatly inform future planning and help ensure that underserved communities receive the services they require (Vaidyanathan 2018). Diligent and creative use of transportation data in planning processes will not only provide cities with better tools for addressing issues of transportation equity and inclusivity, but will also help improve system-wide safety and efficiency outcomes. Second, access to real-time multimodal data can provide residents with real-time information on multiple mobility options, thereby reducing the reliance on single-occupancy trips or pushing travel to off-peak periods for both conventional vehicles and AVs (Tomer and Shivaram 2017). For instance, real-time data can help to decrease transit travel times for individuals, making public transit a more convenient alternative to driving (Tomer and Shivaram 2017). Commuter access to real-time transit data has proved effective at increasing transit ridership in areas with established transit services (Brakewood and Watkins 2015).

LADOT Mobility Data Specification

The City of Los Angeles established its mobility data specification (MDS) in May of 2018. Local micro-mobility companies (shared scooter and bike providers) are required by statute to make their data accessible to the city, and the MDS defines a set of application programming interfaces (APIs) responsible for managing these data (LADOT 2019). The MDS specifies that real-time data on the number, location, and condition of vehicles within the city must be shared, in addition to data on:

- Parking verification
- Operating cost
- Customer cost
- Vehicle utilization
- Battery state of charge
- Trip start time and location
- Trip end time and location

Developmental principles of the MDS include:

- *Open source*. Any party can be licensed to use the MDS without fees or royalty collection from the Los Angeles Department of Transportation.
- *Competition creation*. Competition is encouraged between mobility companies through an easily accessible data platform to facilitate the development of new products and services.
- *Transparency and privacy*. The MDS adheres to best practices of data security and transparency of data collection.
- *Harmony*. The standard encourages regional data interoperability and consistency for service providers.
- *Sustainability*. It primes the city to deliver service options providing more efficient and equitable mobility.

The MDS also specifies tools for actively managing micro-mobility assets in real time, e.g., ensuring the proper parking of vehicles in the public right-of-way (LADOT 2019). The APIs have managed data predominantly from micro-mobility providers up to this point, but it is designed to accommodate input from ride-hailing companies, buses, and taxis as well, and the system could be adapted in the future to accommodate data sharing with connected vehicles.

Mobility data collected on this scale can potentially compromise the privacy of individuals (NACTO 2019). Cognizant of this, LADOT has opted to manage mobility data as though it were PII, anonymizing information and employing limits on how long it can be kept by the city (LADOT 2019). Other cities interested in deploying similar open data systems should make the adoption of comparable individual privacy protection policies a prerequisite to implementation.

To develop the MDS, LADOT worked with the cities of Santa Monica and Austin, the San Francisco Metropolitan Transit Authority, the Seattle Department of Transportation, and the Harvard Kennedy School, as well as the micro-mobility providers Bird, Spin, and Lime.

PRICING MECHANISMS

Policies like congestion pricing and mileage fees increase the cost of driving a personal vehicle and create sources of funding for more efficient mobility options. Such pricing policies can increase the appeal of more efficient mobility options like public transportation, effectively reducing the dependence on autonomous and non-autonomous vehicles alike.

Mileage Fees

Mileage-based user fees, also known as vehicle-miles-traveled (VMT) fees, have long been discussed as a potential alternative or companion to fuel taxes as a means of funding public expenditures on highway infrastructure and maintenance. Federal gasoline and diesel tax rates have been fixed at 18.4 and 24.4 cents per gallon, respectively, since 1993. Fuel tax revenues fall far short of highway spending needs, and a number of states have increased the per-gallon tax on fuel to address shortfalls in transportation funding (Isidore 2019).

Mileage-based user fees are charged per mile driven in a particular vehicle through the use of an in-vehicle tracker or on the basis of self-reported data. Generally this fee is an attempt to account for the direct impact a given vehicle has on the condition of the roads it is driven on, although a more exact approach would consider vehicle size and weight in addition to mileage. While mileage fees have typically been proposed as an addition to or replacement for gasoline taxes at the state or federal level, cities have a critical role to play in supporting state efforts on this front. Besides generating revenue for road maintenance and construction and for transportation services that reduce roadway demand, mileage fees also reduce the number of miles that vehicles travel, on average, thus helping to address congestion and decrease energy use in the transportation sector. Rates can be structured to incentivize walking, biking, or the use of public transport during peak hours (Ecola et al. 2011).

