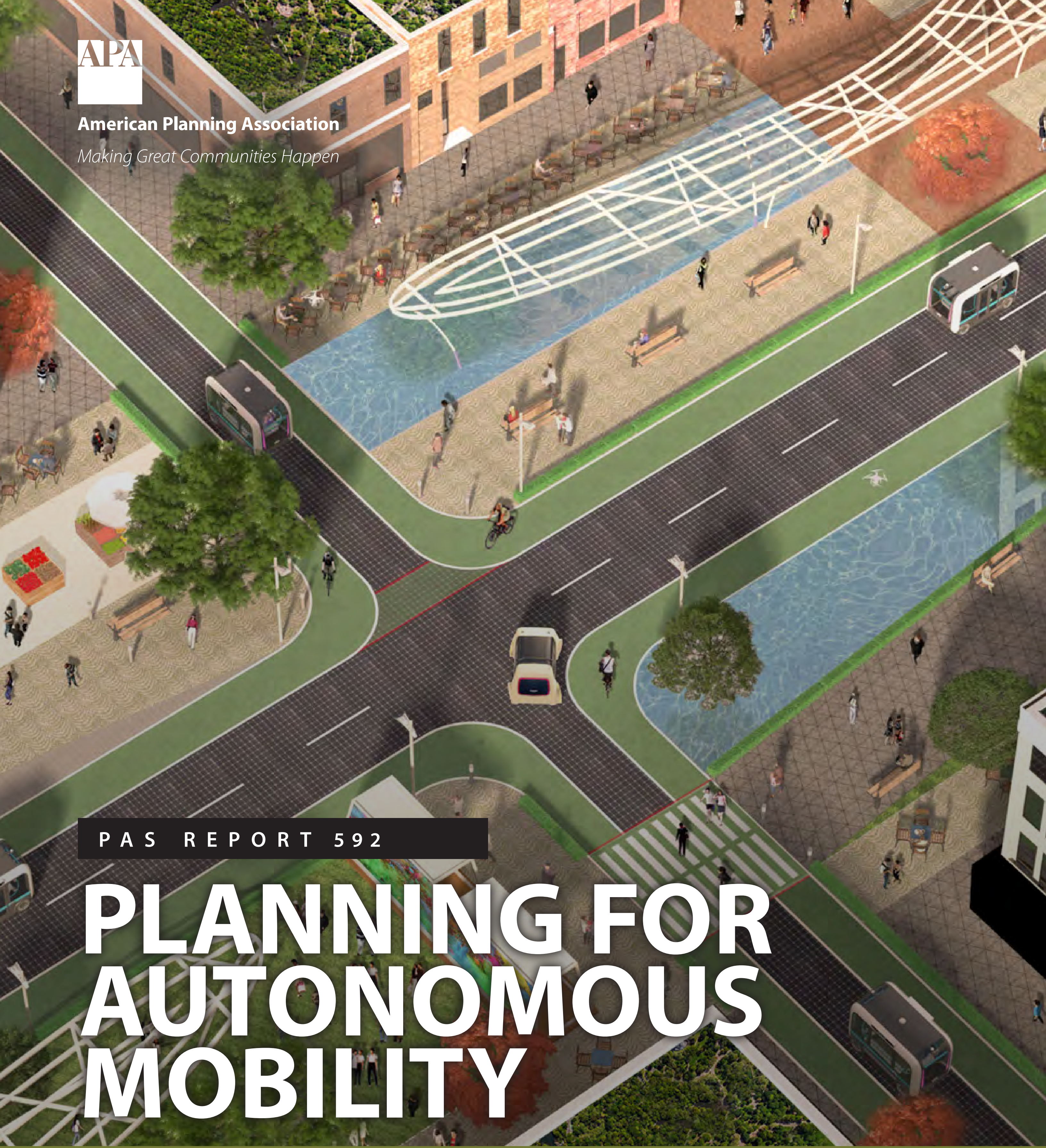

American Planning Association
Making Great Communities Happen

PAS REPORT 592

PLANNING FOR AUTONOMOUS MOBILITY

Jeremy Crute, William Riggs, AICP, Timothy S. Chapin, and Lindsay Stevens, AICP

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ON THE COVER

Preparing cities for autonomous (self-driving) transportation research project, Chicago's West Loop (Stantec's Urban Places)

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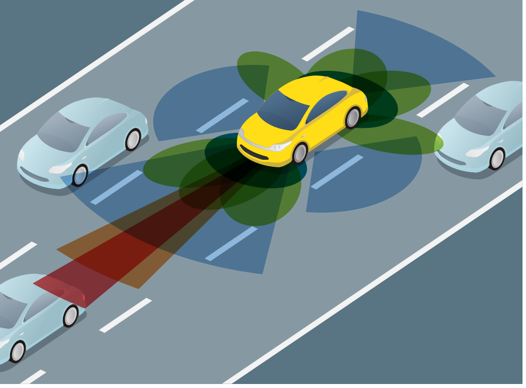
AVs:

Coming to a community near you

A future with autonomous vehicles (AVs) is closer than you may think. PAS Report 592, Planning for Autonomous Mobility, will help you prepare for the implications and changes.



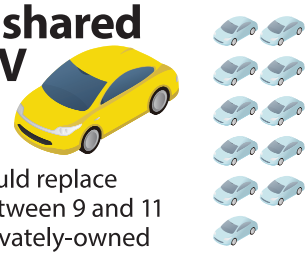
THE FUTURE IS HERE

2020 The earliest year an automaker projects they will have a fully autonomous car available for the public

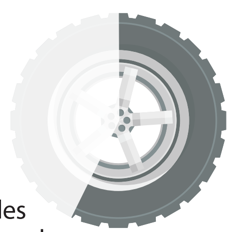
2040 Estimated year when **50%** of cars will be AVs

BIG CHANGES

1 shared AV could replace between 9 and 11 privately-owned vehicles.



43% or more: expected reduction rate in vehicles privately owned

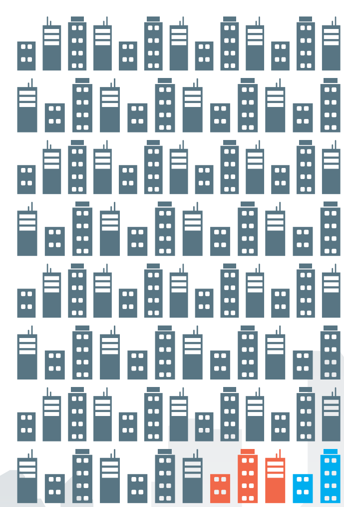


Parking, automotive uses, transit, biking, and walking will all be affected by this shift on our roads.

MORE PLANNING IS NEEDED

AV policies in action

Of the 500 largest US cities, how many of them have AV policies?



- No AV policy: 95%
- AV in the comprehensive plan: 3%
- AV ordinance: 2%

Source: Riggs, Steins, and Chavan 2018

EXECUTIVE SUMMARY

PAS Report 592, *Planning for Autonomous Mobility,* serves as a call to action for professional planners, especially those working in the public sector in the transportation and land-use arenas. Autonomous vehicles (AVs) will transform the built environment in the coming decades, and communities must begin planning for AVs now to ensure that this new technology is harnessed in beneficial ways. The primary goals of this PAS Report are to (1) provide planners and policy makers with the foundational knowledge necessary to anticipate potential impacts of AVs on communities, and (2) support and spur development of policy solutions and infrastructure investments that ensure attractive, people-friendly, equitable, and safe urban environments.

This PAS Report explores the many benefits that AVs may provide, but also looks at the challenges that AVs will bring to communities. The many potential impacts of AVs include the following:

- altering the design of rights-of-way
- changing access management practices
- influencing the form and function of traffic signage and signalization
- bringing massive changes to pedestrian and bicycle networks
- reducing the demand and altering the design and location of parking
- creating redevelopment opportunities in urban and suburban locales

It is imperative for planners to begin considering how AVs will affect our built environment and how this technology can contribute to community livability, efficient transportation systems, and vibrant public spaces.

WHAT ARE AVS AND WHEN WILL THEY GET HERE?

Autonomous vehicles encompass a wide range of emerging technologies that had previously been the stuff of science fiction. Already, advanced driver assistance systems are improving safety by controlling specific driving functions; fully autonomous vehicles will be capable of driving without human operation. Connected vehicle technologies will enable these vehicles to communicate and coordinate amongst themselves and the surrounding infrastructure, further improving travel safety and efficiency. Advancements in electric vehicle and traffic management systems will complement the emergence of AVs and magnify the benefits they promise to provide.

However, this transformative potential does not come solely from AV technology. The convergence of technological advances with the rise of the shared economy and ride-sharing services like Lyft and Uber could transform the predominant mobility paradigm from privately owned to shared vehicles. A transition to shared mobility would have significant implications for the size of the vehicle fleet, traffic congestion, parking, and urban design. Ultimately, shared AVs could lead to a much smaller vehicle fleet as each vehicle completes more trips.

The timeline for AVs' arrival will help determine how planners need to respond, but predicting AV adoption rates is a difficult task. The technology is advancing rapidly and several companies anticipate having AVs available for sale in the early 2020s. The novelty and convenience of autonomous driving could speed adoption, and highly, if not fully, autonomous vehicles could easily represent at least a quarter of the vehicles on the road in less than 15 years. However, vehicle prices, regulatory delays, and uncertainties surrounding insurance, legal liability, testing and validation procedures, and cybersecurity could delay AVs' market availability.

As AVs take on a greater share of the vehicle fleet over time, there will be a complex and messy transition period where autonomous and human-driven vehicles share the road. Regardless of the exact timeline, AVs are coming, and they will irrevocably change transportation systems, the built environment, and our communities.

HOW WILL AVS CHANGE TRANSPORTATION AND THE BUILT ENVIRONMENT?

Like the changes to society already brought by shared mobility and digital ride-hailing services, AVs will disrupt the way that citizens travel and businesses operate. The technology brings both promise and peril.

This PAS Report explains how AVs have the potential to improve the safety and efficiency of transportation systems, reduce vehicle emissions, and improve the mobility of transportation-disadvantaged populations. However, AVs will not solve all planning problems and will create new ones, such as the need for drop-off zones, vehicle storage or circulators for vehicles as they await users, and expensive new transportation infrastructure to maximize the benefits of the technology. AVs may also reinforce urban sprawl by reducing the monetary and perceived costs of travel, further decreasing the friction of distance for households and businesses. In addition, AVs will have important ramifications on several other key planning areas, including transit, public health, and social equity. In each of these areas, proactive steps will be required for planners and policy makers to capitalize on the opportunities while mitigating the challenges.

Two of the most significant areas this report identifies in the planning realm are (1) parking and (2) the curb. Planners and policy makers have seen significant changes in recent years in parking inventory and curbside management. These shifts to reduced parking demands and ride sharing with curbside pick-up and drop-off will only become more pronounced with the rise of AVs.

AVs will also affect the built environment in a myriad of ways, including new right-of-way designs, changes to access management practices, reconsideration of signage and signalization, new models for pedestrian and bicycle networks, and reductions in demand and changes to the location of parking. The report also forecasts redevelopment opportunities in urban and suburban locales from former auto-serving uses, while narrower rights-of-way, enhanced bicycle and pedestrian facilities, and redevelopment may create excellent opportunities to revitalize urban centers.

However, by making travel easier and more convenient, AVs could undermine these opportunities by encouraging sprawl, expanding the already voracious metropolitan development that exists in the United States. Careful planning and policy will be required to shape these built environment impacts to ensure the creation of vibrant, sustainable, and resilient communities.

WHAT CAN PLANNERS DO NOW?

The key takeaway from this PAS Report is this: There is no substitute for quality, comprehensive, long-term oriented planning. It is imperative that the profession remain committed to its foundational principles of protecting sensitive land and productive landscapes, encouraging a diversity of housing types and densities, promoting a range of travel modes, and serving the built environment with quality infrastructure in core urban and suburban areas. Planners must prepare their communities for the wide range of possible impacts that AV technology may have on transportation and the built environment, integrating AV considerations into community planning practices through techniques such as visioning and scenario planning.

This report offers important recommendations for action. First, parking standards and requirements require immediate attention, as parking demand and need is changing with each passing day. While this has been the case for a long while, it is of heightened importance in an autonomous future. Second, cities must bolster transportation demand management efforts and link those more overtly to a shared and autonomous mobility future. These efforts can be enhanced by curbside pick-up and drop-off policies, with this report illustrating some visions for how that can occur.

Third, planners must rethink the right-of-way for alternative modes, recognizing that AVs offer an opportunity to "right-size" roads at the human scale. Building upon the complete streets movement, in the longer run AVs offer the potential for aggressive road diets that reallocate space previously used for automobiles back to human-powered and active travel modes. Communities should prioritize these modes in their comprehensive and general plans and begin to experiment with new roadway typologies that provide accommodation to these modes. Right-of-way reallocation also holds the potential to provide new space for green infrastructure, public gathering places, and other features that can help achieve various community goals.

Finally, communities should pursue the opportunities that AVs bring to improving transit service. Transit planners must welcome this change and seek opportunities to pilot transit-specific applications of AV technology. Numerous jurisdictions are piloting or implementing fully autonomous transit routes on public roads across the country. These efforts showcase the power of AV technology to provide transit services that provide accessibility to underserved portions of communities.

CONCLUSION

The private automobile has played a major role in shaping the built form of cities and suburbs. In almost all communities, development and land-use patterns during the 20th century reflect policies and planning that prioritized it over alternative means of transportation. Although the automobile was originally seen as a technological advance that would improve society as a whole, market conditions and policies yielded a sprawling development pattern with negative environmental, social, and economic impacts—issues that planners still wrestle with every day.

Today, AVs are poised to disrupt the built environment and planning practices in ways that may be hard to imagine and will be difficult to immediately determine. While the private automobile yielded a 20th century dominated by suburban expansion, this report makes the case that AV technology has the potential to support and promote urban (re)development for the next century. With planners leading the way, a sustainable AV future can be made possible through thoughtful visioning, quality planning, and smart investment. Now is the time to begin embracing the transformative power of autonomous vehicle technology to change our communities for the better.

CHAPTER 1

INTRODUCTION

Just over a century ago, the mass production and rising affordability of the private automobile contributed to massive changes in transportation networks, individual travel behaviors, and the built environment (Chapin, Stevens, and Crute 2017). The private automobile provided greater mobility, allowing drivers and their passengers to escape dense, complicated, and polluted urban centers. In the following decades, federal, state, and local governments supported this increased mobility through massive investments in road networks, state highways, and ultimately a massive interstate system that allows for high-speed travel over long distances.

This increased mobility brought about long-term changes in the built environment as well. At the metropolitan level, reduced travel times and costs contributed to the suburbanization of upper-class households in the 1920s, and then middle-class households starting in the 1940s. These moves took shape for a number of reasons, from middle-class families of returning GIs looking for larger homes to historic racial tension resulting in concentrations of minorities in and affluent suburban flight from many large cities. In any case, these new suburbanites consumed far-flung single-family housing at extremely affordable rates, contributing to America's sustained economic boom in the post-World War I and post-World War II eras.

As these wealthier households left the city, retail centers followed. Whereas the early 1900s saw most retail outlets located in downtowns and urban neighborhoods, by the 1960s the suburban shopping mall and strip mall had come to dominate the retail market. The rise of the automobile brought about changes at the corridor and site levels as well. Urban and suburban arterials were designed to promote speed and safety for automobiles, and mobility concerns came to dominate roadway design. At the site level, buildings were pushed back to make room for automobile parking, and parking standards for the busiest parking day of the season came to dominate local codes. In a few decades, the American landscape was largely redesigned to ensure that the private automobile could travel at speed, over long distances, and with easy ingress and egress to the vast majority of land uses in the city.

The central contention of this report is that autonomous vehicles (AVs) will cause the next great transformation in our transportation systems and the built environment (Chapin, Stevens, and Crute 2016; Riggs forthcoming). This rapidly advancing technology offers the promise of increased safety for users and greater efficiency in systems operation. AVs also allow riders to be productive and entertained during their travel times, provide mobility to populations that are unable to drive (children and the elderly), and will almost certainly contribute to changes in vehicle ownership patterns. They offer the potential to launch a wide range of new mobility options that serve targeted populations ranging from urban communities to isolated lower-income populations.

Alongside this potential, AVs (and artificial intelligence in general) offer possible challenges. They could lead to changes in historical housing settlement patterns, causing sprawl to spread farther into exurban areas. In a rapidly aging society with growing social and economic disparities, they may exacerbate spatial and cultural separation. As e-commerce and workplace automation continue, they could reshape how, where, and when community members live, work, play, and shop.

Beyond these very important improvements in safety and mobility, not to mention the possible quality-of-life benefits for a variety of users, AVs have great potential to impact and alter the built environment in the coming decades. While these impacts—positive or negative—are not fully predictable, all indications are that the impact of AVs on roadway design, urban form, and site design may be of a magnitude similar to those that occurred during the rise of the private automobile in the early 20th century. As detailed in the report, there is strong evidence that AVs could enable narrower rights-of-way and travel lanes; influence the location, form, and amount of parking; impact the mobility of bicyclists and pedestrians; declutter urban environments through reduced signalization and signage; and provide opportunities for redevelopment on excess parking lots and rights-of-way.

Nonetheless, it is important to recognize that AVs will not solve all community problems. If increases in driving continue and household car ownership remains as it is, more cars driving more miles each year will only worsen congestion issues. AVs bring the possibility of making biking and walking more difficult, because AVs require more frequent stops and free-flow intersections may become ubiquitous. Lastly, AVs may spell real problems for already challenged mass transit systems, and bus drivers, taxi drivers, and truckers may see their work opportunities disappear. Planners will need to anticipate and mitigate these new challenges to continue building better communities. Consequently, planners need to harness the opportunities AV technology provides, mitigate potential concerns, and ensure sustainable and people-oriented communities. Autonomous vehicles will cause the next great transformation, impacting not only transportation systems, but the built environment of our cities. How we respond will shape this impact.

PLANNING, UNCERTAINTY, AND THE REVOLUTION

The adoption of and planning for AVs is surrounded by a large degree of uncertainty. All of the major car manufacturers are actively working on AV technology and several have already tested vehicles on the roads. Technology companies such as Google and Apple also have vehicles, with others such

TABLE 1.1. POTENTIAL MANUFACTURERS, FUNDING, AND PLATFORM NOTES

Company	Approximate Funding	Level 3 Availability	Level 4/5 Availability	Shared / Fleet	Notes
BMW		2021	2025	Y	Shared at first; partnership with Intel and Mobileye
Daimler / Mercedes		TBD	TBD	Y	Partnership with Uber; freight introduced first
Ford	$1–2B	2021	TBD	Y	Potential partnership with Waymo or Lyft
Fiat-Chrysler		2021	TBD		Potential partnership with Waymo or Lyft
GM	$581M	2018	TBD		Partnership with Lyft
Honda		2020	TBD		Potential partnership with Waymo or Lyft
Hyundai	$1.7B	2020	TBD		Level 3 (highway capable) by 2020
Renault-Nissan		2020	TBD		Partnership with Nissan
Tesla		2017	2020	N	Claims Level 3 capability with autopilot and that Level 4 can be achieved without Lidar
Toyota	$1B	2020	TBD	TBD	Being led by Toyota Research Institute
Waymo		2020	TBD		May develop vehicles independently
Volvo	$300M	2021	TBD		Partnership with Uber; will self-insure for liability

Sources: Venture Beat.com, IDC, BMW

as Tesla claiming that their vehicles could be autonomous (Crothers 2016; Harris 2015).

There are still questions about when vehicles will be deployed and ready for purchase. While much of these are speculation, as shown in Table 1.1 (p. 8), synthesized data from numerous sources suggest the most basic form of AVs will be widely available in three to five years. This basic level of autonomous driving is called Level 3 technology, which is the equivalent of "lane assist" or systems that correct a vehicle's course when it drifts out of its lane. (More detail about the different "levels of autonomy" is provided in Chapter 2.)

While this report provides more information about these levels of autonomy, ultimately, the availability of AVs and when they will become fully autonomous is subordinate to how they will be owned and used in the future. This relates to three concepts that will be discussed as a part of this report—what researchers have referred to as the "three revolutions in urban transportation" (3Rs) (Fulton, Mason, and Meroux 2017). Planners have speculated that three key revolutionary aspects of AVs (that they will be autonomous, electric, and shared) will impact cities. Yet, the future is uncertain and a 3R scenario is highly dependent on the decisions automakers (sometimes called original equipment manufacturers, or OEMs) and land-use planners make now.

In light of this, this report argues that the current uncertainty is not an excuse for inaction. There has been very little policy development addressing the potential benefits or limitations of the AVs of the future. Moreover, the policy that has been developed is highly speculative.

The planning and infrastructure projects that planners provide guidance on shape the form of cities every day, and these recommendations and insights have long-term implications. Agencies like the World Economic Forum already speculate that the technology is developing faster than expected and that cities will likely not be prepared for self-driving vehicles (Abrams 2016). Work by Guerra (2015a, 2015b) found that in 2015, only two of the 25 largest metropolitan areas mentioned autonomous or connected vehicles in their planning documents. This work cites (1) the uncertainty of the impact of AVs and (2) the disconnect between present investments and future technology as two of the primary reasons why governments are not planning for the AV systems of the future. See the sidebar on pp. 10–11 for examples of planning policy language addressing AVs that does exist.

Planners and policy makers should be anticipating a changing and uncertain future by practicing scenario planning and providing incremental guidance. For example, many communities are making significant investments in expanded roadways and parking garages, but AVs may change the demand for parking and spatial siting variables. City planners and leaders should begin asking questions and preparing for this potential future. By looking at different AV-future scenarios, planners can develop plans that are flexible and adaptable.

ABOUT THIS REPORT

The primary goals of this PAS Report are to (1) provide planners and policy makers with the foundational knowledge necessary to anticipate potential impacts of AVs on communities and (2) support and spur development of policy solutions and infrastructure investments that ensure attractive, people-friendly, equitable, and safe urban environments.

In this report we attempt to envision the impact of AVs on communities as a starting point for planning agencies to begin preparing and planning for the emergence of AV technology. This report focuses on issues and policy interventions for planners to consider so that they can develop more thoughtful, robust, and adaptable plans to prepare for the adoption of AVs. Planners can begin rethinking things such as parking, street design and engineering, streetscape and urban design, asset investment, municipal finance, transit and bikes, and land use, among others.

The emergence of AVs is almost upon us, and how the AV revolution takes hold largely depends on the actions planners and policy makers take now. Consequently, planners have an important opportunity to shape sustainable, resilient urban forms where AVs contribute to a successful multimodal system. The structure and content of the report is outlined below.

Chapter 2 provides a primer of baseline information on the state of AV technology today. For planners to make informed policy decisions, they need to understand the capabilities and limitations of the technology. To this end, this chapter describes what AV technology is and is not capable of. It then outlines the implications of several other advancements in transportation technology, such as connected vehicles and advanced traffic management systems that could complement AVs and amplify their benefits. The convergence of autonomous technology with car- and ride-sharing trends could shift the predominant model of automobile use from private ownership to shared mobility, particularly in urban areas. This chapter highlights how the use of shared AVs could further their impacts on travel behavior and the built environment. Finally, Chapter 2 draws from professional and academic projections to provide an expected timeline for AV adoption.

AV POLICY LANGUAGE FROM EXISTING PLANNING DOCUMENTS

Austin, TX, Smart Mobility Roadmap: Austin's Approach to Shared, Electric, and Autonomous Vehicle Technologies (2017)
www.austintexas.gov/smartmobility roadmap

Autonomous Vehicles Recommended Actions:

1. Engage citizens, businesses and visitors on how this technology can meet their needs and address community issues
2. Hire an Executive Level Officer of EV/AV Transportation
3. Develop a Master Plan roadmap for emerging electric–connected and autonomous vehicle (E-CAV) technologies
4. Create an interdisciplinary AV Work Group
5. Create an infrastructure task force to examine electric, technology and land use infrastructure requirements
6. Test Dedicated Short Range Communication (DSRC) technology for vehicle to infrastructure (V2I) reciprocal safety messages
7. Test 5G technology for vehicle to infrastructure (V2I) reciprocal safety messages; compare to DSRC
8. Increase public awareness of electric autonomous (E-AV) shuttles in various Austin locations through EV/AV pilots
9. Increase public awareness of last mile E-AV delivery robots
10. Establish an EV/AV Commercialization Opportunities/ Economic Development Work Group
11. Create Shared/EV/AV focused team
12. Increase public awareness of electric and autonomous vehicle benefits
13. Create a regional New Mobility Workforce Training task force for new job training and educational opportunities for those with legacy occupations

Boston Transportation Department, Go Boston 2030 Vision and Action Plan (2017)
www.boston.gov/departments/transportation/go-boston-2030

Goal: Flexibility to accommodate disruptive mobility technologies

The arrival and adoption of new technology—such as autonomous cars, electric tricycles, and self-driving buses—is imminent. Boston will accommodate these and other emerging vehicle types by creating infrastructure networks that can be easily repurposed. Car and curbside lanes on major corridors like Columbia Road or in dense areas such as the Theater District will offer parking at some times and bus or bike lanes at others and serve as designated pick-up and drop-off locations for passengers and parcels. Traffic signals will adapt automatically, relying on sensors and algorithms to optimize the movement of people. New buses will be compatible with older fleet vehicles while leveraging emerging technology.

Los Angeles Department of Transportation, Urban Mobility in a Digital Age (2016)
www.urbanmobilityla.com/download

Transportation Technology Strategy 5: Prepare for an automated future

Policy Recommendations

1. Call for mobility innovation in California.
2. Collaborate regionally to promote interoperability.
3. Launch a taskforce on data monetization strategies.
4. Advocate for new approaches to financing infrastructure projects.

TODAY (0–2 years)

1. Develop a business plan for a city AV fleet.*
2. Create a dedicated staff position focused on connected and automated vehicle tech.
3. Implement blind spot detection systems for public transit vehicles.*
4. Expand LADOT connected bus technologies fleet-wide.
5. Invest in lane markings that enhance effectiveness of lane departure warning and prevention systems.

TOMORROW (3–5 years)

1. Create better access to ATSAC data and enhance transparency of network prioritization for planning.
2. Develop an AV road network along transit and enhanced vehicle networks.
3. Launch a Data as a Service program to provide real-time infrastructure data to connected vehicles.

FUTURE (6+ years)

- Convert the public transit vehicle fleet to fully automated.

* Action already planned or underway.

Portland, OR, Draft Connected and Autonomous Vehicles Policy (2017)
www.portlandoregon.gov/transportation/article/643814

Policy 9.xx Connected and Autonomous Vehicles. Ensure that connected and autonomous vehicles advance

Portland's Comprehensive Plan multiple transportation goals and policies, including vision zero, climate pollution reduction and cleaner air, equity, physical activity, economic opportunity, great places, cost effectiveness, mode share, and reducing vehicle mile traveled.

Seattle Department of Transportation, New Mobility Playbook, Appendix C: Preliminary Automated Mobility Policy Framework (2017)
https://newmobilityseattle.info

EQUITY AND ACCESSIBILITY
The following policies ensure that automated mobility and other future transportation innovations are designed with a racial and social justice lens, accommodating the wide cross section of Seattleite's abilities and backgrounds.

Policy EA1: Ensure the benefits of automated mobility are equitably distributed across all segments of the community and that the negative impacts of automated mobility are not disproportionately borne on traditionally marginalized communities.

Policy EA2: Ensure shared automated vehicle fleets consider the safety needs of vulnerable populations and loading needs of seniors, families with children, and individuals with mobility impairments.

Policy EA3: Establish equitable performance standards and penalty structures for shared automated vehicle fleet wait time and declined rides as a way to eliminate discriminatory practices.

Policy EA4: Require a percentage of shared automated vehicle fleet vehicles to be ADA-compliant to meet the needs of people with disabilities.

Policy EA5: Identify and require shared automated vehicle fleets to serve markets that are underserved by transit and focus on connecting people to high quality transit spines.

Policy EA6: Acknowledge and mitigate the labor implications of automated mobility, particularly in the for-hire, freight, and public transit industries, among others.

Policy EA7: Conduct a publicly-visible community consultation and outreach process to understand concerns, needs, and opportunities related to the impending automated mobility paradigm.

Policy EA8: Establish a City-owned transportation network company digital platform to incubate smaller shared automated vehicle fleet businesses, mitigating the risk of mobility monopolies in Seattle

[Other policies address regulation and parameters, infrastructure and street design, pilots and partnerships, mobility economics, and land use and building design.]

San Antonio, TX, SATomorrow Multimodal Transportation Plan (2016)
www.satransportationplan.com

The City of San Antonio should consider the following planning and policy activities to manage the impact of CV/AV on the city:

» Update the City's travel demand model. The City's travel demand models should ideally reflect updated information regarding who is traveling (e.g., elderly and disabled may travel more due to AVs), where people are living and working, how many trips they are taking, people's value of time while traveling, what level of shared rides are occurring, and the vehicle ownership model. It should also capture any changes associated with freight delivery. This update needs to be on the City's horizon as the industry matures its approach to forecasting this new future.

» Encourage open data sharing. While it is important to preserve people's privacy, open, anonymized data can improve the City's decisionmaking and help to develop more informed policies and plans.

» Introduce polices that can influence how driverless vehicles can affect VMT, urban sprawl, and/or parking requirements. Examples include tolls for single-occupancy vehicles, new HOV/HOT lanes, create and enforce urban growth boundaries, reduce (or even subsidize) costs and parking fees for shared ride services, and explore parking requirements in zoning laws and encourage more pick-up/drop-off locations at developments.

San Jose, CA, Smart City Vision
www.sanjoseca.gov/index.aspx?NID=5289

Demonstration City: Reimagine the City as a laboratory and platform for the most impactful, transformative technologies that will shape how we live and work in the future.

Fully develop the city's transportation innovation zone to test new products and services, such as autonomous vehicles, that will dramatically shape transportation in the future and mitigate traffic congestion.

Build an "Internet of Things" platform employing transit vehicles and infrastructure by using smart sensor technologies to improve safety, mobility, and optimize our transit system.

Create pathways for start-ups and innovators to easily access opportunities to pilot and test new products and services with the City, such as by hosting "demo days" to highlight the most innovative "smart city" companies in Silicon Valley, and sponsoring public competitions to encourage crowdsourcing of innovative solutions to civic challenges.

Chapter 3 outlines the major opportunities and challenges likely to emerge as AV technology becomes ubiquitous in communities around the country. AVs have the potential to improve the safety and efficiency of transportation systems, reduce vehicle emissions, and improve the mobility of transportation-disadvantaged populations. Unfortunately, AVs will also bring challenges that threaten to negate their potential benefits. In particular, AVs may reinforce auto-oriented sprawl, which could increase vehicle miles traveled (VMT) and congestion. Without careful planning, AVs could also compromise bicycle and pedestrian mobility. Further, AVs will have important ramifications for several key urban issues, such as public transit, public health, and social equity. Since private companies are investing so many resources in developing the technology itself, these secondary effects of AVs will be the main concern for planners to ensure the technology does not have adverse ramifications for placemaking or quality of life. This chapter summarizes each of these issues to identify how they will shape AVs' impact on the built environment and appropriate policy responses to capitalize on the important opportunities the technology provides.

Building on the findings of the first three chapters, Chapter 4 makes the case that AV technology will catalyze the next great transformation in the built environment. This section draws heavily upon a Florida Department of Transportation-funded study completed at Florida State University (Chapin, Stevens, and Crute 2016) to identify six major areas where AVs may impact the built environment: (1) new designs of rights-of-way, (2) changes to access management practices, (3) reconsideration of the form and function of signage and signalization, (4) new models for pedestrian and bicycle networks, (5) reductions in demand and changes to the location of parking, and (6) new redevelopment opportunities in urban and suburban locales. Each of these is explored in detail to develop a potential vision of the future in an AV world.

Chapter 5 then provides guidance on how planners should prepare for and respond to these far-reaching changes. This will provide a place for communities to start to address the planning opportunities and challenges identified in Chapter 3 and the ways AVs will shape the built environment described in Chapter 4. Throughout this discussion, the chapter highlights the need for proactive planning efforts to ensure that future development patterns and urban form are shaped by sound planning principles rather than by the technology. In other words, cities should be designed for people and not for technology to be attractive, people-friendly, equitable, and safe urban environments. Given the uncertainty surrounding how and when AVs will be developed and adopted, this chapter also emphasizes the need for nimble planning processes and policies that proactively accommodate the technology's rapidly evolving capabilities. Key considerations to incorporate into infrastructure investments and redevelopment decisions moving forward are also highlighted. Finally, Chapter 6 wraps up the report with a final call to action.

CHAPTER 2

AUTONOMOUS VEHICLES 101

Autonomous vehicle technology is a rapidly developing technology that promises to revolutionize the form and function of our urban spaces. To understand how it will do that, it is important to become familiar with what the technology is and how it works. AV technology is often presented as an easy solution to many of our planning problems. Understanding what the technology is and is not capable of will enable planners to more effectively use it as a tool to improve their communities without expecting it to solve safety and congestion issues or neglecting sound planning practice.

AV technology is advancing so rapidly that it is vital for planners to stay up to date on the latest in technological advancements. This is especially important because, as will be described in more detail later, the exact form and capability of the technology will ultimately be a major determinant of its impact upon the transportation system and the built environment. For example, the size of AVs may determine lane width and other roadway design features. Consequently, this section will provide an overview of the current state of the technology, but given the speed at which the technology is advancing, this may be out of date by the time this report is published. Therefore it is important that this chapter is viewed not as the definitive guide to AVs but as a first step in a continuous learning process.

THE TECHNOLOGY: WHAT IS IT AND HOW DOES IT WORK?

AVs have captured the public's imagination and have been the main focus of the media's discussion of intelligent transportation systems. However, recent advancements in technology

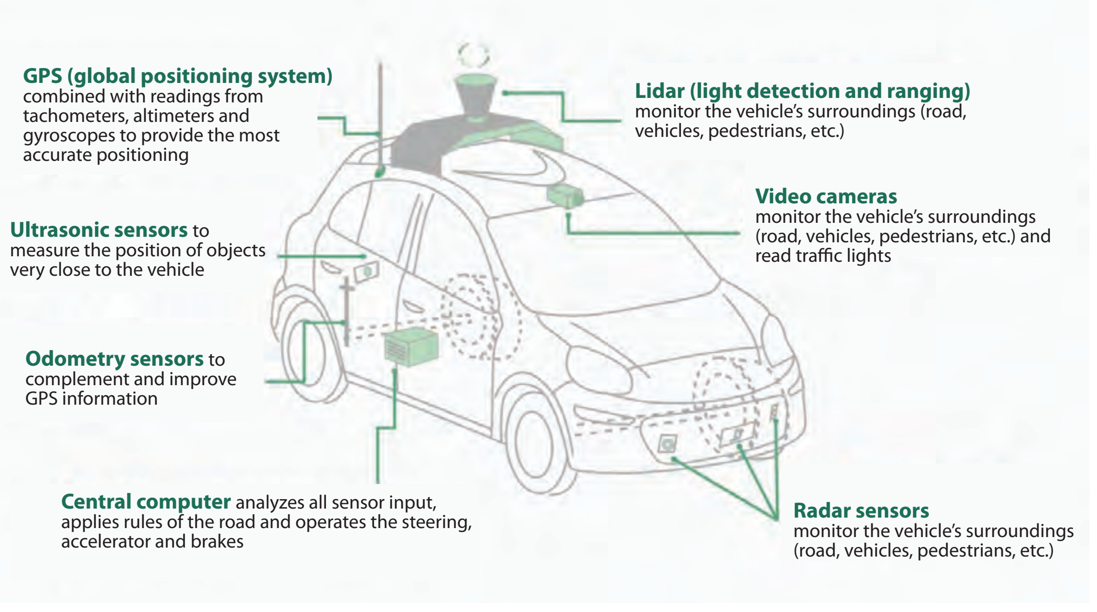


Figure 2.1. Diagram of automated vehicle technologies (adapted from BCG 2015)

DEFINITIONS AND ACRONYMS

Autonomous Vehicle (AV)— A vehicle that is capable of driving itself without human intervention

Advanced Driver Assistance Systems (ADAS)—A range of vehicle technologies that enhance driver safety by taking temporary control of one or more driving functions (speed, lane position, braking, etc.)

Connected Vehicle (CV)—Features that enable vehicles to communicate with other vehicles, the infrastructure, or pedestrians

Vehicle to Vehicle (V2V)—CV technology that enables vehicles to communicate with other vehicles

Vehicle to Infrastructure (V2I)—CV technology that enables vehicles to communicate with the smart infrastructure

Vehicle to Pedestrian (V2P)—CV technology that enables vehicles to communicate with nearby pedestrians

Vehicle to Everything (V2X)—CV technology that enables all vehicles and infrastructure to be interconnected

Intelligent Transportation System (ITS)—Advanced technologies that improve the safety and efficiency of the transportation system by collecting, analyzing, and communicating information in real time

Connected Autonomous Vehicle (CAV)—A vehicle that has both connected and autonomous capabilities

Shared Autonomous Vehicle (SAV)—An autonomous vehicle that is available on a short-term, "as-needed" basis

have included much more than just AVs. The development of advanced driver assistance systems and connected vehicle technology has quietly provided growing opportunities to improve the safety and efficiency of the transportation system. Ultimately, the greatest benefits will come from having all these technologies and systems working together in harmony, but while fully autonomous vehicles are being tested and piloted, these additional technologies may provide exciting opportunities, particularly in the near term. Consequently, it is important for planners to be aware of the full range of available technologies to make informed decisions as to what will provide the most benefit for their communities. The sidebar on this page offers a list of definitions and acronyms as a resource for planners on AV terminology.

Automated Vehicle Technology

Automated vehicle technology is an umbrella term that includes a wide variety of features and technologies that enable vehicles to take control of some or all of the major driving functions normally completed by the driver (Figure 2.1, p. 15). This includes fully autonomous vehicles that no longer require a human driver to operate them, as well as a range of advanced driver assistance systems (ADAS) that enhance driver safety by taking temporary control of one or more driving functions (speed, lane position, braking, etc.).

A fully autonomous vehicle no longer requires a human operator to drive. Instead, the vehicle navigates streets safely and efficiently through a complex mix of software and hardware that combines remote sensing, recognition algorithms, network analysis, and "experience" drawn from millions of hours of driving that is shared across AVs. The vehicle's combination of sensors, cameras, light detection and ranging (Lidar or light radar), high-definition maps, and advanced software create a digital picture of its surroundings and make

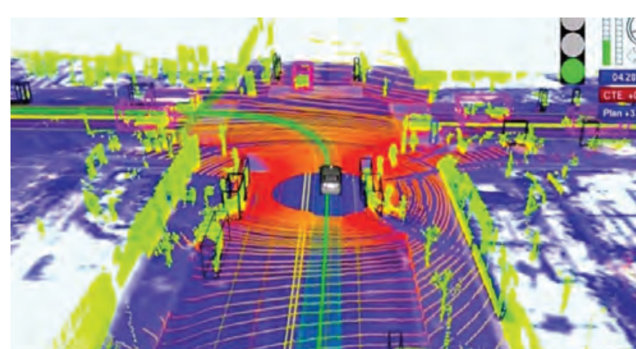


Figure 2.2. Example of a Lidar cloud (source: Waymo)

intelligent driving decisions on routing and maneuvering without any input from an operator or information broadcast by infrastructure or other vehicles.

More specifically, just as radar does with radio waves, Lidar shoots pulses of light and measures how long it takes for the light to return to the sensor to assess how far away an object is. As seen in Figure 2.2 (p. 16), placing an array of rotating lasers on top of an AV provides a continual 360-degree "point cloud" or picture of the vehicle's surroundings. The vehicle's central computer can then be programmed to recognize specific Lidar returns as another car, a pedestrian, or even a stop sign.

Lidar systems are typically supplemented by cameras and other sensors to provide redundant detection systems that will not fail to detect objects that Lidar could miss, particularly in the area immediately surrounding the vehicle. More sophisticated systems add another layer to this by assessing how surrounding vehicles and pedestrians are moving and predicting where they will go next. In the case of a pedestrian crossing the street, the vehicle can predict the pedestrian's movements and begin slowing down before the pedestrian enters the street instead of waiting until the pedestrian is directly in the vehicle's path.

Unfortunately, whether an AV uses Lidar or cameras or both, it is very difficult for these systems to work properly in inclement weather conditions and poor visibility. Rain and snow can refract the laser returns and cameras struggle to identify objects accurately through precipitation, functionally blinding the AV. However, using both technologies in tandem could overcome this problem as the technology continues to advance.

Most of the attention on AVs is centered around fully autonomous vehicles because many of the technology's most significant effects on the transportation system and the built environment will only be viable when fully autonomous vehicles are adopted. However, AV technology includes a range of levels of automation. It is important for planners to be familiar with the full array of AV technology, because many semiautonomous features and applications are already available today and will likely play a major role in the transition to a fully autonomous world.

In addition to fully autonomous vehicles, there is a wide range of automated technologies that can operate as standalone features. These range in sophistication and complexity from cruise control to autopilot. To classify these ever-evolving technologies, the National Highway Traffic Safety Administration (NHTSA) and the Society of Automotive Engineers (SAE) International developed a classification system that divides automated technologies into six levels of vehicle automation (Figure 2.3, p. 18). These range from "0," where the driver is in complete control of all driving tasks at all times, to "5," where the vehicle is designed to perform all driving tasks without an operator (SAE International 2016).

With Level 1 automation, the driver remains in control of the vehicle, but the technology can assist the driver by controlling one of the vehicle's functions, either its speed or lane position. Level 2 takes this a step further by allowing the vehicle to control two driving functions at the same time. A vehicle with Level 3 automation can take full control of the vehicle for certain parts of a trip, but the driver must be ready to take back control of the vehicle when the vehicle prompts her. The vehicle takes full control of all major driving functions in Level 4. Level 4 vehicles can even drive themselves for the entire trip, but they are only able to do so under specific conditions. Finally, Level 5 automation refers to fully autonomous vehicles that can operate without an operator in all conditions and without the capability for a human to retake control.

Automated driving features that aid the driving process but do not fully control the vehicle (Levels 0, 1, and 2) are generally referred to as ADAS. Even though fully autonomous vehicles have received most of the attention and are the focus of this report, ADAS can significantly improve driver safety, thereby improving user mobility. For example, one of the most common crash scenarios among aging drivers is misjudging oncoming traffic while making a left turn. Simulator studies have shown that even a simple Level 0 automation feature that informs drivers when they have enough space to turn left could significantly improve the safety of aging drivers, thereby enabling them to continue driving and maintain their personal mobility later into life (Davidse 2006).

Most of the first applications of AV technology will be increasingly sophisticated ADAS. Even Tesla's Autopilot feature, introduced in 2015, would be classified as Level 2 automation, as it only controls the vehicle's speed and lane position and requires the driver to be "in control of the car" at all times (Tesla 2015). Consequently, it is vital for planners to be aware of the development and use of these features to take advantage of the benefits they can provide and to effectively manage the transition from human-driven vehicles to vehicles equipped with ADAS to fully autonomous vehicles.

Connected Vehicle Technology

Connected vehicle (CV) technology includes the vehicles and infrastructure that enable vehicles to communicate with other vehicles, infrastructure, or pedestrians to make better driving decisions. CV technology relies on information gathered by vehicles and the transportation infrastructure about real-time

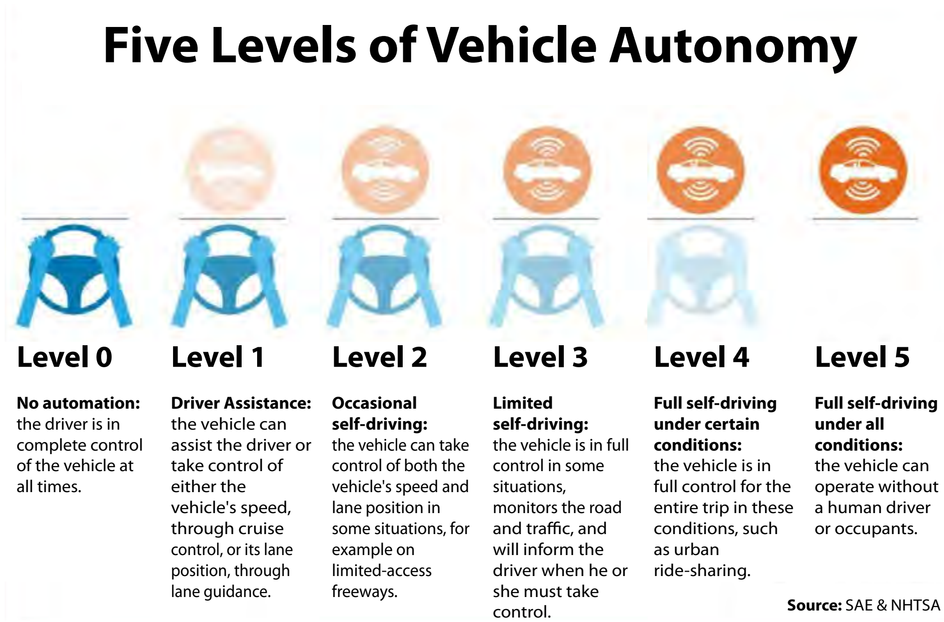


Figure 2.3. The levels of vehicle automation (SAE and NHTSA)

operations of the transportation network. Based on a specific vehicle's location, information is broadcast to the vehicle so the driver is able to make informed decisions regarding routing and maneuvering. Yet, by itself, this technology does not impact safety-critical functions of the vehicle and the driver must remain in full control of the vehicle at all times.

Simple examples of CV technology include transmitting information typically given on street signs to a heads-up display in the vehicle. For instance, a sensor embedded in the roadway could tell the vehicle what the speed limit is at all times or it could provide a warning whenever the vehicle begins traveling the wrong way down the road. More sophisticated examples could include an ambulance warning other vehicles to move out of the way or platooning, in which two or more vehicles "link" and travel together like a train. The driver remains responsible for using this information to operate the vehicle, but the information provided helps the driver to make safer and better-informed driving decisions.

AV and CV technology could each provide positive safety and efficiency benefits to the transportation system on their own, but it is commonly accepted that the most significant benefits will only be achieved by vehicles that are both autonomous and connected. For example, a fully autonomous vehicle can safely navigate a traffic jam, but a connected AV could avoid the traffic jam altogether by finding the fastest alternative route in real time. In addition, CVs could inform other vehicles they intend to brake or change lanes before they begin slowing down or turning. This would enable AVs to travel in even safer harmony.

Like ADAS, applications of CV technology will be implemented well before fully autonomous vehicles are adopted. In 2016, the U.S. Department of Transportation awarded New York City, Tampa, and Wyoming more than $45 million in collective funding to "design, build, and test" operational CV systems through the CV Pilot Development Program (U.S. DOT 2016). As part of this program, Tampa will have 10 buses, 10 streetcars, and 1,600 personal vehicles equipped with CV technology on the road by 2018 (Tampa Hillsborough Expressway Authority 2017). In addition, companies such as Peloton and Daimler are already piloting connected semi-truck applications on highways across the country that promise to significantly improve the fuel efficiency of the trucking industry.

CV technology is generally divided into three major types: Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P) communication. These technologies are not mutually exclusive, meaning that a single vehicle can be equipped with more than one type of CV. Vehicles equipped with all three are considered to have Vehicle-to-Everything (V2X) capabilities, as these vehicles would be able to communicate with anything that may affect their operation in real time. In many cases, several redundant systems will likely need to be in place to ensure uninterrupted communication in the event of a system failure.

Vehicle-to-Vehicle Communication

V2V technology includes systems that allow vehicles to communicate their location, speed, heading, and other information to other vehicles on the road. V2V communication can add an important redundancy to AV sensor data, thereby ensuring the vehicle detects surrounding vehicles even if the Lidar sensors fail to identify this information. More importantly, it can enable AVs to travel in harmony with each other, further improving the efficiency of an automated transportation system. By enabling two or more vehicles to link together in a platoon, CV technology can eliminate the time it takes to detect a change in another vehicle's movement and allow vehicles to safely travel even closer together, further improving fuel efficiency by reducing wind resistance.

Vehicle-to-Infrastructure Communication

V2I communication enables vehicles to exchange information with roadway infrastructure and traffic management systems. The infrastructure can provide vehicles with data and information to make safer and more efficient driving decisions by informing the vehicle of traffic signs and signals, road conditions, traffic incidents, and optimal routes. Similarly, the vehicle can communicate with the infrastructure to facilitate more efficient traffic operations. For instance, vehicles can inform the infrastructure of the location of traffic congestion or hazardous roadway conditions such as icy roads or standing water. A traffic management system could warn other vehicles to avoid these areas or find faster routes.

Vehicle-to-Pedestrian Communication

CVs could also communicate with bicyclists and pedestrians. The majority of V2P systems provide the vehicle operator with visual and audible warnings that a pedestrian may move into the vehicle's path to ensure the driver or the AV detects and reacts to pedestrians. Some of these systems also provide bicyclists and pedestrians with warnings of oncoming traffic via their cell phones. V2P communication could be especially important because detecting bicyclists and pedestrians is one of the most difficult challenges for AV technology (Fairly 2017). Bicyclists and pedestrians are "small, unpredictable, and hard for computers to see" (Sorrel 2017).

While pedestrian detection data for companies like Waymo (formerly Google's self-driving project) remains proprietary, a Deep3DBox three-dimensional object detection algorithm recently developed by researchers from George Mason University, in conjunction with the robotic taxi company Zoox, was only able to successfully identify bicycles 74 percent of the time (Fairly 2017; Mousavian et al. 2017). AV and CV technology is advancing so rapidly that detection accuracy is expected to improve dramatically, but V2P communication that informs the vehicles of a bicyclist's location could add a vital layer of redundancy to a vehicle's detection system that may enable vehicles to safely navigate a dynamic urban environment.

Other Technological Advances That Will Affect AVs

In addition to AV and CV technology, there are several other transportation technology advancements that could complement the emergence of AVs and magnify the benefits AVs promise to provide.

Electric Vehicles

Many proponents of AVs point to automated vehicle technology, electric vehicle (EV) technology, and on-demand ride sharing as three converging trends that promise to undo many of the problems created by our current transportation system. By providing a more efficient transportation system that utilizes cleaner energy sources, on-demand electric AVs could drastically reduce energy emissions. In fact, many of the environmental and efficiency benefits AVs could provide will only be possible if AVs are powered by electricity. Otherwise, the transportation system will remain completely dependent on combustion engines and AVs at best will be a temporary fix for the global carbon emissions crisis and at worst will exacerbate the problem by increasing vehicle miles traveled (VMT).

Many have speculated that because AVs will require a significantly more extensive electrical system to power the sensors and computers necessary to drive autonomously, it will be easier and more efficient to engineer AVs that are electric-powered rather than combustion-powered (Gardner 2016). The fact that many AV prototypes on the road today, including models being used by Waymo, Uber, and Lyft, are hybrid vehicles may provide an early sign of how AV technology may complement the increasing development and use of EVs. Similarly, recent announcements from General Motors, Volvo, and other major auto manufacturers of their intentions to work toward an all-electric future (Davies 2017) may provide a positive indication of the potential for a fully electric and fully autonomous future. Many of these announcements have been driven by the major innovations in battery technology that have significantly improved the cost effectiveness of electric vehicles. The cost of EV battery packs fell by 80 percent between 2010 and 2016 (McKinsey & Company 2017). While the per-mile cost of EVs will need to continue to drop for them to be a viable option for mass adoption, these trends are projected to continue and AV production is expected to largely comprise EVs (Collie et al. 2017).

Advanced Traffic Management Systems

Advanced traffic management systems (ATMS) utilize intelligent infrastructure and real-time traffic data to improve traffic flow and vehicle safety. Different versions of ATMS have been in use for decades; however, AV and CV technology will create opportunities to significantly increase the utility of ATMS. Today, most ATMS use traffic data gathered from sensors and cameras embedded in the roadway infrastructure to make adjustments to speed limits, traffic light timing, and ramp metering to improve vehicle flow and mitigate traffic congestion. CV technology could revolutionize ATMS by enabling them to be informed by data inputs from every vehicle on the road.

Yet even more transformative is the potential for ATMS to communicate with or even control the movements of vehicles across the transportation system. All data and information collected by AVs and CVs theoretically could be fed into a centralized ATMS that could provide each vehicle with optimal routing information based on real-time traffic conditions. The ATMS could safely reroute traffic away from traffic jams and safety hazards and could ensure AVs are aware of road work, detours, and new roadway infrastructure. In this way, the combination of AV, CV, and ATMS technology could maximize the efficiency of a city's roadway infrastructure in real time. While ATMS with this level of complexity have yet to be developed and may raise important privacy issues, it is clear that AV and CV technology will create exciting opportunities for ATMS to improve the safety and efficiency of the transportation system.

AV OWNERSHIP AND THE RISE OF SHARED AVS

As the adoption of AV technology transforms the nature of transportation safety and travel demand, changes to the predominant automobile ownership model are likely to follow. Up until recently, with the exception of taxis, almost everyone owned the car they drove. However, the rise of ride-sharing services like Lyft and Uber have begun to challenge the traditional vehicle ownership model by offering a shared, on-demand mobility system.

The convergence of ride sharing with autonomous driving has the potential to shift the predominant automobile ownership model from private ownership to a shared mobility model. While AVs will be a transformative technology regardless of the ownership model, using AVs in a shared system would amplify their impact on travel behavior and the built environment.

The Rise of the Sharing Economy and On-Demand Mobility

The digital age and the connectivity it provides opened the door for the emergence of the sharing economy. Often defined as the "peer-to-peer based activity of obtaining, giving, or sharing access to good and services" (Hamari, Sjöklint, and Ukkonen 2015), the sharing economy has exploded into a $18.6 billion phenomenon (Juniper Research 2017). One of the major drivers of the sharing economy has been the emergence of the shared mobility industry. While shared mobility services such as ZipCar, Uber, and Lyft make up a small fraction of total VMT today, the convergence of recent demographic trends and the emergence of AV and EV technologies may help shared mobility become an increasingly popular and cost-effective option.

Recent trends of declining car ownership rates among younger generations who prefer a multimodal urban lifestyle have been well documented. However, cost and convenience are the primary drivers of mode choice, and until shared mobility options become cheaper than owning a vehicle, the majority of the population is unlikely to shift to on-demand mobility options for daily travel. According to a study by Morgan Stanley (2016), shared mobility options today cost almost twice as much per mile as vehicle ownership on average. Yet, AV technology may significantly alter the cost structure of vehicular transportation. First, the additional technology may significantly increase the price of purchasing a vehicle, making vehicle ownership less viable for individuals. Until the price of an AV comes down, the high costs of purchasing a vehicle may primarily be feasible for mobility companies like Uber and Lyft, which can utilize and monetize the vehicle 24 hours per day. Secondly, AVs may significantly reduce the cost of on-demand mobility service. By removing the driver, and therefore the labor costs, AVs may significantly reduce shared mobility providers' operational costs. This may decrease the price of on-demand mobility. Consequently, numerous studies have projected that the per-mile cost of shared autonomous mobility will become significantly cheaper than the cost of driving a personal vehicle (Burns, Jordan, and Scarborough 2013; Johnson and Walker 2017; Bosch et al. 2017).