One of the primary concerns as AVs become a widely available option is their potential to increase VMT. Personally owned AVs will not only provide door-to-door service but also expand the range of activities their owners can engage in while traveling, which in turn could increase suburban residents' tolerance for long commutes. This would likely detract from commuter rail ridership and promote sprawl, to the detriment of urban areas. Mileage fees could discourage personal ownership of AVs and promote the shared usage model that is described in the outcomes section of this toolkit.

In urban environments, even ride-hailing fleet vehicles may accumulate many miles with no passengers as they search for their next rides or, in the case of electric AVs, seek charging stations. Mileage fees can push shared electric vehicle fleets and ride-hailing companies to limit the number of "deadhead" miles and reduce these vehicles' needless contribution to congestion by increasing the cost of operating an empty vehicle. Mileage-based fees would also ensure that high-mileage AVs contribute their share of the cost of highway maintenance and services (NLC 2018).

Mileage fees are a system-wide approach that can minimize some of the unintended system impacts of AVs. In tandem with transit service expansion and the creation of compact, walkable communities, a mileage fee can lead to energy savings and emissions reductions, among other benefits.

OREGON PAY-PER-MILE PILOT PROGRAM

The state of Oregon was one of the first jurisdictions to pursue the application of a per-mile fee to replace the state gasoline tax as a funding mechanism. In 2001 the Legislative Assembly created the Road User Fee Task Force to investigate alternative sources of revenue for road maintenance and construction (Oregon LPRO 2018). Settling on the prospect of a VMT fee, the task force created a pilot study with 285 test vehicles equipped with GPS trackers between 2006 and 2007 to evaluate the feasibility of implementing a per-mile fee and investigate potential outcomes (Oregon LPRO 2018). The study showed that drivers responded to mileage-fee pricing structures by reducing vehicle miles driven, especially during peak periods, when fees per mile were higher (Sorenson, Ecola, and Wachs 2012). A second, expanded pilot ran from 2012 to 2013 to test a larger set of payment options. This second pilot demonstrated an open architecture system where users could choose a mileage tracking and payment option that worked best for them (Oregon LPRO 2018).

In 2015 Oregon introduced the permanent, voluntary OReGo program, which allowed up to 5,000 light-duty vehicles to enroll. Drivers pay 1.5 cents per mile to drive on Oregon state roads (Oregon LPRO 2018). The 5,000-vehicle cap was removed in 2019, and all drivers can now choose between continuing to pay traditional fuel taxes or enrolling in the OReGo program. Although all participants will continue to purchase fuel, and therefore continue to pay the state gasoline tax, each vehicle owner enrolled in the per-mile plan will receive either a bill for additional taxes or a refund, depending on their actual road use (Oregon LPRO 2018).

The permanent program has been in place for only three years and has not yet tracked changes in travel trends as a result of the fee (although it soon will). Given the increased likelihood that AVs will be electric vehicles, which incur no gasoline taxes, programs such as Oregon's would be a means of discouraging proliferation of unproductive AV miles.

Congestion Pricing

Like mileage-based fees, congestion pricing increases the cost of using personal vehicles. Congestion pricing is a market-based concept that can be applied in larger, denser urban areas as a means to reduce traffic and improve travel efficiency. Charges can be applied when vehicles transmit information about their location or pass through toll collection locations, or through technologies like automatic license plate recognition and electronic road pricing (ERP), which uses checkpoints and an electronic receiver inside the vehicle to apply fees to individual drivers. This pricing mechanism shifts highway users to other modes of transportation or to off-peak hours, thus allowing traffic on the road system to flow more efficiently and reducing the overall miles driven within a metropolitan area (Vaidyanathan and Mackres 2012). It also generates revenue that can be used to expand transit service and improve travel options. The New York State Legislature approved the first congestion pricing program in the United States this year, to go into effect in Manhattan's central business district in 2021. Other cities, including Portland, Seattle, and Los Angeles, are looking at similar policy mechanisms to solve their own transportation challenges and generate funding for their aging public transit systems (Hawkins 2019a). In many cases, cities will need to work closely with state decision makers for approval to pass a congestion fee. This is particularly the case with Dillon Rule states, where state law dictates the actions that local governments can take.

In cities outside the United States, revenues from congestion pricing have been used to bolster public transportation infrastructure and service, and the same will be true of New York City's program. An equally important goal is to free up road space, reduce congestion, and reduce energy use and emissions (both climate-harming and local pollution), given that some drivers will opt for other forms of transportation if they must pay for a resource that was once free (Hawkins 2019a).