Such a shift in transportation costs could create a dramatic shift in vehicle ownership rates, particularly in urbanized areas where on-demand mobility is more feasible. Consequently, the Brookings Institution has estimated that the sharing economy will grow to become a $335 billion market segment by 2025 and that this growth will be driven in large part by the shared mobility industry (Yaraghi and Ravi 2017).

Companies like Uber and Lyft are racing to capitalize on this massive opportunity by developing their own AV technology. With ongoing autonomous testing in several U.S. cities, these ride-hailing companies are near the forefront of AV development and implementation. Major auto manufacturers have also recognized that their business model may need to shift from private to shared ownership. In the last couple of years, multiple manufacturers including GM, Toyota, and Volkswagen have invested hundreds of millions of dollars into ride-hailing services (General Motors 2016; Bomey and Woodyard 2016). The CEO of Ford Motor Company (2015) even announced a future vision to be "both a product and a mobility company."

The shift toward shared AVs does not mean that private car ownership will completely disappear. There likely will be a mix of shared and privately owned vehicles on the road, and private ownership will likely remain the dominant model in rural areas. Yet shared vehicles are expected to make up a significantly larger percentage of the vehicle fleet than they do today. As such, planners will need to be prepared for a gradual shift toward shared ownership and the effects this may have on congestion, parking, and urban design.

Implications of a Shared AV System

Moving toward a shared mobility model will have a host of ramifications for travel behavior, traffic congestion, and the transportation infrastructure necessary to support a fleet of shared vehicles. Many of the specific implications of a shared vehicle system will be discussed in more detail in the following sections of the report. This section will outline some of the general impacts that will trickle down into the specific aspects of the built environment.

The first impact is that shared mobility could significantly reduce the size of the vehicle fleet. The typical privately owned vehicle in the United States is parked 95 percent of the day. Instead of parking, a shared AV could immediately pick up another passenger, thereby completing significantly more trips than a privately owned vehicle. In fact, studies have found that one shared AV could replace between nine and 11 privately owned vehicles (Fagnant, Kockelman, and Bansal 2015).

Such a drastic reduction in the vehicle fleet could have considerable ramifications for the built environment. Most notably, it would radically decrease the demand for parking. Even if private vehicle ownership remains the norm, researchers from the University of Michigan found that privately owned AVs could reduce vehicle ownership by 43 percent (from 2.1 to 1.2 vehicles per household) (Schoettle and Sivak 2015). Thus, regardless of whether AVs facilitate the rise of a shared ownership system, AVs are expected to reduce the size of the vehicle fleet. Yet the impact to the vehicle fleet would be significantly greater if they operated within a shared system.

However, reducing the size of the vehicle fleet does not necessarily mean that shared AVs would lead to a reduction in VMT or traffic congestion; each vehicle would simply travel significantly more miles per year. In fact, the introduction of "empty vehicle miles" while the vehicle is traveling from one passenger to another will likely increase VMT. It is difficult to predict exactly how much empty vehicle miles would contribute to VMT because it will depend on the efficiency of the shared system as a whole. Total VMT could even decrease if enough passengers were willing to share rides in addition to sharing the vehicle. Ride sharing is generally considered to be less popular than car sharing, but the relative success of UberPool may indicate that ride sharing may become more popular when it is cheaper than car sharing, as UberPool made up 20 percent of Uber rides in 2016 (Lunden 2016).

TIMELINE FOR AV ADOPTION

It is vital for planners to understand when fully autonomous vehicles will become available to the public and how long it will take AVs to replace human-driven vehicles. The adoption timeline will be a major determinant of how planners will need to respond to the emergence of AVs. Unfortunately, as with any forecasting effort, predicting AV adoption rates is a difficult task due to the host of factors that could speed or hinder adoption. AV adoption is particularly difficult to predict because of the rapid pace at which AV technology and the associated regulatory framework are changing.

The speed of technological change has increased over time, as evidenced by how quickly the smartphone was adopted and how quickly startups like Uber and Lyft made on-demand mobility a major part of the transportation system. While it is difficult to predict whether the same will be true of AVs, the novelty, convenience, and mobility provided by AVs may speed public acceptance and adoption. In fact, surveys evaluating the public perception of AVs have shown a steady increase in the level of trust of AVs (AAA 2018). In addition, industries such as freight and public transit may lead the way

FEDERAL POLICY ON AVS

The policy guidance outlined in this PAS Report focuses primarily on the response of local planning agencies to the adoption of AVs. However, federal and state policy will affect when and how AVs are deployed and will shape local planning efforts to address AVs.

In the report *Automated Driving Systems: A Vision for Safety 2.0* (NHTSA 2017b), the U.S. Department of Transportation (DOT) provides broad policy guidance on AVs. The report is divided into two sections. The first section, "Voluntary Guidance for Automated Driving Systems," provides 12 safety elements to support the safe testing and implementation of highly automated (Levels 3–5) technology. It is designed to help AV manufacturers "identify and resolve safety considerations prior to deployment" (NHTSA 2017b). For each element, the report provides safety goals and best practices for attaining those goals.

The second section, "Technical Assistance to States," starts by outlining the federal and state roles in regulating AVs: "NHTSA is responsible for regulating motor vehicles and motor vehicle equipment, and States are responsible for regulating the human driver and most other aspects of motor vehicle operation." From that foundation, it then provides state legislators and highway safety officials with a framework of best practices for developing their own laws and regulations. The goal of this guidance is to develop a "consistent, unified national framework" of laws and policies that promotes the development and implementation of AVs (NHTSA 2017b).

U.S. DOT plans to release another update to its guidance for AVs in 2018 and is currently in the process of receiving public comment to inform that document (U.S. DOT 2018).

because they have a greater financial incentive to transition to autonomous technology. Seeing the successful implementation of AVs in these industries may pave the way for general market acceptance by calming the public's fears over entrusting their safety to robots.

However, a major factor that could slow the public's willingness to purchase AVs is the high cost of the technology. Cost premiums for autonomous capabilities are expected to be high when AVs first become available (Mosquet et al. 2015). While consumer surveys have shown that many are already willing to pay substantial premiums for fully autonomous capabilities (Daziano et al. 2017), others may be unwilling or unable to pay the extra cost, especially since the average American already spends about 15 percent of his or her income on transportation costs. Consequently, how quickly the cost of AVs goes down may be a primary determinant of when privately owned AVs are adopted. However, by taking the driver out of the equation, shared AVs could significantly decrease the cost of ride sharing. ReThinkX has projected that the per-mile transportation cost of shared AVs will quickly drop lower than privately owned vehicles (Airbib and Seba 2017). This could lead to faster adoption of shared AVs.

Another factor that could impede the adoption of AVs is how the federal and state governments regulate the use of AVs. Continued support from the federal government in the form of enabling regulation, mandates, or infrastructure could help the process. (See the sidebar on this page for an overview of federal policy guidance on AVs.) However, regulatory delays in a number of different arenas, including insurance, legal liability, testing and validation procedures, and cybersecurity, could delay AVs' market availability.

The timeline for when AV technology will be adopted will vary significantly based on the level of automation. Level 1 features such as cruise control have been widely used for some time, and many Level 2 features are already available in luxury cars and are likely to become widely accepted in the next several years. However, while lower levels of automation promise notable safety benefits, they are not expected to have significant impacts on the form or function of the transportation system. Consequently, the remainder of this section will focus on the adoption of fully autonomous vehicles unless otherwise specified.

The first determinant of AVs' adoption timeline is when fully autonomous vehicles will become available for sale to consumers. Designing an autonomous vehicle that can make proper driving decisions in every situation, context, and condition is a monumental task. OEMs are making rapid progress, but the challenges of designing vehicles that can consistently detect bicyclists and pedestrians, function in inclement weather, and have enough operational redundancy to correct mistakes remain.

Despite these challenges, many major auto manufacturers have aggressive timelines for when they anticipate offering highly automated vehicles. Several companies, including Waymo, GM, Ford, and Volvo, have stated that they anticipate having AVs available for sale in 2020 or 2021. However, in many cases, these aggressive timelines are regarding Level 4 automation at best. Consequently, some researchers have predicted that fully autonomous (Level 5) vehicles will not become available for sale until around 2025 (Mosquet et al. 2015; Underwood 2015). Yet considerable uncertainty remains as more conservative scenarios that anticipate technical and regulatory delays predict that Level 5 automation may not become available until after 2030 (McKinsey & Company 2016). While these conservative predictions are the minority, they do underscore how difficult it is to predict an autonomous future and they highlight some of the factors that could slow the development and adoption process.

Regardless of when AVs become available for sale, it is generally accepted that there will be a long transition period between when the technology is introduced and when AVs reach full adoption. With approximately 260 million vehicles in the United States and only about 17.5 million vehicles sold every year, if every vehicle sold was fully autonomous it still would take close to 15 years to replace the existing vehicle fleet (Kuhr et al. 2017). However, due to the expected cost premiums and consumer hesitance to trust AV technology (Schoettle and Sivak 2014), AVs could make up a very low percentage of vehicles sold in the early years of availability. Litman (2018) predicts that AVs will only make up two to five percent of vehicle sales in the 2020s and that they will not make up 100 percent of vehicle sales until the 2050s. Consequently, most researchers agree that autonomous and human-driven vehicles will share the road for decades before 100 percent of the vehicle fleet becomes autonomous.

Due to the uncertainties surrounding when AVs will become available for consumers, when they will be affordable, and how quickly the public will adopt the technology, timelines of AV adoption vary widely. This is especially true the further into the future the projection looks. One study found that fully autonomous vehicles could make up anywhere between 10 and 90 percent of the vehicles sold in 2040 (McKinsey & Company 2016).

However, shorter-term projections, such as those estimating adoption over the next 15 years, have produced fairly similar results and provide useful insights into how and when AVs will be adopted. Several projections for AV adoption have agreed that by 2030 AVs will constitute around 15 to 20 percent of vehicle sales (Mosquet et al. 2015; McKinsey & Company 2016; Walker Consultants 2017). Similarly, three studies have projected that AVs would make up about 25 percent of the vehicle fleet in 2035 (Mosquet et al. 2015; Bierstedt et al. 2014; Kuhr et al. 2017), while another study proposed a slightly more conservative estimate of about 20 percent by 2040 (Litman 2018). These findings strongly suggest that in just over 15 years, AVs could represent a quarter of the vehicles on the road. This may not sound like much, but these estimates provide important indications that it is not a question of if but when AVs will become available. In addition, if many of the AVs on the road are shared, then AVs could account for significantly more than 25 percent of vehicle trips. ReThinkX projected that by 2030 40 percent of vehicles will be privately owned vehicles, but they would only represent five percent of passenger miles (Airbib and Seba 2017). Finally, it is a very rare and notable occurrence for a quarter of the population of any community, let alone an entire country, to change their dominant mode of transportation in less than 15 years.

Unfortunately, extending these projections further into the future yields greater uncertainty. Several studies estimate that AVs will reach about 50 percent adoption sometime between 2045 and 2055 (Litman 2018; Kuhr et al. 2017). However, McKinsey & Company's (2016) high-disruption estimate projected that AVs will total more than 50 percent of the vehicle fleet long before 2040. Unfortunately, there is very little literature predicting exactly when fully autonomous vehicles will make up 100 percent of the vehicle fleet. Early forecasting studies conducted in the first half of the 2010s were generally more optimistic concerning the rapid adoption of AVs. For example, a study by Morgan Stanley (2013) projected that AVs would reach full adoption by 2035. However, as OEMs delayed their expected release date for fully autonomous vehicles from the late 2010s to the early 2020s, projections have become more conservative. Very few recent projections have made claims concerning when AVs will reach full adoption. Consequently, a key takeaway from these projections is that once AV technology becomes available, there will be an extended transition period of several decades where autonomous and human-driven vehicles will share the road. Yet, given the potential cost-effectiveness of shared autonomous mobility, the percentage of autonomous trips could increase very quickly even if they represent a relatively small portion of total vehicles.

It is also important to recognize the role that planners will play in determining the rate of AV adoption. By and large, the technology is advancing much faster than the regulatory framework AVs operate within. In this way, the regulatory framework, or lack thereof, could govern the adoption timeline of AV as much if not more than technological development or market acceptance. While the regulatory framework necessary extends beyond the control of planners to legal liability, licensing, and a host of other issues, planners will play a key role in paving the way for AVs to be allowed to be tested, piloted, and implemented on a wide scale.

CONCLUSION

Technologies that had previously been the stuff of science fiction are becoming reality and are already being successfully tested on public roadways around the globe. If the technology continues to advance rapidly, highly, if not fully, autonomous vehicles are expected to become available to the public within the next 10 years (Kuhr et al. 2017). These advanced transportation technologies could have major implications for the safety and efficiency of the transportation system. In short, AV and CV technology is here and it is here to stay, and it is vital for planners to begin preparing for AVs now.

The technology is evolving so rapidly that planners will need to embrace an attitude of continuous learning. The summary of the emerging technologies' capabilities provided in this chapter is merely a snapshot of where the technology is today. The array of options available for implementation by planners and policy makers may be radically different in three to five years. Planners will need to monitor technological developments and successful pilot programs to stay informed of the technologies that are available to them and for which they need to be planning. In particular, planners should study the successes and failures of early adopters and their implications for long-range planning efforts in their local contexts. These collective lessons learned will be vital in order to avoid repeating the same mistakes.

The bottom line of this chapter is that AVs encompass a wide range of emerging technologies that are expected to reshape the design of transportation systems and of our urban spaces. While the most notable impacts will only be viable once Level 4 and 5 AVs are the majority of the vehicle fleet, the time to start preparing for AVs is now. Building upon this background information regarding what the technology is capable of and when AVs are expected to become available, the next chapter will outline the major opportunities and challenges AVs offer that will shape the technology's effect on the transportation system and on the built environment.

CHAPTER 3

PLANNING OPPORTUNITIES AND CHALLENGES IN AN AV WORLD

As with any major advancement in transportation technology, autonomous vehicles will present planners with a set of opportunities and challenges to address as they work toward building better communities. Planners and policy makers will have the responsibility of striving to capitalize on the opportunities while mitigating the challenges.

This chapter will lay out some of the major opportunities and challenges that will shape AVs' impacts on cities and the appropriate policy responses to them. Chapter 4 will then detail the effects AVs are expected to have upon the built environment. Finally, Chapter 5 will tie all of this back to practice by identifying planning and policy interventions that can capitalize on AVs' opportunities to create vibrant urban spaces.

What opportunities and challenges exist for planners as we enter an AV world? Several recent articles illustrate potential downsides of AVs and provide rationales for robust policy responses (Riggs and Boswell 2016a; Riggs and Boswell 2016b). This report identifies several major opportunities AV technology provides to improve the form and function of our communities and to better the lives of those living in them. These opportunities include the potential to improve the safety and efficiency of the transportation system, the ability to reduce vehicle emissions, and the chance to improve the mobility of transportation-disadvantaged populations.

Unfortunately, AV technology also brings challenges that threaten to negate its potential benefits. In particular, AVs may reinforce auto-oriented sprawl, which could increase vehicle miles traveled (VMT) and congestion. AVs could also compromise bicycle and pedestrian mobility by fragmenting bicycle and pedestrian networks. Finally, AVs will have important ramifications on several other key planning issues such as public transit, public health, and social equity. This chapter will discuss some of these primary opportunities, constraints, and concerns, and will offer potential policy solutions.

AV-RELATED PLANNING OPPORTUNITIES

All of the public attention that AVs have received in recent years is not without justification. AVs provide several remarkable opportunities to address today's most pressing transportation problems. While claims that AVs will solve all of our urban problems may overlook the difficult challenges the technology will create, they are indicative of the revolutionary opportunities that the technology promises to provide. Most notably, AVs will provide opportunities to address some of the issues created by the automobile by

- Improving traffic safety
- Increasing traffic efficiency
- Reducing vehicle emissions
- Improving mobility for special populations

This section will explore each of these potential benefits.

Improved Traffic Safety

In 2015, 6.3 million automobile crashes occurred in the United States. Of these crashes, 94 percent were attributable to human error. These crashes cost the U.S. more than $200 billion in medical costs, property damage, traffic congestion, and lost productivity (NHTSA 2015). More importantly, traffic accidents take the lives of more than 30,000 people every year in the U.S. alone, with 37,461 fatalities in 2016 (NHTSA 2017a). Worldwide there are more than 1.25 million traffic fatalities per year (WHO 2015). Motor vehicle crashes consistently rank as the number one cause of death among people ages 16 to 24 (NHTSA 2016). Even beyond the loss of life, traffic accidents create substantial public health costs; for example, such incidents resulted in more than $23.4 billion worth of medical costs in 2010 (NHTSA 2015).

Technological advancements such as the seat belt and the air bag have played a major role in improving traffic safety over time. Between 1975 and 2015, the fatality rate per 100 VMT declined from 3.35 to 1.18. Advanced driver assistance systems (ADAS) and automated vehicles promise to be the next major advancement in vehicle safety technology. While estimates vary, ADAS such as forward collision warning and automatic braking systems have been found to reduce rear-end crashes by as much as 39 percent, which equates to a 12 percent reduction in the total number of crashes and 15 percent reduction in injuries (Cicchino 2016). Fully autonomous vehicles are expected to be the next momentous innovation in transportation safety.

Since more than 90 percent of traffic crashes are caused by human error, removing humans from the driver's seat has the potential to improve traffic safety. While AVs will not eliminate traffic accidents, their ability to reduce or remove human driving errors, such as mistakes made while drowsy, distracted, or intoxicated, may significantly reduce traffic crashes and traffic-related fatalities. According to NHTSA's traffic safety data, 28 percent of traffic fatalities in 2016 involved alcohol impairment. Another 9.2 percent of fatalities in 2016 were caused by distracted drivers, and 2.1 percent involved a drowsy driver. Since AVs do not get distracted, intoxicated, angry, or sleepy, AVs are expected to significantly reduce traffic crashes and traffic-related fatalities.

While the sample of AV testing in real-world environments remains too small to draw definitive conclusions, early testing of highly and fully automated vehicles by Google, Tesla, and others has provided promising indications of AVs' potential to reduce traffic accidents and traffic-related injuries (Richland, Lee, and Butto 2016). Between 2009 and 2017, Google's AVs had driven more than 3.5 million miles on public roads and only caused one accident (Waymo 2017a). Over the same 3.5 million miles, human-driven vehicles caused 24 traffic incidents with Google's driverless fleet (California Department of Motor Vehicles 2017). Consequently, as seen in Figure 3.1, Google's total incident rate remains relatively high (about equal to the average young adult driver), but the at-fault rate is significantly lower than the average driver's.

These early tests provide promising evidence that AVs will be able to deliver on their promised safety improvements; however, additional testing will be necessary to verify whether AVs will improve the safety of users in real-world conditions. Since these companies can choose the conditions (weather, time of day, traffic level, etc.) in which the testing occurs, there remains insufficient data to demonstrate with certainty that the AVs of today are safer than human drivers. This is particularly true because Google and most other companies testing AVs on public roads use trained technicians who take back control when the vehicle comes to a situation it is unsure how to handle. As such, more testing will be necessary before the AV promise of improved traffic safety can be verified.

However, as the technology improves, the promising safety benefits that AVs are already demonstrating are only expected to increase. Waymo's 2016 *Disengagement Report to the California Department of Motor Vehicles* indicated that its rate of safety-related disengagements dropped from 0.8 per thousand miles in 2015 to 0.2 disengagements per mile (Waymo 2017b). This means that a human operator was only required to retake control of the vehicles once every 5,128

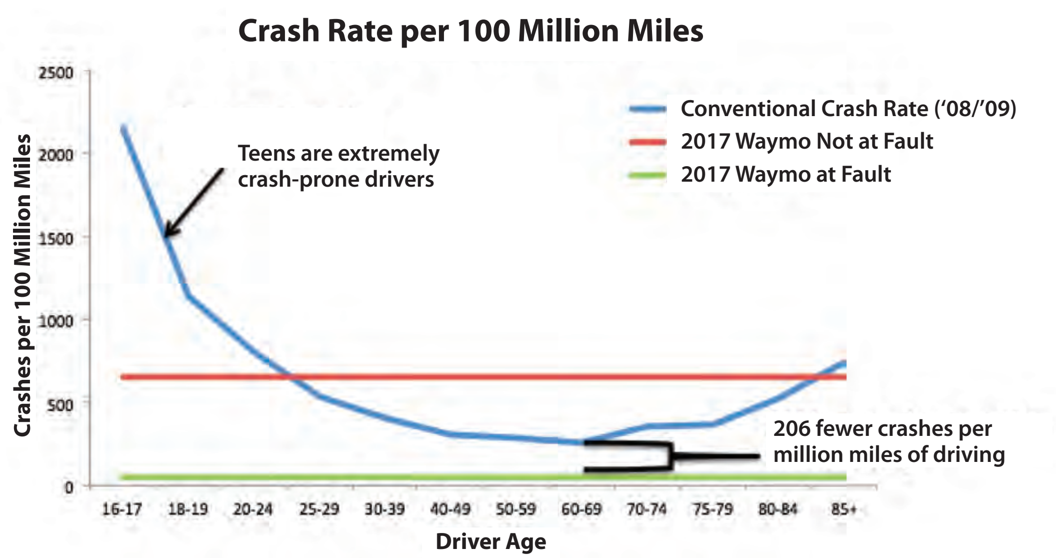


Figure 3.1. Google's self-driving car crash rate per 100 million miles (Crow 2017)

miles on average, compared to every 1,244 miles in 2015, indicating a substantial improvement in Waymo's ability to safely maneuver real-world driving situations. AVs' traffic safety is expected to continue to improve because, unlike conventional vehicles, AVs utilize self-learning tools so the more miles they travel, the safer they become. This machine learning can then be shared with other vehicles, making the entire fleet safer over time.

Yet in spite of all of AVs' promise to improve driver safety, there are several safety considerations and threats that planners need to be aware of, particularly as our roadways transition from primarily human-driven vehicles to AVs. The first is that during the transition AVs may introduce new safety risks. As previously alluded to, the rapid introduction of such new and revolutionary technology is likely to bring with it some level of equipment malfunctions and machine error as the technology is perfected and developers determine how to address difficult driving situations and road conditions. Hopefully, most of these issues will be mitigated by the extensive testing process that companies across the country are conducting, but some level of machine error is inevitable.

In addition, traffic safety risks may increase as human drivers learn how to share the road with AVs. Drivers not familiar with AVs' capabilities and limitations may drive more recklessly if they overestimate AVs' abilities to avoid collisions, which may partially offset the safety improvements provided by AVs. In some cases, these public safety challenges may be alleviated by dedicated infrastructure for AVs. However, dedicated infrastructure will not be feasible in every context, and drivers will need to learn to adapt to the AVs' driving behavior.

Another safety risk may be caused by miscommunication between the AV and human operators. Many of the early AVs are expected to possess Level 2, 3, or 4 automation instead of Level 5. This would require the operator to retake control of the vehicle in certain situations. Unfortunately, studies have shown that when human operators are not required to pay attention at all times, they are much less likely to remain alert enough to retake control in a timely manner when necessary (Blanco et al. 2015). The most highly publicized example of this is the Tesla operator who died as a result of a traffic incident while the vehicle was in autopilot mode. A report by the National Transportation Safety Board found that the driver "was not attentive to the driving task" because he had an "overreliance on the automation." It also indicated that Tesla's system of monitoring the driver's interaction was "not an effective method of ensuring driver engagement" (NTSB 2017). Tesla has since addressed this issue, but it is indicative of the types of problems and vehicle-to-operator miscommunications that AVs may bring during the early stages of adoption.

Finally, vehicle hacking may pose a new cause of traffic incidents and injuries, particularly in the early years when cybersecurity systems may not be as robust. Although not directly related to AVs, recent cyberattacks on municipalities, such as the city of Atlanta, highlight the importance of cybersecurity and how crippling a cyberattack on AVs or smart infrastructure could be. While it remains unclear how big of a problem hacking will be for AVs, vehicle manufacturers and local, state, and federal government agencies are putting enormous effort into ensuring that adequate cybersecurity systems are in place to prevent hackers from gaining control of AVs.

However, even with the introduction of these new safety risks, AVs' abilities to improve traffic safety and save the lives of thousands of people every year is the most significant benefit that AVs may provide and represents one of the most exciting examples of how good planning practice can promote public health.

Greater Traffic Efficiency

In addition to the anticipated reduction in auto accidents, the adoption of AVs is expected to improve the efficiency of the transportation system. AVs promise to positively affect traffic efficiency and throughput in several different ways (Table 3.1).

First, if AVs' expected safety benefits come to fruition, reducing traffic accidents will also significantly reduce traffic congestion caused by traffic incidents. Since AVs, particularly vehicles that are both connected and automated (CAVs), will have faster reaction times than human drivers, they will be

TABLE 3.1. WAYS AVS MAY IMPROVE TRAFFIC EFFICIENCY

Reducing congestion caused by traffic incidents
Allowing vehicles to travel closer together
Allowing vehicles to travel in harmony
Improving throughput through intersections
Reducing vehicle size
Encouraging car sharing and ride sharing

(Source: Authors)

able to travel closer together than human-operated vehicles, thereby increasing vehicle throughput. Studies modeling how platooning could improve traffic throughput have found that improvements will occur gradually as AV adoption rates rise, but that full market penetration of CAVs could more than double vehicle throughput (Talebpour and Mahmassani 2016; Lioris et al. 2017).

Similarly, as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies improve, AVs may significantly improve the efficiency of intersections. Futurists have suggested that CAVs may eliminate the need for traffic signals altogether. Instead, the vehicles would coordinate with each other or with the infrastructure to ensure each vehicle could safely pass through the intersection without coming to a complete stop, potentially reducing traffic congestion by as much as 60 percent (Dresner and Stone 2008; Tonguz 2011). While these drastic improvements to vehicle throughput may represent the upper bound of potential AV impact on efficiency of the transportation system, they certainly highlight the promising opportunities that AVs will provide.

As previously discussed, AVs are expected to encourage additional use of on-demand car-sharing and ride-sharing services. Increasing use of shared on-demand mobility could improve transportation efficiency by combining trips and reducing the number of cars on the road. Studies have found that a fully autonomous shared system could reduce the size of the vehicle fleet by up to 90 percent (Fagnant, Kockelman, and Bansal 2015). While this figure represents the upper bound of fleet reduction assuming a perfectly efficient shared-vehicle system, significant declines in vehicle ownership are possible. However, shared mobility's ultimate impact on throughput and congestion would depend on the extent to which the public is willing to share rides, as a car-sharing model could make congestion worse by introducing empty vehicle miles without reducing the number of vehicle trips.

Finally, AV technology may improve vehicle throughput by reducing the size of vehicles. Vehicles are as large as they are today to provide safety and versatility. Since AVs are expected to reduce automobile crashes and since 35 percent of trips can be served by one- to two-person vehicles, AVs (especially shared AVs) could be significantly smaller than today's vehicles, which would enable greater vehicle throughput.

AVs are certainly not expected to eliminate congestion caused by any of these categories, but by making notable improvements in each area, the cumulative impact on traffic flow could be significant. Moreover, cities may not need to wait for 100 percent adoption to begin to experience these benefits. Even if only five percent of vehicles on the road were autonomous, stop-and-go waves commonly experienced on busy interstates could be significantly diminished (Stern et al. 2018).

However, AV efficiency improvements will fail to alleviate traffic congestion and carbon emissions if AVs prompt significant increases in VMT. Consequently, AVs' ability to improve traffic flow will create many exciting opportunities, but AVs will also provide planners with the important challenge of ensuring these improvements are not offset by sprawling urban environments and increasing VMT.

Reduced Vehicle Emissions

Closely related to AVs' traffic efficiency benefits is their potential to reduce carbon emissions and improve the sustainability of the transportation system. AVs are expected to provide opportunities to significantly reduce vehicle emissions, provided the lower cost of travel and empty vehicle miles do not drastically increase VMT. Of the 6,587 million metric tons of the CO_2 emitted in the U.S. in 2015, 27 percent was generated by transportation emissions (U.S. EPA 2017). More than half of transportation emissions are caused by passenger and personal vehicles.

In addition to the negative effects these carbon emissions have on the environment, air pollution from vehicle emissions has been linked to heightened rates of respiratory disease (asthma, bronchitis), cardiovascular disease, adverse reproductive outcomes, cancer, and even premature death (APHA 2009). The Federal Highway Administration has estimated that air pollution from traffic generates between $50 and $80 billion per year in health care costs (FHWA 2000). In short, AVs' potential impacts to travel behavior and transportation efficiency could have major implications for environmental sustainability and public health outcomes in communities across the country.

As will be discussed later in this chapter, AVs' influence on travel behavior and VMT remains difficult to predict. However, AVs are capable of reducing vehicle emissions for several reasons, provided the lower cost of travel and the empty vehicle miles do not drastically increase VMT. First, AVs promise to significantly improve the fuel efficiency of automobile travel. Previous efforts to improve fuel efficiency have revolved around improving the efficiency of the engine. AVs introduce a new dynamic by improving fuel efficiency through more efficient traffic patterns and driving behavior. AVs' ability to safely drive very close together and platoon could reduce the energy consumption of road transportation by four to 25 percent by decreasing wind resistance. At the same time, AVs can easily incorporate fuel-optimizing acceleration and deceleration patterns that could further reduce energy consumption by as much as 23 percent (Wadud, MacKenzie, and Leiby 2016). AV technology may also reduce vehicle weight as safety features become less necessary, which would bring even greater fuel savings.

Many researchers are also anticipating a convergence of autonomous and electric vehicle (EV) technology. Several automobile manufacturers have recently announced their intentions for an all-electric future in which every new vehicle sold will eventually be an EV (Davies 2017). The added efficiency of using electricity to power the computer systems necessary to control an AV instead of converting it from gasoline may provide a strong incentive for more auto manufacturers to transition to electric power. It has been estimated that a fully autonomous fleet of EVs could reduce emissions by as much as 90 percent (Greenblatt and Saxena 2015). While it is unlikely that the impacts will be that drastic, these estimates demonstrate the potential for the convergence of advancements in AV and EV technology to work together to significantly reduce the transportation system's negative environmental externalities.

Finally, as discussed in the previous section, AVs may also reduce emissions by improving traffic efficiency and throughput, as AVs are expected to travel closer together, travel in harmony, and reduce accident-related congestion. If AVs facilitate a drastic increase in ride sharing and car sharing, then AVs may even reduce VMT by further amplifying the impact on vehicle emissions. However, as will be discussed further in the next section, each of these effects could easily be offset if AVs substantially increase travel demand. AVs pose a major risk of drastically increasing VMT by reducing the perceived cost of travel, by improving mobility for those who previously were unable to drive, and by introducing empty vehicle miles as the vehicle travels without a passenger to find parking, return home, or find another passenger.

Consequently, planners' ideal roles regarding AVs' impacts on emissions will remain similar to what they have been since the introduction of the automobile. Planners will need to continue to seek creative ways of addressing traffic congestion, promoting the use of transit and active modes of transportation, mitigating potential increases in VMT, and promoting the development and use of EVs. AVs will simply add the new challenges of minimizing empty vehicle miles and preventing AVs from escalating urban sprawl farther into rural areas. Yet, AVs' potential efficiency improvements will provide important opportunities to reduce transportation emissions and improve the health of communities across the country.

Increased Mobility for Special Populations

AVs possess a special capability to restore the personal mobility of the aging and transportation disadvantaged. In today's transportation system, aging and disabled people who are unable to drive are often left with few transportation options. As suburban populations age in place, greater numbers of aging adults will live in areas with limited public transit service and poor bicycle and pedestrian infrastructure. Consequently, when age- or health-related declines in driving ability force them to limit travel behavior or cease driving altogether, older adults often feel trapped in their own homes (Kostyniuk, Trombley, and Shope 1998; Yassuda, Wilson, and von Mering 1997). This process of driving cessation and the subsequent loss of mobility and freedom causes significant deterioration to their health and quality of life. Among older adults, driving cessation has been found to cause higher rates of depression, social isolation, and even mortality (Edwards et al. 2009; Marottoli et al. 1997). This will become an increasingly pressing issue as baby boomers age.

AV technology promises to restore mobility and independence to a growing segment of the population and to improve the quality of life of these populations and their caregivers. Many of the existing strategies for addressing the issues related to driving cessation can help to mitigate the mobility and quality-of-life difficulties faced by retired drivers. However, no current strategy can provide the same level of mobility retired drivers enjoyed prior to giving up driving, regardless of where they live or how strong their support network is. The emergence of AV technology may be the first initiative with the potential to provide older adults with personalized rapid transit. In particular, AVs could help to improve the mobility of the growing number of older adults who reside in suburban and rural areas and to minimize risks associated with aging drivers. A 2003 study found that 79 percent of adults age 65 and older live in car-dependent suburban and rural communities, which typically require frequent, long-distance trips by automobile (Rosenbloom 2003). Since providing public transit to these areas is extremely difficult, AVs may be a better way of ensuring older adults can maintain their quality of life.

Even Levels 1 and 2 of automated technology could serve to keep aging drivers behind the wheel longer by reducing the risk of crashing and driving-related anxiety in stressful situations (Duncan et al. 2015). For drivers who have completely stopped driving, a fully autonomous vehicle offers complete use of the automobile and restores their independence. AVs could serve to improve and extend older adults' quality of life, independence, and mobility, as well as to reduce their likelihood of being admitted to long-term care facilities. AVs provide a strategy that can potentially accommodate the travel behavior of aging populations within the context of a predominately auto-focused transportation system.

AVs may also provide opportunities to improve the mobility of lower-income and transit-dependent populations. While the higher costs of purchasing an AV may make vehicle ownership more difficult, the potential cost-effectiveness of shared AVs could provide additional mobility options to transit-dependent populations. As further discussed later in this chapter, there will also be opportunities to integrate shared-mobility applications into the transit system as first- and last-mile connections. Especially if trends toward the suburbanization of poverty continue, shared AVs may be an effective way of providing access to transit systems and meeting the mobility needs of lower-income households. As will be discussed in more detail later, AVs may also provide new challenges to transit-dependent populations, but it is important for planners to recognize and work toward the potential benefits.

AV-RELATED PLANNING CHALLENGES

Like any disruptive technological improvement, the rise of AVs will bring an entirely new set of challenges and difficulties that planners will have to navigate to work towards building better communities. In fact, many of AVs' most difficult challenges could offset the technology's most notable benefits, creating the opposite effect. For example, in spite of the potential efficiency benefits of AVs, they could ultimately lead to more congestion if AVs significantly increase VMT. Consequently, planners have the responsibility of determining how to use the opportunities the technology provides to address current planning problems and to proactively avoid the problems the technology may create.

This section will describe a few of the planning-related challenges that AV technology may present. The widespread adoption of AVs will also have massive implications for privacy concerns, insurance, legal liability, and cybersecurity. While these issues may affect when and how AVs become available, planners will not have an influence on shaping how these issues will be resolved. Consequently, this section will not address these issues but will instead focus on AVs' planning-related challenges.

Potential to Reinforce Auto-Oriented Sprawl

There is little debate that the increase in personal mobility provided by the introduction of the automobile in the early 20th century caused massive changes to land-use patterns by enabling people to live significantly farther away from central cities and employment centers. The suburban development patterns and edge cities made possible by the automobile still dominate the urban form of most American cities today. As AVs represent the most significant advancement in personal mobility since the mass production of the automobile, AVs will certainly have a dramatic impact upon the urban fabric. AVs' impacts on the cost and ease of transportation will inevitably affect the location decisions of both residents and businesses. However, there is an ongoing debate over whether AVs will spark another wave of urban sprawl or whether they would prompt the reurbanization of urban centers.

The majority of researchers contend that AVs have the potential to induce sprawl by encouraging people to move farther away from urban centers. By removing the responsibility of driving, AVs will make traveling much more enjoyable and less stressful. People may be willing to commute significantly farther if they are able to sleep or be productive during the trip. In addition, if AVs improve the efficiency of the transportation system, then commuters may be able to travel farther in the same amount of time. The average commuter typically is unwilling to commute much more than an hour (Kung et al. 2014). By increasing the distance commuters can travel in an hour, AVs could create pressure to push suburban development farther into previously rural areas.

Some have also suggested that AVs may encourage sprawl by reducing the monetary cost of travel (Burns, Jordan, and Scarborough 2013; Litman 2018). This likely will not be true in the near term, because AVs' sensors and computer systems will raise vehicle costs. Yet, if AVs reduce car ownership by sparking a rise in on-demand automated mobility, they may reduce travel cost per mile because the traveler does not have to purchase or maintain the vehicle. While it remains to be seen whether automated car sharing will become a popular model and whether on-demand AVs would cost less than owning an automobile today, lower monetary cost would encourage an intensification of sprawl. In this way, AVs' potential reduction of the generalized cost of travel (time, stress, and money) may make people more willing to live further away from central cities, greatly expanding already sprawling communities.

However, many proponents of AV technology suggest that the technology will provide opportunities for promoting more compact development patterns. Recent urbanization trends and lower rates of car ownership among younger generations have been well documented. A shared-AV system could reinforce these growing trends by enabling people to discard their private vehicles and move into more walkable city centers that are better served by shared-AV systems. Since it would be easier to provide on-demand AV service to densely populated areas, the convergence of AV technology with the rise of the sharing economy could serve to improve the accessibility of urbanized areas while further reducing the cost of travel. By providing better and more affordable service in urbanized areas, AV could provide additional fuel for the recent urbanization trends.

However, it is unlikely that either of these of scenarios would occur exclusively. Even today, urbanization and further suburbanization are occurring simultaneously in different parts of our metropolitan regions. AVs may make the urban core (and urban lifestyle) more attractive to some while making the exurbs and rural areas more attractive to others. Ultimately, planners will need to be prepared for both scenarios to happen simultaneously. It is conceivable if not likely that AVs will make urban living even more attractive to younger generations while also enabling the remainder of the population to move farther and farther into rural suburbs. Yet, AVs' potential to reinforce and amplify suburban sprawl will pose a real threat to the vibrant urban communities that planners strive to create.

Potential for Increased VMT and Vehicle Emissions

As discussed earlier in this chapter, AV technology will provide notable opportunities to improve the efficiency of vehicular travel as AVs are expected to increase traffic efficiency and throughput, increase fuel efficiency, and improve the viability of EVs. Yet, whether these efficiencies will lead to a decline in congestion and total emissions will ultimately depend on how AV technology affects travel demand. If AVs significantly increase VMT, congestion and vehicle emissions may continue to rise despite the improvements in efficiency (Table 3.2).

While AVs' ultimate impacts on travel demand are not as clear as their effects on safety and efficiency, AVs are likely to affect travel demand in several ways due to their effects on development patterns and the cost of travel. Urban sprawl has always been closely associated with increasing VMT. As people and jobs move farther away from central cities, they must drive farther to reach their destinations, creating traffic congestion and increasing carbon emissions. Consequently, if AVs promote sprawling development patterns, as discussed in the previous section, they may also increase VMT and amplify congestion.

In addition to the impact on development patterns, AVs are generally expected to lower the perceived cost of travel. What used to be a stressful commute to work may turn into the opportunity to nap, read, or get more work done. Consequently, two-hour commutes and long road trips may become more common as people become willing to travel farther and more often.

Beyond lowering perceived costs, AVs may also reduce the monetary costs of traveling. According to researchers at Columbia University's Earth Institute, a fleet of shared AVs could reduce taxi travel cost from $4 per mile to 50 cents per mile (Burns, Jordan, and Scarborough 2013). If AVs reduce the cost of travel this drastically, it could significantly increase travel demand. Yet, whether AVs will provide these cost savings remains up for debate. Researchers at the RAND Corporation claimed that a shared-AV system would eliminate the fixed costs of car ownership, but would also increase the cost per trip, leading to an overall reduction in vehicle travel (Anderson et al. 2016).

AVs could also affect travel demand in several other ways unrelated to the cost of travel. First, AVs may increase travel demand by offering independent mobility to nondrivers, such as children, the elderly, and the disabled (Harb et al. 2018; Litman 2018). Nondrivers have been limited to alternative modes of transportation, which often inhibits their travel behavior. The improved mobility provided by AVs may prompt a substantial increase in travel among these special populations.

Potentially one of the most significant increases in vehicle travel may come from empty vehicle trips made by AVs between passenger trips. Fully autonomous vehicles will be capable of traveling without a passenger to return home while not in use, to find parking, or, in the case of shared AVs, to pick

TABLE 3.2. POTENTIAL AV IMPACTS ON VEHICLE EMISSIONS

Ways AVs Could Reduce Emissions	Ways AVs Could Increase Emissions
• More efficient driving/energy use (platooning, improved fuel economy, lighter vehicles) • Reducing traffic congestion (fewer accidents) • Reducing VMT (if paired with ride sharing and car sharing) • Convergence with electric vehicles	• Increasing traffic congestion • Increasing VMT (more driving, zero-occupancy vehicles, vehicles cruising or double-parking instead of paying to park)

(Source: Authors)

up another passenger. It remains unclear how much empty vehicle trips will increase VMT, but it likely will be substantial.

AVs may also stimulate demand from new types of vehicles, such as those designed specifically to deliver restaurant food, groceries, or clothes. Amazon has made headlines with its Prime Air drone delivery service, but automated ground delivery vehicles may also grow into a notable portion of VMT as unmanned delivery trips increase. Since AVs could reduce shipping costs by removing the need for a driver, demand for the delivery of basic goods needed on a daily basis may increase. On-demand delivery services (Uber for goods and packages) are already growing in popularity, especially in big cities. If AVs promote greater use of these services to deliver groceries and retail goods, this could add another growing source of VMT. Urban VMT growth could be mitigated if shared AVs transported passengers and delivered goods simultaneously, but an increase in the number of semi-trucks making long-distance hauls could still increase VMT on the highways.

In short, AVs are expected to increase travel demand and VMT. However, there is no consensus on whether AVs will ultimately alleviate or exacerbate traffic congestion and vehicle emissions. Due to the lack of data on real-world testing of AVs, estimating their ultimate impact on emissions, throughput, or congestion remains a difficult task. The few attempts that have been made have produced wide-ranging results (Kockelman et al. 2017; Friedrich 2016). A study by the National Renewable Energy Laboratory found that energy use could decrease by as much as 90 percent or increase by as much as 250 percent depending on a wide variety of factors including ownership model (private versus shared), EV use, and development patterns (Brown, Repac, and Gonder 2013).

More testing will need to be done to determine whether AVs' improvements in traffic efficiency will outweigh the associated increase in VMT. However, decades of planning history have taught us that simply increasing roadway capacity, as AVs promise to do, has consistently failed to relieve traffic congestion due to latent demand. Consequently, it is possible if not likely that even if AVs do significantly increase the throughput of existing infrastructure, the combination of the potential increase in VMT and latent demand would prevent AVs from reducing traffic congestion and could threaten to make traffic congestion even worse than it is today.

Potential Impacts to Active Modes of Transportation

Another pressing question is whether AVs will ultimately promote or discourage the use of active modes of transportation. The adoption of AVs promises to improve the safety and efficiency of the vehicular system, but AVs' ultimate effects on bicyclists and pedestrians are difficult to predict. As will be discussed further in the next chapter, AVs may require less space than human-driven vehicles as car ownership decreases, lane widths become narrower, road diets become more common, and the need for on-street parking is reduced (Litman 2018; Airbib and Seba 2017). This could provide opportunities to retrofit vehicular infrastructure such as lanes and parking into bicycle and pedestrian facilities.

However, the emergence of AVs could ultimately reinforce an auto-oriented transportation system. Especially given the novelty of AVs, it would be very easy to give priority to AVs instead of designing urban spaces on principles of human-centered design. Careful planning will be required to ensure that investments in AV infrastructure do not fragment bicyclist and pedestrian networks. AVs' potential to remove the need for traffic signals is a telling example of this. Free-flowing intersections would provide massive improvements to traffic efficiency from the viewpoint of vehicular transportation. However, without pedestrian signals or major investments in above- or below-grade bicyclist and pedestrian infrastructure, free-flowing intersections could become major barriers to bicyclist and pedestrian connectivity.

Ultimately it will be up to planners to balance these issues and to develop context-specific, fiscally responsible solutions that leverage the ways AV technology could enhance traffic flow without compromising bicycle and pedestrian travel. In this way, promoting the use of active modes will remain an important priority for planners to support the development of healthy and sustainable communities.

OTHER SECONDARY IMPACTS OF AVS

AVs' impacts on traffic safety and efficiency have received the most public attention, but their impacts on travel costs, preferences, and patterns will have significant ripple effects on a host of other issues. The impacts to development patterns and the built environment will be discussed in the next chapter, but this section will detail a few of the additional impacts to the transportation system and our communities' quality of life, including transit systems, public health, and equity implications. In all three of these cases, AVs could ultimately have either a positive or negative effect. Ultimately, whether these changes will improve transit service, improve public health, or mitigate transportation equity issues will depend on how planners prepare for and respond to the adoption of AVs.

AV Impacts on Transit Systems

Automated vehicle technology offers a number of exciting opportunities to improve the coverage and efficiency of transit service. Yet as in so many other aspects of the technology's impact, it brings some disruptive possibilities along with the opportunities. Most researchers and practitioners agree that AVs will only have a limited influence on high-capacity rail systems, because even if AVs could provide affordable door-to-door service to everyone, the roadways may not have the capacity to accommodate the additional trips. However, the introduction of AV technology could have a significant effect on the roles and service models of bus networks and paratransit.

The first and most exciting opportunity that AV technology will provide transit agencies is the potential to significantly reduce operational costs by removing a large part of labor costs. Labor costs typically are one of the largest components of a transit agency's operating budget. By reducing the need for bus operators, transit agencies will be able to operate much more cost effectively. Some of these cost savings will be offset by the higher capital costs necessary to purchase autonomous buses, but a recent estimate found that an autonomous bus could provide more than $3 million in savings over a 12-year bus's life cycle, even after accounting for the increase in capital costs (Quarles and Kockelman 2018). Such substantial cost savings could be used to make significant improvements in service by increasing route coverage or frequency.

In addition, the safety improvements provided by autonomous buses could also improve the cost-effectiveness of transit service by reducing the costs associated with traffic accidents and legal liability. A recent study found that the average transit agency spends an average of 3.9 cents per rider on liability claims and the cumulative cost of claims has been going up (Aon Risk Solutions 2016). This may not sound like much, but it adds up. The Metropolitan Transportation Authority in New York City paid more than $1.1 billion in liability claims between 1996 and 2007, and it estimated that an additional $1.2 billion had been filed but not yet paid (DiNapoli and Bleiwas 2008). AVs will certainly not eliminate these costs, but combining incident savings with operational cost savings provides possibilities for transit agencies to significantly expand their bus transit services without increasing their budgets.

The first- and last-mile problem has been one of the biggest barriers to increasing transit ridership in the U.S. The combination of sprawling suburban development patterns, fragmented bicycle and pedestrian infrastructure networks, and hidden costs of owning and operating an automobile has made it extremely difficult for transit agencies to attract riders who live farther than a quarter- or half-mile away from a transit stop. The automobile's ability to provide door-to-door travel to a destination make the "first mile" from home to the transit stop and the "last mile" from the transit stop to a final destination a major contributor to low ridership. Whether the first- and last-mile gaps can be filled by a fleet of shared AVs or by low-capacity autonomous shuttles remains to be seen. However, the expected cost savings and the potential for low-capacity (10–12 passengers) feeder shuttles promise to provide opportunities to expand coverage beyond major roads into neighborhoods. Some have even suggested that AVs will transform the dominant transit model from a fixed-route system to personal rapid transit, in which fleets of low-capacity AVs provide personalized or even door-to-door transit service (McKinsey and Company 2017). While such a revolutionary transformation may be less likely, AVs offer opportunities to reinforce the importance and viability of public transit by providing millions more potential riders with easy access to transit stops.

The rise of shared AVs and the growing popularity of transportation network companies (TNCs) such as Uber and Lyft could have another transformative impact on the public transit system by having large private companies become an important part of the transit network. It remains to be seen how that would play out, but there may be significant opportunities for public-private partnerships to provide the best possible transit service to all residents. However, this also presents the danger of relying too heavily on TNCs to meet the mobility needs of transit-dependent populations. Significant equity issues could be created if local governments begin to redirect resources away from transit systems because they assume TNCs will meet the needs of transit-dependent populations.

Another way AV technology could significantly alter the transit model prevalent today is by reducing the need for paratransit service. Since paratransit is designed for those unable to use traditional transit systems, it primarily serves those who are also unable to drive. As previously discussed, AVs promise to restore personal, independent mobility to these special populations by removing the need to be physically able to drive. As such, many paratransit riders may simply be able to use a personal AV. In addition, if transit agencies move toward point-to-point service models, as will be discussed later, then a separate paratransit service may not be necessary because the predominant transit model would function much like paratransit does today.

Having paratransit operate as an integrated part of the larger system could improve the quality and efficiency of service to disabled populations. This is especially relevant for transit agencies because paratransit and shuttle services are the most expensive modes of transportation for any public agency to operate. In this way, automated vehicles could serve to further reduce costs while expanding services to the rapidly growing demographic of aging citizens.

Finally, the positive public attention accompanying the novelty of AV technology may provide opportunities for new funding sources and marketing opportunities during the transition to autonomous buses. Federal and state governments have already begun offering numerous funding opportunities for innovative transportation technologies. The U.S. Department of Transportation and the Department of Energy are allocating millions of dollars toward the development and implementation of smart-city and connected vehicle (CV) technologies. In particular, the U.S. Department of Transportation allocated $160 million to the Smart Cities Initiative in 2015 to support communities' efforts to develop infrastructure that harnesses the growing availability of data to improve the lives of residents (White House Office of the Press Secretary 2015). Similar funding sources may become available for local transit agencies to pilot and implement automated transit systems. For example, the Federal Transit Administration (FTA) announced the Strategic Transit Automation Research Plan that will promote transit applications of automated technologies through enabling research, integrated demonstrations, and strategic partnerships (FTA 2017). As part of this program the FTA has committed funds to support Valley Metro's shared-AV pilot in Phoenix (FTA 2017). These funding sources may only be available in the near term but they provide excellent opportunities for communities to leverage the funding to improve existing service.

Similarly, the public attention surrounding AVs will likely bring novelty riders to use public transit for the experience of riding in an AV. Granted, once the novelty wears off, mode choice decisions will still be determined by cost, convenience, and commute time. Yet, during the transition to an automated future, local transit agencies can use the positive public attention to find creative ways to market and promote long-term ridership. This could help to overcome the negative perception of public transit.

Impacts on Public Health

AVs' potential to save lives lost in traffic accidents is the most commonly cited benefit this technology could provide. Yet, AVs' impact to public health reaches well beyond traffic safety. The technology could also provide opportunities to address a host of other health issues associated with the automobile, such as air pollution, healthy aging, changes to active transportation, and commuter stress (Crayton and Meier 2017). However, just like the automobile, AVs will likely be "accompanied by a plethora of unintended consequences" that may threaten the health, safety, and welfare of drivers and nondrivers alike (Richland, Lee, and Butto 2016). Many of these issues, listed in Table 3.3, have been discussed in previous sections but they are worth highlighting again here because of the significant impacts AVs may have upon health outcomes.

In summary, AVs offer several exciting opportunities to improve the public health of communities across the country. More specifically, AVs may:

- Significantly reduce injuries and fatalities caused by traffic incidents
- Improve air quality and decrease pollution-related rates of respiratory disease, cardiovascular disease, and cancer
- Improve health and quality-of-life outcomes of aging and disabled populations by increasing personal mobility
- Relieve the mental toll of commuter stress

Many of these opportunities may not come to fruition until fully autonomous vehicles make up the majority of the vehicle fleet. Yet, in the near term, policy makers and auto manufacturers can work to ensure that as many cars as possible are equipped with emergency braking and other ADAS that have been shown to prevent traffic incidents.

TABLE 3.3. POTENTIAL HEALTH IMPACTS OF AVS

Impact	Expected Net Health Impact
Traffic safety	+
Air quality (emissions)	+/-
Reduction in travel stress	+
Use of active modes of transportation	+/-
Improved mobility for transportation-disadvantaged populations	+
Health equity	-

(Source: Authors)

However, AVs' impacts on travel behavior and urban form will have important implications for how the technology affects our communities' health and well-being. In fact, if AVs promote further sprawl and drastically increase VMT, the new technology could have several negative health externalities, including:

- Lowering air quality
- Reinforcing sedentary lifestyles by promoting inactive modes of transportation
- Widening the health divide between wealthy and poor communities

The importance of careful planning is highlighted by the fact that many of these potential externalities are the exact opposite of AVs' possible health benefits. Planners will need to ensure that "decisions about AVs are made in the context of AVs' overall impact on society" (Richland, Lee, and Butto 2016), as AVs' influence on travel behavior and urban form will have important implications for our communities' health and well-being. Planners will face the challenge of promoting the use of AVs in a way that provides the expected safety benefits without causing a host of other health issues.

Social Equity Impacts

Like many other disruptive technologies before them, AVs have the potential to mitigate or exacerbate numerous social equity issues. Unfortunately, even though most researchers acknowledge that AVs will have notable ramifications for social equity, particularly as it relates to equitable access to resources, jobs, and amenities, there has been a very limited amount of research conducted on the equity impacts of AVs (Milakis, van Arem, and van Wee 2017). While it is too soon to determine who will benefit most from AVs and whether AVs will improve or hinder access to affordable mobility, it is vital for planners to begin considering the equity implications sooner rather than later to ensure that the safety and mobility benefits of AVs are not only for those who can afford them.

One of the most commonly cited potential positive equity impacts of AVs is the improved mobility that autonomous technology could provide to transportation-disadvantaged populations such as the young, the aging, and the disabled. This has been discussed previously, but it is worth mentioning again as the lack of viable transportation options for those unable to drive a car has become one of the most pressing transportation equity issues of our time. While ADA requirements and paratransit help to mitigate accessibility issues and provide mobility options to those unable to drive, they often fail to fully resolve the transportation problems faced by disabled populations. As such, aging and disabled populations often experience social isolation and feel trapped in their own homes (Yassuda, Wilson, and von Mering 1997). In addition, as already discussed, the relative expense and inefficiency of paratransit puts a considerable burden on transit agencies trying to meet the mobility needs of the aging and the disabled. By promising to restore personal mobility to the blind and otherwise disabled, AVs could solve both of these problems at the same time. In this way, AVs present the potential for an exceptional advancement in equitable transportation.

Unfortunately, AVs' improvements to personal mobility may only be available to those who can afford them. It is too soon to predict whether AVs will raise or lower the cost of driving in the long run. However, in the early stages of the transition from human-driven to automated vehicles, AVs are expected to be significantly more expensive than traditional automobiles due to the high costs of the sensors, Lidar, and computer systems necessary for an AV to operate. Consequently, the costs of owning a car will likely go up, making it more difficult for lower-income populations to maintain their personal mobility. As the technology advances and becomes more pervasive, AVs' purchase prices will likely decline. Yet, it is unlikely that AVs will ever cost as little as vehicles today. Since lower-income families already spend a higher proportion of their income on transportation than wealthier households, increasing the cost of car ownership could become problematic for many low-income families to struggling to make ends meet (FHWA 2014).