Congestion pricing is another example of a system-wide policy that can be applied to direct the appropriate deployment of AVs. As discussed earlier, AVs could potentially increase miles driven by reducing the opportunity cost of using a car and allowing commuters to be productive en route. A less onerous commute could potentially push people to look for cheaper housing further away from urban centers, particularly if AVs end up being affordable for an individual or household to purchase (Shaver 2019). Congestion pricing helps to address this concern, among many others, by increasing the cost of accessing dense, crowded urban neighborhoods in a single-occupant vehicle.

The energy implications of using a congestion price to regulate travel patterns and choices are very similar to those of a mileage fee. Such a policy can reduce energy consumption and GHG emissions in several distinct ways. Broadly, a congestion price reduces the number of cars on the road during peak travel times, thus relieving congestion, incentivizing the use of other modes of transportation, and leading to an overall reduction in the total vehicle miles driven. The policy therefore inherently limits the number of AVs that access congested urban areas. Second, congestion pricing smooths out traffic during the day by pushing some traffic to off-peak hours and limiting idling in traffic, thus improving the efficiency of vehicles and reducing GHG emissions. Finally, because of the high cost of accessing congested areas, urban travel will shift toward public transit, bicycling, walking, and other micro-mobility options while simultaneously generating revenue to create and maintain the appropriate infrastructure for a multimodal system. As these services are fleshed out, the opportunity to incorporate autonomous public transit while limiting single-occupancy autonomous trips also grows.

LONDON

London's congestion pricing scheme was introduced in 2003 as a means to reduce congestion while simultaneously improving bus service, increasing the efficiency of distributing goods and services within the city, and improving journey times (Badstuber 2018). Vehicles entering the Congestion Charge Zone (CCZ) today pay £11.50 ($14.84 using the exchange rate at the time of this writing) between 7 a.m. and 6 p.m. on weekdays. Residents pay a deeply discounted rate, and public transit vehicles, emergency services, motorcycles, and taxis are exempt from the fee altogether (Badstuber 2018). The CCZ boundary encompasses the city's primary financial district and the West End, the main commercial and entertainment zone.

The congestion charge has been a success in many ways. The number of private cars entering the CCZ fell by 39% between 2002 and 2014 (Badstuber 2018). Nevertheless, the rise of ride-hailing services like Uber in recent years has undone some of the initial benefits of the charge. Since these vehicles are technically classified as taxis or private-hire vehicles and are exempt from paying the CCZ fee, there is still steep competition for road space within central London. The number of private-hire vehicle registrations increased by a whopping 75% from 2013 to 2017 (Badstuber 2018). The proliferation of these vehicles is also impacting bus ridership. A study by the London Assembly found that the reduction in bus passengers was a direct result of congestion (Badstuber 2018). The city is currently evaluating changes to the charge to address these unintended impacts.

NEW YORK CITY

As mentioned above, New York City is the first city in the United States to adopt a congestion pricing program to improve traffic patterns and flow while simultaneously generating funding for public transportation, in this case the Metropolitan Transit Authority's subway and bus system. Contentious debate over a congestion price went on for at least 10 years but was ultimately resolved through close collaboration between the New York City Mayor's Office and state government.

Starting in 2021, a boundary will be drawn around Manhattan from 60th Street south, and cars and trucks will be charged electronically to enter the cordoned area. While rates have not been set yet, during peak traffic times they are expected to range from $11 to $14 for passenger cars and around $25 for larger trucks. Vehicles will be charged once for the day and will be able to enter and leave the congestion zone an unlimited number of times that day (Hu 2019).

The policy is very much in line with New York State's ambitious targets for greenhouse gas emissions reduction and the city's sustainability plan, PlaNYC. Estimates suggest that the city's congestion pricing scheme will directly reduce transportation GHG emissions by 6% and also contribute to further reductions by helping the city function better, thereby preventing the large-scale movement of urban residents to inherently more inefficient suburbs (Komanoff 2018).

IMPROVED, MORE ATTRACTIVE TRANSIT SYSTEMS

Public transportation is a fundamental component of dense, urban environments, as it is the most efficient way to move people across long distances. Transit needs to compare favorably with personal vehicles and ride-hailing on cost, convenience, and speed in order to grow or even maintain its share of trips taken by the residents of a given metropolitan area.