However, due to the high costs of AV ownership and the emergence of the sharing economy, many believe that AVs will encourage greater use of shared on-demand mobility systems. By placing the cost of purchasing the vehicle on the service provider instead of the individual, shared AVs could significantly reduce the cost of transportation to the user. This would still be profitable for the service provider because the vehicle would be running almost continuously instead of sitting in a parking lot or a garage most of the day. Users would only pay for the cost of the miles they travel, which could reduce the per-mile cost of travel. Estimates vary on how much travel costs could be reduced, but most agree that shared AVs may likely become the cheapest form of motorized travel (Burns, Jordan, and Scarborough 2013; Johnson 2015; Bosch et al. 2017). In this way, the widespread use of shared AVs would help to reduce one of the largest barriers preventing the economically disadvantaged from enjoying the mobility benefits of the automobile and could greatly improve access to economic opportunities. However, it remains to be seen whether a shared-AV system will rise to prominence as the dominant ownership model or whether a shared system would drive down transportation costs by as much as it is predicted.

Historically, transportation inequalities have centered around mobility and accessibility and whether everyone has access to affordable mobility options. However, if the safety benefits of AVs are only affordable to wealthy populations, then AVs could introduce inequalities in transportation health and safety outcomes. Although AVs will likely improve the safety of all road users, human-driven vehicles will likely be responsible for a greater percentage of traffic accidents. In this way, transportation could become more dangerous for those unable to afford an AV, making safety while driving functionally dependent on income, which opens up a host of difficult equity and public safety issues.

The transformative impacts of AV technology will extend far beyond the operations of the transportation system to the business models of the transportation industry and the economy at large. While this transformation offers some promising opportunities, it will also have some disruptive effects that could negatively impact specific interest groups. In particular, automated technology's ability to replace the driver may be a relief to the average commuter, but it poses a threat to the livelihood of motor vehicle operators such as truck, bus, and taxi drivers. A recent study by the Department of Commerce found that the introduction of AVs could affect 15.5 million workers (Beede, Powers, and Ingram 2017), including 3.8 million motor vehicle operators who could lose their jobs as a result of AV technology. The other 11.7 million include construction workers, waste management professionals, first responders, health care professionals, and others where driving is a major part of the job. This larger group may not lose their jobs, but they may still experience significant changes due to the growing use of automated technologies.

Suggesting that AVs will replace millions of jobs may be a little misleading because it does not account for the jobs that a potentially trillion-dollar industry may create (Lanctot 2017). In addition to the information technology opportunities that will continue to develop, AVs will likely transform the role of motor vehicle operator jobs from operator to support. Particularly in the early stages of implementation, many AVs will likely need an operator to retake control of the vehicle in case of a system failure. Freight operators may still be necessary to handle vehicle maintenance and delivery. Automated buses will likely still need an operator to act as a security guard and to assist disabled riders in using the system. While it is clear that AVs will have a transformative effect on numerous industries, it is uncertain how AVs will ultimately affect total employment. However, it seems likely that AVs will reinforce the growing mismatch between jobs and skills as more and more blue-collar jobs are replaced by white-collar tech jobs.

Finally, some have expressed concerns that the attention surrounding AVs may "serve as another distraction from the urgent need to design (or redesign) cities for people" (Kodransky 2016). The energy and resources given to developing the infrastructure and legal framework for AVs could be put toward solving more pressing issues such as the need for affordable housing, access to healthy food, environmental justice, and the creation of vibrant urban spaces where all people have access to urban jobs and amenities. While it is a false dichotomy to suggest that adopting AVs and addressing these important equity issues are mutually exclusive goals, these concerns do raise the important point that AVs will reinforce the auto-dominated U.S. transportation system and all of the problems that come with it. Consequently, it will require a concerted effort to prevent AVs from exacerbating many of the urban development patterns that led to the social exclusion, spatial (job/housing) mismatch, lack of multimodal mobility, and other equity issues faced by many low-income families today.

One example of this is AVs' potential to pull resources away from public transit. Some have suggested that the resources and funding necessary to enable a smooth transition to AVs could leave less funding for public transit (Richland, Lee, and Butto 2016). This neglect of public transit could be detrimental for those lacking access to other forms of transportation. However, as discussed previously, AVs will also provide notable opportunities to improve transit systems by reducing operating costs and providing a first- and last-mile solution. Realizing these goals will take a concerted effort by planners and policy makers to ensure that the resources put toward promoting AVs do not simply go toward private AVs but toward incorporating AVs into the design of great urban places that provide all residents with opportunities and access to jobs, service, and amenities.

In summary, whether AV technology will improve or exacerbate transportation equity issues will depend on whether AVs reduce or increase the cost of travel. It is too early to determine exactly how AVs will affect the cost of transportation and whether AVs will improve access to affordable mobility. A shared-AV system offers exciting opportunities to reduce transportation costs and improve access to reliable transportation, thereby improving economic opportunities and outcomes. Yet AVs also threaten to reinforce several growing equity issues by impacting millions of jobs, reinforcing development patterns that disadvantage those with limited transportation options, and impacting service to transit-dependent populations. It is vital for planners to be mindful of AVs' equity effects to ensure our cities are designed for people and not for AV technology.

CONCLUSION

Too often the conversation around AVs envisions either a utopian future where the technology will neatly solve many of the problems planners have been trying to address for decades, or a dystopian future where AV technology exacerbates urban sprawl to the point of gridlock, speeds climate change, and creates major cybersecurity and data privacy problems. While recognizing the potential for both of these extreme futures to be useful, it is vital to keep in mind that the technology itself will not bring about either of those scenarios. The auto-oriented suburban development patterns that dominate our cities today were not created solely by the adoption of the automobile. The technological transformation was supported by subsidized infrastructure, a booming economy, and a lack of growth management. The ultimate impact of AVs will largely be determined by infrastructure and policy decisions made by local governments across the country.

Consequently, we planners are better served by framing our approach to AVs around the recognition that, like any major technological innovation in transportation, the rise of AVs will bring a new set of opportunities and challenges that we will have to navigate in order to work toward building better communities. As such, we have the responsibility to determine how to use the opportunities the technology provides to encourage the utopian future instead of the dystopian. In other words, there is a growing need for planners to develop policy and infrastructure solutions that enhance the societal benefits that AV technology promises to provide while mitigating the potential problems the technology could create. To that end, this report hopes to provide planners with information and guidance on how to begin planning and preparing for the adoption of AV technology. To do this, planners need to understand the range of potential built environment changes AVs may bring. The following chapter will detail possible impacts to the design and functioning of the built environment and will provide a starting point for state and local agencies to consider how best to leverage these effects to improve communities across the country.

CHAPTER 4

POTENTIAL IMPACTS OF AVS ON THE BUILT ENVIRONMENT

It is clear that autonomous vehicles are poised to revolutionize the way people travel and to have a profound impact on the built environment (Chapin, Stevens, and Crute 2017). While there is uncertainty surrounding the exact form these effects may take, there are numerous ways that AVs will affect the way planners prepare for an AV future. These impacts include smaller roadways, more efficient rights-of-way usage, access management changes, signage and signalization changes, and pedestrian and bicycle interface effects, as well as parking reduction and location changes. These changes will also present significant redevelopment opportunities. Each of these effects is explored in the following sections.

Exactly how and when AVs will impact the built environment is difficult to predict due to the uncertainty surrounding major factors, including the size and design of AVs, anticipated changes to the vehicle ownership model (from private ownership to shared), the cost of AVs, and their observed impacts on development patterns and vehicle miles traveled. This chapter presents a vision of the future that illustrates some of the built environment challenges and opportunities that may arise with the transition to an AV fleet in the coming decades. It takes a longer-term view of the impact of AVs on the built environment, as many of the impacts discussed are only possible once AVs constitute most or all of the vehicle fleet.

As there likely will be a long transition period where AVs share the road with human-driven vehicles, built environment changes during the transition are also given some attention. However, the main focus of this report is on the long-term effects of AVs, which provides some direction for planners as they review and update their communities' long-range plans. The impact of AVs is likely to vary based on the community context (i.e., different impacts in urban cores and rural areas), and we have chosen to focus primarily on AVs' impact on urban and suburban areas.

RIGHTS-OF-WAY

Widespread adoption of AV technology will likely have a substantial impact on street design, with the potential for narrower pavement widths and more efficient vehicular rights-of-way. Slimmed-down pavement and rights-of-way will be made possible by a number of factors. First, autonomous vehicles are expected to be smaller with the ability to drive more precisely (Fagnant and Kockelman 2014; Litman 2018). Even when drivers try their best to keep their vehicle in the center of the lane they inevitably will move back and forth within the lane. Consequently, roadways today are designed to provide space to move side-to-side without crossing into an adjacent lane and putting other vehicles at risk of a collision. AVs are expected to remove the need to design roads and lanes to account for human error. AVs' ability to move more precisely than human-operated vehicles will enable roads to be designed with narrower lanes.

Exactly how much lane widths could be reduced will depend on how AVs will be designed (i.e., how wide AVs are). It has been suggested AVs will be smaller than cars today, which could enable substantial width reductions once 100 percent of the vehicle fleet becomes automated. During the transition to a fully automated fleet, narrower traffic lanes may only be possible in dedicated AV lanes, which could be designated and striped much like high-occupancy vehicle lanes are now. But as AVs are adopted, all roadways may be designed with narrower lanes, which will leave more space for bicycle and pedestrian facilities, active streetscapes, or green spaces.

Second, AVs offer the potential for increased throughput (Anderson et al. 2016). As was discussed in Chapter 3, AVs are expected to improve the efficiency of automobile travel by reducing congestion caused by crashes, enabling vehicles to travel closer together, and improving traffic flow through intersections due to the emergence of free-flow intersections. When combined, these factors could significantly improve the vehicular throughput of existing roadways, although that could have negative consequences for bicyclists and pedestrians. The space needed to accommodate auto traffic could be reduced without negatively affecting throughput or congestion. At the very least, this may reduce the need for lane expansions. However, it is possible that AVs will enable road diets that accommodate the same amount of traffic with fewer lanes.

Traditional policies of roadway widening to support auto mobility may become irrelevant. According to Richard Biter, assistant secretary of the Florida Department of Transportation, there may be opportunities to condense public right-of-way by reducing the number of auto travel lanes and narrowing the width of travel lanes to less than the normal 11 or 12 feet. In fact, the state could use 9.5- or 10-foot lanes to "turn [a] four-lane express highway into a six-lane express highway with literally the same right-of-way footprint" (McFarland 2015).

If AVs reduce the space required for vehicular traffic, cities could retrofit the excess right-of-way to address a host of issues, including promoting active modes of transportation and stormwater management. The extra space no longer needed to move automobile traffic might be used to provide

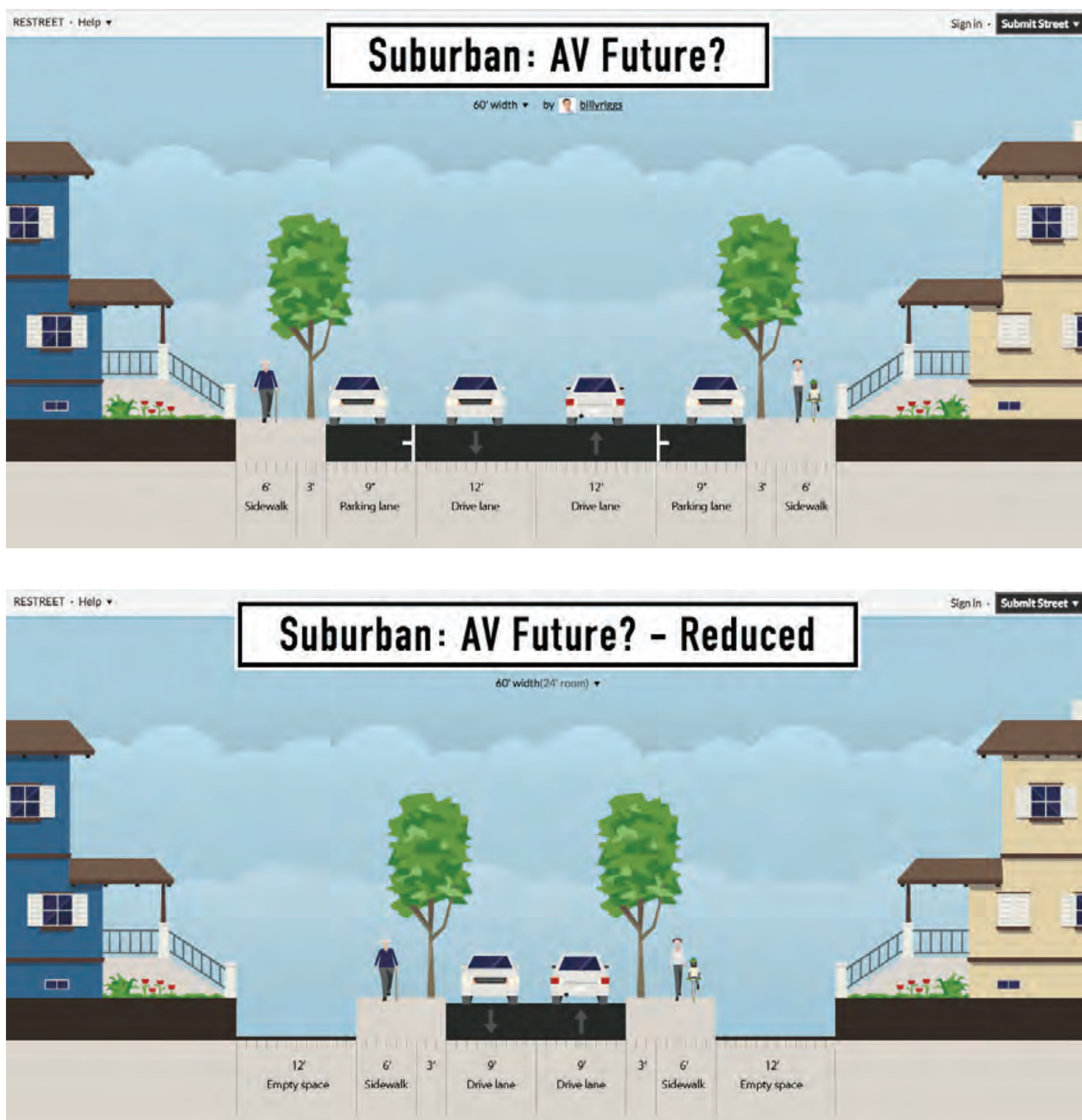


Figure 4.1. The possible transformation of a typical neighborhood streetscape in an AV future (app.restreet.com)

wider sidewalks, bike lanes, and more green space without requiring more right-of-way. Take for example a typical urban neighborhood street section (Figure 4.1, top). Schlossberg, Riggs, Shay, and Millard-Ball (2018) suggest there is a strong likelihood that on-street parking could be eliminated and lane width could be reduced to 10 or even nine feet on urban and suburban arterials.

As illustrated on the bottom of Figure 4.1, this right-of-way "recapture" is consistent with the idea of a road diet, in which traffic lanes previously dedicated to automobiles are repurposed for other uses. AVs' potential to reduce lane widths could yield ample space that could be allocated for other purposes, perhaps even resulting in repurposed private driveways and garages, as well as public reuse of former on-street parking areas (Schlossberg et al. 2018).

This also has implications for expanding complete streets and bicyclist and pedestrian facilities. In this way, AVs open the possibility of safer and more inviting urban places with more space for bicyclists, pedestrians, and other creative uses such as drop-off infrastructure (see the next section). However, opportunities to recapture right-of-way to promote complete streets may be limited until AVs have reached full adoption. Until every vehicle on the road is automated, lanes will still need to be designed to account for human-driven vehicles.

Ultimately, AVs offer opportunities to create a built environment that is more responsive to humans, but only if planners and engineers are willing and able to prioritize moving people over moving automobiles. With the emergence of truly human-centered design—as opposed to automotive-centered design—there is also potential for ripple effects on corridors and district land use. If AVs reinforce recent urbanization trends, then rezoning or upzoning for superfluous auto-serving uses, such as parking lots, service stations, and repair facilities, may follow. At the same time communities can and should plan for appropriate (potentially mixed use) facilities that can service and charge high-tech vehicles. These land-use policies are discussed in greater depth in Chapter 5.

ACCESS MANAGEMENT

The ability of AVs to drop off passengers before going to park themselves or to pick up another passenger is expected to bring a drop-off revolution to the transportation system. Space previously used for on-site parking is expected to be transformed into drop-off areas, and businesses will likely explore new site designs to allow for quick and easy ingress and egress onto adjacent roadways. Consequently, the transition from parking to drop-off areas will have far-reaching implications for access management, including the form, location, and design of curb cuts and drop-off/loading areas.

AVs remove the need for passengers to be with the vehicle when it parks, enabling passengers to be dropped off instead of having to exit the vehicle wherever parking is available. Users will likely want to be dropped off and picked up as close to their destinations as possible. In this way, AVs will shift the priority at the site level from parking to drop-off areas. Drop-off areas will no longer be relegated to special uses like bus stops, train stations, and airports but will become a staple in the design of urban spaces.

Drop-off areas can take different shapes and sizes and could be incorporated into the designs of various urban settings in different ways. In many cases, the form of the drop-off areas may be influenced by the existing built environment. In fact, several features of today's built environment could easily be retrofitted into drop-off areas, including turn lanes, frontage roads, and service roads. Since space will be at a premium in downtowns, there will likely be less space available for downtown drop-offs, particularly separated drop-offs. However, if AVs shift the priority from parking to drop-offs, on-street parking spaces may be retrofitted into drop-off lanes.

Although retrofitting existing infrastructure may provide opportunities for drop-off areas during the transition to AVs, once AVs are the predominant mode of transportation drop-off/pick-up areas will likely be fully integrated into the design of almost all urban spaces. Drop-offs may take several different forms, including pull-offs, cul-de-sacs, and frontage roads, but in all cases drop-off areas need to be separated from traffic lanes to ensure the safety of those entering and exiting the vehicles. Although drop-offs and pick-ups are a minor feature in today's transportation system, they are expected to be one of the most important design elements in an AV-dominated world. Transportation engineers and planners will need creative ways to reuse existing infrastructure and to develop completely new features to enable people to arrive at and depart from their destinations safely and efficiently.

SIGNAGE AND SIGNALIZATION

Traffic signs and signals are among the most important features of today's transportation system. They provide drivers with all the information they need to keep the transportation system running smoothly and efficiently. Signs and signals inform drivers when, where, and how fast they may go, and ensure traffic keeps moving safely and efficiently through intersections. In short, traffic signs and signals are necessary to prevent the transportation system from devolving into chaos.

However, the emergence of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technology is poised to revolutionize how information is transmitted to drivers and how traffic moves through intersections. Although this technology is not essential to AV technology, it will significantly improve traffic flow, reduce congestion, and help to bring all of AVs' potential benefits to fruition. The emergence of this technology will also have important effects on the built environment. Most notably, automated and connected vehicles offer the opportunity to declutter roadways by removing the need for many traffic signs and signals.

The Digitization of Street Signs

In the coming decades, information previously given to drivers through traffic signs (speed limit, road signs, stop signs, etc.), will be transmitted to the vehicle through V2I sensors embedded in the roadway infrastructure. AVs can then adjust their speed, direction, or route according to the information provided by the V2I "signs."

When AVs are first adopted and they share the road with human-operated vehicles, additional signs and signals may be necessary to delineate where automated and human-operated vehicles are and are not allowed to drive. However, once AVs make up most or all of the vehicle fleet, physical signs and signals are not expected to be necessary. Even lane striping could be phased out once vehicles can sense where other vehicles are on the road. While some AVs currently rely on road lines to help their navigation systems, the primary function of lane striping is to guide human eyes. More sophisticated systems may not need them, and they could be replaced by virtual lane systems embedded in the infrastructure.

In addition to serving as virtual signage, V2I technology could provide vehicles with real-time information on traffic delays and road work. AVs could then use this information to find the fastest and most efficient routes to their destination. While this could bring more traffic to neighborhood streets, the transition from street signs to V2I technology could serve to reduce traffic congestion and shorten travel times.

The Decline of Traffic Signals

V2I and V2V technology will also contribute to the replacement of traffic signals. Just like traffic signs, traffic signals will no longer need to be visible; instead sensors embedded in the road or placed in traffic towers will communicate traffic information to vehicles on the road.

At the very least, this means that physical traffic signals could be removed from intersections. However, the combination of automated and connected vehicle technology may completely revolutionize how intersections function by removing the need for traffic to stop at intersections. Instead, AVs able to sense and communicate with other vehicles will be able to flow freely through intersections. Each vehicle will simply react to other vehicles and cross traffic when an opening is available. While an overhaul of how intersections function (from a start-stop system to a free-flowing system) will likely not be possible until most or all vehicles on the road are automated, these ideas promise to significantly improve traffic flow and reduce congestion.

The Reorientation of Signage and Signalization

The only road signs and signals needed in an AV world are for pedestrians and bicyclists. AVs offer opportunities to reorient street signs and traffic signals from automobiles to pedestrians and redesign spaces to be more inviting to pedestrians and other modes of transportation. Street signs could be replaced by creative pedestrian wayfinding or other features that make streetscapes more appealing and attractive to pedestrians. In this way, AVs could make complete streets easier to implement, and could help create more attractive urban spaces and communities.

Redesigning Roadways and Intersections

The geometry and capacity of existing roads is designed for human drivers, so augmentations to accommodate AVs will be necessary—including how roads support multimodal travel for trains, bicycles, and pedestrians. As referenced in previous sections, it is likely that neighborhood streets could be narrower, intersections may not need signalization, and speed controls can become context sensitive (e.g., responding to inclement weather or other conditions). Road diets may become easier, given the increased level of service on existing roadways, and context-sensitive speed areas will be become more prevalent.

Yet these road diets may be only a part of what planners need to anticipate. The design of roads will likely need to evolve and city planners and policy makers will need to be ready to work with transportation engineers to address this. In a fully autonomous environment, reversible lanes or advanced traffic control could be extended to dynamically allocate major portions of infrastructure (Smolnicki and Sołtys 2016; Bertozzi, Broggi, and Fascioli 2000).

At the same time, the adoption of AVs may not support recent planning efforts to change one-way streets to two-way, increase bicycle and pedestrian levels of service, or create more informal, Dutch woonerf-style streets that transform auto-dominated rights-of-way into shared spaces that accommodate all modes of transportation (Minneapolis Department of Public Works 2010; Brant 2016). While research has suggested one-way streets are less safe and efficient (Riggs and Gilderbloom 2016a, 2017; Gayah and Daganzo 2012), driverless cars may function better on one-way corridors than human-operated vehicles, and they perform better in roadway environments with formal rules and clearly indicated pathways for different modes (Kelly et al. 2006). During the period of transition from few AVs on the road to AV predominance, AV technology will likely require mode separation.

While advances in autonomous traffic control and reversible lanes may provide opportunities to improve pedestrian facilities that planners should advocate for at the federal level, there is also a need to create protected streets that support bicycle and pedestrian travel and vibrant and attractive urban spaces and places. While this does not preclude shared streets or less formally designated pathways for various modes, it does mean that rules of engagement and modal priorities need to be clearly articulated.

Riggs and Boswell (2016a) suggest that service expectations should be codified for human-centered modes, something that will be further explored in the next section. This may provide a starting point in thinking about future roadway infrastructure. Clearly AV technology will continue to evolve, and it is important that we co-evolve our thinking about street infrastructure to optimize safety in an autonomous and connected system.

INTERFACE WITH BICYCLES AND PEDESTRIANS

The coming AV revolution offers substantial benefits for the efficiency and safety of vehicular travel. Less clear, however, is the impact of AVs upon travel by bicyclists and pedestrians. While AVs have the potential to improve the functioning of vehicular systems, one view is that AVs may make bike and pedestrian travel within urban settings far more complicated and less easily achieved. Alternatively, because AVs will require less urban space than traditional vehicles, the technology offers some promise for the development of high-quality, attractive, separated bicycle and pedestrian infrastructure.

How AVs Might Hamper Bicycle and Pedestrian Travel

The transition from human-driven to automated vehicles promises to bring radical changes, but without significant investments in bicycle and pedestrian infrastructure it would fundamentally remain an auto-oriented system. As AVs become the dominant mode of transportation, travel by nonvehicular modes may be hampered by two key factors. First, AVs require no signalization and signage to regulate traffic flow. As a consequence, red lights and stop signs that provide for safe intersection crossings may become a thing of the past. Pedestrians and bicyclists attempting to travel in dense urban settings where traffic never stops could be left waiting for long periods for a break in traffic, slowing their travel.

Second, AVs will likely require regular drop-off and pick-up zones along most corridors. These zones allow riders in AVs to access their final destinations easily, as well as allow riderless vehicles the ability to pick up passengers. These zones require space for the AVs to access individual sites and space for AVs waiting to pick up their riders. Depending upon their design and location, these loading and unloading zones could fragment bicycle and pedestrian networks and make travel via these modes more cumbersome. Poorly designed urban streetscapes that are dominated by AV drop-off and idling zones could have the effect of depressing bike and pedestrian travel.

How AVs Might Support Bicycle and Pedestrian Travel

While free-flow traffic conditions and drop-off zones may complicate bicyclist and pedestrian travel in urban areas, the AV revolution also holds some promise for urban settings that serve humans first and vehicles second. AVs may require far less space within urban settings; lane widths will become narrower, fewer vehicles on the road will make road diets more feasible, and the need to provide parking at every destination will evaporate. Urban environments will also be less cluttered by traffic signalization and signage, offering opportunities for more attractive bicycle- and pedestrian-friendly corridors.

Taken together, these possibilities suggest that roadways and urban environments could be redesigned in ways that will yield more enjoyable travel for bicyclists and pedestrians. Many more urban corridors could become complete streets, with separate rights-of-way for AVs, bicyclists, and pedestrians. Reduced vehicular signage could open up opportunities for signage and advertising aimed at bicyclists and pedestrians, such as wayfinding signage, rather than drivers and riders in vehicles. Surface parking and monolithic parking garages will become surplus and ultimately can be replaced with more residential and nonresidential development or parks and plazas that serve as social spaces and places for physical activity.

PARKING

Without the need for a human driver to park the vehicle, the adoption of AVs will likely lead to a significant change in the design of parking in urbanized areas. As parking currently constitutes a significant percentage of the developed land in urbanized areas, the impact of AVs on parking location, design, and amount required may be among the most significant changes to the built form of cities. Ultimately, far less space will need to be dedicated to parking, and the need for human-centered, human-scaled design for parking areas will be significantly reduced or eliminated once AVs become the dominant mode of transportation.

Parking Location

AVs are expected to significantly affect the location of parking facilities in urbanized areas. As AVs can drop passengers off at a destination and drive elsewhere to park, parking will not necessarily need to be provided on-site at every business, office, or residence. As a result, it is possible that parking in urban areas could be consolidated outside of city centers. Larger-scale, AV-only parking garages or lots could be located on the periphery of urban centers where land values are not at a premium and development pressures are less intense. This relocation of parking facilities away from the urban core will likely open up significant infill redevelopment opportunities.

Additionally, it is probable that on-street parking will not be needed for AVs as human passengers will no longer require parking at or near their destinations. The space once used for on-street parking could be repurposed to accommodate drop-off lanes or other right-of-way features, such as bike lanes or sidewalks.

Parking Facility Design Considerations

The shift from on-site to remote parking facilities will not occur all at once, as human-driven vehicles will need to be accommodated on-site or nearby until the entire vehicle fleet is automated. It is probable that during this transition, automated and human-driven vehicles may need separated parking facilities to ensure AV efficiencies can be realized. For example, AVs are expected to be able to park much closer together, as vehicle doors will not need to be opened after the car parks itself. As a result, AVs could provide significant parking efficiencies in terms of the size and number of parking spaces accommodated within a particular building footprint or surface parking lot.

However, during the transition, human-driven vehicles will still require parking designed for humans. Separate parking facilities for automated and human-driven vehicles could capitalize on the space efficiencies of AVs while still meeting the parking needs of human-driven vehicles. The most efficient parking paradigm to guide the transition to AVs would thus include on-site parking facilities designed for human-driven vehicles and off-site parking facilities for AVs. Over time, the on-site facilities would gradually shrink to accommodate the decreasing number of human-driven vehicles on the road, while off-site AV parking facilities grow to take their place. As will be discussed further in Chapter 5, this likely would require cities to develop separate parking standards for automated and human-driven vehicles, including different dimensions and different minimum parking requirements.

Ultimately, parking structures for AVs will likely not need to take humans into consideration in the design and location of the facilities. Therefore, structured parking for AVs would not need to include human-friendly design and safety features such as lighting, elevators, and other amenities. Rather, AV structured parking could be located underground or in other underutilized or out-of-the-way locations, with relatively little lighting or climate control. Some parking in highly accessible areas may still be necessary to allow for quick vehicle response when hailed, but in this scenario, only limited access for humans would need to be provided, such as maintenance stairways and other limited facilities to allow for human access.

Reduction in Amount of Parking

In addition to the substantial changes in where parking is located and how it is designed, AVs are also expected to significantly reduce the amount of parking required to meet demand. AVs promise to do this in two ways: by making more efficient use of existing parking and reducing the overall demand for parking.

V2I communication could enable a more efficient use of the parking supply by notifying AVs as to the location of the nearest available parking spots. Previously underused parking would become an important part of the parking supply.

More importantly, if AVs are owned under a shared model, some vehicles may not need to park after dropping off a passenger but would instead move on to the next human user. It is also possible that after passenger drop-off a privately-owned AV could return to the owner's residence, travel to a remote staging area for maintenance and fuel, or circle the block instead of parking. All of these potential factors would result in the reduction in the amount of needed parking.

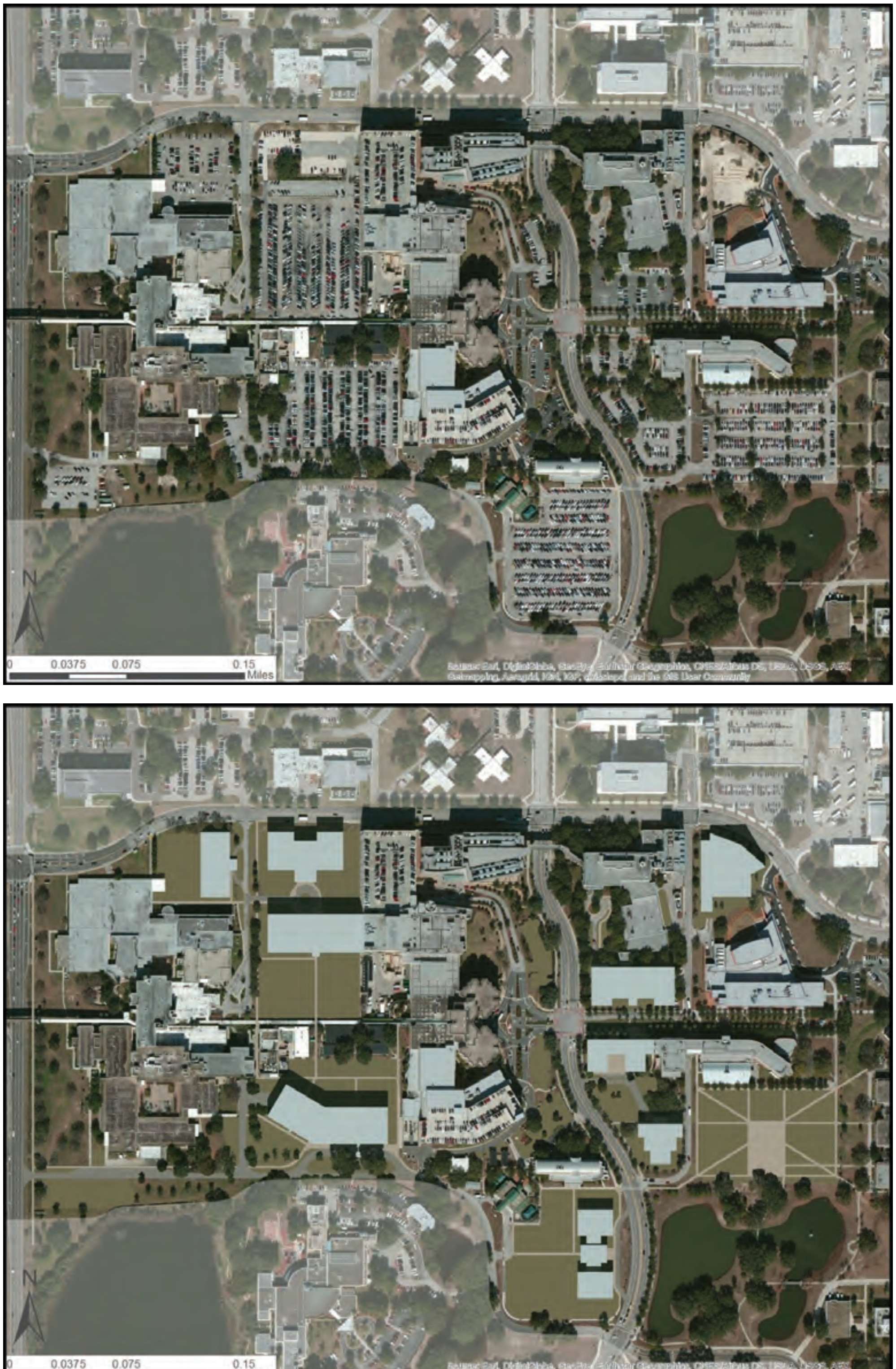


Figure 4.2. Conceptual site plan of parking redevelopment opportunities on the University of South Florida's campus (Chapin et al. 2016)

Figure 4.3. Example of a typical streetscape today (Chapin et al. 2016)

Figure 4.4. Conceptual design of a partially automated streetscape (Chapin et al. 2016)

Figure 4.5. Conceptual design of a fully autonomous streetscape (Chapin et al. 2016)

REDEVELOPMENT OPPORTUNITIES

By reducing the amount of needed parking and relocating parking away from city centers, the widescale adoption of AV technology will create significant urban redevelopment opportunities. In particular, the reductions and relocation of parking will allow the transformation of urbanized areas. Potential site design norms may be revolutionized with the ultimate adoption of a fully automated vehicular fleet.

Transformation of Urban Centers

With the anticipated reduction in the number and size of parking spaces, AVs provide an important opportunity to rethink, revitalize, and redevelop urban centers. The reduction and relocation of parking could open up significant land area for infill development within these areas.

While market forces will play a large role in how newly available land is redeveloped, policy makers will also have roles in determining how publicly owned land once used for wider roadways and parking lots will be repurposed. Underutilized parking lots could become an important resource that could be used to achieve community goals. Available land could be used to enhance placemaking or beautification efforts, or for recreational facilities, parks, drainage, or other similar purposes. Market demand may also lead to the redevelopment of newly available land for residential or commercial uses.

A transformation in urban land uses due to AVs will undoubtedly occur gradually over a period of decades. During this transition period, urban settings where a clearer separation between human drivers and AVs is possible could feature prominent land-use changes. For example, enclosed environments where AV-only zones are more plausible, such as college campuses, could be among the first places to experience significant land-use changes. Figure 4.2 (p. 47) provides a vision for how parking at the University of South Florida's Moffit Cancer Center could be redeveloped into research facilities, classrooms, and park space. Simply by redeveloping the surface parking (parking garages were left in place), the university could increase the square footage of facilities by more than one-third and still have plenty of space left over for parks and green spaces. Land-use changes may also be more prominent along highways with dedicated AV lanes, along AV-only drop-off and pick-up areas, and in the areas surrounding AV-only parking facilities.

Site Design

As on-site parking is reduced, site plans for commercial and residential development will change. Local develop-

Figure 4.6. AVs' transformation of a city block—before and after (Chapin et al. 2016)

ment regulations will likely reduce—or completely eliminate—on-site parking requirements. This will result in an evolution of site planning from a focus on meeting parking requirements to designing building envelopes and amenities that more efficiently use sites.

Since AVs will likely drop off passengers at their destinations, newly constructed buildings may be located closer to the abutting road frontage and site plans may include drop-off areas that are adjacent or connected to the building. In areas with high traffic volumes, multiple drop-off areas could be designed to mitigate crowding and congestion. Commercial strip centers alongside major highways could consolidate entrances and exits, increasing buildable area on a site-by-site basis and potentially improving traffic flow. This could also allow for fewer turn lanes and the ability to repurpose existing turn lanes. Access roads off main thoroughfares may also be redesigned to act as drop-off areas easily accessible from highways.

NEW DESIGN PARADIGMS

By combining all six of these major types of built environment changes, we can begin to get a picture of what the future in an AV world might look like. This section provides two visualizations of how AV technology may transform public spaces over time.

Figures 4.3 through 4.5 (pp. 48–49) show how a typical arterial road might change over the next 50 years. The first image (Figure 4.3) depicts a roadway in Tallahassee, Florida, in 2016. It is characterized by wide lanes, frequent curb cuts, large traffic signals, and parking located in front of buildings.

As AVs begin to be adopted (Figure 4.4), some notable changes are expected, including separated AV lanes. These lanes are narrower and allow room for added bicycle lanes. Turn lanes, medians, and traffic signals remain.

Once AVs become the dominant mode of transportation (Figure 4.5), all of the lanes could become narrow AV lanes, which allows for separated or protected bike lanes and more attractive pedestrian infrastructure. In other areas, drop-offs would replace on-street parking or be prioritized over bike lanes. Medians would disappear, and in some cases lane striping itself may be a thing of the past. Traffic signals would be replaced with V2I communication infrastructure. Pedestrian wayfinding signage will be the only signage needed. Instead of typical strip mall-style buildings with parking in front, buildings can move up to the street. Overall, what was an uninviting arterial whose primary purpose was simply to move traffic as fast as possible has now been turned into an attractive, people-friendly, efficient, and safe urban environment that could draw people in and provide more inviting spaces to live, work, and play.

Similarly, Figure 4.6 (p. 50) shows how AVs could transform a typical city block. Before the adoption of AVs, most city blocks needed to include a significant amount of parking to accommodate the block's residents and commercial patrons. This included large surface lots as well as on-street parking. However, in an AV world, on-street parking could easily be retrofitted into a drop-off lane providing easy access to the blocks' destinations. Since vehicles could drop off passengers instead of parking, surface lots become significant opportunities for urban infill development.

CONCLUSION

Like many technological advances before it, the rise of AV technology is poised to have a significant impact on the built environment in our communities. In particular, the widespread use of AVs could have major impacts on roadways and rights-of-way, access management, signage and signalization, pedestrian and bicycle facilities, parking, and development opportunities. However, none of these land-use changes will happen in a vacuum independent of the other impacts. Right-of-way implications will affect pedestrian and bicycle spaces. Revolutionary changes to intersections and signage will change both the experience of those in vehicles and that of pedestrians and bicyclists near the roadway. Parking implications will affect demand for drop-offs and opportunities for redevelopment. Site design will change to address this new demand.

In short, by coupling a denser urban environment with the ability to narrow rights-of-way and enhance bicycle and pedestrian facilities, AVs provide planners and policy makers with excellent opportunities to revitalize urban centers and create thriving urban spaces. However, the technology will also create major challenges to capitalizing on these opportunities and achieving these goals. Careful planning will be required to shape AVs' built environment impacts to create safer, more efficient, and more vibrant communities. The following chapter will provide planners with information and guidance on how to begin proactively planning for the coming built environment impacts.

CHAPTER 5

CONSIDERATIONS FOR POLICY MAKING AND INFRASTRUCTURE INVESTMENTS

As described in Chapter 4, autonomous vehicles will cause the next great transformation, not only in our transportation systems, but in the entire built environment. How planners respond to this opportunity will shape the impact AVs will have on our communities.

By proactively leveraging AV technology to create great urban places, planners could reshape urban areas in ways that promote safe, sustainable, and people-centered environments. However, a concerted effort will be required if planners are to take advantage of AVs' placemaking potential.

The challenges described in Chapter 3 suggest that without careful planning, AVs may: (1) exacerbate auto-oriented sprawl, (2) increase vehicle miles traveled (VMT) and emissions, (3) adversely affect active modes of travel and public health, (4) impact transit, and (5) lead to more acute social equity issues.

In a white paper published by the American Planning Association, Henaghan et al. (2018) present four principles to guide AV planning efforts. These principles are:

- The time to begin planning is now.
- Good planning principles still hold.
- Planning must anticipate the disruptive effects of technology, both positive and negative.
- Planning must account for uncertainty.

Planners need to begin proactively applying sound planning principles and best practices to the comprehensive impacts of AV technology, as outlined in Chapters 3 and 4, in ways that consider a range of possible futures and are flexible enough to account for rapid changes in technology and behavior. To do this, planning agencies may need to move toward more iterative, scenario-based planning processes to inform their long-range planning efforts. This chapter will provide planning policy ideas and infrastructure investments that apply these principles first to AVs' opportunities and challenges and then to AVs' built environment impacts.

ADDRESSING PLANNING OPPORTUNITIES AND CHALLENGES

Like any major technological innovation in transportation, AVs offer a host of important opportunities and difficult challenges that planners will have to navigate if they are to work toward building better communities. These issues were introduced in Chapter 3, and here we tie back directly to these challenges, as addressing them appropriately leads to much of the promise of AVs. It is vital for planners to understand the implications of AV technology for their communities and to develop policy and infrastructure solutions that will address them. To that end, this section is intended to provide guidance on how to capitalize on AVs' opportunities while mitigating their challenges.

Addressing Impacts on Auto-Oriented Sprawl

As discussed in Chapter 3, it is expected that AVs will both promote sprawl and support reurbanization at the same time. By reducing the cost of travel and enabling people to work or relax during their commute, AVs threaten to exacerbate sprawling development patterns by allowing people to live even further away from urban centers. However, AVs will simultaneously provide opportunities for reurbanization by opening underutilized parking lots for infill development and by supporting shared mobility services that would bolster urban, carless lifestyles. Planners' policy responses to this challenge may affect whether AVs ultimately encourage sprawl or more compact development.

Discouraging Auto-Oriented Sprawl

If AVs reduce travel time and stress so that living farther from city centers is not a burden, the only factors keeping development from moving farther into exurban and rural areas would be land-use regulations, the relative cost of development, and demand for an urban lifestyle. Land-use regulations that constrain exurban development and promote infill may be the primary ways to prevent further sprawl and encourage urban revitalization. However, since AVs open the potential for long commutes that extend well beyond jurisdictional boundaries, AVs will also elevate the need for regional growth management strategies that consistently apply growth management tools across jurisdictional lines. Regional strategies would require extensive coordination efforts, but they could work to constrain development to activity centers within each jurisdiction.

To enhance these growth management efforts, municipalities could also consider providing incentives to redevelop underutilized parking facilities into higher and better uses. The reduction in the demand for parking opens new opportunities to create vibrant urban spaces through infill development. However, given the relative expense of redeveloping parking facilities compared to greenfields, these incentives may have to be coupled with growth management strategies (e.g., urban growth areas) that focus development. Otherwise the incentives are not likely to be strong enough to entice infill development and to prevent greenfield development from stretching farther and farther away from city centers.

If shared AVs develop into a primary mode of transportation, shared mobility service may naturally reinforce growth management strategies. Similar to transit systems today, shared mobility providers could likely provide better service within dense urban environments. If AVs, especially shared AVs, encourage a decline in car ownership as some researchers have suggested (Fagnant, Kockelman, and Bansal 2015; McDowell 2014; Schoettle and Sivak 2015), many people may be dependent on shared service and would be more likely to live near urban centers for the mobility benefits. In this way, shared AVs may naturally mitigate sprawl and encourage compact development.

Rethinking Parking

Parking is one of the key links to the land-use and sprawl-related impacts of AVs. AV technology is expected to transform the design and location of parking infrastructure in our urban centers. As the need and demand for on-site parking is significantly reduced, and ultimately eliminated, parking infrastructure is likely to be pushed to and consolidated at the city periphery where land is more readily available and affordable. For policy makers, regulatory considerations include issues related to the permitting of consolidated and structured parking.

Local jurisdictions should identify appropriate areas to locate AV parking, and determine how peripheral parking structures may influence adjacent land uses. Special consideration may need to be given about whether to locate these parking structures in industrial areas, or whether other areas on the urban fringe are more appropriate. These areas should be appropriately designated in comprehensive plans and other planning documents. Also, once specified areas are designated for these parking facilities, transportation agencies will need to consider whether appropriate road infrastructure exists to serve these parking locations or if additional roadway capacity will be necessary. If the majority of AVs are electric vehicles, then parking facilities will also need to be designed to incorporate charging facilities. Finally, as noted above, local governments may consider if and how they might incentivize the redevelopment of existing parking facilities to revitalize urban cores and make better use of largely underused parking spaces.

State, regional, and local agencies must also consider how to revise building and engineering codes to accommodate the design and construction of consolidated AV parking structures. Building codes may need to be revisited to relax requirements for human-centered amenities in parking facilities, such as climate control, passageways, turning radii, elevators, and potentially even lighting.

Addressing Impacts on Increased VMT and Vehicle Emissions

As noted in Chapter 3, the lowering of both perceived and monetary costs of travel by AV has the potential to increase automobile travel by commuters, riders that have traditionally relied on transit or other transportation services, and nondrivers. VMT and the resulting vehicle emissions also have the potential to increase through "zero-occupancy" trips as empty AVs travel between use and parking. An important factor in both reducing the overall number of AVs on the road and achieving maximum efficiencies in their use is the shared use of AVs.

Promoting Use of Shared AVs

As was introduced at the beginning of this report, many have speculated that a large part of the AV future will be shared. In fact, many researchers have predicted that the three revolutions in urban transportation will be the automation, electrification, and sharing of the transportation system (Fulton, Mason, and Meroux 2017). While this has been largely fueled by the rise in transportation network companies (TNCs) such as Uber and Lyft, and by the urban lifestyles of many millennials, it also is a product of vehicle cost. Many manufacturers are pursuing driverless electric fleets as they roll out their highly autonomous (Levels 4 and 5) vehicles. This shift to shared mobility will be key in capitalizing on the planning opportunities and addressing the planning challenges identified in Chapter 3. Shared AVs could reduce VMT compared to single- and zero-occupancy vehicles and could also promote social equity by reducing the cost of travel.

Highlighting the land-use and environmental benefits of car- and ride-sharing services will be an important part of planners' roles going forward, particularly since research is already showing that these services are likely to result in increased reliance on on-demand access to cars (Clewlow and Mishra 2017). Planners need to consider multiple policies, particularly in the arena of equitable access, as the highest levels of vehicular access will continue to be in urban centers with higher levels of density to support these services. As such, this could increase the gap between the urban rich and the poor (both rural and urban), and planners should work to implement the following policies.

- **Strengthen and link to TDM efforts.** Policies should be linked to transportation demand management efforts and discourage increased and longer trips. Some partnerships are already being explored by TNCs to reduce single-occupancy vehicle ownership and use (e.g., Lyft's pilot trip reduction program). Incentives for vehicle sharing might be established and linked to development conditions of approval. Further shared mobility policy frameworks can be found in PAS Report 583, *Planning for Shared Mobility* (Cohen and Shaheen 2017). Table 5.1 (p.56) provides a summary of three policy frameworks outlined in PAS Report 583.
- **Plan for increased densification and intensification.** Similar to transit systems, shared mobility and TNCs are more viable in dense urban environments as higher densities of riders improve the efficiency and cost-effectiveness of these systems. Continuing to pursue sound planning principles and strategies to create vibrant urban environments by progressively increasing the density and intensity of development will support the use of shared AVs and improve the cost-effectiveness of shared mobility. These initiatives will need to take different forms in different contexts, as appropriate densification strategies should be tailored to downtowns, other urban districts, and suburban areas.
- **Explore car-free downtowns.** In conjunction with increasing the prevalence of drop-off zones (discussed further below), consider limiting single-occupant automobile access to downtowns, business districts, or academic and medical campuses, especially in the most congested areas. Such restrictions can be accomplished through street closures, traffic calming, and time-of-day pricing or access.
- **Look at data sharing and behavior.** At the same time as they are managing and encouraging shared use of AV platforms, planners and policy makers need to explore opportunities and partnerships to assess and facilitate sharing behavior. Efforts to create partnerships with TNCs are especially important as they capture travel data that would be useful for planning purposes. At the same time, it is important to develop transportation demand management policies, including monetary and behavioral strategies, that reduce the number and duration of trips.

Reevaluating Access Management

An important piece of the shared-AV puzzle is providing appropriate infrastructure. As AVs grow in popularity, more and more users will likely want to be dropped off near their destination instead of parking farther away and walking. Designated areas for dropping off and picking up AV passengers will likely become a common feature for roadways and site plans. However, if unregulated, these areas could cause congestion problems by backing up traffic into streets.

To accommodate drop-off areas without creating traffic or safety problems, state and local agencies will need to create new design standards for drop-off areas and drop-off lanes. In particular, specifications for the length, number of drop-off points, or number of lanes required for a site's drop-off area may be necessary. These standards need to be tailored to the size and expected demand of drop-off areas to prevent a traffic backup. Separate standards for different categories of drop-off areas may even be necessary (e.g., shopping malls would require larger drop-off areas than small businesses). In high-density areas such as downtowns, it may also be important to separate drop-off areas from pick-up areas to make the arrival and departure process as efficient as possible and to ensure that drop-off areas do not impede the flow of traffic. Another option to reduce the number of ingress and egress points in dense urban areas would be to strategically place drop-off areas to serve an entire block (Dennis et al. 2017).

Regardless of the setting or the design of drop-off/pick-up areas, another vital feature of pick-up areas in particular will be passenger waiting areas. Riders will need safe and comfortable spaces to wait for their vehicles. The design of these areas could borrow cues from existing best practices of bus stop design, including the need for shaded and covered places to sit.

TABLE 5.1. SHARED MOBILITY POLICY APPROACHES FOR LOCAL GOVERNMENTS

	Shared Mobility as an Environmental Benefit (maximum governmental support)	Shared Mobility as a Sustainable Business (moderate governmental support)	Shared Mobility as a Business (minimum governmental support)
Allocation of Rights-of-Way	Jurisdiction may allocate public rights-of-way (such as parking, loading zones, etc.) on a case-by-case basis or through more informal processes, such as nonbinding council/board of director resolutions.	Jurisdiction that once allocated public rights-of-way through an informal process formalizes this process.	Jurisdiction maintains a highly formalized and established process for the allocation of public rights-of-way, including a process for allocation among multiple operators.
Fees and Permits	Recognizing the social and environmental benefits of shared mobility, jurisdiction provides public rights-of-way free of charge or significantly below market cost.	Fees may be based on cost recovery of providing rights-of-way (e.g., fees based on foregone meter revenue and administrative costs) associated with providing on-street parking. In other instances, fees may be reduced to reflect environmental goals, such as charging a reduced carpooling rate for car-sharing parking.	Fees are based on a cost-recovery or profit-based methodology. This could include permit costs, lost meter revenue, and administrative expenses for program management.
Signage, Markings, and Installation	Jurisdiction pays for the sign installation and maintenance, striping, and markings associated with the shared modes.	Jurisdiction pays for the installation, and the operator pays for the maintenance of signage, striping, and markings.	Jurisdiction requires shared operators to pay for the installation and maintenance of signage, striping, and markings.
Social and Environmental Impact Studies	Jurisdiction requires that shared operators study and document local social and environmental impacts at regular intervals.	Jurisdiction may require that shared mobility operators study and document local social and environmental impacts on a one-time basis or at regular intervals.	Jurisdiction does not require any social and environmental impact studies of shared mobility.
Public and Stakeholder Involvement	Informal process, if any, led by the jurisdiction to elicit public input into the location and scaling of shared modes on public rights-of-way. For example, staff may internally determine the location and number of car-sharing parking spaces or public bike-sharing stations without public comment.	Informal process where the jurisdiction and shared mobility operator seek public input into the locations of shared services through public notification and staff management of possible public concerns.	Highly formalized process where shared mobility operators are responsible for obtaining public input and approval on the locations of services through neighborhood councils, commissions, or formal hearings.

Source: Cohen and Shaheen 2017

Local governments may also consider making some changes to existing zoning codes to better accommodate drop-off areas, including reducing the required number of parking spaces, reducing setbacks, and specifying drop-off design standards. In effect, parking requirements may be replaced by specifications for the number of drop-off points required for a site's drop-off area depending on the number of trips the destination was projected to generate. In addition, drop-off areas could consistently be integrated into small area and corridor plans to ensure sufficient vehicle access is provided while minimizing conflicts with bicyclists and pedestrians. Specific policies are outlined as follows:

- **Establish locations for pick-up and drop-off zones for passengers and deliveries.** To ensure lively downtown environments, cities should put curb policy into practice by first considering appropriate locations for drop-offs. Such locations should be areas with high curbside activity (existing or planned) for passengers and goods. Cities should determine where to best locate drop-off zones to serve several buildings at a time and to minimize conflicts among modes. This could include use of side streets, alleys, or hubs. For example, in 2017, New York City adopted a suite of measures to ease roadway and curbside congestion. This initiative involves six city departments and comprises five focus areas, including curb lane flow and curb access restrictions (New York 2017). Such initiatives offer a preview of how to manage the growing demand for curbside access.

- **Design pick-up and drop-off zones to minimize conflicts and optimize flows.** Design is important to minimize conflicts, facilitate seamless transfers, and moderate flows of multiple vehicles. For example, many buildings use circular driveways for passenger pick-up; however, this creates two curb cuts, increases stress for pedestrians, and occupies valuable sidewalk space. It also creates a complex navigation system for autonomous vehicles of multiple types: cars, transit vehicles, and delivery ground drones. Rethinking the designs of pick-up and drop-off zones will be important to improve flows and minimize conflicts in the AV future.
- **Create pick-up and drop-off regulations and management schemes**. Controlling the operation of vehicles on the street will be essential to manage the constant flow of vehicles expected with shared autonomous travel and deliveries. Again, New York City's new measures to manage congestion may provide a glimpse of how to prioritize and manage flows among personal, transit, and delivery vehicles, as well as pedestrians and other sidewalk uses. Operating parameters can be programmed to limit or provide access; for example, AVs can be limited to certain locations in the city or their curb access limited to certain hours. Curbside regulation should prioritize transit to ensure the rise of shared AVs does not prevent transit vehicles from accessing the curb at bus stops (NACTO 2017).

Addressing Impacts on Active Travel and Public Health

The impacts of AVs on active travel and public health could be quite significant, particularly if they make automobile use easier and induce more demand. That said, there are numerous opportunities to reinforce planning values and shape the built environment to support AVs alongside other modes, especially in the near term. Much of this involves rethinking the right-of-way in terms of modal priorities, which academics and practitioners are beginning to do.

This section is not intended as a step-by-step guide to navigate the transition to an AV world, but rather as a starting point for preparing for AVs' influence on the built environment. Key considerations to incorporate into infrastructure investments and redevelopment decisions are highlighted as they relate to different elements of the built environment.