Autonomous public transit vehicles have the potential to increase transit ridership by improving access in underserved parts of the city at significantly lower operating costs than traditional public transport services, since these vehicles require no drivers. While losses of driver jobs could lead to income inequalities, shared-use AVs and autonomous transit services also have the potential to increase job opportunities by improving access to job centers. Cities will need to ensure that incorporating AVs leads to a net increase in jobs, and they must create policies and programs to help transition drivers to other occupations.

Smaller AVs could also serve as direct competition to public transportation, since AVs may not require downtown parking and their passengers may have higher tolerance for congestion since they can accomplish tasks while stuck in traffic. While pricing of urban roadways and easy connections between modes will support increased transit share, such an increase will also require expansion of transit service and infrastructure along with policies and programs that help make public transportation a more attractive option for residents and that better accommodate public transport vehicles on busy, congested roads.

Planning and Payment Integration across Transportation Modes

Access to real-time transit data has already become a part of life for many urban commuters. Faced with the need to get to their destinations efficiently and on time, commuters can benefit greatly from bus- and train-tracking systems, dynamic transit maps and schedules, and fare-based applications (Vaidyanathan 2018) (figure 2). Readily accessible transit data, in tandem with reliable, frequent, and convenient transit service, increase the likelihood that an average urban resident will use public transportation to replace driving (Brakewood and Watkins 2015).

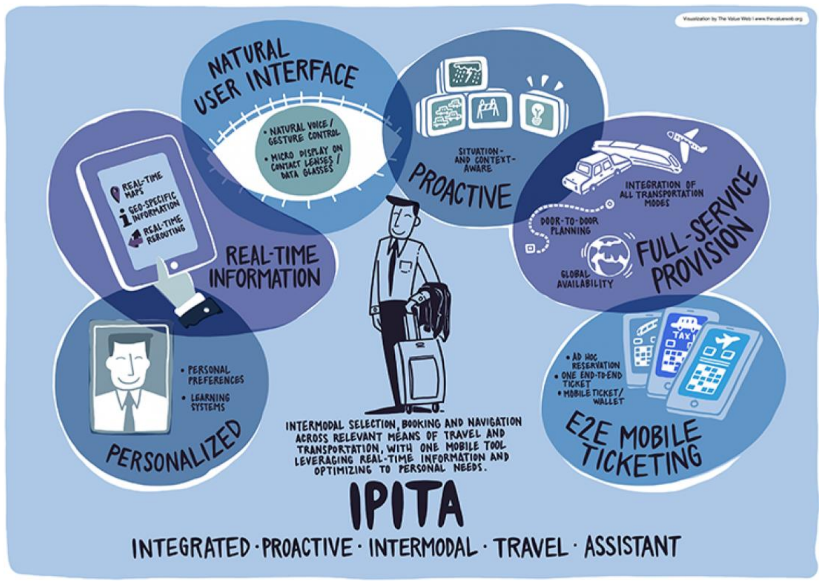

Figure 2. Integrated proactive Intermodal travel assistant. *Source:* World Economic Forum 2018.

Making cost and time information available to commuters at what is effectively the point of purchase for transportation services could help to boost ridership on public transit and increase active transportation options like walking and biking. Multimodal payment and planning apps help to reduce wait times, increase predictability, and coordinate connections between different mobility options. In addition, with real-time data that allow for better control over personal schedules, people accustomed to driving may be more open to using other modes, thereby lessening their dependence on personal vehicles for certain trips and reducing overall vehicles miles traveled. More sophisticated versions of these apps could potentially include data on time taken to find parking as well as plan detailed travel routes on multiple modes to further encourage people to get out of their cars.

Many cities are looking to consolidate services and information for multiple modes of passenger transport through the use of integrated planning and payment applications. Integrated or multimodal payment and information platforms (usually smartphone applications) provide travel time and cost information for all the mobility options available at a given point in time to help urban residents make the most efficient transportation choices (DOT 2018b). The integrated payment element of these interfaces makes moving from one mode of transport to another seamless, improving the convenience of using modes of transportation other than personal vehicles. Integrated planning and payment systems will also help commuters identify when choosing autonomous ride-hailing vehicles over other mobility options will be quicker, more environment-friendly, and more cost effective as these services are increasingly integrated into urban transportation systems.

Cities that are looking into the creation of unified information and payment systems include a number of the finalists for the US DOT's Smart City Challenge. Six of the seven finalists proposed creating integrated mobility marketplaces that would consolidate real-time arrival and departure data, route information, travel time, and costs across multiple modes of transportation (SFMTA 2016). Similarly, since the completion of the Smart City Challenge, the city of Portland has received DOT funding to integrate shared-use mobility options into its existing transit planning app. Portland has also proposed to integrate dynamic pricing into its mobility marketplace to encourage travelers to use modes of transportation that are more efficient than personal vehicles during high-traffic events (DOT 2017).

SMART COLUMBUS

Since winning the US DOT's Smart City Challenge in 2016, Columbus, Ohio, has poured a significant portion of its winning monies into the creation of a centralized Smart Columbus open-source operating system, a key component of its efforts to create a smart city (figure 3). Through a smartphone app, users will be able to identify whether bus, train, or Lyft would be fastest for their journey and learn whether any micro-mobility options are available for their first and last miles (Frost 2019).

Figure 3. Smart Columbus operating system. *Source:* Smart Columbus 2019.

In partnership with Siemens, the city is also planning to add a single-payment system that will allow customers to use the same app to pay for both public and private mobility options. Users will be charged just once even if they move from one mode to another, with the app tracking their journey and fares for the services they use. The Smart Columbus app is the first payment solution and mobility platform in the United States that is directly managed by a city rather than a transit agency or private operator (Frost 2019).

Traffic Signal Priority for Transit Vehicles

Traffic signals can be a major delay in transit systems. To address reliability and service issues on public transit lines, traffic signal priority technologies modify the signal operation to reduce or eliminate wait time for transit vehicles such as buses, bus rapid transit, and light rail or streetcars (Smith, Hemily, and Ivanovic 2005).

Transit signal priority can support mode shifting, increase transportation energy efficiency, and help lower GHG emissions. The significant reduction in transit delays brought by signal priority applications makes transit a more attractive alternative to personal vehicles by increasing the reliability and speed of service, and it also saves fuel by reducing the need for transit vehicles to idle at intersections. Recent research has shown that signal prioritization has cut travel time in the United States by anywhere from 2% to 18%, with most applications seeing a typical reduction of 8% to 12%. In Chicago, buses traveling along a transit signal priority corridor saw a 15% reduction in travel time, on average, while Los Angeles's MTA bus rapid transit routes with signal prioritization experienced a whopping 35% reduction in delays at key intersections (Danaher 2010).

Traffic signal prioritization is best applied in the following urban contexts:

- Areas where signals are a major source of delays
- Long street corridors with long signal cycles
- Intersections with long signal cycles
- Intersections with signal cycles that favor the cross street
- Turning points in transit routes (NACTO 2016)

Traffic signal prioritization is a particularly important element of bus rapid transit (BRT) systems, which typically involve dedicated bus lanes or stations and rely on signal prioritization to ensure that they can pass through intersections with minimal negative effect on other road users (Global Traffic Technologies 2019).

Signal prioritization comes in a variety of forms. Certain systems use a combination of on-board GPS technology in transit vehicles and built-in technology in traffic lights to determine whether the vehicle in question can be given priority. Other applications involve the use of Wi-Fi to communicate a transit vehicle's time of arrival at a problematic intersection as well as passenger load and schedule delays when signal priority requests are submitted. Finally, physical in-ground loop detectors can be used to identify approaching vehicles authorized to operate on the given signal priority system (NACTO 2016).

Chicago RTA

Since 2016 the Chicago area's Regional Transportation Authority has been deploying transit signal priority (TSP) as part of a regional system that covers not only Chicago Transit Authority (CTA) buses but also Pace buses run by the Illinois Department of Transportation, Chicago Department of Transportation (CDOT), and other local transit agencies (figure 4). The technologies are being installed in 13 priority corridors within the region, across 500 different intersections (RTA 2019), and are expected to be fully integrated soon.