Rethinking and Reprioritizing Rights-of-Way

Retrofitting existing roadways and rights-of-way to accommodate the efficiencies of AVs may be among the first and most important steps for state and local transportation agencies to prepare for the emergence of AVs. Agencies will need to adjust how streetscapes are designed and engineered, as well as how and where roadways are planned and built. When changing roadways to accommodate new vehicle types, planners and policy makers should highlight the benefits of designs that use placemaking to retrofit roadways and create strong and healthy places.

What will not change:

- The placemaking imperative and how walk/bike integration is key to gaining multiple benefits, economic benefits in particular
- The importance of efficiently moving more people through space
- The need to manage multiple modes of transportation
- The need for variety in street networks and designs to serve a variety of contexts and users

What will change:

- The consideration of rights-of-way as amenities rather than infrastructure to move cars
- The ability to digitally control traffic (in addition to controlling via curbs, medians, paint, and signage)
- The need for redundant systems, given technology's vulnerabilities
- The introduction of speed as a determinant of street management (for example, there will be low, medium, and high-speed automated vehicles; there is already growing tension between electric bikes or scooters and human-powered bikes)

Schlossberg et al. (2018) recommend three basic principles in rethinking streets: thin the lanes, remove parking, and think shared. These provide general guidance for policy development and are also consistent with what planners might consider "good planning." They might serve as primary goals, but what specifically should planners and policy makers be doing to rethink their roads? This is an important consideration that revolves around the two basic approaches to right-of-way design—planning and engineering.

First, in the planning sphere, it is important that AV considerations be integrated with the design of streetscapes and road networks. Trip generation, level-of-service (LOS) models, and planning documents for all modes need to take AVs into account. In that light the following policies are of great import.

- **Create a modal hierarchy for roadway space and modes.** Local plans should create modal hierarchies that frame project and funding priorities. These hierarchies can be broken out by roadway type (e.g., neighborhood, collector, arterial) or be consistent citywide. They should set policy thresholds for how roadway space can and should be allocated in planning and transportation documents. An example of this kind of modal hierarchy is provided in the circulation element from the general plan of San Luis Obispo, California (Table 5.2). The planning document allocates funding along the same lines.
- **Integrate AVs into current plans.** Proactively addressing AVs in current plans is vital because the planning horizons of most long-range transportation plans extend well beyond when AVs are projected to become available. At the regional and local levels, agencies will need to begin considering the impact of AVs on travel demand and throughput as they develop their long-range plans. In particular, regional transportation planning bodies will need to reconsider whether future lane-expansion projects will be necessary if AVs reduce congestion and increase the throughput of each lane. To inform this process, continuing research assessing the effect of AVs on throughput and travel demand will be necessary to provide guidance on how many lanes are required and where road diets could be appropriate.
- **Transition to VMT-based models.** Planning documents should reflect the potential for AVs to reshape roadways and increase efficiency, and they should plan for that space. In some cases that will mean accepting a LOS that is below local thresholds, as well as moving to using models based on VMT or person-miles traveled instead of traditional LOS models. VMT models are already being used in many cities in the U.S. These models plan for trips and trip length while not penalizing dense urban development through the environmental review process by allocating them greater numbers of auto trips than more suburban developments with fewer people. Emerging policy must focus on VMT as an environmental impact (regardless of fuel type or efficiency standard) and underscore efforts to shift away from LOS traffic analysis.
- **Expand LOS analyses to include pedestrian, bicycle, and transit service.** LOS analyses have traditionally focused solely on service to automobiles. Expanding LOS analyses to account for other modes of transportation, particularly at the local level, will help to shift the focus from moving vehicles to improving the mobility for everyone. This will also serve to ensure investments in AV infrastructure do not fragment bicyclist and pedestrian networks or reinforce an auto-oriented transportation system, as was discussed in Chapter 3.
- **Incorporate AVs into transportation demand models.** AVs will need to be incorporated into travel demand modeling standards and practices. Pilot projects and ongoing testing of AVs, particularly AVs in real-world settings, will be a vital part of informing the data and assumptions underpinning the demand modeling process. Once AVs are

TABLE 5.2. CITY OF SAN LUIS OBISPO, CALIFORNIA, MODAL HIERARCHY

Complete Streets Areas	Priority Mode Ranking
Downtown & Upper Monterey Street	1. Pedestrians 2. Bicycles 3. Transit 4. Vehicles
Residential Corridors & Neighborhoods	1. Pedestrians 2. Bicycles 3. Vehicles 4. Transit
Commercial Corridors & Areas	1. Vehicles 2. Bicycles 3. Transit 4. Pedestrians
Regional Arterial & Highway Corridors	1. Vehicles 2. Transit 3. Bicycles 4. Pedestrians

Source: Table 3.3, City of San Luis Obispo General Plan, Circulation Element (2017)

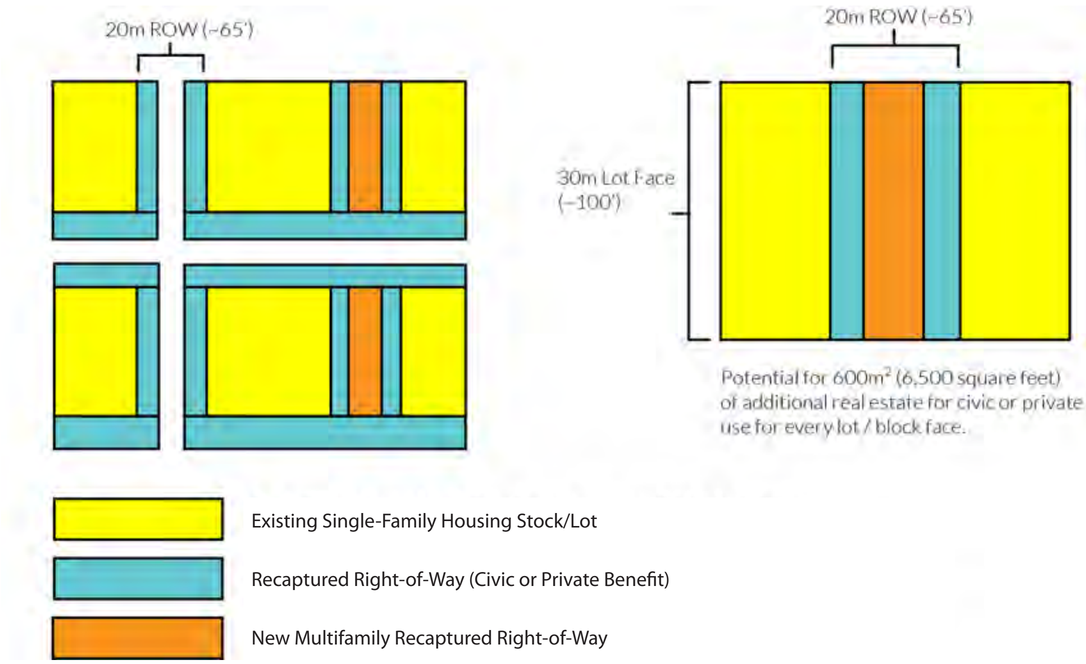


Figure 5.1. Right-of-way recapture concept (Appleyard and Riggs 2017)

integrated into modeling methods, they can be an integral part of informing the long-range transportation planning process determining when and where new roads, roadway expansions, and potential lane reductions are necessary. As technology improves, planners could even begin exploring how the same algorithmic and machine-learning processes that run AV technology might inform new ways of thinking about activity-based transportation models in land-use and transportation planning processes.

Secondly, in the engineering realm, roadway design manuals need to be refreshed so planners and engineers can take advantage of opportunities for multimodal and complete street solutions that harness the power of potential right-of-way gains. As suggested in a 2018 Transportation Research Board paper by Appleyard and Riggs (2017):

> In neighborhood right-of-ways and areas of high pedestrian activity, pedestrians, cyclists and vulnerable road users should be protected by (a) reduced auto right-of-way; (b) routing traffic onto appropriate streets (commercial over residential) and recognizing road hierarchy; and (c) by limiting speed of AVs to 20 kilometers per hour to improve safety and livability…Pedestrian and cycling based infrastructure [should] be given similar or equal investment in comparison to autonomous vehicle infrastructure and street re-design.

In this context, Appleyard and Riggs argue that larger lanes may be reduced and the space left over from the narrower lanes (indicated in blue in Figure 5.1) should be apportioned back to bike lanes, pedestrian malls and sidewalks, play areas, and even housing through right-of-way recapture programs. They suggest that this could be a value proposition for cities and for residents because streets could transition to other uses, such as housing, on the recaptured right-of-way. On larger rights-of-way there could even be opportunities for creative small-unit multifamily dwellings (indicated in orange in Figure 5.1). Given the opportunities this creates, cities might consider deeding back this real estate to private owners to increase municipal property tax revenue on an annual basis.

While this warrants more dialogue among the planning and research community, it clearly underscores the opportunity that AVs offer in terms of reusing and repurposing rights-of-way, which can serve to benefit mobility and public health at the same time through increasing walking and biking and mitigating the potential negative impacts of AVs. Planning organizations should look to the following policies when rethinking the design and engineering of roadways.

- **Adopt bicycle- and pedestrian-friendly roadway design standards.** Local planners should build upon complete streets best practices. They should consider design for bicyclists and pedestrians from the beginning of any AV system-related planning initiatives and infrastructure designs and avoid impairing the pedestrian experience.
- **Transition additional roadway capacity to bicycles, pedestrians, transit, or shared vehicles.** Rights-of-way should be reused in ways consistent with modal priorities—most notably to support modes that are environmentally friendly and promote public health. Excess rights-of-way should be used for facilities such as dedicated bike or transit lanes and expanded, more attractive sidewalks, as opposed to increasing auto mobility. This is consistent with the June 2016 National Association of City Transportation Officials policy statement, in which the first priority of planning for AVs is that they "promote safety for pedestrians, bicyclists, transit riders, automated vehicle passengers, and all street users within the multimodal urban context" (NACTO 2016).
- **Rethink smart road and intelligent transportation systems roadway infrastructure and invest in basic roadway infrastructure.** Within the automotive industry there has been much debate over the necessity of "smart" infrastructure, given the costs. Literature indicates that fully autonomous vehicles will eventually be capable of handling all urban and rural driving conditions without surrounding roadway infrastructure. Given this, it might be wise to pause all but the most basic technology infrastructure investments—particularly vehicle-to-everything (both infrastructure and vehicles) communication platforms. This technology may play an important role in the future, but it is still evolving. To best optimize funds, planners should pursue consistent design standards for signage and lane markings across all roadways; federal, state, and local roads should not have different standards. Especially in the short term, it may be more cost-effective to pursue basic infrastructure investments. This could allow technology to advance using consistent infrastructure that driverless machine learning processes can detect (e.g., signage, lane markings, etc.). The more consistent policy and standards are across space, the easier it will be for AVs to achieve full functionality.
- **Explore creative and experimental right-of-way use.** Planners should explore new uses and the innovative ways streets can be used, thinking beyond the typical streetscape. There are many ways that a traditional street might change, and the existing size and character of street may dictate the opportunity this presents. For example, Schlossberg et al. (2018) show that a typical 80-feet-wide, four-lane arterial with two lanes of parking offers an opportunity to remove the parking, thin and reduce the lanes, and provide space for 40 or more feet for bikes, pedestrians, and transit. In the spirit of experimentation happening in places like Barcelona, where officials are shutting down every other street to auto traffic, cities may decide to eliminate roadways altogether and to use those spaces for parks, housing, or other needed uses. As shown in Figure 5.2 (p. 61), ultimately policies and plans should enable streets to be transformed to achieve community goals—for example, affordable housing and linear parks. Excess right-of-way provides a significant opportunity to green our communities and to creatively manage stormwater.

Balancing AV Needs with Bicycles and Pedestrians

Paralleling the importance of prioritizing roadways for active travel, one key challenge during the AV revolution will be balancing the needs of AVs with the needs of other travel modes. This balance is particularly important for bicycle and pedestrian travel in urban settings—trips that offer physical, mental, and emotional health benefits, as well as environmental benefits due to the use of human effort rather than fossil fuels or electric power. However, AVs may lead to a predominance of free-flow intersections and will require pick-up/drop-off areas at more locations, which make travel better for AV riders—but at a cost to bike and pedestrian travel.

If transportation and land-use planning agencies are proactive, AVs can be integrated into urban settings in ways that encourage rather than hinder travel by bicyclists and pedestrians. To do so requires attention to these non-AV travel modes from the beginning of any AV-related system planning initiatives and infrastructure redesigns. Assessing and then factoring in the needs of bicyclists and pedestrians at the outset promises greater efficiency in the transition and less expense in the long run.

In anticipation of the transformation of streetscapes, transportation planners and engineers need to adapt roadway design guidelines to factor in how AV technology will impact these systems. Building upon best practices in the complete streets literature offers a path forward, although these guidelines will need to evolve to take into account the different functionalities of AVs. As noted above, guidelines will also need to be developed for the frequency, design, and size of AV pick-up and drop-off areas to ensure that these elements do not fragment bicycle and pedestrian networks.

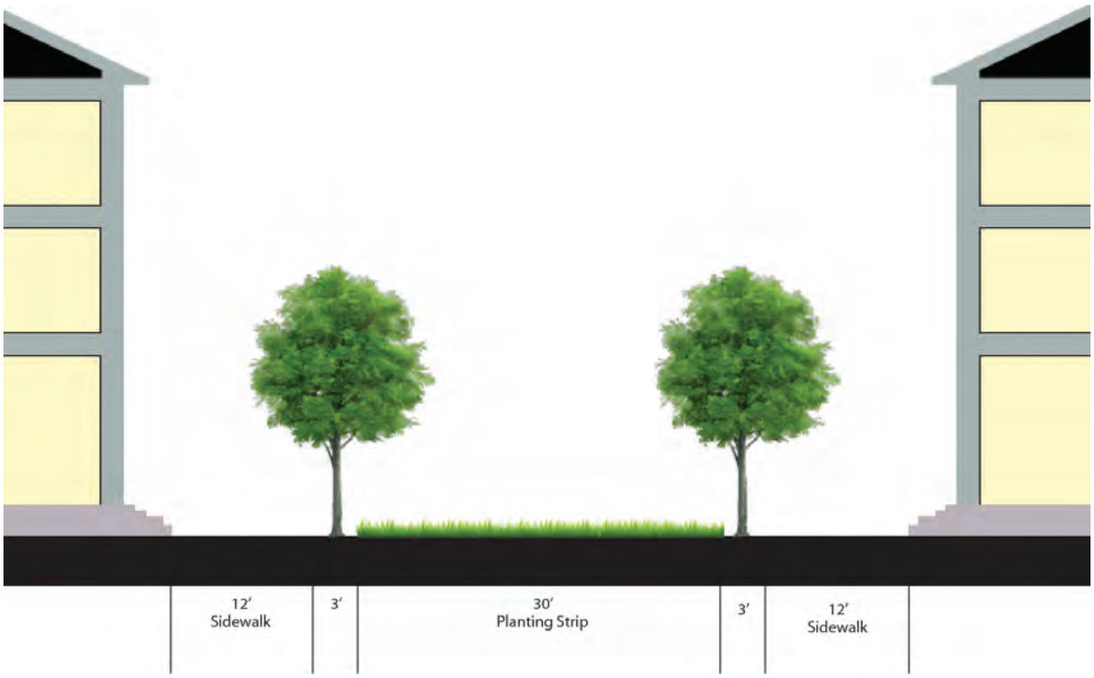


Figure 5.2. A post-AV street might become a linear park (Schlossberg et al. 2018)

Important system or infrastructure changes will be required to promote bicyclist and pedestrian mobility in an AV world. Solutions will be needed to allow for safe and regular crossing of free-flow intersections in busy urban settings. These solutions can take the form of regularized, dedicated bicycle and pedestrian crossing periods, priority signalization for pedestrians, or separated systems for crossing busy streets in the form of tunnels or bridges. The overriding issue is the need to ensure that bicyclist and pedestrian mobility is not compromised by the transition to an AV-only system.

The greatest promise for successfully accommodating AVs along with bicyclists and pedestrians in urban settings revolves around the extra available space within the right-of-way that will follow from the narrower vehicle lane widths. This surplus pavement holds opportunities for dedicated bike lanes and expanded, more active sidewalks, spaces that are no longer as cluttered with signage and signalization aimed at vehicular traffic. Given that these surplus spaces should be systemwide, there will likely be opportunities for transforming existing roadways into dedicated bike boulevards, as found in many European cities.

In this way, AVs present an opportunity to rethink streets, and particularly to support bicycle and pedestrian travel. While there are design opportunities, there are also potential concerns with regard to how AV technology detects and interacts with these modes. While Google claims that its AVs will be able to detect and share the road safely with bicyclists (Rosen 2016), and there have been experiments at test sites around the country to resolve some of these challenges (Messner 2017; Marshall 2017), there is still much work to be done in advancing the technology.

In light of that, planning academics Riggs and Boswell (2016c) have called for standards to advance certain levels of safety, particularly for cyclists. These call for a baseline service standard to guide technological development and the related policy decisions that regulate the relationship between bicycles and AVs. As a starting point, these principles provide a series of expectations to guide both policy and technology development between active transportation modes and AVs (see sidebar on p. 62). Local governments can support this approach by adopting the following planning policies to support bicycle and pedestrian travel.

- **Embrace recommended practices in bicycle and pedestrian planning.** Cities should establish recommended practices in planning and design for bicycles and pedestrians. This includes integrating multimodal LOS analysis in infrastructure design and planning, adopting "vision-zero" plans and policies that aim to eliminate traffic fatalities, and supporting NACTO guidelines that provide

BICYCLING MANIFESTO FOR AN AV FUTURE

Since bicyclists will share the road with AVs, they have the greatest chance of conflict. Riggs and Boswell (2016c) developed 13 principles as a manifesto for cyclists in an AV world. These are intended to provide a "starting point for dialogue" to promote the safety of cyclists sharing the road with AVs.

1. AVs should be able to detect bicyclists and detect and understand all bicycle signage and lane markings.
2. AVs should be able to detect and understand bicyclists' hand signals.
3. AVs should cede the right-of-way to bicyclists.
4. AVs should have an ability to signal (visual and audible) their detection of bicyclists and pedestrians and basic intent.
5. AVs should follow bicyclists at a safe distance when unable to pass.
6. AVs should exceed the three-foot minimum passing rule, especially as speed increases.
7. AVs should leave an ample margin of safety when making decisions about turning, passing, ceding right-of-way, and other decision-making scenarios involving bicyclists.
8. AVs should be able to detect approaching bicyclists and prevent "dooring" (instances when cyclists are struck by the doors of parked cars along a roadway as passengers exit).
9. AVs should be designed (size, shape, weight, materials) to minimize injury to bicyclists should an impact occur.
10. AVs should travel at speeds appropriate for urban conditions to facilitate safe travel for nonautomotive users (for example, not more than 20 miles per hour on downtown and neighborhood streets, 40 miles per hour on arterial connectors, etc.).
11. AVs should minimize travel on streets designated as bicycle boulevards or that have high bicycle usage but no facilities.
12. Companies deploying shared AVs should ensure adequate supply of vehicles equipped with bicycle racks or carriers to meet demand.
13. AV companies should record and share all collision data with local, state, and national law enforcement and regulatory agencies.

high LOS to nonautomotive users. Further, cities should consider adopting more aggressive policy-based service standards for cyclists and pedestrians consistent with the expectations set by Riggs and Boswell.

- **Advance design in transportation engineering.** While engineered solutions often fit within a finely described box of what is acceptable under the terms of state and federal manuals, namely the U.S. Federal Highway Administration's *Manual on Uniform Traffic Control Devices*, this can be an impediment to innovation at the local level. Planners should encourage and educate local engineers on recommended practices, and should help them experiment with new interventions to provide innovative yet affordable ways to enable pedestrians and cyclists to engage with and cross through AV traffic and intersections.
- **Continue to invest in and develop transportation demand management (TDM) and other travel behavior programs.** Many scenarios on the future of transportation predict changes in consumer and housing preferences; and while those are shaped by individual behaviors, they are also shaped by the policy and programmatic environment. Planners should continue to design programs to support activity and health-centric behaviors, including walking, bicycling, and social interactions. Existing outreach and TDM programs should be enhanced so that they continue to offer balanced transportation choices that clearly articulate the benefits of walking and cycling to enhance and sustain active transportation (Aitken et al. 2016), but also contribute to other factors that have been found to frame travel choices—including socialization and understanding of environmental impacts (Jariyasunant et al. 2015; Riggs 2017). New programs might include walking and bicycling lunch programs, promotion of after-dinner strolls at restaurants, or ride sharing, particularly for people who have yet to establish work trip habits.

Addressing Impacts on Public Transit and Other Roadway Uses

Along with ensuring that the needs of bicyclists and pedestrians are addressed when transitioning to an AV future, planners must also consider the potential impacts of AV on public transit and other uses of the roadway system, including freight.

Integrating AVs into Transit Systems

Autonomous and shared technology has the potential to dramatically influence the way we think about transit. It is vital to make sure the provision of quality transit service does not become a low priority in an AV world to ensure that the mobility needs of transit-dependent populations are being met. If AV technology increases the cost of owning and operating a personal vehicle, it will be especially important to provide adequate public transit service to accommodate the travel needs of those who may not be able to afford an AV. Integrating AV technology into public transit service may be the best way to ensure AVs do not exacerbate transportation equity issues.

As discussed in Chapter 3, AV technology will provide transit agencies with significant opportunities to improve transit service by improving safety and reducing operating costs. To begin capitalizing on the benefits that AVs could provide, transit planners must pilot transit applications of AV technology. Numerous jurisdictions, such as Las Vegas, are piloting or implementing fully autonomous transit routes on public roads across the country.

Universities are also leading the way in autonomous transit adoption, as the University of Santa Clara began testing an autonomous shuttle in November 2016. Other universities, including the University of Michigan, the University of Florida, and the University of Cincinnati, are preparing to introduce autonomous shuttle service in 2018. The lessons learned from these early adopters should pave the way for other jurisdictions to implement autonomous transit service.

In the early stages of AV adoption, retrofitting existing Bus Rapid Transit (BRT) routes with autonomous buses presents an outstanding opportunity to incorporate AV technology into the transit system. This is especially true of BRT routes with dedicated infrastructure that would enable the vehicle to operate on a dedicated lane without the need to acquire more right-of-way or to reduce the number of vehicle lanes. Providing AVs with dedicated infrastructure reduces the number of variables the autonomous technology must account for and prevents the vehicle from needing to execute more difficult driving maneuvers, such as changing lanes in heavy traffic. Dedicated infrastructure would also serve to ease public concerns over the safety of driving with AVs.

Another way dedicated bus lanes can support autonomous vehicle navigation is by having consistent and informative lane markings that will help guide the bus. Magnetic markers could help the vehicle navigate in weather conditions that make Lidar less accurate. In fact, researchers have already designed and deployed an automated steering control system made up of magnetic markers on an EmX BRT Line in Eugene, Oregon (Huang and Tan 2016). This control system consists of magnetic markers under the roadway every meter or so to provide information to the bus for lane-keeping assistance and precision docking that allows the bus to pull

TABLE 5.3. AV CANDIDATE PERFORMANCE MEASURES AND FRAMEWORKS

TRANSPORT PERFORMANCE MEASURES
Transport Effectiveness
• Percent population served • Revenue passengers per service area population • Total passengers per vehicle • Revenue passengers per revenue vehicle mile • Revenue passengers per revenue vehicle hour
Street Level Multimodal/Livability Effectiveness
• Percent vehicle sharing • Speeds • Vehicle size • Percent nonautomotive • Miles of roads over 25 MPH • Intersection density
Transport Efficiency
• Revenue vehicle miles per vehicle • Total vehicle miles per vehicle • Revenue vehicle hours per vehicle • Operating expense per seat mile • Operating expense per revenue vehicle • Mile operating expense per total vehicle mile • Operating expense per revenue vehicle hour • Energy consumption per revenue vehicle mile • Energy consumption per total vehicle mile • Energy consumption per revenue vehicle hour • Operating expense per total passengers • Operating expense per revenue passenger • Operating expense per passenger mile
LAND-USE PERFORMANCE MEASURES
Land-Use Accessibility Effectiveness
• Jobs / housing balance • Land-use mix (entropy) • Number mixed use developments / housing units • Human scale / intersection density
Land-Use Efficiency
• Sprawl indices • Regional land consumption • Greenbelt acres
DEHUMANIZATION INDICATORS
• Large automated vehicles • Fast automated vehicles • Pedestrian and bicycle intimidation • Perception of safety for biking and walking • Sociocognitive and physiological health • Superhuman-scale streets, blocks, development

Source: Appleyard and Riggs 2017

right up to the edge of the curb at each station. On rainy or snowy days, the bus is still able to navigate seamlessly because of the magnetic markers helping to guide it with location information. Similar systems with increasingly higher levels of automation are likely to soon follow. Mercedes-Benz has programmed its new Future Bus (an autonomous bus) to operate in bus-only lanes to make the design easier to develop and implement (Thompson 2017). It could also provide an excellent opportunity to pilot CV signal prioritization technology.

In short, retrofitting BRT lanes with AV technology provides an excellent opportunity to test autonomous buses in real-world environments to determine whether they can provide the promised cost savings in a way that is safer, more feasible, and more publicly acceptable than simply replacing buses on traditional bus routes. Yet retrofitting BRT routes is just one example of the types of autonomous pilot programs that could help to jumpstart the transition to autonomous transit. The lessons learned from these early tests will be vital to promote the use of AV technology.

For many years public transit has struggled with financial pressures as well as service, ridership, and reliability issues. A second transit-related change will be the ability to customize transit vehicles and vehicle types to fill different roles than in the past. This can be used to eliminate some of the challenges of proximity, specifically the first- and last-mile issues that relate to the initial and final portions of a transit-based trip between home or work and a destination (Scott 2017). New forms of transit will require thinking about investments and innovations in current systems.