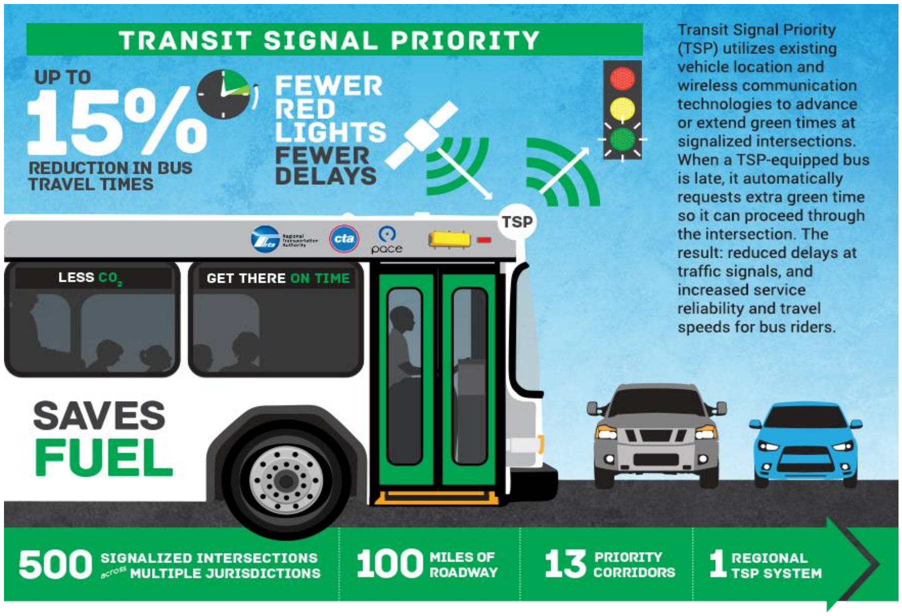

Figure 4. Chicago RTA traffic signal priority system. *Source:* RTA 2019.

Implementation is being handled by a multi-organization collaboration funded through a combination of Regional Transportation Authority monies and federal support from the Congestion Mitigation and Air Quality Improvement program. The project cost is expected to amount to approximately $40 million once all the priority corridors have been addressed. CTA and CDOT have already installed TSP technologies at two sites in Chicago and will add a third on Western Avenue by the end of 2019. Pace deployed signal optimization on six corridors and will be developing a TSP project for Milwaukee Avenue, which connects downtown Chicago to the northern suburbs, also to be completed in 2019 (RTA 2019.)

On-Demand Flexible Route Services

Transit agencies across the country are experimenting with on-demand flexible services, which can be viewed as precursors to completely autonomous transit options. Mass transit systems are restricted by their set routes and the number of stops and stations. To make use of these services, individuals often must use another form of transport from their starting point to the nearest service station, as well as for the last mile from service stop to destination. Navigating the first-mile and last-mile connections is rarely an issue in dense communities since train stations and bus stops are never very far away. However, in areas that are less dense or have lower demand, fixed-route systems may not meet the needs of residents because stops are widely spaced or service is not frequent enough (Jaffe 2011).

Transit agencies are attempting to close these service gaps and improve the efficiency of routes by deploying on-demand flexible bus service where passengers are collected at their origin and dropped off at their final destination within a specific zone (Potts et al. 2010). Service is typically requested online or through a smartphone app, merging the convenience of ride-sharing with the affordability of public transportation. In less dense cities, suburban communities, and even rural areas, such services can encourage residents to look to transit as a reliable alternative to driving for at least some of their trips, possibly reducing vehicle miles traveled (Potts et al. 2010). Flexible routing is also useful for serving the elderly or those with disabilities.

Dynamic and flexible routes set the stage for fully autonomous transit service and shuttles that integrate into a broader transportation system. AV transit vehicles can be used by transit agencies as a lower-cost option to serve lower-density corridors on an on-demand basis (ACEEE 2019). Additional route optimization through vehicle-to-infrastructure or vehicle-to-vehicle communication would allow transit vehicles to avoid congested areas and identify the most efficient routes, further increasing the attractiveness of public transportation as a replacement for driving personal vehicles.

RIDE ON FLEX, MONTGOMERY COUNTY, MARYLAND

The Montgomery County Department of Transportation (MCDOT) recently introduced limited flexible-demand bus service in two zones during specified service hours (figure 5). The Ride On Flex service has no fixed stops or schedules, instead allowing residents to book a ride when they need it to any destination within the outlined zones. Transit riders pay the same fares as traditional MCDOT bus riders. They can reserve a ride through a mobile app and are provided an estimated time for pickup and drop-off (MCDOT 2019).

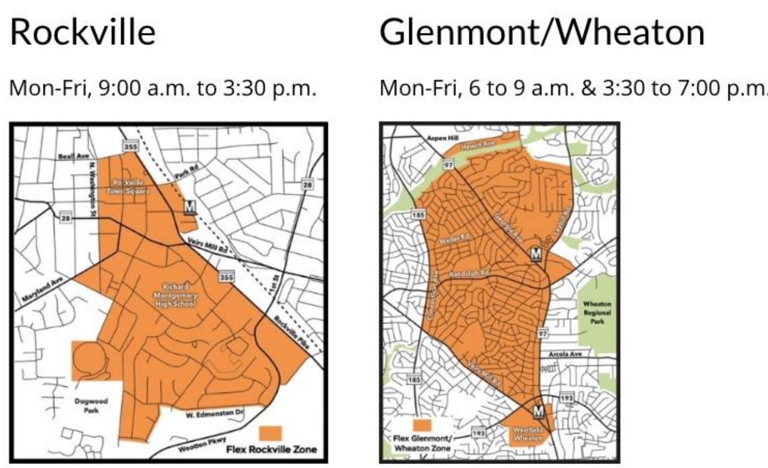

Figure 5. Flexible-demand bus service in Rockville and Glenmont/Wheaton. *Source:* MCDOT 2019.

Recognizing the need to connect households to areas that typically cannot be accessed by fixed-route services, Montgomery County officials partnered with ride-hailing company Via to come up with a low-cost alternative to traditional transit options. The pilot was officially implemented in June 2019, and the county hopes that the program will help fill first- and last-mile gaps in service for daytime and commuter trips (Go Montgomery 2019).

Summary and Conclusion

This toolkit provides cities with guidance on how to incorporate AVs into their urban areas. In doing so they can achieve their sustainability goals while addressing existing transportation barriers and the additional challenges that these vehicles bring. Table 1 summarizes AV-friendly transportation outcomes and the policies and strategies that cities can use to achieve them.

Table 1. AV outcomes and enabling strategies

Outcome		AV purchase & use	Modified parking requirements and pricing		Transportation data	Pricing mechanisms		Improved, more attractive transit systems		
		Requirements for vehicle purchase and use	Elimination of minimum parking requirements	Intelligent pricing of curb space	Collection & sharing of transportation data	Mileage fees	Congestion pricing	Integrated planning & payment across modes	Traffic signal priority for transit vehicles	On-demand flexible route service
Shared-use low-emissions vehicles	Shared ownership of AVs		•	•		•	•			
	Shared ride-hailing rides	•	•	•		•	•			
	Adoption of EVs as shared AVs	•								
	Equitable access to AVs	•			•		•			•
Robust system of multiple efficient modes	Increased public transit ridership and investment in public transit service and infrastructure		•			•	•	•	•	•
	Automated transit service		•			•	•	•	•	•
	Use of other first- and last-mile solutions for passenger mobility		•			•	•	•	•	•

Outcome		AV purchase & use	Modified parking requirements and pricing		Transportation data	Pricing mechanisms		Improved, more attractive transit systems		
		Requirements for vehicle purchase and use	Elimination of minimum parking requirements	Intelligent pricing of curb space	Collection & sharing of transportation data	Mileage fees	Congestion pricing	Integrated planning & payment across modes	Traffic signal priority for transit vehicles	On-demand flexible route service
Smart, optimized use of public space	Deployment of smart infrastructure			•	•					•
	Reduced amount of urban space devoted to private vehicles	•	•			•				
	Public lands reclaimed for AV operation, e.g., curb management, narrower lanes		•			•				

With climate, energy, and transportation goals to achieve and a wide array of policies at their disposal, cities should begin planning for the arrival of AVs now. These vehicles will bring enormous opportunities as well as significant challenges for urban transportation systems, making their potential impact on GHG emissions and energy consumption very uncertain. New technologies are already enabling shifts in the way people move around urban areas. Ride-hailing helps solve many mobility problems even as it threatens existing low-emissions modes of transportation. The arrival of fully autonomous vehicles will only expand these possibilities and problems, and cities should take steps today to ensure that the results are consistent with their vision for a sustainable transportation system.

AVs will need to have both high fuel efficiency and high occupancy. They will need to contribute to—rather than detract from—an environment where public transit, walking, and biking thrive, connect seamlessly, and provide convenient and affordable mobility to all of a city's residents. And AVs will need to facilitate a reduction in the number of urban vehicles by promoting a shift from individual to fleet ownership, allowing cities to reclaim space currently dominated by the automobile for more productive uses. Cities in the vanguard are already developing the modal interconnections, pricing regimes, and data systems to usher in these fundamental changes in urban mobility, which will help them reorient their transportation systems away from the personal automobile and toward more efficient modes for their residents and visitors.

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