Autonomous last-mile solutions are sometimes referred to as micro-transit, but as Larco has suggested (2017), these new forms of transit raise challenges in terms of service and integration. While the rise of shared AVs is often discussed as creating a future that eliminates the need for fixed-route transit, he argues that:

> Both Lyft and Uber have recently made moves to make their ride services more efficient by having riders walk to higher volume streets. Lyft has introduced "Pickup Suggestions" and Uber has their "walk to the corner system"—incentivizing people to walk to the nearest avenue or arterial instead of being picked up on a more minor street. This reduces travel time which allows more people to be picked up (without becoming frustrated as they wait).
>
> From a city development perspective, this points to the continued importance of higher volume streets as

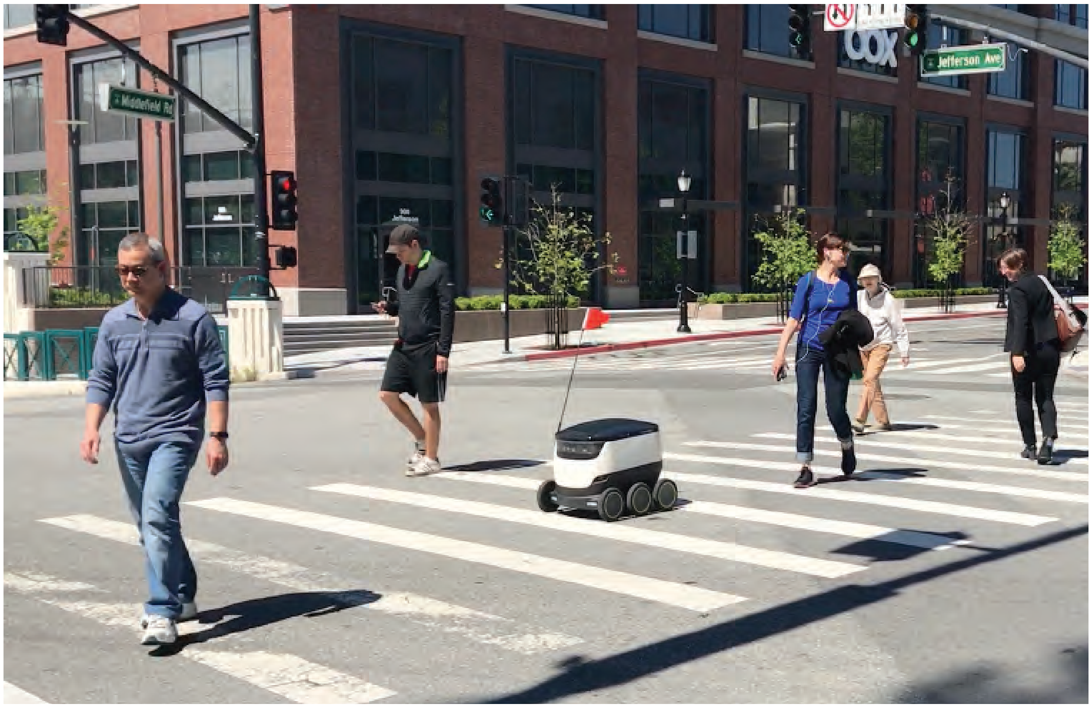


Figure 5.3. Local delivery robot pilot in Redwood City, California (William Riggs)

transit hubs (even if it is not traditional transit) and begs the question of how to make pickups and drop-offs most efficient along these high-volume routes (a designated spot on each block?). There are obvious benefits to having some kind of hierarchy in micro-transit—how should we design streets that can accommodate this?

While we have discussed the design implications for streets in a previous section, the notion of how we assign transit access to these corridors is an important one—and one that will need focus as our systems become reinvented. Planners will need to focus on reinventing roadway access through seamless fare and payment integration. They will also need to consider performance standards, an area that has been explored by Appleyard and Riggs (2017).

In considering AV performance measures, Appleyard and Riggs have suggested building on the work of Fielding to develop candidate measures and metrics of performance (Fielding, Glauthier, and Lave 1978; Fielding, Babitsky, and Brenner 1985). They provide a conceptual framework and list of candidate performance measures that could be useful in helping to evaluate the livability, efficiency, and functionality of a transportation system that includes AVs (Table 5.3, p. 64).

Integrating Automation into Freight and Delivery Service

Along with transit operations, the movement of goods is an important consideration for cities. Freight is expected to be one of the first sectors to adopt AVs. Automated technology has been an important part of the freight industry for decades. Robots transport containers from ships to railcars, automated freight trains transport goods across the country, and highly automated distribution centers have significantly improved the efficiency of freight logistics. The rise of AVs will simply extend freight automation to semi-trucks and delivery vehicles.

The primary reason the trucking industry is excited about autonomous technology is the cost savings the technology will provide. In addition to potentially reducing labor costs, AV technology could reduce fuel cost by more than 10 percent through the aerodynamic improvements of platooning (ITF 2017). Since trucking fleets turn over twice as quickly as consumer vehicles, autonomous trucks likely will penetrate the market significantly faster than consumer cars once they become available.

While the automation of freight and delivery services may have narrower impacts on urban form and on the built environment, it is vital to carefully consider the ramifications autonomous technology will have upon freight. Specifically, this technology will have notable implications for traffic operations, traffic safety, travel behavior and demand, and the infrastructure necessary to support freight. Planning for autonomous freight will also involve special considerations as its development will extend beyond the automobile to unmanned aerial vehicles or drones.

One of the biggest implications of autonomous trucking for transportation planning is the need to address platooning. Although connecting "trains" of autonomous trucks may provide significant efficiency benefits, during the transition period when AVs and human-driven vehicles must share the road, platooning could create safety problems for human-driven vehicles trying to navigate around truck platoons. One option to address this issue would be to dedicate lanes for freight usage, but this likely would require significant infrastructure investments. A more cost-effective option may be to restrict the length of platoons to two to four trucks. This would enable the efficiency benefits of platooning while also ensuring proper safety standards.

Consistent with trends in the consolidation of parking at the city periphery, there will likely need to be a transition for land at the periphery of cities to adjust to new distribution- and logistics-oriented uses. Facilities that move goods from long-distance trucks to local delivery vehicles will likely also be consolidated at the edges of urban areas. Planners and policy makers should consider flexible zoning overlays alongside greenbelt protections in these areas to facilitate this use, while limiting potential environmental impacts.

At the local level, freight should be integrated and seamless and allowed to evolve innovatively. Autonomous delivery systems are already being tested across the world (Edelstein 2018; Marakby 2018; Nagata 2018). In the U.S., Amazon and Google have begun parcel delivery and 7-Eleven has been piloting delivering Slurpees via drones (Hidalgo 2017). Non-automotive logistics (e-bike, cargo bike, or handheld parcel delivery) could reduce traffic from multiple sources ranging from cars to drones to delivery robots at the neighborhood level (Figure 5.3, p. 65), thereby promoting the livability of the local communities.

Expanding on this idea, planners will need to explore how new and emerging forms of freight impact users at the local level. Scenarios are already being painted of a world in which there is constant movement of autonomous vehicles, but it will be important to ensure this does not have adverse effects on neighborhoods or quality of life. Partnership and experimentation with shared autonomous technology companies will be important for achieving the benefits of this technology while mitigating concerns related to it.

Addressing Impacts on Social Equity

As was discussed in Chapter 3, the social equity implications of AVs are highly significant and echoed throughout this document. While this issue touches on many of the items already discussed with regard to land-use considerations and transit access, it is important for planners to encourage and lead dialogue around the development of more specific policy—particularly in the areas of accessibility and jobs.

In the final chapter of his book, *Disruptive Transport* (forthcoming), William Riggs discusses the magnitude of these potential issues:

> …what happens when transit and shared rides become owned by a private company. Should that company have the right to deny you access to their platform? Should they have a right to deny cities data about the vehicles they are running on city roads? Should they have a right to leave a city, or a portion of a city without notice? This could yield a trouble reality of data-driven transportation, meaning that certain parts of the city, perhaps those that are less dense, less safe or less profitable, become less served by future mobility. Lyft CEO John Zimmer recently pledged transportation equity and to provide service to low-income communities as they roll out scooters (Zimmer and Green 2018). Yet, absent policy, what is the long-term certainty of such a commitment. There may always the temptation to capitalize on or profit from (as opposed to serve) populations that are under-represented and have limited transportation access.

Ensuring that the benefits of AVs and disruptive transportation are accessible is just one challenge, and he goes on to discuss another issue of equal importance: jobs.

> With replacement of professional human drivers there is a need to address how these jobs will be replaced in a fair and equitable manner. Job loss and replacement will not be limited to ridesharing jobs but result in far reaching impacts that affect everyone from traditional taxi drivers, mail carriers, and freight and cargo drivers, to name a few.

Estimates vary about the ultimate impact of these two issues, access and jobs, but the research is clear: They will likely have a disproportionate impact on vulnerable and at-risk populations that have historically been ignored as a part of planning and land-use processes. There are actions that cities can take now to buffer potential negative impacts of new transportation innovations. These include potential policies for local governments outlined below—again, this list is not intended as a prescriptive roadmap but an agenda for dialogue and customization in every community.

- **Maintain robust transit service and explore becoming an AV provider.** With rising budgets and new mobility options, the temptation for cities can be to reduce public service in favor of mobility-on-demand or paid-service/for-profit options. Cities should set clear priorities in comprehensive and general planning documents to provide transit access, particularly in locations with less density where cheaper, private-sector service may not be available. They should also conduct feasibility analyses and explore the viability of becoming autonomous transit providers. There are many emerging autonomous shuttle providers that can function well in dense, urban, and even mixed traffic scenarios (Figure 5.4). These may be able to better serve at-risk populations at lower cost than existing transit platforms.
- **Establish access standards for TNCs and fleets.** Policy makers could set up policies to maintain equitable access to public spaces and infrastructure and to enforce adequate privacy standards. This should include shared mobility policies relating to social equity, particularly with regard to pricing and infrastructure burdens. Acceptable policies should be linked to transportation demand management efforts and not create regressive effects that inhibit mobility for low-income residents or certain geographically concentrated areas. Fleet service companies should be able to demonstrate standards that ensure AV access, perhaps by sharing scrubbed data showing access throughout a city. This is particularly important for shared AVs.
- **Protect vulnerable roadway users.** Underscoring the call to protect cyclists and pedestrians in the prior policy proposals, cities have a social equity impetus to adopt vision-zero plans and adopt vision-zero guidelines to protect users who may have no auto access.

TRANSITIONING TO AN AV-DOMINATED SYSTEM

Many of the major changes to the built environment and the benefits AV technology could provide will not be viable until most or all of the vehicle fleet is made up of AVs. Roadways and parking spaces shared by autonomous and human-driven vehicles will still need to be designed to safely accommodate the latter. For example, narrower pavement widths will not be possible until virtually 100 percent of the vehicle fleet is autonomous, because human-driven vehicles may not be able to safely navigate narrower streets. However, the transi-

Figure 5.4. Cities might partner with autonomous shuttle providers to maintain efficient service in certain locations (May Mobility)

tion period in which human-driven and autonomous vehicles will share the road is not expected to be short. As discussed in Chapter 2, it typically takes about 15 years to replace the majority of a vehicle fleet (Kuhr et al. 2017). While the novelty of AVs may help to speed this process, the higher price tag of autonomous technology may prolong the transition.

Consequently, before planners will be able to pursue many of the important opportunities described in this report, careful consideration will need to be given to facilitating a smooth transition to an AV fleet. One option would be to simply wait until AVs are the predominant mode of transportation before implementing the policy changes and infrastructure investments outlined in the previous sections. However, passively awaiting full adoption would repeat the same mistake planners made during the rise of the automobile by allowing the technology, rather than good planning principles, to shape development patterns.

Proactive planning will be required throughout the transition to ensure that AV technology is used to create urban spaces that are safer and more efficient than ever before. In addition, proactively planning for AVs during the transition could enable communities to enjoy some of the safety and efficiency benefits the technology promises to provide during the transition instead of waiting for full adoption.

Rights-of-Way in Transition

A prime example of these benefits can be seen in how roads and rights-of-way could undergo iterative transformation processes to capitalize on the efficiency of AVs without compromising the safety of human-driven vehicles.

The top image in Figure 5.5 (p. 69) shows a simple representation of a typical right-of-way today. With four 11- to 12-foot lanes, some on-street parking, a median, no bike lanes, and a relatively narrow five-foot sidewalk, this auto-oriented road is primarily designed to move traffic as quickly as possible. As discussed in Chapter 3, AVs' ability to travel close together could increase throughput and traffic flow. However, during the transition from human-driven vehicles to AVs, platooning AVs could distress or endanger human drivers unless separated from human-driven traffic.

With these considerations, capitalizing on AVs' efficiency benefits without compromising the safety of human-driven vehicles during the transition will likely require separate infrastructure for autonomous and human-driven vehicles. The second image in Figure 5.5 provides an example of a roadway with dedicated AV lanes. The inside AV lanes are several feet narrower than traditional driving lanes. The median has also been removed because AVs are not in danger of falling asleep or drifting into oncoming traffic. The on-street parking has also been removed from one side of the street to accommodate the gradual decline in the demand for parking. All of these reductions create space to add a bike lane to both sides of the street.

As AVs grow in popularity and approach full adoption, more significant right-of-way changes may become possible. The third image in Figure 5.5 shows one example of a fully autonomous right-of-way. Assuming all vehicles are autonomous, lane widths for all four lanes can be reduced to eight feet, drop-off lanes can replace on-street parking on both sides of the street, and all of the additional space can be transformed into a protected bike lane and wider sidewalks. With the same total right-of-way, AVs can transform the streetscape, making room for bicycle and pedestrian facilities without causing more congestion. As discussed in Chapter 4, full automation could open the door to more intensive streetscape improvements, such as road diets. The fourth image provides an example of this.

Providing dedicated lanes for AVs would allow for two lanes that are smaller and more efficient than traditional vehicle lanes. This could improve congestion and provide more space for bicycle and pedestrian facilities years before AVs reach full adoption. In this way, the second image in Figure 5.5 provides an example of the types of roads that could be constructed during the transition to an AV-dominated system. Making these infrastructure improvements while AVs are being adopted would be vital for enabling a faster and smoother transition to fully autonomous roadways. In Figure 5.5, apart from the protective barriers for the bike lanes, the only changes that would be required to move from the 50 percent AV right-of-way to the 100 percent AV right-of-way would be to restripe the lanes. This would prevent the need for massive infrastructure investments when AVs approach 100 percent adoption. Investing in dedicated AV infrastructure throughout the transition period would help to spread out the investments necessary to capitalize on the benefits AVs could provide.

Consequently, an important consideration during the early stages of AV adoption will be identifying and prioritizing roadways where dedicated AV lanes could be implemented. State and federal highways may present easier opportunities for dedicated lanes initially because they have simpler traffic patterns, fewer intersections, and fewer points of ingress and egress than local roadways. However, over time many local roads could likely benefit from AV-only lanes. Although dedicated AV lanes present the need for system prioritization, future transportation systems may also ben-

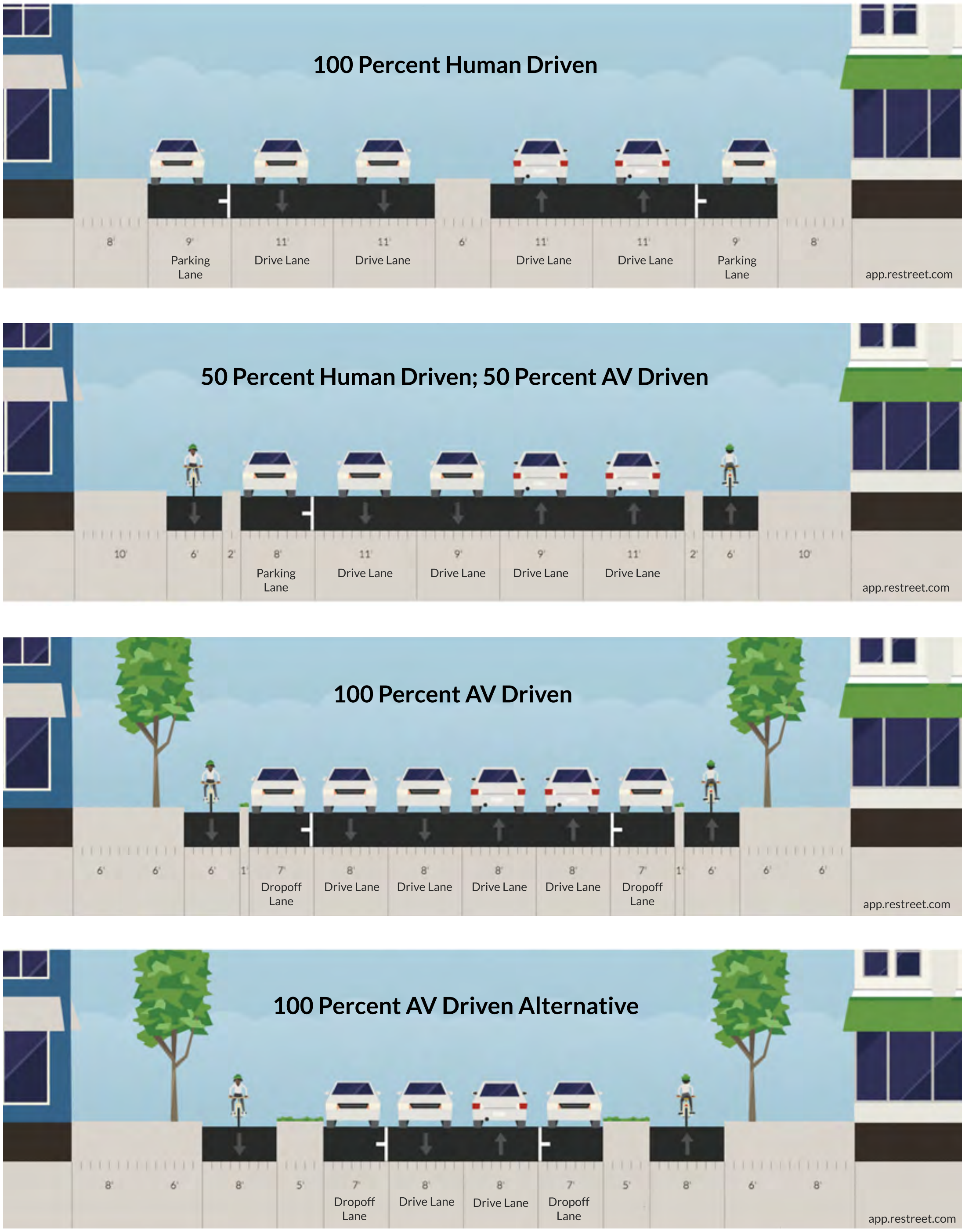


Figure 5.5. Potential streetscape transformations as AVs are adopted (app.restreet.com)

efit from similar prioritization systems for the transition of intersections, parking structures, and virtual infrastructure.

Transitioning to AV Parking

As seen in Figures 4.3–4.5 in Chapter 4 (pp. 48–49), while right-of-way changes enabled by the transition to AV use are taking place, new opportunities for infill development are expected to arise as parking is able to be redeveloped into higher and better uses. This will provide opportunities to catalyze vibrant urban spaces that are compact and walkable.

During the transition to AVs, as discussed in Chapter 3, planners should support on-site facilities designed for human-driven vehicles as well as off-site parking facilities to capitalize on AVs' smaller parking footprints. Over time, the area devoted to on-site facilities would gradually shrink as the numbers of human-driven vehicles decline. Off-site AV parking facilities would be developed to take their place. Gradually transitioning to off-site parking would open the door to more efficient land-use patterns.

A reduction in the demand for parking would also offer opportunities to begin replacing on-street parking with pick-up and drop-off areas. As discussed earlier in this chapter, local planners may want to establish guidelines for the placement of these initial drop-off areas. Land-use codes could provide developers with the option of providing either a certain number of parking spots or a pick-up/drop-off area, or require them to replace a certain number of parking spots with a pick-up/drop-off area.

ADDRESSING AV IN COMMUNITY PLANNING PROCESSES

Beyond understanding the potential impacts of AVs on the built environment and the challenges and opportunities this technology will bring to communities, planners will also need to consider how the methods of planning practice might need to change to address AV technology. This report focuses on the built environment implications of and policy considerations for AVs, but planners should also be thinking about how to integrate this new technology not just into modeling but into planning processes and community engagement.

Two strategies, visioning and alternatives generation, will be especially important in addressing AVs within community planning processes. These strategies offer the opportunity for citizens and policy makers to look at a range of future alternatives and choose the vision and policy outcomes that best suit their community goals.

Planners can use visioning to start a community conversation about AVs, educating the public about the potential impacts of AVs and the importance of preparing with proactive policy making. In Florida, a team from Florida State University engaged in award-winning visioning sessions about the future of AVs. They asked participants to envision how AVs would impact their communities and helped them develop a variety of design solutions to help achieve their vision of the future. For example, participants placed a strong emphasis on providing separate facilities for automated and human-driven vehicles during the transition to AVs. These findings helped to expand the AV planning discussion in the state of Florida to include considerations of this technology's implications for the built environment and community design (Chapin et al. 2016). The findings also helped to inform many of the built environment impacts discussed in Chapter 4 of this report. While these sessions primarily engaged planning practitioners for research purposes, similar visioning sessions could be conducted with local communities to identify how they would like to integrate AVs and other smart technologies into their communities. Planners and policy makers can then use this information to backcast with specific actions (both design and policy) that communities could take to achieve those visions.

Likewise, this same process of visioning can be intertwined with scenario planning and alternatives generation. Since AVs could have a wide range of impacts, visioning efforts often produce several different visions of the future. Scenario planning processes can help develop and plan for each of these visions. This could offer a more robust approach to preparing for AVs by providing the flexibility to prepare for and adapt to multiple visions of the future. For example, in the realm of transit, Milam and Riggs (2018) discussed looking at a range of options for planning and developing alternative scenarios based on the following principles: increasing frequency of service; extending operational hours; providing transit-only lanes; automating transit service; better matching or "right sizing" transit demand to type of service; and integrating equity into service performance. Scenarios can be modeled in different ways and then mapped to distinct policy outcomes. For example, this could include establishing vehicle requirements (clean energy, shared use, etc.) implementing roadway fees, making changes in land use, or extending a greenbelt.

Given the uncertainty surrounding AVs, scenario planning processes that prepare for a range of options are better positioned to develop plans agile enough to adapt to changes in technology and travel behavior. In addition, focusing on incremental actions can help create plans capable of adapting to future risk and uncertainty. Policy actions can be mapped to actions that are triggered when certain thresholds or situations arise. While this type of nimble action may require constant revisiting through annual reporting and staff-level data analysis, it is essential as AVs shape our cities in ways we only partially understand at this point in time.

CONCLUSION

The planning policy response to AV technology should be comprehensive in scope, addressing a range of issues including streetscape design standards, parking requirements, bicycle and pedestrian facilities, curbside management, traffic and intersection operations, and local and regional growth management strategies. Yet policy efforts will need to be targeted to strategically address key concerns at the right time in order to capitalize on opportunities within a rapidly evolving field. Planners cannot wait for full AV adoption to begin preparing for the technology's effects. Proactive planning policy will be necessary to avoid making the same mistakes made during the rise of the automobile.

However, given the uncertainty surrounding the development, adoption, and usage of AVs, planners must also embrace an approach of continuous learning. The technology is evolving so rapidly that today's best practices may not be relevant in five to ten years. Planners need to stay abreast of technological innovation, federal and state regulation, and the implications of early adopter successes and failures to inform long-range planning efforts.

Planning processes may also need to be refined to better account for the uncertainty surrounding the future in an AV world. Proper community planning responses to AVs will be in part dependent on the technology's deployment timeline and predominant ownership model (private versus shared). Planning efforts may need to consider a range of possible futures to account for this uncertainty. Consequently, scenario planning and visioning need to become regular parts of long-range planning efforts to address the range of possible futures.

In addition to addressing this uncertainty, planning policy for AVs will need to be nimble and flexible to adapt to the technology's rapidly evolving capabilities. Planning interventions should be phased in over the long transition period from human-driven to autonomous vehicles and should be adjustable in order to react to new developments in technology and behavior. For example, parking requirements need to be readjusted over time to account for declines in automobile ownership. Regional growth management and land-use plans need to be regularly reevaluated to stay ahead of the ways AVs influence travel behavior and exurbanization trends. Consistently updating comprehensive plans and other long-range planning documents every few years is vital to ensuring that plans adjust to the disruptive nature of AVs (Henaghan et al. 2018).

Balancing the need to be nimble with the need to be proactive will be especially challenging in the area of infrastructure investments, as their lifespans are long and it is not cheap or easy to retrofit roads or bridges. However, as seen in the example of utilizing dedicated AV lanes to gradually transition to AV roadways while human-driven vehicles are still on the road, planners may need to adopt a paradigm of gradual, iterative infrastructure investments to remain nimble enough to adjust to changes in the technology and how it is used.

In spite of, or better yet, because of the radical changes that AVs are expected to bring, it is vital that planners promote sound planning principles and placemaking practices that ensure access for all, including the most vulnerable groups. The desire to create attractive, vibrant places where people want to live, work, and play has not changed. The planning profession has long struggled to balance the demands of growing the economy, protecting the environment, and supporting equity for all, and these challenges will not abate with the coming of the AV age. While technology can improve our lives, there is no guarantee that it will improve the lives of all people.

This chapter has attempted to present some of the ways planning practice will need to evolve and adapt as AVs become an integral part of the transportation system, but the overarching goals and many of the best practices in planning practice and urban design will not change. Consequently, promoting the use of AV technology at the expense of other planning goals would be counterproductive. It is vital that planners do not allow the novelty of AV technology to distract them from striving to create livable, sustainable, and affordable communities. Instead, planners need to find innovative ways of utilizing AV technology in pursuit of these established planning goals. This report hopes to provide a starting place for these efforts.

CHAPTER 6

CONCLUSION: THE TRANSFORMATIVE IMPACTS OF AVS

Autonomous vehicle technology promises to reshape the transportation system and the built environment in ways not seen since the introduction of Henry Ford's Model T more than a century ago. By revolutionizing the nature of personal mobility and removing the need for passengers to be in the car at all times, AVs have the potential to dramatically impact roadway design and the built environment to yield urban spaces that are safer, more efficient, and more attractive.

There is compelling evidence that AVs will allow for smaller and more efficient rights-of-way, increase the speed and throughput of roadways, and open up spaces for bicycle and pedestrian facilities, green spaces, and other urban amenities. The ability of AVs to wirelessly obtain information on destinations, traffic patterns, and intersections promises to declutter urban environments by removing traffic signs and signals. Drop-off and pick-up areas are expected to replace parking lots as the predominant locations for passenger entry and exit. As the majority of parking is relocated into consolidated parking facilities away from urban centers, large amounts of previously underutilized space will be made available for redevelopment opportunities.

Much like the Model T of the early 1900s, AVs will usher in massive changes in the way people travel, the form and function of our transportation systems, and the look and feel of the environments in which we live, work, and play. However, unlike the American experience with the Model T, it is hoped that this time policy makers will recognize and take advantage of this opportunity to reshape our urban areas in ways that promote safe, sustainable, and people-centered environments. AV technology offers an opportunity to balance what have long been seen as conflicting goals of safer and more efficient transportation systems on the one hand and urban environments founded upon the principles of sustainability and human-centered design on the other.

The twin goals of efficiency and urbanity can be achieved only through proactive planning and investment by federal, state, regional, and local transportation agencies. As introduced in this report, agencies need to look to the following concepts to best capitalize on the opportunities afforded by AVs to create safe, efficient, and livable places:

- Promote community conversations that identify risks and benefits associated with AVs, set goals and priorities, and identify potential policy and funding levers to better meet goals and harness benefits.
- Work now to incorporate AV considerations into the design of streetscapes and road networks, including revisiting roadway design manuals and long-range transportation plans.
- Begin identifying ways to establish separated AV infrastructure, such as dedicated AV lanes, to ensure that the efficiencies of AVs can be capitalized on during the early stages of AV adoption.
- Convene design and development stakeholders to develop standards for the size and location of drop-off areas to accommodate the growing demand for drop-offs without backing up traffic.
- Investigate opportunities to use excess pavement and rights-of-way to promote complete streets through protected bicycle and pedestrian infrastructure, active streetscapes, and green spaces.
- Task researchers and engineers with developing innovative yet affordable ways to enable pedestrians to safely cross free-flowing AV intersections.
- Recognize and begin planning for changes in parking demand by identifying long-term opportunities for AV parking structures or large surface lots away from city centers, revising codes for parking requirements, and incorporating AV parking areas into comprehensive plans and other planning documents.

Clearly, further research is required to assess how best to integrate AVs into the transportation system and to understand how AVs will reshape the built environment. This report provides a first step toward envisioning the future in an AV world, a future that can yield attractive, people-friendly, efficient, and safe urban environments. To achieve that future, transportation and land-use planning agencies need to begin preparing for the AV revolution by focusing on not only the transportation impacts of the technology, but also the built environment impacts.

Few understood and foresaw the massive impact of the Model T upon travel behaviors, transportation systems, and the built environment. Autonomous vehicles will have a similar significance for our landscapes, and it is our hope that this remarkable opportunity is grasped and not squandered.

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